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Crack and Concrete Deck Sealant Performance

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The objective of this project is to define the current state-of-the-art regarding the use of bridge deck sealants and crack sealers to extend the life of reinforced concrete bridge decks. The report includes the information generated from a literature review and survey which focused on current and significant studies in the field of deck and crack sealing. The intent of the survey was to determine common practices for the use and application of these sealers in different States throughout the United States. Based on the information collected from the literature review and the survey, the best sealant materials and application practices are recommended for use in Minnesota and throughout the Midwest. The report consists of four sections including: (1) a synthesis of the literature review on the background, application, and performance of concrete deck sealants and crack sealers; (2) a summary of the survey conducted by Mn/DOT to determine the current selection criteria, materials, application practices, and findings from different states in United States; (3) an assessment of selection criteria, materials, application practices, and performance; and (4) conclusions, recommendations and areas in need of further research.

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Executive Summary

The objective of this research project was to define the current state-of-the-art regarding the use of bridge deck sealants and crack sealers to extend the life of reinforced concrete bridge decks. The role of deck sealants and crack sealers is to prevent chloride ion ingress, originating from deicing materials spread on the road, from penetrating into the concrete bridge deck and corroding the steel reinforcing bars. The prevention of corrosion in reinforcing bars is important because corrosion generates expansion and produces local tensile forces in the concrete deck. Due to the weakness of concrete to carry tensile forces, the deck will spall and eventually deteriorate.

The report includes the information generated from a literature review and survey on current and significant studies in the field of deck and crack sealing. The intent of the survey is to determine common practices for the use and application of these sealers in different states throughout the United States. After all of the information is collected and compiled from the literature review and the survey, the best materials and practices are recommended for use in Minnesota and throughout the Midwest.

The first option for slowing chloride ingress is to coat the entire deck with a penetrating or barrier sealer. Many of the issues regarding this practice are considered. The report discusses how solids content for a penetrating sealer affects penetration depth and effectiveness. A discussion is included regarding the potential negative effects to steel reinforcement when chloride ions are already present in the deck prior to sealant application. Information on the effectiveness of recoating a bridge with penetrating sealer is also discussed, as well as the number of coats before reapplication becomes ineffective.

Because chloride ions can penetrate the cracks much faster than solid concrete, cracks pose a more immediate danger to the reinforcement. By preventing this fast ingress of chloride ions, potential years can be added to the life of a deck. Important issues such as the amount of time a sealed crack can prevent chloride ingress are discussed. Expansion and contraction of cracks due to traffic loading and thermal cycles will also vary the effectiveness of sealed cracks. Information is collected regarding whether new cracks can form near repaired cracks. The length of time crack sealing products must be allowed to cure before normal traffic is allowed to traverse the bridge deck is documented. Finally questions regarding the past performance of crack sealants are also answered.

The report consists of five chapters. Chapters 1 and 2 provide a synthesis of the literature review on the background, application, and performance of concrete deck sealants and crack sealers, respectively. Chapter 3 presents a summary of the survey conducted by Mn/DOT. The survey, as previously mentioned, is used to determine the current selection criteria, materials, application practices, and findings from different states in the United States. Chapter 4 discusses the results of several chloride studies conducted in Minnesota. Chapter 5 combines the information gathered Chapters 1 through 4 to create an assessment of all selection criteria, materials, application practices, and performance. Finally, Chapter 6 draws some conclusions from the previous sections, develops recommendations, and identifies areas which could benefit from further research.

Chapter 1 addresses commonly used deck sealants. Sealants are typically classified into two categories (e.g., penetrating sealants and film formers). Penetrating sealants (e.g., silane, siloxane) are used to create a hydrophobic barrier on the concrete surface to repel water and chloride ions. Film formers (e.g., linseed oil, epoxy) are used to form an impenetrable barrier to block the water and chloride particles from penetrating into the concrete substrate. Four performance measures are used to evaluate the test results for concrete deck sealants obtained from the source literature, namely chloride ingress, absorption, depth of penetration, and vapor permeability. Variables that affect the performance of deck sealants include concrete parameters such as moisture content at time of application and water-cement ratio. Other concrete parameters such as finishing and curing, surface preparation, coverage rate, abrasion, and freeze-thaw exposure are also discussed in the report. The environmental conditions (e.g., temperature and wind speed) at the time of application can have a direct effect on sealant performance.

Chapter 2 addresses concrete crack sealers, the most common which are epoxy, high molecular weight methacrylate (HMWM), methacrylate, and polyurethane. HMWM sealers have a low viscosity and are typically applied using a flood coat. Epoxy sealers typically have a higher bond strength, higher viscosity, and are typically (but not exclusively) applied to individual cracks. The four performance measures used for evaluating crack sealing performance are depth of penetration, bond strength, seepage, and chloride ingress and corrosion. General trends such as lifespan of sealed cracks, presence of re-cracking, and track-free time for sealers are also discussed. Variables affecting performance such as effect of temperature, moisture, crack cleanliness, and crack age are also discussed.

Chapters 3 and 4 document a performance survey and a chloride study, respectively. Approximately 20 people throughout the Midwest and the United States participated in the survey. The survey focused on materials, application procedures, application timing, and material testing used. The chloride study investigated how the application of concrete deck sealants and crack sealers affected the chloride levels in the bridge deck. The effect that sealing had on deck inspections was also taken into consideration. Most of the information covered in the chloride study either reiterated the results determined from the literature review or was inconclusive.

The product assessment chapter (Chapter 5) compiles the information from the first four chapters. The deck sealant section of this chapter reiterates the superior performance of silane over either siloxane or linseed oil, and that solvent-based penetrating sealants perform better than their water-based counterparts. Moreover, water-based sealants were found to be inadequate for reapplication, and a high content of solids was determined to be beneficial for penetration depth and resistance to chloride ions. The most common product that fits this description is a solvent-based silane with a 40 percent solids concentration. The crack sealer portion of this chapter indicates that HMWM and epoxy sealers can both be effectively used. HMWM products are best suited for decks with extensive cracking due to the flood-coat application procedure, and they are beneficial for decks with fine cracks due to their very low viscosity. Epoxy sealers are more effective for decks with few cracks because they are typically applied to individual cracks, and epoxy is better suited for larger cracks because they have higher bond strengths.

Finally the last chapter of the report (Chapter 6) discusses conclusions and recommendations for material selection, application, and testing. The following conclusions and recommendations are pertinent to concrete bridge deck sealants:

- 90-day ponding (AASHTO T259) and absorption (ASTM C642) tests are commonly used acceptance tests.
- NCHRP 244 Series II testing is widely used to quantify performance.
- NCHRP 244 Series II requires 75 percent reduction in water absorption and chloride intrusion while maintaining 100 percent vapor transmission.
- Depth of penetration and chloride content tests are the most common QA/QC tests conducted on bridge decks, if any are used, but the results are highly variable.
- Silane products typically outperform Siloxane products.
- Water-based products are not suitable for reapplication.
- Solvent-based products typically outperform water-based products.
- High solids content is typically desirable.
- S40Si is the commonly produced sealant that best fits the criteria above.
- Sealants should be applied between temperatures of 40 and 100°F.
- A drying period of at least two days should be enforced if the deck is moist.

The conclusions and recommendations for the crack sealers are as follows:

- Many states do not conduct acceptance tests to identify acceptable crack sealing products, and products are typically chosen based on well-known research (e.g., Pincheira 2005).
- Depth of penetration and chloride content tests are the most common QA/QC tests conducted on bridge decks, if any are used, but the results are highly variable.
- HMWM products typically provide better penetration (suited for smaller cracks).
- Epoxy products typically provide higher bond strength.
- Although test results are variable, epoxy sealers tend to demonstrate good resistance to freeze-thaw effects.
- Crack sealers should be selected with:
    - viscosity less than 500 cP (or 25 cP for HMWM sealers),
    - tensile strength more than 8 MPa, and
    - tensile elongation larger than 10 percent.
- Crack sealers should be applied between temperatures of 45 and 90 °F.
- If possible, crack sealers should be applied between the 11:00 pm and 7:00 am.
- Some form of surface preparation should be used to clean the cracks.
- A drying period of two to three days should be enforced if the deck is moist.

Chapter 1 – Literature Review on Concrete Deck Sealants

1.1. Background on Deck Sealants

This chapter classifies the different types of deck sealants that are discussed. In addition to the sealant classifications the section will discuss the primary performance measures that are used to quantify results.

1.1.1 Classifications of Deck Sealants

This chapter introduces the two broad classifications of concrete deck sealants: penetrating sealers and film formers. The section also introduces four common performance measures for sealers: depth of penetration, absorption, vapor transmission, and chloride ingress, as well as the test procedures used to commonly quantify these respective measures of performance.

(a) Penetrating Sealants
Products commonly marketed as penetrating sealers include silicates, siliconates, silanes, and siloxanes. These four products are all silicon-based materials and can be further divided into two subcategories: hydrophobic sealers or “water-repellants” and pore blockers. Silanes, siloxanes, and siliconates fall within the hydrophobic category and impart water-repellency on the concrete substrate by virtue of lowering the substrate’s surface tension. Because the surface tension of the substrate is lower than that of water, the substrate repels the ingress of water. These hydrophobic sealers or “water-repellants” still allow water vapor transmission because water vapor does not have a surface tension. The silicate sealer, or pore blocker, retards water ingress much differently than hydrophobic sealers. Instead of penetrating the capillary structure of the substrate and lowering its surface tension relative to that of water (as in the case of silanes, siloxanes, and siliconates) silicates penetrate the capillary structure and fill the pores, thus blocking moisture and subsequent chloride ingress. However, vapor transmission also has a tendency to be inhibited by pore blockers, leading to possible durability issues for the concrete due to freeze-thaw exposure.

Numerous studies have evaluated the effectiveness of silanes and siloxanes to seal concrete. It is important to note that not all silanes and siloxanes exhibit the same performance. Silane and siloxane composition and function (McGettigan 1992) is addressed below to help the reader understand fundamental differences among individual silanes and siloxanes. Silanes and siloxanes contain a organofunctional group and silicon functional group; these organofunctional and silicon functional groups are known as alkyl and alkoxy groups respectively. The alkyl group (organic hydrocarbon group) of these two products lowers the surface tension of the concrete substrate below that of water, thus rendering the substrate hydrophobic (i.e., water repelling). The alkoxy group controls how the silane and siloxane bonds to the substrate.

Silanes and siloxanes can be either solvent or water-based, and the concentration (i.e., percent solids) of silane and siloxane by weight, respectively, can vary. Solvent-based implies the silane or siloxane is carried in either alcohol, mineral spirits, or petroleum-based solvents. Water-based implies the silane or siloxane is carried in water. 100% silane formulations exist and contain neither solvent nor water as the carrier because silane is liquid at ambient temperatures. Silanes and siloxanes both release VOCs (volatile organic compounds); VOCs are released both due to the solvent evaporating in solvent-based products and when the alkoxy groups hydrolyze in the substrate. Due to faster evaporation, silanes are much more reactive and, thus, more volatile than siloxanes with the same solids content and carrier. The higher volatility of silanes explains why application of silanes is not recommended in hot, windy conditions because the product can evaporate very quickly without adequately penetrating the concrete substrate. This inadequate penetration has a negative influence on the performance of the sealant.

Currently, national VOC regulations set by the Environmental Protection Agency (EPA) make manufacturers of water-repellant sealers limit the VOC content to 600 grams per liter, and some states, such as California, have even more restrictive guidelines than the national standards. Minnesota does not employ more stringent guidelines than the national requirements. Current, national VOC limits for water-repellant sealers are more easily being met by increased production of water-based silane and siloxane products and silane/siloxane mixtures. Manufacturers of water-repellant sealants can produce products with VOC contents higher than the national standard as long as they pay an exceedance fee, though in states with more stringent guidelines than current EPA regulations, these products cannot be sold.

As noted earlier, the alkyl group of the silanes and siloxanes is primarily responsible for rendering the substrate hydrophobic. Further expanding on this issue, higher molecular weight alkyl groups such as iso-butyl and n-octyl impart a larger degree of hydrophobicity upon the substrate than lower weight alkyl groups such as methyl and ethyl. Also, the structure of the alkyl group is also responsible for the hydrophobic effect of the silane or siloxane. Alkyl groups with a branched structure provide more water-repellency than straight chained alkyl groups which provide more water-repellency than alkyl groups of cyclic structure.

The size and structure of the alkyl group is also responsible for the resistance to deterioration of silanes and siloxanes to alkaline environments. Concrete is naturally a very alkaline environment; the high concentration of hydroxide ions in the substrate tend to break apart the sealant's bond with the substrate, thus minimizing the effectiveness of the silanes and siloxanes at repelling moisture ingress. Larger molecular weight alkyl groups with a branched structure tend to provide the most alkaline resistance.

The type of alkoxy group used (most commonly ethoxy or methoxy) affects the subsequent depth of penetration of the silane or siloxane. Ethoxy reacts more slowly with the substrate and allows for greater depth of penetration. However, the degree of water repellency provided throughout its depth is not as consistent as that provided by the more quickly reacting and shallower penetrating methoxy group. The size of the silane and siloxane molecules also affects depth of penetration; silane molecules, which are smaller than siloxane molecules, generally penetrate deeper.

McGettigan (1992) addressed many specific compositional issues of silanes and siloxanes that can affect performance, particularly concerning the type of alkyl and alkoxy groups used. McGettigan also noted that performance can be affected by whether the product is solvent or water-based, as well as the percent solids content. It should be noted that many manufacturers of silanes and siloxanes list the specific alkyl and alkoxy groups used in their formulations as proprietary, thus direct investigation of the effect of the type of alkyl and alkoxy group used proves to be difficult. However a separate study using gas chromatography could be used to discover the alkyl and alkoxy groups in the sealant. By conducting this study, sealants containing desired alkyl and alkoxy groups such as iso-butyl, n-octyl, and Ethoxy can be specified.

(b) Film Formers
Common film formers (also referred to as surface coatings) consist of linseed oil, epoxies, and methacrylates. These surface coatings behave in similar fashion as pore blockers; they form a somewhat impenetrable barrier on the concrete surface to help prevent moisture ingress into the concrete substrate. Film formers are not marketed as penetrating sealers and hence the distinction between pore blockers and film formers.

1.1.2 Performance Measures for Deck Sealants

This section discusses four primary performance measures of concrete sealers: chloride ingress, absorption, depth of penetration, and vapor transmission. Also, the manner in which these performance measures are quantified is also addressed. A 1989 survey of 50 U.S. state and 11 Canadian provincial highway agencies conducted by Whiting (1992) indicated the two most frequently cited laboratory test procedures used to evaluate sealer performance were the NCHRP 244 Series II and AASHTO T259/T260 test sequences. The NCHRP 244 Series II test procedure measures salt-water absorption, vapor transmission, and chloride ingress through sealed concrete while the AASHTO T259/T260 procedure solely measures chloride ingress.

ASTM C642 (measures absorption through a sealed face) and other non-standardized absorption tests proved to be the next most common laboratory test procedures used among the agencies. Penetration depth and vapor permeability tests developed by the Oklahoma DOT followed close behind. Only one or two agencies reported using tests for deicer scaling resistance (ASTM C672), freeze-thaw resistance (ASTM C666), rapid chloride permeability (AASHTO T277), and skid resistance testing.

Whiting (1992) also queried whether the agencies evaluated/differentiated sealer performance through field testing. Most agencies did not indicate use of field testing; for those that did, the majority evaluated sealer performance by chloride sampling either with cores or drill dust samples. A small percentage of the agencies specified a procedure to qualitatively measure sealer performance by flooding the treated areas of the deck with water and observing whether the water formed “beads” indicating water repellency.

(a) Chloride Ingress
Reducing chloride permeation and resulting bridge deck deterioration is the primary reason concrete sealers are used on bridge decks. Consequently, chloride ingress is an important quantity to consider in evaluating sealer effectiveness.

The AASHTO T259/T260 procedure is used to evaluate acid or water-soluble chloride ingress into treated slabs. Slab specimens are wet cured, subjected to a drying period, sealed, and then the sealant is allowed to cure. Abrasion (0.13 in. +/- 0.063 in.) of the sealed surface is implemented after curing according to AASHTO T259 provisions if the sealer is to be subjected to vehicular abrasion. The slab specimens are then ponded with 3% sodium chloride solution for

90-days by creating a dike around the perimeter of the slabs; the fill height of the solution is kept constant and evaporation is controlled by covering the solution. Following the 90-day ponding period, powdered concrete samples are obtained at selected one-half inch depth intervals (i.e., 1/16 to 1/2 in. and 1/2 to 1 in.) using a rotary drill hammer. The top 1/16 in. of the slab surface is discarded due to possible chloride precipitation on the top of the slab. The powdered samples are then analyzed for either acid (total) or water soluble (free) chloride content via AASHTO T260 procedures. The background chloride content of the concrete and aggregates is not always subtracted from chloride contents obtained via the AASHTO T259/T260 procedure as in the case of Pincheira's (2005) study.

Modifications of the AASHTO T259/T260 procedure exist including freeze-thaw exposure. Pincheira subjected treated specimens to freeze-thaw cycling during chloride ponding to study the durability of the water-repellants he analyzed.

As noted previously, the NCHRP Series II procedure is another laboratory method used to determine how well sealers safeguard against chloride permeation into the concrete. For both the AASHTO and NCHRP test methods, control specimens are subjected to the same procedures as treated specimens so the effectiveness of respective sealers can be established (i.e., chloride concentrations of untreated and treated concrete is compared to determine how well the respective sealer prevented chloride ingress).

In the field, chloride permeation into treated/untreated decks is most commonly determined by drilling into the concrete with a rotary hammer drill and collecting the resulting dust samples in a similar fashion to the AASHTO T259/T260 procedure. The chloride concentration with depth profile can also be obtained by extracted cores. Usually one-half inch thick discs are cut from the top of the cores until a depth at which chloride penetration is no longer desired to be analyzed is reached. These one-half inch thick discs are then pulverized and analyzed for either acid-soluble (total) or water-soluble (free) chlorides. The top 1/16 in. of the cores is again usually discarded to eliminate the possibility of chloride contamination from precipitates on the pavement surface skewing the depth profile data.

It should be noted from the literature review, that very few researchers determine water-soluble chloride content, regardless of the field or laboratory chloride sampling procedure used.

(b) Absorption

Absorption through a sealed concrete interface yields a qualitative indicator of the ability of the sealer to block/repel chloride ingress because chlorides permeate the bridge deck through moisture intrusion. The absorption characteristics of sealers in the laboratory are commonly determined by the NCHRP 244 Series II test procedure.

The NCHRP 244 Series II test procedure (Pfeifer 1981) is not standardized allowing possible variance in test procedure and interpretation of results. The test series resulted from a 1981 investigation by the National Cooperative Highway Research Program on the effectiveness of concrete sealers. NCHRP Series II tests consist of moist curing cubic specimens in plastic bags after removal from the forms. After all sides of the specimen are sealed the specimens are then allowed a drying period during which the sealant is allowed to cure. The specimens are then immersed in a 15% sodium chloride solution for 21 days. Weight gain or salt-water absorption is measured every 3 days. Following the immersion period, cubes are air dried in an environmentally controlled chamber for 21 days where weight loss, or vapor transmission, is measured every 3 days. After the vapor transmission period, each cube is split in half where one of the halves is crushed. Acid soluble (total) chloride content is then measured using an acid digestion potentiometric titration procedure. The background chloride content of the concrete and aggregates used to construct the specimens is subtracted from the measured value to determine chloride ingress during the salt-water soaking period.

It should be noted that the NCHRP Series II procedure, which is commonly used by vendors and state highway agencies to evaluate sealer performance, does not implement abrasion or freeze-thaw exposure to which sealers on bridge decks are frequently subjected. However, in determining the absorption properties of concrete sealers, a test was developed by Alberta Department of Transportation and Utilities which is essentially a modification of the NCHRP 244 procedure that incorporates abrasion (Kottke, 1987). Absorption is measured before and after abrading 0.04 in. off the faces of treated, cubic specimens to measure quantitatively the effect of abrasion on the absorption characteristics of sealers.

As noted by Whiting (1992), absorption characteristics of sealers are also commonly measured in the laboratory using a modification of the ASTM C642 procedure. Block specimens are oven dried and their top surfaces are subsequently treated. The treated blocks are then submerged in deionized water and weight gain measurements are taken after 2 and 50 days of being immersed. The modification in the ASTM C642 procedure is to coat the five untreated surfaces of each block specimen with wax so absorption only occurs through the sealed face.

Absorption characteristics of sealers applied to bridge decks in the field can be measured with extracted cores. Researchers (Rasoulian, 1988; Wright, 1993) have quantified water permeability of sealers by creating dikes around the top periphery of the cores. The tops of these extracted cores were then ponded with 15 percent sodium chloride and the resulting absorption (i.e., weight gain) was measured over time. Absorption characteristics of treatments in the field have also been measured by immersing extracted cores in water. Before immersion, the untreated surfaces of the cores are coated with wax so water only permeates through the treated surface. In all cases, control specimens (i.e., untreated) are needed to quantify the water repellency of the tested products.

(c) Depth of Penetration

The depth of penetration of a sealer is believed to give an indication of how well the sealer will perform in the long term due to concrete abrasion. Bridge decks are exposed to vehicular abrasion, so naturally, deeper penetrating products will provide longer protection than shallower penetrating products that are abraded off the bridge deck surface rather quickly. Also, deeper penetrating products better protect the active ingredient of the concrete sealer from ultraviolet light degradation (McGettigan, 1995).

Depth of penetration is commonly measured in field and laboratory investigations of concrete sealers. No current standardized test procedure exists as far as determining the depth of penetration of concrete sealers. Depth of penetration of sealers is commonly quantified by wetting a fractured specimen, perpendicular to the sealed face, and measuring the depth of the visible non-wetting band. This "visible non-wetting band" appears lighter than the rest of the wetted concrete due to the sealer resisting or preventing water ingress into treated concrete. This method for determining sealer penetration closely resembles the depth of penetration tests developed by the Oklahoma Department of Transportation. In the field, cores are extracted and split perpendicular to the sealed face to measure the visible non-wetting band. In laboratory investigations, constructed specimens are sealed and fractured in order to measure the depth of penetration of the sealers.

It should be noted that water-repellant sealers (i.e., silanes and siloxanes) do not always experience the same water-repelling capacity throughout their depth of penetration. It is possible for the majority of the silane or siloxane solids to be concentrated within the uppermost depths of the concrete substrate (McGettigan, 1995; Smith, 1986). Thus, water-repellant effectiveness of the silane or siloxane is not consistent throughout the entire depth of its visible non-wetting band; only an effective portion of the non-wetting band efficiently repels water ingress.

Weyers (1995) determined that abrasion rate for a bridge deck with an AADT of 24,270 to be approximately $6.69\text{x}10^{-3}$ in. per year. Varying levels of traffic will cause the abrasion rate of the bridge deck to fluctuate. Taking this information into account, one should be able to determine the lifespan of the penetrating sealant by dividing the effective water-repelling depth by $6.69\text{x}10^{-3}$ in. Alberta Transportation and Utilities developed a test procedure which qualitatively measures the effective depth of penetration by measuring absorption before and after abrading 0.04 in. off the faces of treated (sealed) specimens (Bush, 1998; McGettigan, 1992; Kottke, 1987). The Alberta Transportation and Utilities test is again referred to in Section 1.1.2(b) on absorption.

(d) Vapor Permeability

The vapor permeability of concrete sealers is important for the long term durability of the concrete substrate. Encapsulated moisture in the concrete could lead to increased freeze-thaw degradation of the deck; allowing sufficient water vapor transmission through the deck surface helps negate this possibility.

Vapor transmission data is commonly obtained using the NCHRP 244 Series II laboratory procedure. In NCHRP testing, the vapor transmission percentage of sealers is determined by the amount of weight gained during the immersion process that treated cubes are able to lose after the final drying period (i.e., weight loss after final drying reported as percentage of weight gained during submersion). Another common laboratory method for determining the vapor permeability of sealers is that developed by the Oklahoma DOT (Test No. OHD L-35). In this test method, block specimens are cured and oven dried to a constant weight. These untreated, bone-dry blocks are then immersed in de-ionized water for 48 hours. Specimens are then brought to a saturated surface-dry condition and sealed. After sealer application, specimens are once again oven dried to a constant weight. Vapor transmission for each sealer is reported as a percentage of the weight loss by the respective treated specimen to that of the weight gained by the uncoated specimen.

The two test procedures (i.e., NCHRP 244 Series II and OHD L-35) measure slightly different aspects of the vapor permeability of a sealer. The NCHRP test procedure determines how much water that permeates though a sealed surface will be lost due to subsequent vapor transmission. The ODOT procedure evaluates how much of the water present in the substrate can transmit through the treated surface after sealer application.

No examples were found in available literature where vapor permeability of sealers was quantified in the field. However, it may be possible to implement a test method similar to that of the NCHRP or ODOT procedures using extracted cores.

1.2. Analyzing Performance Measure Data for Deck Sealants

This section points out some trends that were noticed in the data. These subsections include: scatter in data, correlation among performance measures, and effect of difference in test procedure. The scatter in data section points out were scatter is and why it may have happened. The correlation among performance measures section discusses how results from different performance measure (i.e., penetration depth and chloride ingress) relate to each other. The last section discusses some fundamental differences in test procedure that may cause different results.

1.2.1 Scatter in Data

(a) Penetration Depth
Pincheira’s (2005) laboratory investigation provided depth of penetration data that exhibited a large degree of scatter; standard deviations were found to be as large as 83% of the mean penetration depth for the hydrophobic deck sealants. Pincheira suggested this as a reason for the scatter in chloride ingress measurements for a particular penetrating sealer.

Considerable scatter was also noticed by Whiting (2005; 2006b) in the Mn/DOT Stillwater Bridge and Mn/DOT Bridge of Hope penetration data respectively for silanes and siloxanes. For example, Whiting (2005) observed penetration depth measurements to vary as much as 0.08-0.31 in. across a 5.3 in. representative piece of bridge deck when obtaining mean penetration depth for the silanes and siloxanes used on the Mn/DOT Stillwater Bridge. This large variance in penetration depth of a hydrophobic sealer was also noticed by Whiting (2006b) for the Mn/DOT Bridge of Hope where only a single water-based 40% silane solution was applied. For a 2 in. representative piece of concrete in the north-bound (NB) lanes penetration depths ranged from 0-0.16 in. For a 2.8 in. representative piece of concrete in the south-bound (SB) lanes penetration depths ranged from 0-0.28 in. It should be noted that for the SB lanes, the water-based 40% silane solution had been applied frequently since the bridge was constructed ten years prior to Whiting’s (2006b) investigation. For the NB lanes, the water-based 40% silane product was only applied at the time of bridge deck construction.

(b) Chloride Ingress
In analyzing chloride penetration results from laboratory investigations, considerable scatter was noticed in the data. Pincheira (2005) observed standard deviations as large as 90 percent of the mean chloride content for treated specimens. Bush (1998) also observed a high degree of scatter

in chloride data; standard deviations were found to be as large as or larger than mean chloride values.

Chloride ingress measurements were also noted to be highly variable in the field by Smutzer (1993) and Whiting (2006b).

1.2.2 Correlation among Performance Measures

(a) Penetration Depth and Chloride Ingress

In analyzing the correlation between the depth of penetration of a sealer and its respective resistance to chloride ingress, Pincheira (2005) discovered a direct, but not perfect relationship. In Pincheira's study, which was a laboratory investigation, the treated face of block specimens underwent surface abrasion before subsequent chloride ponding (i.e., AASHTO T259/T260). Chloride concentrations and penetration depths of sealers were only compared for treated, abraded specimens that were not subjected to freeze-thaw exposure during the ponding process. Thus, the effect of sealer degradation due to freeze-thaw exposure was not taken into consideration. Pincheira showed that deeper penetrating silanes and siloxanes provided better resistance to chloride ingress after surface abrasion than respective shallower penetrating products (without considering durability of sealer).

However, Pincheira (2005) noted that the abrasion depth required by AASHTO T259 (mean depth ~ 0.13 in.) may have been too large to accurately represent sealer performance exposed to traffic wear. For example, for the majority of the silanes and siloxanes studied, respective mean penetration depths were smaller than the required abrasion depth by AASHTO T259. Only one sealer, a solvent-based 40% silane solution, was able to penetrate to a mean depth larger than that of 0.13 in. As noted previously, a large degree of variance was noted in the penetration depth profile of individual sealers. Thus, with mean penetrations generally smaller than the required abrasion depth and a large degree of scatter in penetration depth measurements for each sealer, exposed, untreated areas of the block specimens were inevitable.

Basheer (1998) investigated the correlation between the penetration depth of silanes and siloxanes and respective resistance to chloride ingress. Results indicated the correlation to be little, if at all (i.e., $R^2 = 0.0827$). All the sealers analyzed exhibited a mean penetration depth of 0.039 in. Basheer concluded that because all of the sealers studied were able to penetrate to a mean depth of at least 0.039 in., penetration depth of a sealer did not affect its chloride resisting capability. It should be noted that Basheer's investigation took place solely in the laboratory; also, sealers were not subjected to freeze-thaw exposure or surface abrasion. Thus, in not being exposed to abrasion, the benefit of deeper penetrating products was not seen in Basheer's analysis as in Pincheira's study.

Pincheira's observed correlation between penetration depth and resistance to chloride ingress for silanes and siloxanes was likely attributed to the shallower penetrating products leaving more exposed, untreated areas of the concrete following the surface abrasion. The question becomes how much of the treated surface should be abraded in the laboratory to accurately represent vehicular wear that occurs on bridge deck surfaces. As Basheer (1998) observed, as long as there is a certain minimum threshold penetration depth, resistance to chloride ingress between silanes and siloxane products will not be notably different. If the abrasion depth required by AASHTO

T259 was not so large, many of the sealers tested by Pincheira (2005) that were deemed ineffective may have performed to a satisfactory standard.

Further corroborating this idea, Whiting (2006a) discovered little to no correlation between penetration depth and resistance to chloride ingress for the silanes and siloxanes analyzed in a one-year field investigation. All sealers had a minimum penetration of 0.04 in. Because all sealer penetrated past this value (0.04 in.) there was no significant difference in the sealants' ability to resistance to chloride ingress after one year. Whiting's (2006a) study was a field investigation, thus sealers were subjected to freeze-thaw exposure and surface abrasion. Whether one-year of vehicular wear was long enough to distinguish a benefit of a deeper penetrating product is difficult to say. It should also be noted that individual sealers could have responded differently to freeze-thaw degradation; this fact could help explain why penetration depth and the sealant's ability to resist chloride ingress did not correlate.

In the above discussion of correlating penetration depth and resistance to chloride ingresss for silanes and siloxanes, one must remember that the same products are not being analyzed. First, penetration depths and chloride ingress for section treated with silanes and siloxanes are being compared; silanes and siloxanes are two different types of generic water-repellants. Second, among sealers that fall within the same generic group (i.e., silanes), subtle differences in composition such as the alkyl and alkoxy group, solids content, and the carrier can all affect the overall performance of the sealer. Thus, the effect of penetration depth is not being isolated in the above analyses due to compositional differences of the sealers. A study which directly correlates the depth of penetration of a particular product to chloride ingress might clear up some of the inconsistencies. This would give a better indication if depth of penetration has a direct effect on chloride ingress or if it is one of the many variables that indirectly affects chloride ingress.

(b) Salt-Water Absorption and Chloride Ingress

Bush (1998) analyzed concrete with three different water-cement ratios, all treated with the same solvent-based 40% silane. Absorption values and chloride ingress concentrations correlated well using the NCHRP Series II test procedure (i.e., relative performance of the three treated concretes was the same from the absorption and chloride content results). However, when the treated concretes were tested for absorption weight gain and chloride content using different test methods, the results did not parallel with each other. Absorption testing was conducted according to ASTM C642 and chloride sampling/analysis was conducted according to AASHTO T259/T260 procedures. As noted previously, treated concrete with a respective water-cement ratio who gained the most weight during immersion in de-ionized water (ASTM C642) did not exhibit the highest chloride concentrations in the 1/16 to 1/2 in. depth interval (AASHTO T259/T260, did not include surface abrasion). Bush (1998) concluded that the NCHRP Series II and ASTM C642 absorption tests were fundamentally different due to test procedure (see Section 1.2.3 Effect of Differences in Test Procedure).

In evaluating the relationship between salt-water absorption and chloride ingress, Pfeifer (1981) found a strong correlation between the two parameters in his Series I through Series III laboratory tests. Wiss, Janney, Elstner, and Associates (1984) also discovered a strong correlation between chloride accumulation and salt-water absorption. It should be noted that both research efforts implemented the NCHRP Report No. 244 test procedure when analyzing the correlation between salt-water absorption and chloride concentration. Wiss, Janney, Elstner, and Associates concluded that treated cubes who gained more weight during salt-water soaking would exhibit larger chloride concentrations than treated cubes who gained less weight during salt-water immersion.

1.2.3 Effect of Differences in Test Procedure

There are two studies that compare the procedures used to test deck sealers: Whiting (1992) and Bush (1998). The two studies use the NCHRP 244 Series II, Oklahoma DOT series, and AASHTO T259/T260 tests. By using these studies to compare the tests, a better understanding can be made as to why the tests yield different results.

Whiting (1992) used the NCHRP 244 Series II and AASHTO T259/T260 tests to determine the chloride content of sealed specimens. Five different sealants were tested using the two previously mentioned methods: two silanes, one siloxane, one silicate, and one epoxy. The NCHRP Series II and AASHTO tests both included treated and untreated specimens; however there were some fundamental differences in the test procedures used. The NCHRP Series II tested two different moisture conditions (dry and moist) with a 4 x 4 x 4 in. specimen. The AASHTO test only considered dry samples and used a 12 x 12 x 3 in. specimen. Both tests allowed the concrete to cure for 28 days which was followed by a 21 day drying period. The moist samples (NCHRP Series II test only) were subjected to moisture cycles for 15 weeks after the curing process was completed. The coverage rate and applications method was kept constant for all test samples.

The AASHTO T259/T260 test used in Whiting's 1992 study called for the 12 x 12 in. face of the specimen to be flooded to a depth of ½ in. with a three percent sodium chloride solution for 90 days. The ½ depth was kept constant and the specimens were covered to prevent evaporation. After 90 days, the specimens were dried and the exposed surface was brushed clean. A power drill then took samples at two different depths: 1/16 to ½ in. and ½ to 1 in. The total (acid-soluble) chloride was measured from these samples. The NCHRP 244 Series II test called for the 4 x 4 x 4 in. cubes to be completely submerged in a 15 percent sodium chloride solution for 21 days. After being allowed to dry for 21 days in an environmentally controlled chamber at 73^{o} F ± 3^{o} F and 50% ± 5% relative humidity, half of the cube was crushed and analyzed for total (acid-soluble) chloride content.

The fundamental differences in the two test procedures of Whiting's 1992 study cause varying results for the five sealants tested. The AASHTO test floods the top 12 x 12 in. surface while the NCHRP Series II test submerges the entire specimen. Also the duration in which the specimens were subjected to the sodium chloride solutions differs in both tests (90 days and 21 days for AASHTO and NCHRP Series II respectively). The sodium chloride solution strength varies for both tests (three verses 15 percent). Lastly the AASHTO test uses a drill to extract samples at two different depths of the specimen. The NCHRP test crushes half of the specimen to obtain the test samples.

Bush (1998) studied the depth of penetration, chloride content, absorption, and vapor transmission of a solvent-based silane with 40 percent solids. The results for the NCHRP 244 series II and the Oklahoma DOT series tests were compared. Refer to the appendix for Bush's procedure for each test method implemented. Differences in the Oklahoma DOT test series (contains methods from ASTM C642 and AASHTO T259/T260) and the NCHRP Series II test procedures were studied to determine the reasons for discrepancies in the absorption results. The following comparison list summarizes the differences.

1. For the ASTM C642 procedure, specimens were oven dried before immersion, thus absorption equaled the moisture content because the initial moisture content was zero. For the NCHRP Series II procedure, specimens were not oven dried before immersion (they were air dried). Thus, the initial moisture contents for the NCHRP specimens could not be controlled.

2. For the ASTM C642 procedure, specimens were immersed in de-ionized water. The NCHRP Series II procedure immersed the specimens in 15% NaCl.

3. For the ASTM C642 procedure, the rate of initial moisture content increase (0-2 day immersion period) was 3-6 times larger for sealed mix classes and at least 10 time larger for unsealed mix classes when compared to the rate of initial moisture content increase (0-3 day immersion period) for the NCHRP Series II specimens. The greater initial rate of moisture content increase for the ASTM C642 specimens was a result of the moisture content of the concrete equaling zero before immersion. The rate of moisture increases for longer periods (2-50 days for the ASTM C642 procedure and 3-21 days for the NCHRP Series II specimens) were much more similar for the two tests.

4. For the ASTM C642 procedure, five of the faces were waxed for sealed specimens. Thus, absorption occurred though the sealed 8" x 8" face resulting in an exposed surface area to volume ratio of 0.5. For the sealed NCHRP specimens, absorption occurred through all of the sealed six faces resulting in an exposed surface area to volume ratio of 1.5.

5. For the ASTM C642 procedure, the moisture content was 0% at the time of silane application, thus the depth of silane penetration was much greater for the ASTM C642 specimens than the NCHRP Series II specimens.

No specific difference between the tests could be attributed to the reason for the discrepancy in absorption results. The question of which test to use then becomes the important. Bush brings up the point that field concrete will likely have a certain amount of moisture at the time of sealer application and the NCHRP test may better simulate these field conditions. Also for bridge decks in northern climates such as Minnesota, the presence of salt in ingress moisture better simulates field conditions. However, the initial moisture content of the concrete in the NCHRP test can not be controlled which is not a desirable quality of laboratory test methods. Also, no specific recommendation is given on which test produces a better estimate of sealer performance based on the chloride ingress results. If chloride ingress measurements are desired, Bush suggests that the NCHRP Series II test might be a better choice simply due to the time requirement to obtain chloride ingress results (100 days vs. 140 days for the AASHTO T259/T260 test).

1.3. Best Performing Deck Sealants

This section consists of four subsections which represent the primary performance measures for concrete sealers: Chloride Ingress, Absorption, Depth of Penetration, and Vapor Transmission. Each subsection presents laboratory and field results for concrete deck sealants for the respective performance measure discussed. If a researcher implemented a laboratory and field investigation, results from the laboratory and field investigation are discussed separately under the laboratory investigations and field investigations headings respectively in each subsection. The subsections describe the differences in performance among surface coatings, silanes, and siloxanes.

The primary surface coatings discussed include linseed oil, epoxies, and methacrylates. If the researchers distinguished whether the silanes and siloxanes studied in their investigations were solvent or water-based and/or the percent solids by weight of the silanes and siloxanes were analyzed, the subsection is written to allow the reader to see any difference in solvent vs. water-based products and/or the effect of higher solids content. For example, if a laboratory investigation analyzed solvent-based 40% silanes, water-based 40% silanes, water-based 20% silanes, solvent-based 12% siloxanes, water-based 12% siloxanes, and epoxy surface coatings, the performance of the three silane products, the two siloxane products, and the epoxy surface coatings would be compared to each other under the laboratory investigations heading in the respective subsection to distinguish the better product in descending order.

In isolating the effect of solvent or water-based, the performance of the solvent-based 40% silanes would be compared to that of the water-based 40% silanes and the performance of the solvent-based 12% siloxanes would be compared to that of the water-based 12% siloxanes. To isolate the effect of higher solids content, the performance of the water-based 40% silanes would be compared to that of water-based 20% silanes. If 100% silanes were analyzed, in distinguishing the effect of higher solids content, the 100% silanes would be compared to any silane of lower solids content whether water or solvent-based. At the end of each subsection, a summary of laboratory and field investigation results is presented to further synthesize the information.

1.3.1 Chloride Ingress

(a) Laboratory Investigations

Whiting (1992) observed the two silanes (water-based, 40% solids and solvent-based, 40% solids) and one siloxane (solvent-based, 20% solids) exhibited much lower total chloride ingress values than the two epoxy and one sodium-silicate surface coatings analyzed. Two test procedures were administered: NCHRP 244 Series II and AASHTO T259/T260. For the NCHRP 244 Series II test procedure, the effect of "moist" and "dry" concretes was analyzed; the AASHTO T259/T260 procedure only analyzed "dry" specimens. After the specimens were taken from the mold they were allowed to cure for 28 days. The "dry" specimens were placed in an environment that was 73±3 °F with a relative humidity of 50 percent. After the 28-day curing period, the "moist" specimens were subjected to two different environments. For eight hours on a weekly basis, the cubes were placed in the same room used to cure the concrete. The slabs were covered with wet burlap and were soaked twice a day on a weekly basis. In distinguishing the difference in performance between the silanes and siloxanes, the difference in test procedures and moisture content of the concrete substrate appeared to affect mean chloride results. For the

NCHRP Series II test procedure “dry” specimens yielded siloxane as the best performer where as results for the “moist” specimens exhibited the two silanes as the best performers. The AASHTO T259/T260 mean chloride results for the 1/2 in. depth interval for “dry” specimens indicated the two silanes outperformed the siloxane.

A clear trend of silanes outperforming the siloxane or vice versa cannot be drawn from the above results. However the trends could be impacted by differences in test procedures, differences in moisture content, or simply due to the scatter in data when obtaining mean chloride ingress. The NCHRP 244 Series II test procedure for “dry” and “moist” specimens and the AASHTO T259/T260 test procedure for “dry” specimens all consistently indicated the solvent-based 40% silane to outperform the water-based 40% silane. The solvent-based 40% silane exhibited total chloride contents that ranged from ~9% to 36% lower than that of the water-based 40% silane.

Wright’s (1993) laboratory investigation demonstrated siloxane and linseed oil to be more effective than silane at reducing chloride ingress. Duplicate specimens were also produced and a major difference in chloride results for linseed oil made it difficult to differentiate performance between linseed oil and siloxane. Silane clearly performed the worst of the three sealers studied. Pfeifer’s (1981) Series I tests again demonstrated generic surface coatings such as epoxy and methacrylate did not exhibit similar performance within their respective generic group. Some epoxies and methacrylates performed better than silane while others did not. Siloxane again performed the worse with respect to chloride ingress for the 21 concrete sealers analyzed. The low solids content of the siloxane (~6.5%) may be partly responsible for its poor performance. Specimens treated solely with linseed oil were found to notably outperform siloxane but silane clearly outperformed linseed oil. Though, when linseed oil was aged with significant ultraviolet light exposure in Pfeifer’s (1981) Series IV tests, linseed oil demonstrated much less chloride ingress than silane.

Weyers (1995) showed the silane and siloxane studied reduced chloride ingress much more effectively than the two epoxies analyzed. Hagen’s (1995) laboratory results showed that the epoxy surface coating studied demonstrated as large or larger chloride reduction than the majority of the silanes and siloxanes studied. Chloride reductions relative to uncoated concrete did not show large variations in performance among the sealers tested. Most importantly, chloride reductions relative to uncoated concrete indicated all sealers tested to be extremely effective (chloride reductions relative to uncoated concrete ranged from 83% to 94% for the sealers analyzed). This observation becomes important in the discussion of Hagen’s field results.

No clear performance trend was seen in solvent-based 40% silanes vs. water-based 40% silanes. Also, the benefit of higher solids content was not observed among the solvent-based 40% silanes, solvent-based 30% silane, and the solvent-based 20% silane studied. Smutzer’s (1993) laboratory results also demonstrated minimal variation in performance among the silane, two siloxanes, modified aluminum siloxane, and siloxane/silane mixture studied. Again, most importantly, laboratory results indicated all the tested sealers to be extremely effective in chloride reduction relative to uncoated concrete (sealers exhibited chloride reduction ranging from 90% to 98%). The fact that laboratory results indicated all tested sealers to be extremely effective in reducing chloride ingress is discussed with Smutzer’s field results. Laboratory results indicated the following for chloride ingress reduction in order of descending performance: modified aluminum siloxane, silane, siloxane/silane mixture, and the two siloxanes.

Pincheira's (2005) chloride results indicated silanes as a whole outperformed siloxanes for specimens not exposed to freeze-thaw cycles. In analyzing solvent vs. water-based products, the four solvent-based 40% silanes studied exhibited notably lower mean chloride contents than the two water-based 40% silanes analyzed. However, the solvent-based 10% siloxane demonstrated a larger mean chloride content than the water-based 10% siloxane studied. Whether this discrepancy solely resulted from scatter in chloride data, one cannot say. It should be noted that the four solvent-based 40% silanes studied exhibited the lowest mean chloride contents of the thirteen penetrating sealers analyzed; these four silane products also exhibited the largest depths of penetration. In trying to differentiate the effect of solids content, Pincheira's (2005) results for mean chloride content did not clearly indicate a difference in performance among the two water-based 40% silanes and the two water-based 20% silanes.

For specimens exposed to freeze-thaw, Pincheira's (2005) mean chloride content results did show any clear trends to be seen as far as silanes vs. siloxanes, solvent vs. water-based, and the effect of solids content. This is because freeze-thaw exposure led to an increase in variation in performance within silanes of specific composition (i.e. solvent-based 40% silanes, water-based 40% silanes). Freeze-thaw exposure proved to cause a decrease in nearly all of the silanes' and siloxanes' ability to deter chloride ingress. This decrease in performance was noticed to vary among silanes of the same specific composition mentioned previously. Thus, not all silanes that were solvent-based and 40% solids and not all silanes that were water-based and 40% solids were impacted the same by freeze-thaw exposure. The top three performers from mean chloride content results for specimens subjected to freeze-thaw were two solvent-based 40% silanes and one water-based 40% silane.

(b) Field Investigations

For Wright's (1993) three-year field investigation, linseed oil treated sections demonstrated noticeably lower mean chloride contents than those treated with silane and siloxane for both the street and highway. Silane exhibited poorer performance than siloxane for the highway; the opposite was noticed for the street. The poorer performance of the silane relative to the siloxane at the highway site could be related to its shallower depth of penetration than siloxane at the highway site due to the windy conditions at time of sealer application. Whiting (2006a) observed simular chloride concentrations among the 100% silane, solvent-based 40% silane, and water-based 40% silane. Thus, any benefit of solvent vs. water-based or higher percent solids content was not observed. In comparing siloxane vs. silane, the solvent-based 12% siloxane studied proved to be the least effective in comparison to the silane products.

Chloride reductions relative to uncoated concrete from Hagen's (1995) three-year field investigation did not correlate well with his laboratory results. The best and worse performers from the laboratory results did not parallel the field results. Chloride reductions observed in the field proved virtually all of the sealers were much less effective than the laboratory results indicated. (Field results indicated chloride reductions relative to uncoated concrete ranged from 3% to 67% after the third year.) The majority of the sealers experienced decreases in their effectiveness in reducing chloride ingress from year to year, suggesting the negative impact of freeze-thaw exposure and/or abrasion which Hagen (1995) did not simulate in his laboratory investigation.

Field results indicated the water-based 40% silanes and solvent-based 40% silanes exhibited substantial variation in performance within their respective groups. This suggests that all specific formulations of silanes (i.e. water-based 40% silanes and solvent-based 40% silanes) do not exhibit the same chloride resistance under freeze-thaw exposure. Hagen’s (1995) field results indicated no clear performance trends as far as silanes vs. siloxanes, solvent vs. water-based, or the effect of higher percent solids content from the silanes and siloxanes studied. However, silanes and siloxanes notably outperformed the thermoplastic emulsions and sodium-silicate surface coatings. The epoxy surface coating was only comparable to the poorest performing silanes and siloxanes in the last year of the field study. Laboratory results contradicted this finding indicating epoxy to be one of the top performers among the sealers analyzed. The most effective sealers after the three-year field study in terms of chloride reduction in descending order were found to be a water-based 40% silane, solvent-based 40% siloxane/silane mixture, and a solvent-based 15% siloxane.

Smutzer (1993) also demonstrated that the reduction in chloride ingress levels relative to uncoated concrete through three field investigations did not correlate well with his laboratory results. Again, the chloride reductions for sealers observed from the laboratory results proved to be much greater than chloride reductions observed in the field results. (At the end of the third year, chloride reductions ranged from 10% to 64%.) This observation most likely stems from the fact that Smutzer did not include abrasion and freeze-thaw exposure in his laboratory analysis. Results from Smutzer’s field investigation indecated silane was the top performer for all three years with the largest chloride reduction. The epoxies and siloxanes were found to be the next best performers but statistical analysis indecated no difference in performance between the two. The siloxane/silane mixture and the modified aluminum siloxane had the least chloride reductions (worst performance) of the sealers analyzed; thus laboratory results did not parallel the field results for these two sealers. Statistical analysis indicated the siloxane/silane mixture performed slightly better than the modified aluminum siloxane. Chloride reduction relative to uncoated concrete generally decreased each year for the sealers; silane was the only sealer to notably contradict this trend showing increased effectiveness each year. Thus, chloride ingress through uncoated concrete increased due to abrasion and freeze-thaw exposure each year relative to that of silane treated concrete.

(c) Summary of Chloride Ingress Studies

Whiting (1992) demonstrated silane and siloxane exhibited much less chloride ingress than epoxy and sodium-silicate surface coatings analyzed for both test procedures and moisture contents of the concrete. Weyers (1995) also showed the chloride contents of epoxy-coated concrete were much lower than those of silane and siloxane treated concrete. The performance of epoxy coated concrete proved to be as good as or slightly better than that of silane and siloxane coated concrete according to Hagen’s (1995) laboratory results. Hagen’s (1995) field results indicated that epoxy reduced chloride ingress as well as the worst peforming silane products for only the last year of the field study. Silanes and siloxanes reduced chloride ingress through concrete substantially more than the thermoplastic emulsions and sodium silicate surface coatings analyzed. Smutzer (1993) found silane to reduce chloride ingress more effectively than epoxies through his field results (laboratory investigation did not test epoxies), but the performance of the siloxanes and epoxies were statistically the same. Field results indicated the modified aluminum siloxane and the siloxane/silane mixture reductions of chloride ingress were far worse than those of the silane, siloxanes, and epoxies, while the laboratory results contradicted this finding. Pfeifer (1981) proved some epoxy and methacrylate surface coatings performed worse in chloride ingress tests than silane while other epoxy and methacrylate surface coatings performed better than silane. Siloxane was far worse in reducing chloride ingress than silane, in fact it had the worst performance of the 21 sealers analyzed. Silane notably outperformed linseed oil which clearly outperformed siloxane. Aging linseed oil with ultraviolet light exposure caused linseed oil's ability to reduce chloride ingress to be much better than that of silane. Wright's (1993) laboratory investigation showed siloxane and linseed oil to reduce chloride ingress more effectively than silane. Chloride results from duplicate specimens made it difficult to distinguish if siloxane or linseed reduced chloride ingress the best. Field results indicated linseed oil to be the most effective product compared to the silane and siloxane. Discrepancies between chloride ingress results for the field concretes did not allow one to differentiate the performance between the silane and siloxane.

In trying to further differentiate performance of silanes and siloxanes, Whiting's (1992) mean chloride results showed silanes to be more effective than siloxane and vice versa depending on the test procedure and the moisture content of the concrete. Mean chloride results consistently indicated the solvent-based 40% silane to outperform the water-based 40% silane though. Whether these observations actually stem from differences in test procedure and moisture content or just variability in chloride measurements one cannot determine. Mean chloride results from Whiting (2006a) indicated the three silanes studied outperformed the one siloxane studied. However, no performance trends were noticed as far as solvent vs. water-based and the effect of higher solids content in the solvent and water-based 40% silane and the 100% silane. Pincheria's (2005) chloride results for specimens not subjected to freeze-thaw indicated silanes generally reduced chloride ingress more effectively than siloxanes. In analyzing solvent vs. water-based products, solvent-based 40% silanes allowed less chloride ingress than water-based 40% silanes. The benefit of solvent-based was not seen in the solvent-based and water-based 10% siloxane though. No clear benefit of higher solids content was seen in Pinchiera's (2005) chloride results for specimens not subjected to freeze-thaw exposure. Specimens subjected to freeze-thaw exposure also did not show any clear trends regarding the performance of the silanes vs. siloxanes, solvent vs. water-based, and the effect of higher percent solids content. Freeze-thaw exposure also caused a decrease in nearly all sealers' ability to deter chlorides; though not all sealers were impacted the same. This led to substantial variation in performance among silanes of a specific composition (i.e., water-based 40% silanes, solvent-based 40% silanes). The three most effective products turned out to be two solvent-based 40% silanes and one water-based 40% silane. Hagen's (1995) field results also indicated all silanes of a specific composition (i.e., water-based 40% silanes, solvent-based 40% silanes) did not experience the same reduction in chloride effectiveness after freeze-thaw exposure; some were impacted much more negatively than others. Hagen's field and laboratory results did not indicate clear performance trends as far as silanes vs. siloxanes, solvent vs. water-based, and the effect of solids content. Field results yielded a water-based 40% silane, solvent-based 40% siloxane/silane mixture, and a solvent-based 15% siloxane as the top performers in descending order. The fact that the siloxane/silane mixture demonstrated such high chloride effectiveness relative to the top performing silanes and siloxanes contradicts the results from Smutzer’s (1993) field investigation.

Hagen’s (1995) and Smutzer’s (1993) laboratory results both indicated the sealers studied to be much more effective at reducing chloride ingress than field results did. This led to numerous cases of field results proving sealers to virtually ineffective after the third year where laboratory results indicated these sealers be imparted a high level of protection to the concrete. Both of these researchers did not include freeze-thaw exposure and abrasion in their laboratory tests which helps explain the discrepancy between the laboratory and field results. Refer to Tables 1.1 and 1.2 for laboratory and field data pertaining to chloride intrusion.

Table 1.1: Laboratory Results for Chloride Ingress

	Whiting	Wright	Weyers	Smutzer	Pincheira’s
	2002	1993	1995	1993	2005
	Laboratory				
Materials (Solids %, Water/Solvent Based) -list from best to worst performance-	Silane (S, 40)	Siloxane (NA, NA)	Silane (NA, NA)	Aluminum Siloxane (NA, NA)	Silane (S, 40)
	Silane (W, 40)	Linseed Oil (NA, NA)	Siloxane (NA, NA)	Silane (NA, NA)	Silane (S, 40)
	Siloxane (S, 20)	Silane (NA, NA)	Epoxy (S & W, NA)	Siloxane/Silane (NA, NA)	Silane (S, 40)
	Epoxy (S, NA)			Siloxane (NA, NA)	Silane (S, 40)
	Silicate (W, NA)			Siloxane (NA, NA)	Silane (W, 40)
					Silicate (NA, NA)
					Silane (W, 20)
					Siloxane (S, 12)
					Silane (W, 40)
					Silane (W, 20)
					Siloxane (W, 10)
					Siloxane/Silane (W, NA)
					Siloxane (S, 10)

Table 1.2: Field Results for Chloride Ingress

	Wright	Wright	Whiting	Smutzer	Hagen’s
	1993/Street	1993/Highway	2006a	1993	1995
	Field				
Materials (Solids %, Water/Solvent Based) -list from best to worst performance-	Linseed Oil (NA, NA)	Linseed Oil (NA, NA)	Silane (NA, NA)	Silane (NA, NA)	Silane (W, 40)
	Silane (NA, NA)	Siloxane (NA, NA)	Siloxane (NA, NA)	Epoxy (NA, NA)	Siloxane/Silane (S, 40)
	Siloxane (NA, NA)	Silane (NA, NA)[1]		Siloxane (NA, NA)	Silane (S, 40)
				Epoxy (NA, NA)	Siloxane (S, 15)
				Siloxane (NA, NA)	Epoxy (W, NA)
				Siloxane/Silane (NA, NA)	Silane (S, 20)
				Siloxane (NA, NA)	Silane (S, 40)
					Silane (S, 30)
					Silane (S, 40)
					Siloxane (S, 9.2)
					Silane (W, 40)

[1] - High Wind Conditions

1.3.2 Absorption

(a) Laboratory Investigations

Pfeifer (1981) found variations of salt-water absorption performance among generic types of surface coatings such as epoxies and methacrylates in his Series I tests. Some epoxies and methacrylates performed notably poorer than silane while some epoxies and methacrylates absorbed slightly less salt-water than silane (performed better than silane). Interestingly, siloxane exhibited the highest salt-water absorption of the 21 concrete sealers analyzed. No distinction of silane's percent solids content or whether the carrier was solvent or water was given. Siloxane's poor performance relative to the 21 other concrete sealers could be due to its low percent solids content (~ 6.5%); clarification of whether the siloxane was solvent or water-based was not given. Also, Pfeifer's (1981) Series I tests demonstrated linseed oil to perform very poorly with respect to the silane but to notably outperform the siloxane. Wright's (1993) laboratory investigation demonstrated siloxane to be more effective than linseed oil and silane with respect to salt-water absorption. Silane initially exhibited better salt-water absorption characteristics than linseed oil (prior to ultraviolet light exposure) but soon silane's performance fell behind that of linseed oil. Wright's (1993) laboratory investigations showed the following with respect to salt-water absorption performance in descending order: siloxane, linseed oil, and silane. Pfeifer (1981) demonstrated performance in descending order to be silane, linseed oil, and siloxane.

(b) Field Investigations

Wright's (1993) three-year field investigation did not correlate well with his laboratory results. Linseed oil was found to be the most effective sealer with respect to salt-water absorption compared to silane and siloxane in the field. The salt-water absorption characteristics of silane and siloxane tended to increase each year, while salt-water absorption for linseed oil remained much lower than that of silane and siloxane and relatively constant from year to year. In comparing silane to siloxane, siloxane demonstrated slightly better performance than silane.

In comparing the effect of higher solids content, Soriano's (2002) results indicated 100% silane absorbed slightly less water than the 40% silane products analyzed.

(c) Summary of Absorption Studies

Pfeifer's (1981) results indicated that all surface coatings of a generic composition (i.e., epoxies, methacrylates) do not exhibit similar salt-water absortion performance in comparison with silane. Also, siloxane was found to exhibit the most absorption in comparison to silane and linseed oil, with silane displaying the least amount of salt-water absorption of the three. Linseed oil was found to provide superior performance over silane when aged with ultraviolet light exposure. Wright's (1993) laboratory investigation proved siloxane to outperform linseed oil which outperformed silane in regards to salt-water absorption. Wright's field investigation contradicted his laboratory results indicating linseed oil to outperform silane and siloxane; silane exhibited slightly less weight gain than siloxane. The superior performance of linseed oil in Wright's (1993) field investigation could be due to ultraviolet exposure in the summer months prior to the first subjection of deicing chemicals during the first winter.

A slight benefit in absorption performance was seen by Soriano (2002) with silanes of higher solids content (100% vs. 40%).

1.3.3 Penetration Depth

(a) Laboratory Investigations

Wright (1993) found the penetration depth of linseed oil (surface coating) to be roughly twice that of silane and three times that of siloxane. Thus, linseed oil demonstrated a larger penetration depth than silane which exhibited a larger penetration than siloxane. Pincheira (2005) also found silanes as a whole generally exhibited larger penetration depths than siloxanes. Differences in the overall trend could most likely be due to minor variations in penetration depths of some silanes and siloxanes (i.e, $\pm 3.94 \times 10^{-3}$ in.) and the large scatter in data observed when obtaining mean penetration depth measurements for sealers (i.e., standard deviations as large as 83% of the mean).

In comparing solvent-based vs. water-based silanes and siloxanes of the same solids content, Pincheira's (2005) results indicated the four solvent-based 40% silanes and the solvent-based 10% siloxane studied had notably larger penetration depths than the two 40% water-based silanes and the water-based 10% siloxane studied.

In trying to isolate the effect of solids content, Pincheira's (2005) results indicated no clear performance trend of water-based 40% silanes (two studied) exhibiting larger penetration depths than the water-based 20% silanes (two studied). Possible reasons for the lack of distinction could be attributed to the scatter in penetration depth measurements, not large enough difference in solids content, and variability among specific formulations of silanes (i.e., water-based 40% silanes and 20% water-based silanes). Basheer (1998) demonstrated that 100% silane penetrated slightly better than 40% silane. It should be noted that only one 100% silane and 40% silane were analyzed and no mention was given to the fact of them being solvent-based or water-based.

(b) Field Investigations

Wright's (1993) field investigation demonstrated depth of penetration results did not correlate with laboratory trends. First of, depth of penetration measurements decreased substantially from the laboratory to the field (especially notable for linseed oil). This could be due to the extremely high water to cement ratio used in the laboratory concrete (~0.58). Second, results from field sites (7 day old concrete city street and highway) did not correlate well with each other or with the laboratory results. At the city street, silane penetrated notably deeper than siloxane which penetrated slightly deeper than linseed oil. For the highway, the penetration depth of siloxane and linseed oil stayed virtually the same as in the laboratory but depth of penetration of the silane decreased by roughly 40%, thus falling behind both siloxane and linseed oil. The author suggested one of the reasons for the discrepancy in the depth of penetration of silane as the windy conditions at the time of sealer application at the highway site. The suggestion correlated well with the fact the silane is much more volatile than either siloxane or linseed oil, and it would evaporate much faster and not penetrate as deeply. In summary, field results indicated depth of penetration of linseed oil to be comparable or smaller than that of siloxane and silane. Silane appeared to be more effective than siloxane and linseed oil.

Weyers (1995) observed that two epoxy surface coatings, both used on two different bridge decks, were found to be abraded off in less than one year, thus suggesting negligible penetration into the concrete for these surface coatings. Silane and siloxane on the other hand were given service lives of eight years based on abrasion tests.

In further trying to distinguish silanes vs. siloxanes and the effects of slight compositional differences within these products, Whiting (2005) demonstrated two of the three silane products tested (solvent-based 40% silane and 100% silane) had substantially larger penetration than the one siloxane product tested (solvent-based 12% siloxane). The other silane tested, a 40% water-based product, had an equal mean penetration depth as the siloxane product tested. Of the three silane products tested, the solvent-based 40% silane penetrated roughly 60% deeper than the water-based 40% silane. Also, the 100% silane exhibited roughly a 10% larger penetration depth than the solvent-based 40% silane product. Soriano (2002) also observed the benefit of a higher solids content citing the 100% silane product studied exhibited a slightly larger penetration depth than the two 40% silanes studied. Soriano (2002) did not indicate whether the 40% silanes were solvent or water-based so comparison between solvent vs. water-based cannot be made.

(c) Summary of Penetration Depth Studies

Weyer's field investigation (1995) showed that the two epoxy surface coatings exhibited much smaller penetration depths than the silane and siloxane studied (as expected).

Wright's (1993) laboratory and field investigation results did not agree for depth of penetration results. Laboratory results indicated linseed oil to penetrate notably deeper than silane and siloxane (possibly due to the high water to cement ratio), where field results indicated the penetration depth of linseed oil to be comparable to that of silane and siloxane. If one neglects the highway site due to its windy conditions, silane demonstrated a notably larger penetration depth than siloxane in both laboratory and field results. Pincheira (2005) and Whiting (2005) also demonstrated silanes to generally penetrate deep as or deeper than siloxanes.

Pincheira (2005) and Whiting (2005) showed solvent-based silanes and siloxanes penetrated deeper than their water-based counterparts of the same solids content. Basheer (1998), Whiting (2005), and Soriano (2002) all demonstrated 100% silanes to penetrate slightly deeper than 40% silanes. Pincheira's (2005) penetration depth results did not indicate a clear benefit of higher solids content with the water-based 40% and 20% silanes. Refer to Table 2 for depth of penetration results.

Table 2: Summary of Penetration Depth Data

	Pincheira	Basheer	Wright	Wright	Wright	Weyers	Whiting	Soriano
	2005	1998	1993	1993/Street	1993/Highway	1995	2005	2002
	Laboratory			Field				
Materials (Solids %, Water/Solvent Based) -list from best to worst performance-	Silane (S, 40)	Silane (100)	Linseed Oil (NA, NA)	Silane (NA, NA)	Linseed Oil (NA, NA)	Silane (NA, NA)[2]	Silane (100)	Silane (100)
	Silane (S, 40)	Silane (NA, 40)	Silane (NA, NA)	Siloxane (NA, NA)	Siloxane (NA, NA)	Siloxane (NA, NA)[2]	Silane (S, 40)	Silane (NA, 40)
	Silane (S, 40)	Siloxane/Silane (NA, NA)	Siloxane (NA, NA)	Linseed Oil (NA, NA)	Silane (NA, NA)[1]	Epoxy (S & W, NA)	Silane (W, 20)[2]	Silane (NA, 40)
	Silane (S, 40)						Siloxane (S,12)[2]	
	Silane (W, 40)							
	Siloxane/Silane (W, NA)							
	Silane (W, 20)							
	Silane (W, 40)							
	Siloxane (S, 12)							
	Siloxane (S, 10)							
	Silicate (NA, NA)							
	Siloxane (S, 10)							
	Silane (W, 20)							

[1] - High Wind Conditions

[2] - Same penetration depth

1.3.4 Vapor Transmission

(a) Laboratory Investigations

Wright’s (1993) laboratory investigation showed vapor transmission performance in descending order to be silane, linseed oil, and siloxane (more weight loss due to vapor transmission through concrete corresponds to better performance). Pfeifer’s (1981) Series I tests indicated the performance of generic surface coatings such as epoxies and methacrylates varied with respect to vapor transmission characteristics. Some epoxies and methacrylates displayed more vapor transmission (better performance) than silane while others exhibited less vapor transmission (poorer performance) than silane. This suggests variations in performance exist within generic surface coatings (i.e. epoxies, methacrylates). Siloxane did not display the worst vapor transmission of the 21 concrete sealers studied in Pfeifer’s (1981) Series I tests as it did in the absorption results. Siloxane still exhibited less vapor transmission than linseed oil and silane though, with silane demonstrating the best performance of the three sealers studied. Thus, Pfeifer (1981) and Wright (1993) both demonstrated vapor transmission performance in descending order to be silane, linseed oil, and siloxane.

Care should be taken in interpreting Wright’s vapor transmission results. Wright (1993) measured percent vapor transmission as the ratio of weight lost to total weight of the respective concrete cube after salt-water immersion. Thus, treated (sealed) cube specimens that absorbed different amounts of salt-water during immersion started the drying process with varying moisture contents. Specimens with much higher initial moisture contents would presumably experience much greater weight loss due to vapor transmission than specimens with substantially lower initial moisture contents. For example, siloxane demonstrated the least weight loss due to vapor transmission but also gained the least amount of salt-water compared to silane and siloxane. Pfeifer (1981) eliminated the discrepancy in vapor transmission results by expressing vapor transmission as the ratio of weight lost at the end of the drying period to the weight gained at the end of the immersion period.

(b) Field Investigations

No field investigations were found that analyzed vapor transmission characteristics of concrete sealers.

(c) Summary of Vapor Transmission Studies

Pfeifer (1981) demonstrated that all surface coatings within in a generic group (i.e., epoxies, methacrylates) do not display the same vapor transmission characteristics; some epoxies and methacrylates performed better than silane, others did not. Pfeifer (1981) also showed silane to outperform linseed oil which outperformed siloxane. Wright (1993) too proved silane to exhibit more vapor transmission than linseed oil which exhibited more vapor transmission than siloxane. Wright’s (1993) results may not reflect the performance of siloxane because of the differences in moisture content at the beginning of the drying period. Silane and linseed oil had similar moisture contents at the beginning of the drying period and thus performance for these two sealers is more accurately reflected by Wright’s (1993) vapor transmission results.

1.4. Variables Affecting Performance

This section discusses the variables affecting the performance and outcome of the concrete deck sealant. The subsections include: concrete parameters, concrete finishing and curing, surface preparation, drying time after coating, abrasion, freeze-thaw exposure, and field parameters. These results are quantified using the four previously mentioned performance measures.

1.4.1 Concrete Parameters

This section discusses how concrete parameters affect the success of the sealed deck. These concrete parameters are: moisture content at the time of sealer application and concrete permeability. This success will again be measured using the four performance measures.

(a) Moisture Content at Time of Sealer Application

Most laboratory investigations show correlation between the moisture content at the time of application and penetration depth obtained by the deck sealant used. Bush's 1998 study indicated that the penetration depth of silane was reduced due to high levels of moisture in the concrete specimen. Basheer (1998) backs up these finding for multiple deck sealants (silanes, siloxanes, sil/siloxane mixture). Tests indicated that with increased moisture content, penetration depth generally decreased within each w/c ratio group.

Wright (1993) used the NCHRP 244 Series II test in a laboratory study to determine the effect of drying time prior to application on the absorption rate of concrete specimens. One, seven, and 14 days of drying time were allow prior to application after the 14 day cure. The study showed that linseed oil demonstrated increased effectiveness (less absorption) with increased drying time prior to sealant application. The study also determined that silane and siloxane's salt-water absorption did not appear to be dramatically affected by drying time prior to the deck sealant's application (Wright 1993). Pfeifer (1981) also performed a laboratory study using the NCHRP 244 Series II test to determine how moisture content in the cement affected the absorption of water. The test indicated that the drying time (moisture content in concrete) did not significantly effect silane's absorption performance. These results agree with Wright's 1993 study.

Pfeifer's 1981 laboratory study using the NCHRP 244 Series II test also determined the effect that moisture content in the concrete has on the vapor transmission and chloride ingress. These Series II tests indicated that silane performed slightly poorer than the epoxy and the methyl-methacrylate with respect to chloride reduction and water absorption when analyzing drying time after moist curing. The test also noted drying time did not have a significant affect silane's performance for vapor transmission and chloride ingress.

(b) Water-cement Ratio

Bush's 1998 study used the Oklahoma DOT Series test to determine if the water-cement ratio of the concrete specimen effects the depth of penetration of the deck sealant used. The Oklahoma DOT test (no initial moisture content) indicated that depth of penetration for silane did not follow any water-cement ratio trends. The following lists the water-cement ratio's which resulted in the greatest amount of penetration to the least amount of penetration: 0.33, 0.49, and 0.44. Basheer's 1998 laboratory study also showed no specific trend for depth of penetration with varying water-cement ratios within specific moisture conditions.

Bush (1998) also determined the effect of a concrete's that water-cement ratio on absorption. The Oklahoma DOT Series (ASTM C642) portion of his testing determined that both treated and untreated specimen's had a correlation with the concrete's water-cement ratio. Specimens with lower water-cement ratios performed better than specimens with higher ratios. The following is list from best performance to worst performance: 0.33, 0.44, 0.49. The NCHRP 244 Series II portion of the test did not follow the same pattern as the Oklahoma test. The following is a list from best performance to worst performance for the NCHRP Series II test: 0.33, 0.49, 0.44). This study presents results that give conflicting conclusions due to the type of test used.

Chloride ingress measurements did not correlate with absorption results for the Oklahoma DOT series (AASHTO T259/T260) test. The following is a list of the water-cement ratios for the Oklahoma test from best performance to worst performance with respect to chloride ingress: 0.33, 0.49, 0.44. However there was a large degree of scatter in the measurement taken. Chloride ingress results correlated well with absorption results for the NCHRP 244 Series II test. The following lists the best performing specimen to the worst performing specimen for the NCHRP Series II test: 0.33, 0.49, 0.44 (Bush 1998). Basheer (1998) determined that untreated concrete's chloride ingress results correlated with its respective water-cement ratio. The study also documented a sharp increase in chloride content for ratios higher than 0.50. A general trend of penetration depth verses water-cement ratio could not be established for the treated specimens. Varying water-cement ratios did not appear to have an impact on chloride ingress for sealed concrete. Thus, the higher water-cement ratio concretes received more benefit from a sealing treatment.

1.4.2 Concrete Finishing and Curing

This section discusses the affect that deck finishing and curing have on penetration depth. The deck can either be finished with a tined or smooth surface. Also the affect curing compounds may have on the sealants penetration depth.

(a) Finish: Tined vs. Smooth

The difference in depth of penetration for tined and smooth finishes could not be determined in laboratory testing of silane sealants (Bush 1997). Also, field studies concurred with the laboratory studies which showed no noticeable difference in the depth of penetration of tined and smooth bridge decks (Whiting 2005). However laboratory trends did indicate that tined specimens had a greater absorption rate and chloride ingress for silane sealants (Bush 1997). This would indicate that treated smooth deck surfaces should stand up better to chloride ion penetration than treated tined surfaces.

(b) Implementation of Curing Compounds

Silane's depth of penetration was found to be significantly reduced when applied after a water-based white pigmented membrane curing compound in the laboratory (Bush 1997). However silane (water-based 40%, solvent-based 40%, and 100 % solids) and siloxane (solvent-based 12%) all adequately penetrated a sodium silicate curing compound at the manufacturer's recommended coverage rate in a field study. Additionally, the 100% silane applied a three times its normal application rate was able to adequately penetrate a previously applied linseed oil emulsion (Whiting 2005). Bush (1997) recommended that all curing compounds be removed from the deck surface prior to application of the deck sealant. Lastly, Pfeifer's (1981) laboratory study (Series I test) indicated that silane was the only sealer of the 21 materials tested that when pretreatment with linseed oil increased salt-water absorption and chloride ingress.

1.4.3 Surface Preparation

Soriano's 2002 field investigations show that variations in surface preparation did not significantly affect the depth of penetration of the three silane sealants tested. The three options tested for preparing the surface were sandblasting, power broom/forced air, or nothing. The same study determined that sandblasting allowed the most water absorption for all sealants used. Bush's 1997 laboratory study indicated that power washing and shot blasting were both effective ways to remove previously applied curing compounds. Power washing caused specimens to absorb slightly more water. Power washing may be preferable for skid resistance because it polishes aggregates less than dry shot blasting. One must consider that power washing increases moisture content of concrete which affects depth of penetration. Adequate drying time is needed if power washing is implemented (Bush 1997).

1.4.4 Coverage Rate

Pfeifer's 1981 laboratory investigation determined how the coverage rate of the material affected absorption, vapor transmission, and chloride ingress. The study determined that silane's absorption and vapor transmission were not significantly affected by varying the coverage rate. However, the study did indicate that lower chloride contents were discovered in the concrete specimens that received the maximum rate of application. This shows that increasing the application rate of a deck sealant will prevent greater amounts of chloride ions from penetrating the deck.

1.4.5 Drying Time after Coating

Wright's 1993 laboratory experiment used the NCHRP 244 Series II test to determine if the amount of time after the specimen is sealed effects the absorption rate. The specimens were tested seven and 45 days after application. The study determined that Siloxane was most effective at reducing salt-water absorption. Siloxane, silane, and linseed oil demonstrated increased effectiveness in reducing salt-water absorption with increased drying time after sealer application. This was especially notable for linseed oil.

1.4.6 Abrasion

Wright's 1993 laboratory study uses a modification of the NCHRP 244 Series II to determine the affect of abrasion on absorption of the concrete. The cube specimens were air dried 14 days after a 14 day moist cure in plastic bags (100% humidity) prior to the sealant application. After the deck sealant was applied the cubes were air dried for 45 days. The top 0.02 in. were removed from one face of the cubic specimens after sealer dried. The specimens were then immersed in 15% NaCl for 45 days. Silane and siloxane were greatly affected by abrasion. Siloxane was more affected than silane. Linseed oil was not affected at all. These comparisons were drawn from the ratio of salt-water absorption after abrasion to salt-water absorption before abrasion. The following list orders the sealers from best performance to worst performance: linseed oil, silane, siloxane. This performance order follows laboratory depth of penetration results.

Pincheira's 2005 study indicated that the tested sealants exhibited exceptional chloride screening properties when not subjected to abrasion, but marginal to poor protection when subjected to abrasion. This coupled with the Wright's (1993) results would indicate that abrasion negatively affects all sealants. One way to reduce the affect of abrasion is to select sealant with a large penetration depth.

Hagen's 1995 field study documented the chloride ingress performance of 16 different concrete sealers applied to the Western Ave Bridge for three years. These chloride ingress field results were then compared with NCHRP Report 244 Series II results. The Acid-soluble chloride reduction with respect to the control specimen was used as performance criterion. The results of Series II tests indicated much higher chloride reductions than field tests indicated after 3 year evaluation. This difference in results was most likely due to vehicular abrasion and freeze-thaw effects on the concrete.

Other major differences between field and laboratory observations are the following.

1. initial moisture state of concrete not controlled in Series II tests at time of sealant application
2. initial moisture state of field concrete also not controlled
3. field concrete (low w/c ratio), lab concrete (probably w/c ratio = 0.5)
4. field concrete – dust samples, lab samples – crushing of one half of cubes

Chloride reduction with respect to control concrete did decrease each year for virtually all sealants studied suggesting freeze-thaw degradation and traffic wear affected the sealers' effectiveness. For some silanes and siloxanes this reduction in performance was much larger than others, suggesting some sealers were more affected than others. Considerable variability in chloride reduction was also noticed for a specific group of sealers (i.e., 40% water-based silanes). The noted variability within a specific type of penetrating sealer also implies that freeze-thaw degradation and/or abrasion resistance is not consistent within a specific type of penetrating sealer (i.e, 40% water-based silanes).

Smutzer (1993) conducted a three year field study on Indiana concrete pavement (7 sealers studied). Chloride reduction for years 1, 2, and 3 compared to laboratory results from NCHRP Series IV Southern Exposure. Southern Exposure does not include abrasion, but includes cyclic salt-water ponding and ultraviolet light and infrared heat exposure. The results of the laboratory and field results did not correlate well. Chloride reduction with respect to untreated concrete was much higher for the NCHRP Series IV tests for all sealers. Major differences between the laboratory and field tests are the lack of freeze-thaw cycles and vehicle abrasion respectively. Ultraviolet light and infrared heat exposure were also much more severe for the laboratory analysis. Also, the water-cement ratio used for the laboratory analysis is not mentioned which could help contribute to the results. Another factor is chloride sampling was taken just outside the wheel paths, which MnDOT Stillwater Bridge Documentation noted to cause increase in chlorides.

It should be noted that silane and the two epoxies demonstrated increased chloride effectiveness with respect to control concrete each year. This is interesting considering freeze-thaw and abrasion effects decreased sealer performance in other studies. One possible explanation for this phenomenon is the untreated concrete was much more severely affected by freeze-thaw damage than the treated concrete.

1.4.7 Freeze-Thaw Exposure

Wright (1993) conducted a laboratory study (similar to Pincheira's ponding procedure under freeze-thaw, ASTM 1990a) do determine the effect freezing and thawing has on surface scaling. At the end of 60 freeze-thaw cycles, silane exhibited largest degree of surface scaling, followed by the control, then siloxane, and finally linseed oil. Thus linseed oil and siloxane protected the concrete the most under surface scaling. Silane experienced the largest amount of damage to surface scaling. A second test based on ASTM C666-84 Procedure A (Rapid Freeze Thaw test), specimens were soaked in water for 2 days then placed in chest freezer. Siloxane had most material loss this time. The following list orders the sealers from most material lost to least material lost: siloxane, silane, uncoated, and linseed oil. Siloxane was not a good performer with this test. This procedure was not recommended as a good way to evaluate sealer effectiveness due to silane's and siloxane's very poor performance.

Two laboratory tests determined the ability of deck sealants to resist freeze-thaw effects. Pincheira (2005) discovered that freeze-thaw testing caused a decrease in nearly all of the tested sealers' ability to deter chlorides. Total chloride content from the freeze-thaw specimens revealed no clear trends in performance with regards to water and solvent-based products and the percent solids. Silanes as a whole were generally the better performing products. Pfeifer (1981) results contradicted Pincheira's 2005 study. Pfeifer's study indicated that the epoxy and the methyl-methacrylate performed slightly better than the silane with respect to acid-soluble chloride ingress. Boiled linseed aged due to significant exposure of ultraviolet light resulted in the best performance in the Series IV tests. The northern climate exposure demonstrated the importance of exposure to freeze-thaw cycles because the urethane and the other methacrylate performed poorly in this environment compared to their very good performance in the first three test series.

Hagen (1995) and Smutzer's (1993) field investigations (same as abrasion results) indicated that laboratory results, which did not incorporate freeze-thaw and abrasion, provided much greater chloride effectiveness than prolonged field studies. Other factors were also present which could attribute to this inconsistency in field and laboratory results.

1.4.8 Field Parameters

The field parameters section discusses the different situations that may impact the sealant's performance measures. The section discusses the environmental conditions at the time of the sealer and the repeated impact of traffic. With an understanding of these topics a better application process can be used.

(a) Environmental Conditions at Time of Sealer Application
The environmental conditions at the time of a sealants application can have a direct effect on the performance of the sealant. Conditions that must be considered when applying a sealant are temperature, wind, and moisture. This section will document some of the problems created by

adverse environmental conditions and give some guidelines on for future application of deck sealants.

When deck sealants are applied at extremely reduced or elevated temperatures there effectiveness can be diminished. Recommendations indicate that most deck sealants should be applied between the temperatures of 40°F and 100°F (Pincheira 2005). Whiting (1990) noticed the following adverse effects when applying deck sealants in hot and windy conditions: "drifting and evaporation...difficulty in obtaining specified coverage on newly placed concrete…runoff during application, discoloration of concrete, flammability, non-uniform application, and little or no apparent penetration." Wright (1993) documents a decrease in penetration depth (43%) of silane due to high wind increasing evaporation rate during application. The moisture state of the bridge deck is also a concern during application. Multiple studies documented a decrease in depth of penetration with higher levels of moisture in the concrete.

When applying deck sealants in the future the following guidelines should be taken into consideration prior to application. The manufacture should be consulted for an appropriate temperature range for which a specific sealant can be applied. In general temperatures between 40°F and 100°F are desired during and at least 12 hours after application (Pincheira 2005). Application of a deck sealer on a wind day should also be avoided. Due to the higher volatility of silane and solvent-based sealers this becomes an elevated concern. Sufficient drying time should be allowed prior to application. Attanayake (2006) suggests a minimum of two days after rainfall or cleaning. Rain or elevated moisture during or 12 hours after application can also diminish the effectiveness of the sealant (Pincheira 2005). This means the extended forecast of application day should be taken into consideration.

(b) Repeated Impact of Traffic

Whiting (2006a) indicated that chlorides were higher in the top ½ in. in the wheel path extracted samples than in the mid-lane extracted samples for the same sealer. These results indicate that chloride penetration is a larger problem in the wheel paths. This fact should be taken into consideration during application.

1.5. Reapplication

Whiting (2006b) used the same sealant when resealing a bridge deck one, two, three, five, seven, and ten years after initial treatment (only in SB lanes). These reapplications did not appear to lower chlorides any more significantly than a single application ten years prior to study. Statistical analysis could be used to determine if the means of the chlorides for the north and south bound lanes are significantly different. (NB lanes showed more variance than SB lanes most notably in 1/16-.5 in. increment.) Evidence showed that the sealant was still present in the north bound lanes 10 years after initial sealing. The spread in penetration data for the two inch section analyzed ranged from 0-0.16 in. Average penetration depth equal to 0.12in. A 2.8 in. section of pavement was analyzed from the south bound lanes. The range and average of the penetration depths were 0-0.28 in. and 0.15 in. respectively. Resealing did not appear to affect penetration depth greatly. When wetting the specimens though, resealed concrete (SB lane) resisted water absorption much more effectively.

Chlorides levels continued to increase even with repeated applications (no complete prevention of chloride intrusion obtained). One should also note that water-based silanes will repeal themselves during reapplication. This will result in a drastically smaller penetration. When reapplying sealants they should be neat or solvent-based to achieve an effective result (Whiting 2006b).

Weyers (1995) estimates the service life for silane and siloxane to be limited eight years due to traffic abrasion. Chloride ingress through the sealed surface did not control due to the fact that the silane and siloxane would be completely be abraded off and need to be reapplied. Water and solvent-based epoxy were found to be abraded off in less than one year. Reapplication period estimate based on chloride ingress included ultraviolet light exposure and outside weather exposure. Freeze-thaw effects were not included.

Chapter 2 – Literature Review on Concrete Crack Sealers

2.1. Background on Crack Sealers

This section introduces some of the products used to seal concrete bridge deck cracks around the United States. Because there are numerous versions of the same general type of crack sealer, only the generic forms are introduced and described. It should be noted that because different manufacturers produce many forms of these sealers, each specific sealer will have a different variation of chemical and physical properties. This section will also introduce the primary performance measures that have been used to test the crack sealers. The performance measures discussed are depth of penetration, bond strength, chloride content/resistance to corrosion, and seepage. The test procedures used to evaluate the performance of the sealers are also discussed.

2.1.1 Generic Products

Products commonly marketed as crack sealers include: epoxies, reactive methyl methacrylates (MMA), methacrylates, high molecular weight methacrylates (HMWM), and polyurethanes. These different products have distinct characteristics that make them favorable for some situations and unfavorable for others. Some of these common properties include volatility, viscosity, initial shrinkage, tensile strength, and tensile elongation.

A survey conducted by Soriano (2002) queried 40 states and provinces regarding which sealers were preferred in their state. Of the 40 states and provinces questioned, 25 responded to the survey. The highest percentage of respondents (i.e., 15 out of 25 or 60%) indicated that they do not employ a crack sealing program for concrete bridge decks. None of the survey responses indicated the use of polyesters for crack repair. The second most amount respondents (i.e., six of the 25 states and provinces or 24%) indicated the used of either epoxies and methacrylates for used when repairing bridge decks. Although the survey indicated the use of epoxies and methacraylates were the most commonly used crack sealers, questions did not ask about HMWMs, MMAs, and polyurethane resins. A separate survey conducted by Tsiatas (2002) stated that (of the states that replied) the predominant crack sealer was epoxy. Four of the 16 states that had crack sealing programs claimed the use of HMWM sealers.

Epoxies are made from cyclic ethers called oxacyclopropanes that harden during a polymerization process. They are typically developed by a reaction between biphenol A and epichorohydrin. Epoxies are generally known for their high tensile strengths (often four times that of HMWMs); however, many different types are developed with a wide assortment of physical properties. Due to this, epoxies are known for their versatility (Meggers 2002). Epoxies also typically are more expensive than most other types of crack sealers. Epoxies can also cause minor skin irritation and allergic reactions.

HMWMs are polymers made from methacrylate monomers. During the curing process of the sealer, an initiator is added to create an oxidation/reduction reaction. The monomer then develops into a high molecular weight polymer. When mixing the three component system (monomer, initiator, and promoter), it has the potential to become violent. For example, if the initiator and promoter are mixed together prior to the monomer resin, it has the ability to explode. Typically the promoter is mixed with the monomer resin initially to avoid problems. Because of this, reading the mixing instructions for all HMWM sealers is extremely important. HMWM resins are known for their low viscosity and high penetration depths.

Reactive Methyl Methacrylates (MMA) are two-component sealers that have similar characteristics as HMWMs but are much safer to use. MMA is formed from reactive methyl methacrylate catalyzed by a 50% dibenzoyl peroxide powder.

Polyurethane resins can also be used to seal cracked bridge decks. Sprinkel (1991) stated advantages to using a polyurethane resin as the fast curing time, little odor, and ease of application. He also stated that the polyurethane resin used in his experiments had numerous drawbacks. The sealer failed to reach a satisfactory depth of penetration at high temperatures. Also the sealer had trouble standing up to freeze-thaw effects. Lastly, the sealer was less than satisfactory in sealing wider cracks.

2.1.2 Primary Performance Measures

There are four primary performance measures for crack sealers: depth of penetration, bond strength, chloride content/resistance to corrosion, and seepage rate. Because of the lack of standardized tests to investigate these performance measures, different variations in procedures have been used. Occasionally fundamentally different procedures have been used to test the same property of the crack. In these cases, it is more challenging to compare the results. This section provides a summary of the performance measures and the associated tests.

(a) Depth of Penetration

The depth of penetration for crack sealers is very different compared to the depth of penetration of concrete sealants. The sealers used for cracks do not penetrate into the pores of the concrete. They are used to cover or fill already formed cracks. It is presumed that the larger the depth in which a sealer can penetrate into an existing crack, the better seal it will create for the crack. This in turn provides improved resistance against chloride ion ingress brought about by deicing materials used on roads. Due to the variable sizes of cracks, some engineers suggest that percent penetration may be more useful than the actual penetration depth (Meggers 1998; Rodler 1989; Sprinkel 2001). For example, a sealer penetrating 0.1 in. into an unknown size crack is not very helpful. However, if a sealer penetrated 0.1 in. into a 0.15 in. deep crack this would be more significant than a sealer that penetrated ten mm into a 0.50 in. deep crack.

There are a few different methods used to determine the depth of penetration of a crack sealer. Field tests typically require a core to be removed from the concrete deck. Also beams and slabs tested in the laboratory are typically saw-cut to expose the crack. The most common method used for determining penetration depth is looking at the cross section of the crack with a microscope. Typically the microscope alone is enough to see how deep the resin has penetrated. If the resin has faded or is not readily visible, a florescent dye is applied to the crack which is subsequently viewed under ultraviolet light. This process makes the interface between the resin and the concrete stand out much clearer. Another method used to determine penetration depth involves first splitting the core along the crack interface. The split cores are then treated with a

solution that consists of half concentrated sulfuric acid and half water. Heating the split cores in the oven at 140°F for two hours causes the organic compounds (sealers) to turn black.
Depth of penetration is influenced by the properties of the crack sealer used as well as the condition of the crack to which it is applied. The chemical property that is most important to depth of penetration is viscosity. The lower the viscosity, the easier it is for the sealer to penetrate and flow through the crack. The size and cleanliness of the crack also play a role in the penetration depth of the sealer. Studies have found that sealers administered to cracks filled with contaminants and debris had a much lower penetration depth (Meggers 2002; Sprinkel 1991). This idea points out importance of cleaning all cracks prior to administering the sealer. The width and depth of a crack also affects the penetration depth. A crack that is wider and deeper will tend to have a larger penetration depth than a narrower, shallower crack.

(b) Bond Strength
The bond strength of the crack sealer provides a measure of the ability of the resin to repair the structural problems in the cracked deck. The bond strength also gives an indication of how well the resin will hold up over time. This is important because if the resin begins to crack and fail, chloride ions may be able to access the steel reinforcement and cause corrosion. There is no standard method used to measure the bond strength of sealers. Because of this there are a few different tests that engineers use to determine the strength of the sealer. Most of these tests can only determine the sealers ability to repair the concrete because the specimen will not always fail through the bonded crack.

The most common test used to determine the sealer bond strength is the tensile splitting test (ASTM C496). This test involves placing a cylinder or disk (usually sliced from the top of a core) on its side in a compression machine. The repaired crack is positioned so that it is running in line with the compressive load. When the compressive load is applied to the side of the cylinder or disk, a tensile load develops in the crack. The compressive force required to fail a repaired crack can be compared to the compressive force required to fail an uncracked concrete specimen. A ratio can be determined by dividing the repaired specimen capacity by the uncracked specimen capacity. This ratio shows the percent of the strength retained by the sealer. Another method to test the strength of the repair is a three-point bending flexural test (ASTM C293). This test is typically done with beams cast in the laboratory. However, Sprinkel used half circle disks cut from the cores harvested. Again the repaired cracked and uncracked specimens need to be tested to determine the strength ratio.

Once the tests are conducted, the failure surface is observed and documented. The three different types of failure planes that can be produced are concrete, bond, and sealer failure. Sealers with higher tensile strengths tend to cause a concrete failure. This is due to the fact that the sealer’s tensile strength is similar to or greater than that of the concrete to which it bonds. This means the core will not split along the same crack that was sealed. Sealers with lower tensile strengths tend to produce bond or sealant failures. This is due to the concrete having a higher tensile strength than the sealer. Failure to clean the crack and its contaminants can also cause a bond failure. Also when the specimen is exposed to freeze-thaw effects it can lower the bond strength of the sealer. This in turn inhibits the sealer’s effectiveness to seal the crack from corrosive materials such as chloride ions. Due to the varying temperatures in the Midwest region it is important to select a sealer that is not susceptible to this decrease in bond strength.

(c) Seepage

The seepage through the repaired crack gives an indication of how the repaired pavement will prevent chloride ion ingress. This is because the deck seepage is a measure of the amount (or volume) of water that passes through the cracked concrete. Water penetrating through cracks is the fastest way chloride ions are transferred to the reinforcement. This would suggest that a repaired concrete with a lower seepage would protect the rebar better than a deck with a faster seepage.

There are multiple ways in which the amount of seepage through the cracks can be measured. The first test involves forming a barrier around the top of the concrete core. After the sides are waterproofed, water can be poured into the barrier on the top of the core. While keeping the water height constant the rate in which the water passes through the core can be recorded. A field method requires observing the underside of the bridge during a rainfall. The number of leaks before the cracks in the concrete deck were sealed can be compared to the number of cracks after the deck has been sealed. This crude test is used most often in the field to give an indication that the cracks have been successfully sealed.

(d) Chloride Ingress and Corrosion

The existence of cracks in the bridge deck creates a fast track for the chloride ions to infiltrate the concrete and corrode the reinforcement. The crack sealers act as a barrier to slow the ingress of chloride ions into the concrete and reinforcement. The ability of a sealer to lessen chloride ingress is based on the aforementioned performance measures (i.e. depth of penetration, bond strength, and seepage). If a sealer penetrates the cracks completely and has a perfect bond with the concrete, it should hypothetically prevent most of the corrosive agents from penetrating the concrete and reaching the reinforcement. There were a number of ways that chloride content and resistance to corrosion were measured in the laboratory and the field.

One of the first ways used to determine a sealed crack's resistance to corrosion was discussed in Tsiatas' report (2002). He measured the varying weight of the specimen and the fundamental transverse frequency to discover the state of the sealer. This method (conducted in accordance with ASTM C666) was used to determine the effect that freeze-thaw cycles had on the repaired crack. A loss in weight and the decay of the specimen's fundamental transverse frequency signified the failure of the repaired crack. A second method used to measure resistance to corrosion was discussed in Meggers' report (1998). The corrosion rate and potential were measured by applying a voltage to the embedded rebar and measuring the current. A monitor was then used to measure the polarization resistance. This polarization resistance is inversely proportional to the corrosion rate. Therefore when the polarization resistance decreases the corrosion rate increases. The corrosion potential and rate were measured using a Cortest Model PR-4500 device. By subjecting the beam to this test in between cycles of freeze-thaw and moisture change, a feel for the corrosion rate increase can be determined. These methods were only used in the laboratory; however, they could be implemented in field studies with a lot more time and effort.

When finding the chloride content of the concrete, the most common method used requires gathering powder samples from the bridge deck using a hollow bit vacuum drill. Typically samples are taken from two or three different concrete depths. Typically three different depths are investigated: between 0 and 0.75 in., 0.75 and 1.5 in., and 1.5 and 2.25 in. The powder samples were taken to a laboratory to determine the water soluble chloride levels. Meggers used the Kansas Department of Transportation Method 814 to determine the chloride levels. Corrosion can begin to appear with chloride levels as low as 0.6 kg/m^3. When levels exceed of 1.2 kg/m^3 the Kansas Dept. of Transportation considers steel corrosion inevitable (Meggers 1998). Sprinkel (1991) also used ASTM C120 to test the chloride ingress (or permeability) of his concrete specimens.

2.2. Performance of Crack Sealers

This section consists of four subsections which are the primary performance measures for crack sealers: depth of penetration, bond strength, chloride ingress and corrosion, and seepage. Each subsection presents laboratory and field results for crack sealers and their respective performance measure being discussed. If a researcher implemented a laboratory and field investigation, results from the laboratory and field investigation are discussed separately. The subsections are written to enable the reader to see general trends noticed as well as the differences in performance among the crack sealers studied.

2.2.1 Depth of Penetration

(a) Laboratory Investigations
In a 2005 study, Pincheira tested ten specimens that had sealed cracks (2 HMWM, 2 methacrylates, 1 urethane polurea hybrid, 4 epoxies, and 1 epoxy resin). All ten sealers were able to penetrate the entire depth of the cracks (2.5 in.) which were set to three different width. Sprinkel (1995) also determined that all five sealers studied (1 HMWM, 1 polyurethane, and 4 epoxies) could penetrate the entire depth of cracks with different preset widths.

Rodler (1989) tested the percent penetration of three different HMWM sealers. The penetrations of the three sealers were measured at 92.0, 83.3, and 95.7 percent. This averaged to 90.3 percent penetration. High temperature tests were also conducted with the three sealers. The average percent penetration declined to approximately 80 percent when the sealers were applied to a slab with a temperature between 110 to 120 °F. A moisture test was also conducted to determine how long the concrete should dry until 95 percent of the dry specimen’s penetration was met. Rodler determined that the concrete should dry for approximately two days for 95 percent of the penetration to be retained.

(b) Field Investigations
Engstrom (1994) found that a HMWM sealer penetrated between 0 and 3 in. into a D-cracked concrete pavement. The large variation in penetration was attributed to the depth and width of the cracks. No additional information was given on the penetration depth of the sealer (e.g., average penetration depth or what size of crack had the best penetration).

Krauss (1985) conducted field research at four different bridge deck locations. The engineers originally tried to seal the cracks of the first site with an epoxy sealer. It was determined that the epoxy sealer did not reach a satisfactory depth of penetration. After a closer look at the cracked deck, it was determined that the 0.008 in. cracks quickly narrowed to 0.002 in. directly below the surface. A lower viscosity HMWM sealer was then decided upon and applied to the deck. Cores revealed that the sealer penetrated the entire depth of the crack to the reinforcement steel. The same HMWM sealer was used at three other bridge sites. The depths of penetration were not given however Krauss stated that the application of the sealer was a success.

A study using a HMWM, conducted by Lasa in 1990, grouped the cracks on Seven Mile Bridge into three categories. Group one consisted of crack widths smaller than 0.005 in. Group two consisted of cracks between the width of 0.005 and 0.010 in. The final group (group three) contained all of the cracks wider than 0.010 in. The average depths of penetration 11.5 months after application for the three groups were 0.76, 0.93, and 0.95 in., respectively. The depth of penetration was again measured 16 years after application. The cores were again categorized into the same three groups and yielded penetration depths of 0.24, 0.35, and 0.42 in. Lasa assumed that the depth of penetration would not have changed with the elapsed time. Two reasons were given for the reduction in penetration depth. The first was that the resin dulled over time and became harder to see after 16 years. The second was that fewer cores were taken 16 years after application in comparison to 11 months. He suggested that an inaccurate representation of the penetration depth could have been obtained due to the limited number of cores harvested from the deck.

Marks (1998) collected 2 in. deep cores from the US 136 Bridge to determine penetration depth. The core depths were limited to 2 in. because he did not want to damage the epoxy-coating on the embedded rebar. The HMWM sealer penetrated the entire 2in. of the cores.

Meggers (1998) sealed eight bridges of varying ages with three different sealers (2 HMWM and 1 epoxy). The depth of penetration data retrieved from the cores was very scattered and deemed unhelpful. However, the percent penetration of the cracks did give a better indication of which sealers performed the best. The average percent penetration given in descending order (best first) is: HMWM A, HMWM B, and epoxy. Considerable amounts of contaminants were found in the cracks impeding penetration.

A 1989 Rodler study determined the percent penetration of a HMWM sealer used in the Loop 1604 Bridge. The cores showed that the sealer penetrated 60 to 80 percent of the cracks.

Soriano (2002) studied the penetration depth of four different sealers (methyl-methacrylate, polyurethane, epoxy, and a silicon joint sealer). Methyl-methacrylate exhibited larger penetration (~0.010 in. larger) than epoxy, polyurethane, and silicon joint sealers. Soriano attributed this to the methyl-methacrylate's roller application.

Sprinkel (1991) determined the penetration depth of two HMWM sealers (Transpo Industries, Inc., T70M and T70X). There was no significant difference in the penetration depth of the two sealers. Neither sealer penetrated well below 0.5 in. Cracks larger and smaller than 5.91×10^{-3} in. at a depth of 0.25 in. were found to be 92 and 44 percent filled, respectively. Cracks larger and smaller than 5.91×10^{-3} in. at a depth of 0.5 in. were found to be 57 and 35 percent filled. All cracks at depths greater than 0.5 in. were less than 20 percent filled. Considerable amounts of contaminants were found in the cracks impeding penetration.

Whiting (2006c) determined the penetration depth of HMWM sealers used on TH 100 Bridge. Penetration of the sealer could not be seen deeper than 3/8 in. Large amounts of dirt and silt were also found in the cracks impeding the penetration.

(c) Summary of Penetration Depth Studies

There are a number of variables that affect the penetration performance of a crack sealer. Although this report refers to the sealers by their generic names, each sealer used is slightly different. Because most sources do not give the exact name or brand of sealer, it becomes hard to compare results among studies. Also some studies compare multiple sealers that are part of the same generic family. Keeping in mind that generic families are typically similar, one must remember that they are not the same and have different characteristics. One of these varying characteristics that has a large effect on penetration depth is viscosity. In addition to the varying sealer types, the crack widths and depths also greatly affect the sealers penetration potential. Typically wider and deeper crack have a greater penetration depth potential than shallower and narrower cracks. However, Meggers (1998) states that although wider cracks are easier to penetrate, cracks can become too wide and begin to inhibit penetration. Meggers attributes this to contaminants collecting more readily in wider cracks. Contaminants have a large affect on the ability of the sealer to penetrate cracks. This is because the contaminant build up in the cracks can create a barrier that the sealer cannot penetrate.

The laboratory tests indicate that all of the sealers tested were equally effective in penetrating the cracks. There are a few possible reasons why no specific material performed better than the others. One reason may be that the cracks used in the laboratory tests had a fixed or small crack depth. For example, the Pincheira study had a crack depth of 2.5 in. for each of the tests. Because all of the sealers penetrated the entire crack depth, a comparison could not be drawn. Also laboratory tests in general are under clean and controlled conditions. Because there were no contaminants in the cracks, as there would likely be in the field, the sealers were able to penetrate to a much larger depth in the laboratory. This depth would likely be unattainable in the field due to contaminant build up.

The field tests indicate that HMWM and methyl-methacrylates performed the best in penetration tests. Krauss (1985) documented a case in which an epoxy sealer failed to penetrate the cracks of a bridge deck. After the epoxy’s failure, a HMWM was used to successfully seal the same cracks. Meggers (1998) also conducted a study in which two HMWM sealers obtained a deeper penetration than an epoxy sealer. The HMWM and methyl-methacrylate sealers performance is likely due to their lower viscosity in comparison to the other sealers. To state a predicted depth of penetration for either of these two types of sealers is difficult due to varying crack sizes and contaminant build up.

2.2.2 Bond Strength

The bond strength section is subdivided into the following four sections: type of failure, effect of increasing crack width, effect of freeze-thaw exposure, and overall performance. The sections will discuss some general bond strength trends found throughout the literature and the effect different sealers had on these trends.

(a) Type of Failure

There are three types of failures that can occur in repaired concrete specimens. The failure can occur through the concrete, the sealant-concrete interface (bond failure), and the through the sealer. Often a combination of two or three failures can occur when a specimen is loaded. Typically a concrete failure of the specimen is desired. This would indicate that the crack sealer repaired the specimen up to or beyond its original uncracked capacity. Engineers have run tests to determine whether the bond strength of the crack sealer used affects which failure occurs.

Sprinkel (1995) performed a flexural bending test on reinforced concrete beams. The beams were repaired with three epoxies, one HMWM, and one polyurethane. The repaired polyurethane beam retained 100 percent of its original strength. The following failure types were experienced: 20% bond, 80% concrete, and 0% polymer. The first epoxy repaired beams (E1) retained 112 percent of its original strength. The following types of bond failures were experienced with the E1 sealer: 1% bond, 99% concrete, and 0% polymer. The second epoxy repaired beam (E2) retained 114 percent of its original strength. The beam had the following bond failures: 17% bond, 83% concrete, and 0% polymer. The third epoxy (E3) retained 100 percent of its original strength and had the following failures: 2% bond, 97% concrete, 1% polymer. The HMWM sealer retained 116 percent of its original strength and had the following distribution of failures: 1% bond, 97% concrete, and 2% polymer.

Pincheira (2005) tested the bond strength of ten different sealers and recorded their failure mode. The sealers that had higher bond strengths yielded concrete failures. Sealers with lower bond strengths yielded bond failures. Pincheira also tested for freeze-thaw effects. If a bond strength was significantly lowered due to these effects of freezing and thawing a bond failure was typically experienced.

Lasa (1990) gathered cores taken from the Seven Mile Bridge and used a tensile splitting test to determine their bond strength. The splitting test was performed on one inch disks cut from the top of the cores. The compressive load applied at failure and types of failures were recorded. The percentage of the new crack that traveled through the uncracked and previously cracked concrete was recorded (example: 100% through uncracked, 50% through uncracked and 50% through cracked, or 100% though cracked). The load required to break a specimen with the new crack 100% through an uncracked section was compared to a specimen with the new crack 100% through the previously crack section. The average load required to break a specimen with the new crack 100% through uncracked concrete was 1312 pounds. The average load required to beak a specimen with the new crack 100% through the old crack is 732 pounds. As a note the study did not determine if the failures through the old cracks were bond failures or sealer failures.

Tests showed that higher strength bonds produced predominantly concrete failures. This is due to the belief that higher strength sealers typically create a better bond with the crack wall. Also some of the high strength sealers have a higher tensile strength than concrete. Both of these points contributed to the higher strength bonds producing concrete failures. Since lower strength sealers tend to create worse bonds with the concrete crack walls and have lower tensile strengths, one would assume that lower strength sealers would have bond and sealer failures. This was also supported by the test results. However many aspects other than bond strength can effect which failure occurs. Dirt and other contaminants that can coat the crack walls can cause an incomplete bond between the crack and the sealer. Also the temperature and amount of moisture during application can affect the bond strength of sealers.

(b) Effect of Increasing Crack Width

This section will discus how the size of a crack effects the sealer's ability to repair it. Since there is no standardized method for measuring the bond strength of a crack, many methods were used in the studies. The most popular methods used were the tensile splitting strength and flexural strength of a repaired specimen. This repaired strength could then be compared to an uncracked specimen to see what percentage of the tensile or flexural strength has been retained. The laboratory and field results concerning this relationship are listed below.

Sprinkel (1995) performed a flexural bending test on reinforced concrete beams. The beams had four different size repaired cracks. When the five different sealers are averaged according to crack size a distinct trend appears. The 7.87×10^{-3}, 0.02, 0.03, and 0.04 in. wide cracks retained average strengths of 113.6, 109.2, 105.0, and 107.6 percent of their original strength. This data indicates that as the crack gets wider it retains less of its original strength. The epoxy sealers seemed to have the smallest deviation in strength when the crack width changed. However this deviation was only slightly smaller than polyurethane and HMWM.

Pincheira (2005) tested ten different sealers on four different crack widths. Since all of the sealers were not tested in all crack width, it is hard to give and average bond strength for each crack width. However, a clear reduction in bond strength can be seen in all sealers when the crack width increases. For example, one sealer (Sikadur 55SLV) has the following bond strengths for hairline, narrow, and medium cracks: 8560, 7994, and 6321 pounds. Although bond strengths vary between sealers, all of the sealers' bond strengths decline with an increasing crack width.

Lasa (1990) gathered cores taken from the Seven Mile Bridge and used a tensile splitting test to determine their bond strength. As previously stated, the splitting test was performed on one inch disks cut from the top of the cores. The cracks were placed into three groups depending on their crack width. Group one contained cracks that were 0.005 in. or narrower. Group two contained cracks that were between 0.005 and 0.010 in. Lastly, group three contained cracks that were larger than 0.010 in. wide. The average tensile splitting load recorded for group one, two, and three are 888.20, 1053.51, and 784.43 pounds respectively. These results do not give a clear indication whether the bond strength increased or decreased with crack width. However it should be noted that the cores gave a wide range of tensile splitting strengths. Also there was only one core tested from group three. This means the strength results from group three may be inaccurate.

Although there is a slight scatter in data, most of the results support the idea that bond strength decreases as crack width increases. There are a lot of variables that could have contributed to the data in Lasa's study not matching up with the rest of the laboratory data. For example, the number of cores that went into the three groups that Lasa tested were not the same (one group only had one core). Due to the unpredictability of concrete, a proper average was probably not developed for that crack width group. Also cracks tested from the field typically have a large amount of contaminants. The varying amount of contaminants in the cracks can create a wide scatter in the data recorded.

(c) Effect of Freeze-thaw Exposure

The repetition of freezing and thawing can have a detrimental effect on some crack sealers used. The effect of this temperature change can be seen most easily in the reduction in bond strength. The freeze-thaw cycles can also affect the sealers flexibility. Because of this, great care should be taken when selecting a sealer for use in Minnesota.

Tsiatas (2002) tested a repaired beam's resistance to corrosion when subjected to freeze-thaw effects. The process was determined from recording the weight and the transverse frequency of the specimen every 30 to 36 cycles. The beams were subjected to 300 cycles total. The loss of weight and decay in the transverse frequency indicated if the sealer was failing. If the sealer's integrity does not change the transverse frequency should remain at zero. An increase means the sealer has gotten stronger and a decrease means the sealer has weakened. According to the freeze-thaw testing, all of the sealers performed well. The durability factor for each of the sealers was determined from ASTM C666. With a slight improvement in fundamental transverse frequency, the two HMWM sealers performed the best (+4.31 and +1.37). The two epoxy sealers also performed well with only a slight loss in fundamental transverse frequency (-1.36 and -5.01). The modified cementitious material performed slightly worse than the epoxy (-6.37), and the cementitious material performed the worst of all of the sealers used. The cementitious material products were the only sealers that lost a large fraction of their fundamental transverse frequency (-28.11 and -133.4).

Sprinkel (1995) tested the durability of 5 sealer when subjected to ASTM C666 freeze-thaw testing. The test showed that two epoxies and the only HMWM performed the best. The third epoxy performed poorly and the polyurethane performed the worst. Pincheira (2005) tested the freeze-thaw effects of ten crack sealers (2 HMWM, 2 methacrylates, 1 urethane polurea hybrid, 4 epoxies, and 1 epoxy resin). All sealers experienced a significant reduction in bond strength when subjected to freeze-thaw cycles. However the epoxies and epoxy resin (Sikadur 55SLV) performed the best for bond strength before and after freeze-thaw effects.

Meggers (1998) used a Cortest Model PR-4500 device to measure the corrosion potential and rate of repaired beams. The beams were subjected to freeze-thaw, wet/dry, and temperature cycles. This means it is hard to isolate the effect that only freezing and thawing had on the beams. These cycles were proportioned to represent Kansas' typical weather patterns. The sealers are listed in descending order of performance (first is the best): epoxy, HMWM B, HMWM A, HMWM C, and the unsealed control.

No field studies were tested for freeze-thaw exposure. However, it should be noted that a bridge could be subjected to freezing and thawing depending on its geographical location. Unfortunately the effect of freezing and thawing changes every season. Also it is unknown whether a sealer's strength is reduced due to age, cyclic loading, or freeze-thaw effects.

The laboratory tests indicate that epoxy sealers stand up the best to freeze-thaw effects (Pincheira 2005; Meggers 1998; Sprinkel 1995). HMWM resins are a close second to the epoxy sealers.

Polyurethanes and urethane polyurea hybrids did not fair well in freeze-thaw testing. Due to their poor performance, bridges in northern climates should typically select a different sealer for its cracks.

(d) General Performance

Pincheira (2005) determined the bond strength of ten crack sealers (2 HMWM, 2 methacrylates, 1 urethane polurea hybrid, 4 epoxies, and 1 epoxy resin) using prisms subjected to a loading scenario similar to a tensile splitting test. Epoxy and epoxy resins worked best for hairline cracks (1/32 in.). The epoxy resin also performed the best for bonding medium width cracks (1/8 in.). The epoxy and HMWM sealer performed the best for the wide cracks (1/5 in.) tested. Pincheira also stated that the HMWM and epoxy sealer exhibited poor freeze-thaw resistance. Because the epoxy resin provided good freeze-thaw resistance, Pincheira suggested it should be used for the wide cracks as well. With this alteration the epoxy resin (Sikadur 55 SLV) retained the best bond strength for all three crack width categories.

Rodler (1989) used a three-point bending test to determine the bond strength of HMWM repaired concrete. The repaired slabs retained an average of over 84 percent of their original uncracked strength. The sealers were also applied when the slab temperature was between 110 and 120 °F. The high temperature slab retained an average of 84 percent of the uncracked strength. This would indicate the increase in temperature had minimal effects on the resulting bond strength.

Lasa (1990) determined the bond strength of HMWM repaired cracks by cutting 1 in. off the top of the collected cores and subjecting them to a tensile splitting test. He determined that after 11.5 months, the repaired cracks retained 90.5 percent of the uncracked specimen's strength. The 16 year old repaired cores retained between 70.4 and 87.5 percent of the uncracked specimen's strength.

Rodler (1989) determined the bond strength of the HMWM repaired cores from the Loop 1604 Bridge. The bond strength was determined by performing a tensile splitting test on the cores with repaired cracks. The repaired cracks retained at least 80 percent of the original uncracked concrete.

Sprinkel (1991) used two methods to determine the bond strength of two HMWM sealers. The first test subjected 2 in. disks cut from cores to a tensile splitting test. The second test subjected semi-circle disks cut from the cores to a three point bending test (flexural). The average modulus of rupture in the flexural test for the repaired specimen was 110 psi. The uncracked specimen had an average modulus of rupture of 990 psi. This means that the repaired cracks retained approximately 11 percent of their original uncracked strength. The tensile splitting test produced very similar results. Sprinkel attributed the poor bond strength to the large amounts of contaminants that lined the crack walls.

Whiting (2006c) conducted a study of the TH 100 Bridge, which was initially sealed with methacrylate flood coat. Eight cores were taken two years after initial construction. Four cores were taken over cracks. Three of the four cores broke during the coring process or during the test set up to determine water seepage. This suggests the methacrylate did not have adequate bond strength for at least three of the four cracked cores analyzed. Further corroborating this claim, the crack faces were found to be coated with dirt and silt.

There are a number of variables that affect the bond strength of a crack sealer. Some of the primary variables include the sealer properties (i.e., viscosity, tensile strength, tensile elongation, and initial shrinkage). Two sealers with the same generic name (HMWM for example) can have different properties. Also the width of the crack repaired typically affects the repaired strength. Trends seem to indicate that wider cracks retain less strength than narrower cracks. Contaminants in the cracks can greatly reduce a sealer's bond strength. The dirt lining the crack surface creates a barrier between the sealer and the concrete.

Laboratory studies indicate that epoxy sealers performed the best in terms of bond strength. The HMWM sealers also performed well but were second in comparison to the epoxy sealers. The 2005 Pincheira study stated that the epoxy resin (Sikadur 55 SLV) performed the best for all crack widths. The epoxy resin also stood up well to freeze-thaw exposure. The 1995 Sprinkel study stated that all sealers retained 100 percent of the original flexural strength. However, the HMWM and one epoxy were the only sealers that stood up to freeze-thaw effects.

Very few sources could be found testing materials other than HMWM in the field. The HMWM sealers varied in their effectiveness depending on the study. Lasa (1990) stated that the repaired cracks retained 90 percent of their uncracked strength after approximately one year. Also there was a very small drop in strength when the cores were tested again 15 years later. Sprinkel's 1991 study found HMWM repaired cracks retained only 11 percent of their original strength, which was attributed to large amounts of dirt and contaminants that lined the crack walls.

2.2.3 Seepage

No laboratory investigations found on seepage.

A 1985 Krauss study looked at the application of HMWM sealers on four different bridge decks. A crude visual inspection of the bottom of the deck was done to determine if water was flowing through the deck after application. Krauss stated that all HMWM applications were successful in reducing the flow of water through the bridge deck.

Marks' (1988) original assessment of a bridge's leakage showed at least 215 cracks leaked through the bridge deck. A HMWM sealer was used to seal the deck to slow the leakage. To determine if the HMWM crack sealer had successfully sealed the bridge, the underside of the deck was observed during rainfalls to watch for leaking. Initially no leakage was observed on the underside of the deck. However, eventually there were over 300 cracks on the eastbound side of the bridge and 400 cracks on the westbound side of the bridge that leaked. The leakage was at a much lower rate in comparison to the unsealed bridge. Due to this observation, the engineers applied a second coat of the same sealer to half of the bridge. It was observed during June of 1988 with 0.6 in. of rainfall that 50 cracks leaked between piers #4 and #5, and 16 cracks leaked between #5 and #6. Both of these sections had only been subjected to one coat of HMWM sealer. The sections with two coats of the sealer between piers #6 and #7, and #7 and #8, had 14 and 47 leaking cracks, respectively. Marks determined that the HMWM sealer was not successful in preventing all leaks in the deck with one or two coats. However the sealing process did reduce the total amount of leaks that the deck experienced in comparison to when it was untreated.

Whiting (2006c) showed that uncracked concrete exhibited a seepage rate roughly three orders of magnitude smaller than that of the crack which still appeared to be sealed. The “sealed” crack had a seepage rate that was roughly two orders of magnitude smaller than that of the “open” crack. The benefit of a sealed crack over an open crack was clearly seen in the water seepage results. Also, the uncracked concrete proved to exhibit much lower permeability than the cracked concretes.

The amount of seepage provides a measure of how easily water can penetrate through the cracked or uncracked concrete. Because water may transmit chloride ions, the amount of seepage essentially measures how easy the chloride ions can reach and corrode the reinforcement. The performance measures discussed earlier (i.e. penetration depth and bond strength) both contribute to the sealer’s ability to limit seepage through the deck. The deeper penetration enables the sealer to fill more areas of the crack that may be hard to reach. The higher strength bond means the sealer and sealer interface should not crack and fail. The cracks that appear in the sealing materials create an accelerated route for water to flow through the deck.

There were no laboratory investigations regarding the amount of water seepage found among the literature. Also all field sources discovered only recorded the seepage rate of HMWM sealers. The field tests showed that all HMWM sealers were not able to stop the flow of water through the cracks in the deck completely. Marks (1988) stated that the number of leaks was reduced after the first application of HMWM sealer; however the deck still contained a minimal number of leaks. Because of these leaks, the engineers applied a second coat of the same HMWM sealer. The second coat of sealer was also unsuccessful in stopping the leaks in the bridge deck. The rate at which water was leaking though the cracks was reduced after each coat was applied to the bridge deck. Whiting (2006c) found the repaired cracks slowed the seepage of water by a magnitude of two.

2.2.4 Chloride Ingress and Corrosion

The chloride ingress and corrosion section is subdivided into the following three sections: increased chloride concentration locations, trapping chlorines in the deck, and overall performance. The sections will discuss some chloride ingress trends found throughout the literature and the effect different sealers had on these trends.

(a) Increased Chlorides Concentration Locations

This section will discuss where higher levels of chloride ions can be located. Once problem sections are located, engineers can create a plan to alleviate the problem. This also becomes important when testing chloride levels. By knowing where chloride levels are the highest the tester can adjust their reading by knowing the location it was measured from.

Oh (2004) uses an expanded version of Fick’s second law to predict the effect that rebar has on chloride diffusion through reinforced concrete structures. The variables for this model were reinforcement or no reinforcement, the diameter of the reinforcing steel, and the cover depth.

The results showed that the presence of reinforcement caused a build up of chlorides. Further characterizing the results, the larger the diameter of the reinforcing steel, the more pronounced the accumulation of chlorides ions. Increasing the cover depth negated the chloride accumulation in front of the reinforcing bar somewhat. The reinforcement blocked the chlorides from diffusing further into the concrete and thus caused chloride accumulation. The author warns that this chloride build up will lead to a shorter time to corrosion initiation of the reinforcement.

Whiting (2006b) determined that chloride concentrations were significantly higher near cracks than in other sections of the deck. Whiting raises the question: Is this due to cracks solely attracting more chlorides or a combined effect of reinforcement blocking chloride diffusion? The integrity of steel compromised only near cracks after 10 years of service.

Whiting (2006c) also performed chloride analysis on an uncracked, sealed crack, and open crack core. Chlorides were found to be significantly higher near the unsealed open crack than in the uncracked concrete. Chlorides generally decreased as one moved farther away from the sealed and open cracks. This trend was especially obvious in the open crack core. Higher chloride contents were also observed in the open crack core than in the sealed crack core.

Chloride levels are generally higher near the embedded rebar in the concrete and open cracks. Oh described how the reinforcement blocked the chlorides from diffusing further into the concrete and thus caused chloride accumulation. Whiting also documents the buildup of chlorides near cracks. Both of these aspects can cause accelerated corrosion. Two methods suggested to prevent or lessen the effect of the buildup are to seal all open cracks and embed the rebar deeper in the deck.

(b) Trapping Chlorides in the Deck

Some scientists speculate that sealing old decks or cracks can cause the existing chlorides to become trapped in the bridge deck. The deck and crack sealers would prevent any water (high in chloride content or chloride free) from penetration into the deck. This would slow or stop the diffusion of existing chlorides through the deck. Because the chloride ions would not leach out of the concrete they would be free to corrode the rebar.

Meggers (1998) ran 12 beams which contained high chloride concentrations under tap water to simulate the excessive wetting that happens during spring and summer. Seven of the 12 beams showed a significant decrease in chloride levels. This was due to the tap water leaching out the chloride ions.

Meggers (1998) tested the chloride concentrations of eight bridge decks before and after the cracks were sealed. He could not make any conclusion as to which sealer performed the best due to the large scatter of the chloride concentrations. In many cases the sealed sections increased in chloride concentration faster than the control (unsealed) section. The average deepest chloride sample taken from the deck actually decreased over three years. This was the only sample that averaged a decrease. Meggers suggests that the crack sealers may have trapped the chloride content in the old bridges.

Very little literature covers a cracks sealer’s ability to possibly trap chlorides in bridge decks (more may be present for deck sealants). However, Meggers uses it as a possible explanation for his data because the unsealed sections contained fewer chlorides in many cases. Meggers sealed a series of older bridges which probably contained high levels of chlorides in the deck. This problem would probably be avoided if the deck and cracks were sealed soon after construction. However this is not always an option. More research would need to be done on this topic to better understand its importance.

(c) General Performance

Meggers (1998) used a Cortest Model PR-4500 device to determine the corrosion potential and rate of beams subjected to freeze-thaw, wet/dry, chloride pooling, and temperature conditions of the Kansas state area. A corrosion rate of 1.0μA/cm^2 was considered the maximum rate. This is due to that fact that when the corrosion rate gets to1.0μA/cm^2, damage from the corrosion begins to take place. The unsealed cracked beam reached the corrosion rate of 1.0μA/cm^2 in 50 days. After plugging this into an equation, it was determined that the unsealed crack could keep corrosion below 1.0μA/cm^2 in an actual bridge for approximately four to five years. The epoxy sealed beams lasted 271 days. The equation gave the bridge a minimal corrosion lifespan of 15 years or more. The HMWM A sealed beams lasted 156 days. This yielded a time of nine years of protection for the bridge. HMWM B sealed beams lasted 170 days, which meant the bridge should be protected for up to 11 years. The final sealer (HMWM C) which was only used in the laboratory experiment lasted 110 days. This would protect the structure from corrosion for approximately eight years.

Meggers (1998) also performed a field investigation which measured the chloride content of concrete bridge decks before and after the application of three sealers (HMWM A, HMWM B, and epoxy). A hollow bit drill was used to remove concrete powder from three depths per hole. No correlation in the data was found to show that any sealer worked better than the other. In many cases, the unsealed deck performed better than the sealed deck section. One correlation found was that the bridges in the northern region of the state had higher chloride contents than bridges in the southern regions of the states. This can be explained by exposure to harsher winter weather in the upper half of Kansas. Due to this colder weather, more deicing products are used on the roads which cause higher chloride levels.

Sprinkel's (1991) cores gathered in 1988 showed that the top two inch slab had an average chloride permeability of 44 percent in comparison to the base slab. The following years test data revealed that the top two inch slab had an average chloride permeability of 52 percent in comparison to the base slab. It can be concluded that the increase in chloride permeability over the year was due to the resin cracking. This allowed fluid to pass through the cores with greater ease. The tests also showed that the chloride permeability increased in cracks sealed with T70M. This is due to the early cracking that occurred in the resin. Sprinkel attributed the early creaking in T70M due to is lower flexibly in comparison to the T70X sealer. Also the permeability increased more in the transverse cracks in comparison to the longitudinal cracks. One unexplained occurrence was that the uncracked base concrete had a higher permeability than the cracked concrete. Since the resin did not penetrate far enough to reach the base concrete, Sprinkel felt that the sealer played no part in the unexpected readings.

Laboratory tests give mixed results concerning which sealer performed the best in preventing corrosion. Meggers' laboratory study showed the epoxy sealer (subjected to freeze-thaw, wet/dry, chloride pooling, and temperature conditions) outperforming the three HMWM sealers in reducing rates of corrosion. Also, no conclusion could be drawn from Meggers' field studies due to seemingly random results. Because some of the control (unsealed) deck sections performed better than sealed sections, Meggered suggested that crack sealers may trap chloride ions in the cracks.

It should be noted that the flexibility of the sealer played a substantial role in its ability to seal the cracks. Due to changes in live loads and thermal expansion, the cracks in the bridge are constantly changing sizes. Because of this, sealers that are not flexible tend to crack and fail. These sealers allow a greater amount of chloride ions into the concrete deck. Sprinkel (1991) tested two HMWM cracks sealers with varying flexibility. According to inspection of the bridge roughly one year after application, the cracks sealed with T70M had extensive cracking in the resin. The cracks sealed with T70X (a more flexible resin) had very few cracks in the resin. Sprinkel also documented far fewer leaks in the deck sealed with the more flexible resin. Due to freeze-thaw effects and cyclic loading the flexibility of the resins can also wear off. Sprinkel stated the flexibility of T70X wore off 15 months after application.

2.3. General Trends

There are a few common trends found in the literature review on crack sealers. With a better understanding of these tends, one can better understand how the sealers work and pick the best sealer for the job. The section is split into the following topicslifespan of sealed cracks, the presence of recracking, and track-free time for sealers.

2.3.1 Lifespan of Sealed Cracks

Typically studies conducted on sealed cracks test the results of the study within the first year. This means there is not a large amount of literature discussing the lifespan of sealed cracks. However there are some methods that can be used to predict the lifespan of a sealer. Combining the small amount of literature with various methods of prediction, a better sense for how long sealers can effectively protect a bridge deck from corrosion.

(a) Laboratory Investigations

Meggers (1998) used a Cortest Model PR-4500 device to measure the corrosion potential and rate of repaired beams. An estimated lifespan equation was also used to convert the devices reading into a length of time. The equation uses the number of days required to reach a corrosion rate of $1.0\mu A/cm^2$ to determine the lifespan (in years) of the repaired crack. Each day during the test the beam is subjected to freeze-thaw, wet/dry, and temperature cycles. These cycles were proportioned to represent Kansas' weather. The unsealed beam reached the specified corrosion rate in 50 days. This translates to four to five years before the deck starts to show signs of corrosion. The epoxy sealed beam failed after 271 days. This translates to 15 plus years before a corrosion rate of $1.0\mu A/cm^2$ is achieved. The HMWM A sealed beam failed after 156 days. This translates into nine years. The HMWM B sealed beam failed after 170 days.

This translated into approximately 11 years of protection. The final sealer (HMWM C) failed after 110 days. Eight years of protection can be expected for a bridge repaired with this material.

(b) Field Investigations
Lasa (1990) tested the sealers applied to Seven Mile Bridge both 11.5 months and 16 years after application. Seven Mile Bridge is located in Florida. This means that the bridge may not be subjected to as harsh of an environment found in the Midwest. The HMWM resin repaired cracks retained 90.5 percent of their uncracked strength 11.5 months after application. The 16 year old repaired cores retained between 70.4 and 87.5 percent of the uncracked specimen's strength. This would indicate that the HMWM sealer held up fairly well over the 16 years it was in use. The engineers determined that the sealer should still be successful in sealing the cracks for another ten to 15 years. This would mean that the total lifespan of the sealer is 26 to 31 years.

Engstrom (1994) tested the lifespan of a HMWM sealer used on a D-cracks concrete pavement. It should be noted that the study was done on a highway in southwestern Minnesota. Also this test was not done on a bridge deck. Engstrom determined that the lifespan of the sealed cracks was 18 months. He suggested that reapplication could be possible after 18 months to extend the sealers lifespan.

Sprinkel (1991) tested two different HMWM sealers (T70X and T70M) on a bridge deck in Virginia. Extensive cracking of the T70M resin was observed soon after application. The T70X resin (which is more flexible) lasted for 15 months before it started to show signs of cracking. A bond strength test showed that the repaired cracks retained 11 percent of their original strength. Due to the early cracking and poor bond strength, it was concluded that the crack sealer had a fairly short lifespan.

(c) Summary of Sealed Crack Lifespan Studies
A wide range of effectiveness was found in the experiments performed. This wide range of data is probably due to a number of variables. First, the location of the test plays a major role in how long the sealer will last. The environmental conditions create favorable conditions for cracks sealed in the southern half of the United States. This can be seen by looking at the life spans experienced in Minnesota (18 months) compared to Florida (26 to 31) years. It also challenging to compare test performed in the laboratory to test done in the field due to level of contaminants and application procedures. Because of this, laboratory test tend to achieve a higher penetration depth and larger bond strength. However, lab tests are good for comparing the materials used in the test to one another. Meggers' (1998) lab tests indicated that the epoxy sealer outperformed all three HMWM sealers. Laboratory results state that sealers can be effective for eight to 15 years. Field tests (depending on location) showed that HMWM sealers can be effective for only a very short period to approximately 30 years.

2.3.2 Occurrence of Re-Cracking

Sealing cracks in bridge decks is also used to repair the structure in addition to blocking chloride ingress. Cracks form in concrete for numerous different reasons: plastic shrinkage, drying shrinkage, thermal effects, loads, reactive aggregates, and freeze-thaw damage. Most of these reasons cause tensile forces in the concrete which cause it to crack. It must be determined if these tensile forces, which were released after the concrete cracked, rematerialize after the cracks are sealed. If the tensile forces due reappear, parallel cracking will typically occur near the repaired cracks.

No sources included laboratory tests that investigated recracking of concrete.

Wiss, Janney, Elstner, and Associates (2000) state that visual inspections of the 26 decks (sealed with 8 different HMWM sealers) proved that very few new cracks appeared after the old cracks were repaired. This was due to the stress transferring to the steel after the concrete cracked initially. Krauss (1985) also indicated that re-cracking did not occur on the Rio Vista lift Span Bridge. A HMWM sealer was used for the repair of the cracks.

2.3.3 Track-Free Time for Sealers

The track-free time of a sealer is the time required for the sealer to cure before traffic will not interfere with the curing process. Because the bridge deck needs to be closed during the application of crack sealers, a major inconvenience is experienced by commuters. This makes the time required for the sealers to dry to the point where traffic can traverse them very important. By selecting a sealer with a shorter track-free time the bridge can be reopened sooner to reduce the inconvenienced to commuters.

Meggers (1998) lists the track-free time for all of the sealants used in his study. The track-free time for the epoxy, HMWM A, HMWM B, and HMWM C were three, four, four, and six hours respectively.

Marks (1988) allowed the HMWM sealer to dry for eight hours before traffic was allowed to use the bridge. Lasa (1990) documents that the bridge was reopened four hours after the application of the HMWM sealer was finished. Engstorm's study (1994) indicated the surface cure time for the HMWM sealer in his experiment was three to six hours.

The track-free time for most sealers ranged between three and six hours (Meggers 1998; Lasa 1990; Engstrom 1994). Occasionally a wait time of eight hours for the sealer to dry was documented (Marks 1998). Typically waiting times for HMWM sealers ranged between four and five hours. Always consult the sealer's drying properties prior application to determine the track-free time. If the track-free time is not included with the sealer, consult the manufacturer for further details.

2.4. Variables Affecting Performance

There are numerous variables that effect a crack sealers overall performance. Most of these variables can be accounted for during or prior to application of the sealer. Taking time to make sure that all variables are addressed can mean a much greater penetration depth and bond strength in the cracks. This will in turn mean a longer lifespan of the sealed cracks. The variables that are addressed are the effect of temperature, moisture, age of crack, and cleanliness of crack.

2.4.1 Effect of Temperature

The gel time of the crack sealer is greatly affected by the temperature of the sealer. If the sealer is applied to a deck that is too hot, the sealer will cure too fast and not have enough time to effectively penetrate the deck. If the sealer is too cold it will take too long to cure. This becomes a problem when the sealer seeps through the entire deck and drains out the bottom of the cracks. This can cause environmental problems when the resin drains into a river below the bridge deck. A few steps can be taken to prevent the resin from draining out the bottom of the deck. The first option is to seal the cracks on the bottom of the bridge. Due to the option being labor intensive and expensive, tarps can also be suspended below the bridge deck to catch the dripping resin. Both of these options can be avoided if the gel time of the sealers is considered and controlled.

A substantial amount of research has gone into determining the optimum gel time for crack sealers. Three epoxys, one polyurethane, and one HMWM sealer had their gel time tested to determine their relationship with temperature. All five of the sealers' gel time decreased as the temperature increased (Sprinkel 1995). Most sources suggest a gel time of approximately one hour for HMWM resins. Although all HMWM resins are different, sources also suggest applying the sealer on a mild day with the temperature between 45 and 90 °F (Krauss 1985). Accelerators and retardants can be mixed with the sealers to better control gel time. A gel time of one hour is also mentioned to be the goal for an epoxy crack sealer in Meggers' 1998 study.

The bond strength of sealers can be affected as well as the gel time. A laboratory study in which a HMWM sealer was applied to a cracked slab in at high temperatures showed a reduction in bond strength and penetration depth. The slab was between the temperature of 110 and 120 °F when the HMWM resin was applied. The three different HMWM sealers experienced an average reduction in bond strength of 12.6 percent. Also an 8.5 percent reduction in penetration depth was experienced due to the accelerated gel time (Rodler 1989).

2.4.2 Effect of Moisture

Due to cleaning methods and rainfall, bridge decks often have considerable moisture residing in the cracks. Because the moisture in cracks can cause problems with the depth of penetration and bond strength of the sealer, steps must be taken to understand and deal with the moisture problem. A laboratory study conducted by Rodler tests the drying time required for cracked slabs to retain 95 percent of their dry bond strength and penetration depth. The study suggests that a bridge deck be allowed to dry for three days after a rainfall or cleaning to retain 95 percent of the sealers dry bond strength. The study also mentions that a two day waiting period should be observed to retain 95 percent of the sealers dry penetration depth. One should note that since this study is done in a laboratory oven that drying times in the field will vary. The heat and humidity of the climate may prolong the time required for the cracks to dry; however, the test specimens in the lab were not subjected to direct sunlight which may speed up the drying process (Rodler 1989).

2.4.3 Effect of Cleaning Cracks

Cleaning cracks is a very important and often undervalued process in bridge repair. Contaminants like dirt, dust, and carbonation build up in cracks of both new and old bridges. If these contaminants are not removed from the crack prior to application of the sealer, the bond strength and depth of penetration will be greatly reduced. The depth of penetration is reduced because the contaminant build up clogs the cracks and prevents the sealer from properly infiltrating its entire depth. The bond strength is reduced because the contaminants line the surface of the crack. When the sealer hardens it bonds to a combination of the contaminants and the crack wall. A complete bond with the crack wall is desired.

In a tensile splitting test, 30 percent of the failures happened through the concrete. The rest (70 percent) failed through the repaired crack. Crack inspections showed dust, dirt, and carbonation lining the cracks. This build up of contaminants weakened the bond and caused the specimen to fail through the repaired crack instead of the concrete (Sprinkel 1991). Additionally, Megger's 1998 study documented a reduction in depth penetration due to excessive contaminants in cracks.

2.4.4 Effect of Crack Age

Very few studies have been conducted to determine if the age of a bridge deck (or age of a crack) affects bonding ability of a sealer. Meggers conducted a study in which eight bridges between the ages of one and 29 years old were sealed. The test concluded that the sealers were able to penetrate newer bridges easier than older ones. This was concluded because there are less contaminants in newer bridge decks. There were two reasons given for why the newer bridge decks contained less contaminants. The first and more obvious reason is that a newer bridge deck has had less time to collect contaminants in the cracks. The second reason is that a newer bridge deck tends to have narrower cracks. Meggers determined that narrower cracks collect less contaminants than wider cracks (Meggers 1998).

Another concern with sealing old cracks deals with the possible high levels of chloride already present in the cracks. By sealing these cracks it is possible that the chloride ions will be trapped in the deck near the reinforcement bars. If this were the case sealing the bridge cracks could possibly do more harm than good. More research is needed in this area. A few sources mention the topic however none create any tests to indicate if it is an important factor to consider.

2.4.5 Temperature Effect on Crack Width

Due to thermal expansion, the cracks in the bridge deck vary in size throughout the day. This is due to the higher temperatures and direct sunlight that occurs during the middle of the day. The basis behind thermal expansion is that when an object heats up it will expand. The opposite happens to the object when it is cooled. This means that during the middle of the day (when the temperature is the highest) the cracks in the concrete decks are the smallest. The shift in live loads can also compound with the thermal expansion and contraction of the cracks. The expansion and contraction causes a problem because some crack sealers are not flexible enough to expand and contract constantly. Also the temperature (or time of the day) in which the crack sealers is applied becomes a factor due to the size of the crack. It is more beneficial to seal a crack at night because that is when the crack is the largest. This means more resin will occupy (larger penetration depth and width) and cure in the cracks. The bond strength of the resin will hypothetically last longer since the resin will be in compression during the day and neutral at night. This is desired over the resin being in tension at night and neutral during the day. When the resin is in tension the bond between the resin and the crack wall tends to break down sooner.

2.4.6 Type of Initiator Used (for HMWM Resins)

High molecular weight methacrylate, the most frequently documented crack sealer, is mixed as a three-part system. Throughout the literature two different initiators were used to mix the sealers. This section will compare and contrast the results yielded from each initiator. Trends in bond strength, penetration depth, and overall performance are discussed (if applicable). The initiator is used to start the polymerization process of the resin. This process causes the resin to begin to harden and develop strength. The two initiators used in the field and lab studies are benzoyl peroxide and cumene hydroperoxide. It should be noted that the studies were not conducted to contrast the performance of the different initiators. This means other variables, besides the initiator used, are involved in the experiments. Consequently, the performance of the sealers may be due to other chemical properties aside from the initiator.

Rodler (1989) tests three different HMWM sealers. Systems one and two use a benzoyl peroxide initiator, and system three uses a cumene hydroperoxide initiator. A strain test determined that the two systems that used the benzoyl peroxide initiator were much more flexible than the system that used the cumene hydroperoxide initiator. The percent penetration under standard conditions documented systems one and three performing the best (system three performing slightly better). When the systems were applied during elevated temperatures, the percent penetration reduced dramatically for systems one and two (15.6 and 10.2 percent reduction in penetration). System three (cumene hydroperoxide initiator) had a reduction of less than five percent. System three also took the longest to cure. The bond strength of system three outperformed the other two systems in both the standard and elevated temperature tests. Using reinforced beams subjected to flexural loading, the repaired stiffness was determined for the three systems. Systems one and two performed the best (two bettering one) and yield the largest flexibility from the repaired beam. Because of early cracking in the system three's beam, the beam failed prior to reaching service loads. After the laboratory tests were concluded Rodler used the system three sealers on the Loop 1604 bridge in Texas.

Krauss (1985) used a HMWM sealer with a benzoyl peroxide initiator on the Hallelujah Junction Bridge. The sealer penetrated the entire depth of the crack to the reinforcement bars. Marks (1988) used a HMWM sealer with a cumene hydroperoxide initiator on the US 136 bridge in Iowa. Two inch deep cores were extracted from the bridge deck. The sealer penetrated the entire two inches of the extracted cores. Lasa (1990) used a HMWM sealer with a cumene hydroperoxide initiator on the Seven Mile Bridge in Florida. The average depth of penetration varied between approximately ¾ths of an inch and one inch depending on crack width. The cores extracted from the bridge deck 11.5 months after application retained 90.5 percent of their uncracked strength. The cores removed 16 years after application retained between 70.4 and 87.5 percent of their original uncracked strength.

The results do not yield a definite conclusion as to which initiator performed better. Each initiator seemed to achieve an adequate penetration depth. The sealers containing the cumene hydroperoxide initiator penetrate deeper in Rodler’s study. All documented sealers that contained a cumene hydroperoxide initiator achieved a high bond strength. Rodler determined that the sealers containing a benzoyl peroxide initiator were more flexible than cumene hydroperoxide HMWM sealers. Although these trends can be seen from the studies, more research into this area must be completed to come to a definite conclusion. Until tests that only vary the initiator are conducted it can not be determined if the initiator is the sole reason for these results.

2.5. Reapplication

Very little research has been done concerning how often crack sealers should be reapplied to adequately protect the structure from chloride ingress. Engstrom (1994) tested the lifespan of a HMWM sealer used on a D-cracked concrete pavement. It should be noted that the study was done on a highway in southwestern Minnesota. Also this test was not done on a bridge deck. Engstrom determined that the lifespan of the sealed cracks were 18 months. He suggested that reapplication could be possible after 18 months to extend the sealers lifespan. Due to the lack of information on this topic, more research is needed in order to determine the effectiveness of sealer reapplication.

Chapter 3 – Performance Survey

3.1. Introduction

This chapter provides a synthesis of the information obtained from phone surveys administered to representatives from different states around the United States. The survey focused on historical use, materials used, and current practices regarding the implementation of concrete bridge deck and crack sealants. A project background and list of topics were emailed to the participants prior to the interviews. The individual summaries of the participants and an outline of the topics discussed can be found in Appendix A.

Approximately 20 people participated in the interview process. The expertise of these individuals ranged from bridge engineers to materials specialists. Most participants focused on bridge maintenance. If a state did not regulate the use of bridge deck and crack sealants, a major district was to be contacted to determine their common practices. The state and district contacts were obtained from the Mn/DOT TAP panel which includes Keith Farquhar, James Lilly, Gary Peterson, and Nancy Whiting. Referrals from contacts were also questioned during the interview process.

Comments, observations and conclusions taken from individual interviews include a reference to the section of Appendix A which documents the specific interview.

3.2. Materials Used

This section provides an overview of the different types of materials that states around the Unites States use to seal both concrete bridge decks and cracks. The information focuses on current products used; however, materials that were common in the past (such as linseed oil) are also discussed. The section highlights why certain products were selected or discontinued. Additionally, the section highlights any documented problems states have experienced with particular products.

3.2.1 Deck Sealants

This section will discuss the three most common deck sealants: linseed oil, silane, and siloxane. Linseed oil is a barrier sealant while silane and siloxane are penetrating sealants. The advantages and disadvantages brought up during the survey are discussed. Deck sealants that have not made it past the testing phase or which are not widely used are discussed in section 3.5.3 of this report.

(a) Linseed Oil

Most states surveyed had some experience with the use of linseed oil to seal bridge decks. The sealant was typically used between the 1950's through the 1980's. Most states have discontinued its use, however, Missouri still uses linseed oil because of its ability to prevent surface scaling on bridge decks. Also the product performed the best in their 90-day ponding and freeze-thaw test. Originally Missouri applied linseed oil after construction and then reapplied the product annually for five years. In the late 1970's this process was changed to applying linseed oil after construction and once more after one year passed. The change was deemed necessary because the applications following the first year were not deemed cost effective.

Most states have discontinued the use of linseed oil due to various shortcomings. General experience with linseed oil indicates that the sealant only remains on the deck for approximately one year before it is washed or worn away (Kavanagh A.8, Gilsrud A.15). Due to this limitation, many Departments of Transportation concluded that the sealant would need to be reapplied annually to remain effective. This proved to be cost prohibitive. Other states cited that linseed oil yielded unclear results and they experienced problems with application. These problems included having to stop traffic and needing to broadcast sand over the deck due to increased slipping of traffic (Holderman A.12). Kansas discontinued the use of linseed oil because it is typically mixed with environmentally harmful materials like kerosene (Meggers A.6).

(b) Silane

According to the states surveyed, silane is the most common deck sealant currently used. Seven of the 16 states indicated silane was commonly used to seal bridge decks while more states include it on their approved products list. All specified silane sealants had a 40 percent solids content.

Solvent-based silanes are more common than water-based silanes. This is due to the notion that a solvent-based silane achieves a greater depth of penetration than the water-based counterpart (Harajli A.3, Kavanagh A.8). Water-based silanes can also be repelled during reapplications if some sealer remains in the deck from a previous application. Solvent-based silanes tend to penetrate through these previous applications. Water-based silanes do have some advantages over solvent-based products. The water-based products are better for the environment. Additionally, states indicated that solvent-based silanes can evaporate off the deck before adequate penetration during hot days (Mends A.10).

(c) Siloxane

Only two states surveyed (North Dakota and Wisconsin) indicated common use of siloxane sealants; however, other states did include the sealant on their approved products list. North Dakota specified that the Oligomerous Alkyl-Alkoxysiloxane used must be dissolved in a solvent carrier and contain at least 40 percent solids (Schwartz A.13). Most states typically chose silane over siloxane because silane is made up of smaller particles which tend to penetrate deeper into the concrete deck.

3.2.2 Crack Sealers

This section discusses the two most common crack sealers, epoxy and high molecular weight methacrylate, used throughout the United States. The advantages and disadvantages discussed in the surveys will also be mentioned. Lastly the health risks that can occur are summarized. Crack sealers that have not made it past the testing phase or which are not widely used are discussed in section 3.5.3.

(a) Epoxy
According to the contacts surveyed, epoxy was the most commonly used crack sealer. Eight of the 16 states indicated that an epoxy sealer was either used in a flood coat or to seal individual cracks. The choice between sealing the entire deck (flood coat) or individual cracks depended on the severity of cracks and the state's preference. A balance between the cost of labor and materials must be established to determine which procedure is the best choice for individual jobs.

States typically cited the following advantages and disadvantages when discussing their decision making process. Typically epoxy crack sealants are less expensive than HMWM products. There are also very few health concerns with most epoxy materials. The product can cause minor skin irritation. However epoxy materials are typically more viscous than HMWM materials. This will result in less penetration into the cracked deck.

(b) High Molecular Weight Methacrylate (HMWM)
Five of the 16 states surveyed indicated the use of HMWM sealers to seal cracked decks. HMWM sealers are almost always applied using a flood coat which is spread over the entire deck. HMWM sealers are known for their low viscosity which allows them to penetrate deep into the cracked bridge deck.

When using a HWMW sealer the gel time becomes important. If the temperature is too low the sealant will gel too fast and not penetrate the crack. If the temperature is too warm the sealant will take to long to cure. This can cause the sealer to run out the bottom of the crack as well as longer bridge closures. California specifies that the temperature should be above 45 and below 100°F. If the temperature is below 60°F a cold formula for the HMWM must be used (Lee A.2).

There have been some health risks when using HMWM products. Most states indicate that the inhalation of HMWM is not harmful and reparatory equipment is not needed. However on one occasion in Minnesota, workers sustained serious health problems after inhaling the fumes. In the past, if the three component system (monomer, initiator, and promoter) was mixed in the wrong order the sealer had the potential to be explosive. The industry now pre-promotes the HMWM sealer which means the sealer can no longer explode. The only drawback is that smaller batches of the sealer must be mixed.

3.3. Application Procedures

The following sections will discuss the application procedures implemented by different states for deck sealants and crack sealers. These procedures include surface preparation, application type, application rate, and any other important information. Any problems experienced with different methods of application will also be noted.

3.3.1 Deck Sealants

There are four types surface preparation that are commonly used by the states surveyed. Of these four methods sand/shot blasting and high pressure water are used most often. Shot/sand blasting was commonly used if the contractor suspected parts of the curing compound left on the deck. If pressured water was used to clean the deck, most states wait approximately one to two days to dry the bridge. Compressed air and brooms can also be used to clean the bridge deck prior to the application of the sealant. However these methods were not as common. The type of surface preparation used also depended on the age of the deck. Light or no cleaning was used on some new bridge decks prior to application.

Most states used a spray bar mounted on the back of a truck or tractor to apply the product to the deck. The sealant is pumped through the spray bar which produces a mist to distribute the product evenly over the deck. When using this process an application rate of 200-300 ft^2/gallon is typically used. Some states, such as Montana, use hand sprayers to distribute the sealant over the deck. When using this application procedure the sealant is applied with multiple passes until the deck refuses to take the additional sealant. Minnesota has experienced some problems with the deck taking too long to cure when all of the sealant is applied in one pass (using a spray bar). Because of this problem, they apply the same amount of sealant but split it up between two back to back passes. This allows them to open the deck to traffic faster (Kavanagh A.8). When determining the application rate and procedure for any product the manufacturer's recommendations should be consulted.

3.3.2 Crack Sealers

The same four types of surface preparation used for deck sealants are also used for crack sealants. Most states use sand/shot blasting to clean the deck and cracks prior to application. Compressed air and high pressure water the next most common procedure to clean deck cracks. If high pressure water is used, the states typically allow for the deck to dry for approximately one to two days. Sweeping the deck and cracks is rarely used to clean surfaces. Some states use multiple methods for cleaning the deck cracks. For example before the crack sealant is applied in California, the deck is shot blasted, blown, and swept (Lee A.2). Like with deck sealants, the degree of surface preparation depends on the age of the deck. New decks typically only receive a light cleaning prior to application of the crack sealer.

There are two common strategies for applying crack sealers to the bridge deck. When a flood coat is used the sealer is mixed in larger batches and poured over the deck. The sealer is then moved and manipulated with brooms and squeegees to direct it into the cracks. This strategy is used by most states that have decks with extensive cracking. Typically states apply a flood coat of HMWM sealer with rate between 90-150 ft^2/gallon. The second option is to seal the individual cracks instead of the entire deck. This can either be achieved by applying the sealer with handheld bottles or wheel carts. Each apparatus would have a tapered nozzle in which to administer the sealer into the crack. Due to the expense of crack sealing products, states like Oklahoma, South Dakota, and Minnesota prefer this method. As with deck sealants, the manufacturer's recommendations should be consulted when determining the surface preparation and application procedure.

3.4. Application Timing

This section discusses the timing for states to choose to seal bridge deck and cracks. The decision making process will also be discussed to better understand why the specific times are chosen by the states. A discussion of reapplication will also be included.

3.4.1 Deck Sealants

Of the states that use deck sealants, the majority seal decks immediately after construction. This is typically done because the chloride content in a new deck is very low. By sealing the deck immediately the states hope to repel additional chlorides and keep the chloride content low. If states wait to apply a deck sealant until later in the life of the bridge, the chloride content of the bridge will already be high. Since the sealant does not remove existing chlorides, the product can only prevent additional chlorides from penetrating into a deck (which already has a high level of chlorides). This being said, there are some states that apply their first coat to an old deck.

Approximately one-half of the states surveyed that apply deck sealants (not including states that have no deck sealing program) also reapply the sealant. Most states indicate that a three to five year schedule for reapplication of penetrating sealants is ideal. However due to shortages in money and maintenance staff, the reapplication schedule is estimated realistically to occur every five to six years. Barrier sealants such as linseed oil need to be applied more often due to minimal penetration into the deck.

3.4.2 Crack Sealers

Unlike deck sealants, crack sealers are typically applied long after the bridge deck is constructed. This is done because most decks do not have cracks until later in their lifespan. However, most states indicate that early age cracking is a problem on select decks. Early age cracking typically results from improper construction or curing. If early age cracking occurs, most states require the contractor that constructed the bridge to seal the cracks prior to completion. There are a few states that only apply crack sealants right after construction. For example, Nebraska applies a polymer sealant over the entire deck on all new bridges. This is used to seal the deck from chlorides as well as seal any early age cracks. The state feels the application of the polymer sealants have been beneficial to the service lives of the bridge decks.

Most states indicate that they do not reapply crack sealers. Of the states that do reapply crack sealers, there is a large variation in the reapplication schedule. Wisconsin reseals cracks every four years (or as needed). Montana indicates that reapplication should take place every 15 years. Most states' programs are too young to have actually reapplied any crack sealers.

3.5. Other Considerations

This section discusses other topics that were covered during the surveys. These topics include: curing practices, testing, rare products, and other forms of maintenance. All of these topics have effect on the use of deck and crack sealers.

3.5.1 Deck Curing Practices

The deck curing practices implemented by states have a direct effect on early age shrinkage cracking. Most states surveyed use a seven day wet cure on all bridge decks. The deck is fogged during placement and finishing. After the placement of the concrete for the deck is finished, wet burlap is placed over the deck and kept damp for seven days. Occasionally a curing compound is placed on the deck after curing. Some states, such as South Dakota, have moved to a 14 day wet cure. This change was put into effect because South Dakota was having increasing problems with early age shrinkage cracking. The state has noticed significant improvements after the specification change.

3.5.2 Testing

Two different types of product testing can be used for deck sealants and crack sealers. The first type of testing is used to determine which products should be accepted for use. The products that pass these tests are then placed on a particular states approved products list. The second type of testing is done after the product as been applied in the field. This type of testing is called quality assurance/quality control (QA/QC) testing.

The state of Wisconsin uses four tests in order to generate their approved products list for penetrating sealants. The acceptance tests include: ASTM C672 (scaling resisance to de-icing chemicals), AASHTO T259 (90-day ponding), ASTM D5095 (determination of nonvolatile content), and EPA Method 24 (volatile organic compound content) (Karow A.18). The first two tests are used to determine the penetrating sealants effectiveness. The second two tests are used to ensure the penetrating sealant passes specific environmental regulations (VOC content regulations). The state of Missouri uses two acceptance tests for penetrating sealants. These tests are AASHTO T259 (90-day ponding) and ASTM C642 (density, absorption, and voids) (Wenzlick 2007). Many states did not use acceptance testing or generate an approved products list for deck sealants or crack sealers. These states typically reviewed previous literature studies to determine which penetrating sealants and crack sealers performed the best.

Many states did not indicate an extensive history of QA/QC testing associated with deck sealants and crack sealers. Most of the QA/QC field tests performed measured the penetration depth of both deck and crack sealers. Colorado has conducted some penetration test on decks sealants such as silane and siloxane. California is about to begin a program where cores of all bridge decks that are recently sealed with HMWM products will be tested for depth of penetration. Ten years ago, crack sealing became a priority for Montana after chloride tests indicated a spike in the chlorides contained in bridge decks. Typically five pounds per cubic yard is considered poor. Montana began noticing 25-50 pounds per cubic yard of chloride in their bridge deck concrete. This increase in chlorides was attributed to Montana switching to a Magnesium Chloride de-icing material (Mends A.10).

3.5.3 Occasionally Used Products

Minnesota and Missouri have been experimenting with products that react with the free calcium in the concrete. For example, Minnesota uses AccuFlex Gel-Seal which is produced by Superior Coating Specialists. These products seal both the deck as well as small cracks creating a water soluble barrier. Once the product finishes curing the shrinkage cracks are no longer visible. The product can be applied with the same process as a penetrating deck sealer. The drawbacks of these types of sealers are that they do not seal medium to large cracks. Also the effectiveness of reapplication of the sealer is questioned.

Kansas has experimented with products like methacrylate and polyester for sealing cracks. The experiments indicated that the polyester sealer did not have as long of a lifespan as other more commonly used products. Methacrylates (which are another form of HMWM) were occasionally used because of their low viscosity and their ability to cure at low temperatures.

3.5.4 Other Forms of Maintenance

Sealing bridge decks and cracks is only one form of deck maintenance. Most states also use overlays extensively to increase the lifespan of a bridge decks. Decks can also be completely replaced due to extensive damage. These procedures become important for states that to not have a deck or crack sealing program.

(a) Overlays
States which do not have active crack sealing programs, like Indiana, typically use overlays to extend the life of their bridge decks. Overlays may be considered when ten to 30 percent of the deck is damaged. Most polymer overlays are applied using two subsequent coats. Each coat consists of spreading the bonding agent on the deck and applying a coarse hard aggregate over it until refusal. The most common polymer overlay material used is a latex modified overlay. Silica fume overlays are also used. Due to problems with application and curing, Indiana no longer uses silica fume overlays. Many states, including Minnesota, also have extensive experience with the use of low-slump concrete overlays to prolong the life of bridge decks.

(b) *Deck Replacement*
Deck replacement is the final option taken to repair damaged decks. Replacement is typically avoided if possible since it is the most expensive option discussed. States may consider replacing the deck if more than 30 percent of the deck is damaged. The state of Indiana (which has no crack sealing program) expects that a bridge deck may need to be replaced after 35 to 40 years. It should be noted that this time range is based on many variables that may change for different states. Some examples of these variables are weather conditions, traffic density, de-icing practices, concrete mix design, concrete reinforcement cover, etc.

Chapter 4 – Chloride Study

4.1. Introduction to the Chloride Study

This chapter provides a synthesis of information acquired from reviewing deck inspections and chloride content tests that have been conducted on sealed bridge decks in Minnesota and surrounding states. This information was gathered from published resources and state surveys. The information is used to establish how bridge decks benefit from being sealed with penetrating sealants and crack sealers. Most states contacted indicated little or no chloride content data on bridge decks that have been sealed.

4.2. Chloride Tests

This section discusses how sealing bridge decks affected the levels of chlorides present in the concrete. Test results for bridge decks sealed with deck sealants and crack sealers are listed separately. Most chloride samples are extracted using a vacuum drill at various depths. The dust produced from the vacuum drill is then analyzed for chloride content. Any conclusions that can be drawn from individual tests are also discussed.

4.2.1 Deck Sealants

Mark Hagen conducted a three-year field investigation, which was discussed in the literature review, of sixteen different concrete sealants (eight silanes, two siloxanes, one silane/siloxane mixture, one silicate, one epoxy film former, and three thermoplastic resins) on the Western-Avenue Bridge in St. Paul, Minnesota. The bridge was constructed in 1991 and has a low slump concrete overlay. In addition to the sixteen sealants, an untreated area of the deck was established so that chloride reduction relative to uncoated concrete could be calculated for the sealants each year. The results are presented in Table 3.

Table 3: Chloride Contents Western-Ave. Bridge Over Three Years (Hagen 1995)

	Average Chloride Content (PPM)								
	Year 1			Year 2			Year 3		
Sealant	1/16"-1/2"	1/2"-1"	1"-1-1/2"	1/16"-1/2"	1/2"-1"	1"-1-1/2"	1/16"-1/2"	1/2"-1"	1"-1-1/2"
Silane, water, 40	690	130	110	980	260	100	970	240	110
Siloxane/Silane, solvent, 40	390	100	110	1300	470	220	1650	470	160
Silane, Solvent, 40	540	150	120	1620	740	170	1680	460	170
Siloxane, Solvent, 15	650	110	110	1710	510	100	1920	520	140
Epoxy, water	2040	320	50	2930	730	120	2260	330	100
Silane, solvent, 20	550	120	120	1680	400	80	2280	370	110
Silane, solvent, 40	1020	100	80	2610	770	170	2360	440	120
Silane, solvent, 30	560	120	80	1930	670	130	2370	760	140
Silane, solvent, 40	680	100	90	2310	860	130	2560	610	140
Siloxane, solvent, 9.2	420	140	110	2060	770	150	2550	750	220
Acrylic Top Coat	1200	160	120	2170	810	200	2610	790	110
Silane, water, 40	NA	NA	NA	3150	820	80	2630	570	120
Thermoplastic 1	1010	140	80	1620	180	120	2840	450	140
Silicate	2160	300	100	2920	940	140	3010	700	150
Thermoplastic 2	2440	640	120	3670	1050	180	3040	8100	130
Thermoplastic 3	1660	230	90	3120	770	60	3530	510	150
Untreated Control	2060	220	110	3440	1110	220	2710	690	120

The test results indicated silanes and siloxanes reduced chloride ingress more effectively than the thermoplastic resins, sodium silicate, and epoxy film formers. These film formers generally did not provide any more chloride protection than the uncoated concrete after the first year. Epoxy performed slightly better than the thermoplastic resins and sodium silicate. The results generally indicated sealers experienced a reduction in effectiveness from year to year, thus suggesting the negative effects that freeze-thaw exposure and abrasion have on a sealer performance.

Any benefit of solvent or water-based products could not be seen in the measurements. Also, the benefit of higher solids content could not be observed in the solvent-based silanes. However, the benefit of higher solids content could be noted in the solvent-based siloxane products. The four best sealers at reducing chloride ingress after three years of exposure to deicing chemicals proved to be a water-based 40 percent silane, the solvent-based 40 percent siloxane/silane mixture, a solvent-based 40 percent silane, and the solvent-based 15 percent siloxane. It should be noted that the water-based 40 percent silane product provided notably higher long term chloride effectiveness than that of the other three sealers.

Nancy Whiting conducted a field investigation, which is discussed in the literature review, with four different penetrating sealants (one siloxane, one water-based silane, one solvent-based silane, and one 100 percent silane) on a new bridge deck in Stillwater, Minnesota. The deck was placed in September of 2005 and chloride samples were extracted after one winter. The samples were taken from different sections of the bridge deck to determine if the location across the lane had an effect on chloride content. As in Hagen's test, a section of the deck was left uncoated to determine how well the sealants affected the chloride concentration levels.

Whiting concluded that all sealers were successful in lowering chloride ion levels in comparison to the unsealed sections. However, silane sealants were more successful than siloxane in repelling chloride ions. The results indicated little difference between the ability of water-based, solvent-based, and 100 percent silane to prevent chloride ion intrusion. Higher chloride values were found in the samples taken from the wheel path. This indicates that the amount of traffic and the location along the lane influence chloride ion levels (Whiting 2006a).

Whiting conducted a second study on the effect of reapplication of a water-based 40 percent silane sealant. This study was done on the Bridge of Hope, which was constructed in 1995. The deck was sealed in both the north-bound and south-bound lanes prior to being opened up to traffic in 1995. The south-bound lanes were recoated with the silane product in 1996, 1997, 1998, 2000, 2002, and in August 2005. The north-bound lanes were only subjected to initial silane treatment. In 1996, 1997, and 1998 eight representative drill dust samples were taken from the north-bound lanes and three from the south-bound lanes. The results are presented in Table 4.

Table 4: Chloride Content of Bridge of Hope Over Nine Years (Whiting 2006b)

	Average Chloride Content (PPM)			
Depth (in.)	1996	1997	1998	2005
North-bound				
1/16-0.5	984	1257	1394	982
0.5-1.0	195	244	442	631
1.0-1.5	172	129	247	484
1.5-2.0	138	117	162	291
2.0-3.0				197
3.0-4.0				189
South-bound				
1/16-0.5	422	1147	1358	1067
0.5-1.0	127	217	509	562
1.0-1.5	130	180	288	270
1.5-2.0	108	246	233	173
2.0-3.0				205
3.0-4.0				187

The results indicated that the six additional applications of the water-based silane on the south-bound lanes had no significant effect on the reduction of chloride ions. This was observed in the north-bound lanes, which were sealed once, having similar chloride concentration results as the south-bound lanes which had multiple applications. It was later determined that water-based products are not optimal for reapplication. This is due to the already sealed deck repelling the ingress of the water-based carrier. This problem can be alleviated if a solvent carrier is used on subsequent applications. Chloride concentrations were also determined to be larger near cracks in the deck (Whiting 2006b).

4.2.2 Crack Sealers

Dave Meggers conducted a study in which eight bridges of various ages where sealed with three crack sealers (one epoxy, and two HMWM's) and tested for chloride content. The study was discovered during the literature review and discussed in the survey. A control section was also used to compare the crack sealer effect versus an unsealed section. Chloride ion samples were taken in 1992 and 1995. The decks were sealed promptly after the 1992 chloride tests were finished.

The results of Meggers test were not conclusive due to a large amount of scatter in the data. The chloride content in 1995 was divided by the chloride content in 1992 to create an accumulation ratio. If the ratio is over one the chloride content has increased over the three year period. If the ratio is smaller than one the chloride content has decreased. Table 5 indicates the average ratio of the 1992 and 1995 chloride tests. These results indicate that the control and HMWM A gained the least amount of chloride ions between 1992 and 1995. Because the control section performed well, it suggests that very little benefit was gained from the cracks being sealed. Meggers also suggests that sealing older decks may trap chlorides in the deck.

Table 5: Average Ratio of 1992 and 1995 Chloride Tests (Meggers 1998)

Sealer	Sample Depth, mm	Ratio (1995/1992)
Control	0-19	1.35
	19-38	1.04
	39-57	0.96
Epoxy	0-19	1.40
	19-38	1.71
	39-57	1.30
HMWM A	0-19	1.02
	19-38	1.55
	39-57	1.39
HMWM B	0-19	1.52
	19-38	1.92
	39-57	1.65

Ten years ago, crack sealing became a priority in Montana after chloride tests indicated a spike in chloride contained in the bridge decks. Typically five pounds per cubic yard is considered poor. The state began noticing 25-50 pounds per cubic yard of chloride in their bridge deck concrete. This was attributed to the state switching to a Magnesium Chloride de-icing material. In a 1991 test, Montana treated four bridge decks with a HMWM crack sealer. Both bridges saw heavy applications of magnesium chloride and sodium chloride deicing salts. The bridges were then tested for chloride content in 2005 (Mends A.10). The average chloride content results for the four bridge decks are represented in Table 6.

Table 6: Average Chloride Concentration Results (Mends A.10)

	Depth 0.5 in.		Depth 1.5 in.		Depth 2.5 in.		Depth 3.5 in.	
Bridge Deck	% Cl$^-$	lb/yd^3	% Cl$^-$	lb/yd^3	% Cl$^-$	lb/yd^3	% Cl$^-$	lb/yd^3
MP 29.063 (EB)	0.260	10.500	0.086	3.472	0.024	0.952	0.007	0.272
MP 23.063 (WB)	0.201	8.116	0.073	2.951	0.026	1.034	0.008	0.328
MP 23.325 (EB)	0.247	9.991	0.111	4.484	0.044	1.792	0.023	0.929
MP 23.325 (WB)	0.199	8.055	0.063	2.547	0.022	0.909	0.016	0.639

The chloride is well below 25-50 pounds per cubic yard; however, the chloride levels are still above five pounds per cubic yard which Montana deems inadequate. Because the chloride content of these four bridge decks prior to application is unknown, it becomes difficult to draw accurate conclusions. If chloride content tests had been conducted prior to application or if a portion of the bridge was left unsealed better conclusion could be made.

4.3. Deck Inspections

Multiple bridge inspection reports were reviewed in order to determine the effect sealing had on bridge condition. The condition rating versus time was graphed for three bridge decks with known deck and crack sealing activity. Little information became evident after reviewing the plots. The plot for Bridge of Hope (bridge from Nancy Whiting’s study seen in Figure 1) shows that the deck wearing surface rating stayed constant from 1995 to 2007. However, it is not possible to determine if these results would be similar if the seven applications of water-based silane had not been applied to the south-bound section of the bridge deck. The deck is rated with a scale of one through five. A score of one indicates the best condition while a score of five indicates the worst condition.

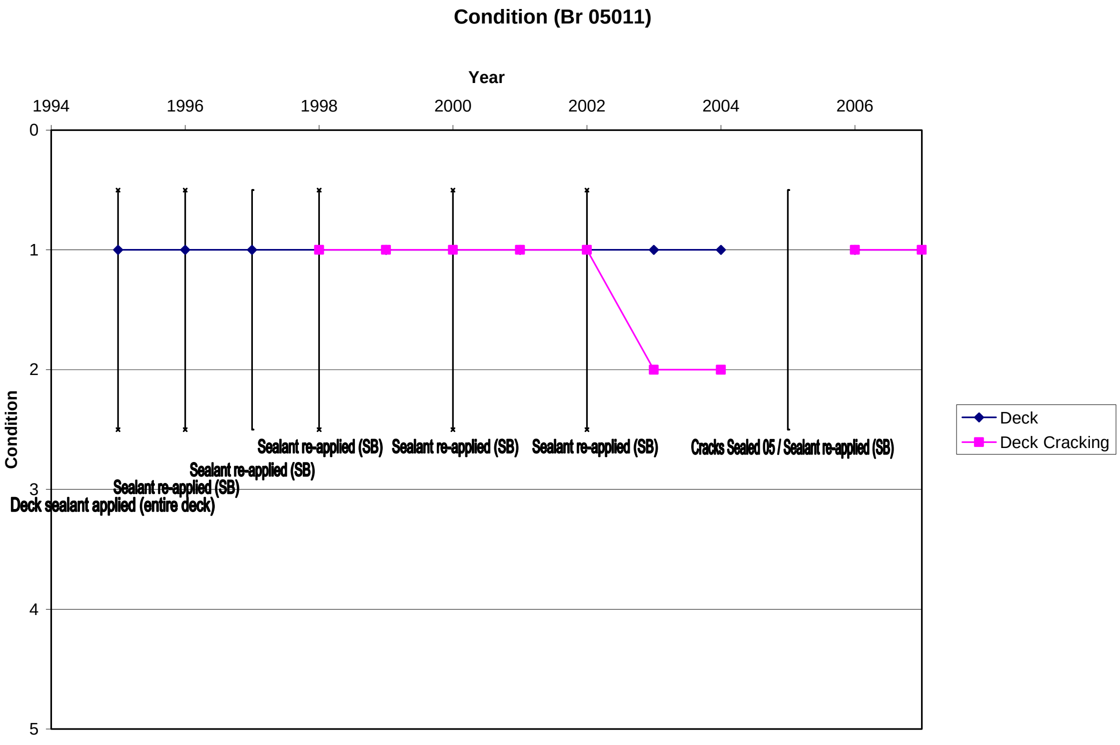

Figure 1. Bridge of Hope Deck Inspection Condition

Bridge number 27254 sustained a large amount of early age cracking after construction in 2004. Because of this, the deck was sealed with a methyl-methacrylate flood coat to repair the cracks. Bridge inspections indicate a perfect rating for deck cracking in the three subsequent years after sealing (seen in Figure 2). However, it cannot be determined if the bridge inspector verified whether debonding or cracking occurred in the previously sealed crack. Because of this limitation, one cannot determine if the sealer did an adequate job of sealing the cracks without some other form of testing (depth of penetration, chloride content, coring, etc.).

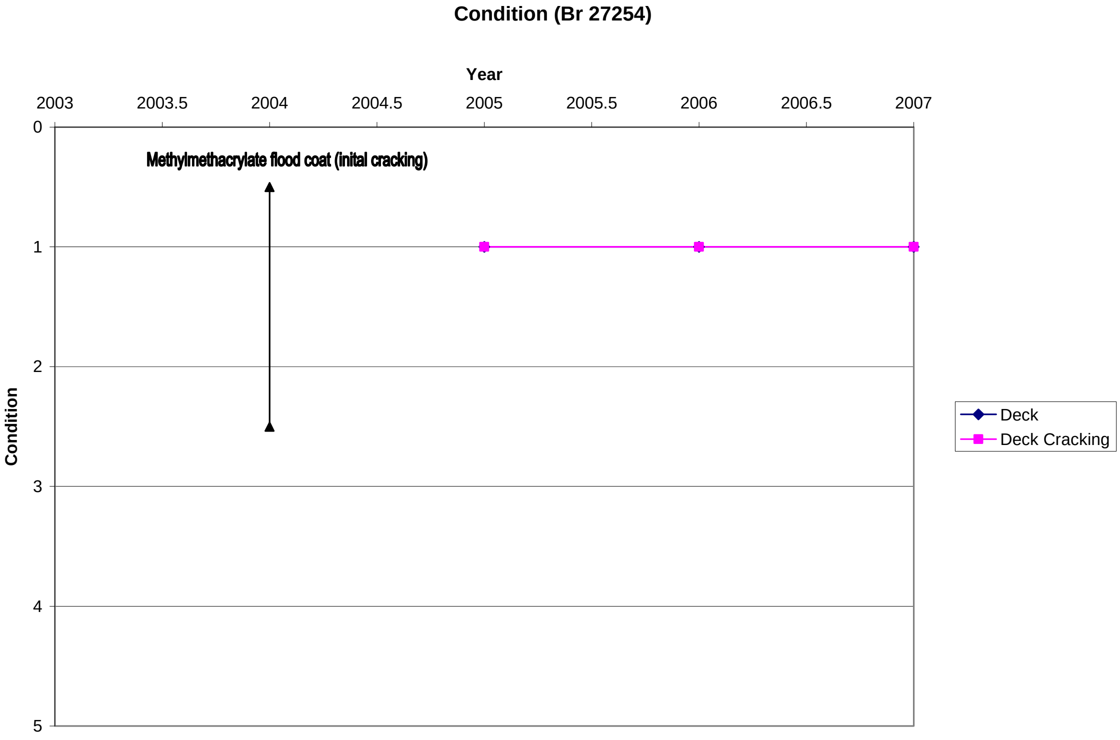

Figure 2. Bridge #27254 Deck Inspection Condition

Chapter 5 – Product Assessment

5.1. Overview of Sealant Assessment

This chapter discusses the selection, application, and testing/inspection process for the different generic products discussed previously in the report. The selection process deals with product performance with respect to each performance measure mentioned in the literature review. Additionally, some information on the application and inspection processes is taken from the survey. The list of products is first subdivided into the two broad categories of deck sealants and crack sealers. The deck sealants portion are further subdivided into subgroups with respect to product type (e.g., silane or siloxane), carrying agent, and percent solids content (Figures 3 and 4). As shown in Figure 5, the crack sealers are simply subdivided into generic sealer type (e.g., epoxy or HMWM).

For ease of understanding, an acronym is used when discussing penetrating sealants. The information provided in the acronym includes the sealant carrier (e.g., “S” for solvent or “W” for water), the percent solids content (a one- or two-digit number indicating the content expressed as a percentage), and the sealant type (e.g., “Si” for silane or “Sx” for siloxane). Using this system, a water-based silane with a 40 percent solids content is designated as W40Si, and a solvent-based siloxane with a 20 percent solids content has the designation S20Sx.

5.2. Deck Sealants

Silane and siloxane, which are the most common deck sealants, are discussed in this section. A comparison of the products is drawn to highlight the products strengths and weaknesses. As previously stated, the products are subdivided into specific groups (Figures 1 and 2) depending on their composition (e.g., carrying agent and percent solids). Some literature studies do not include the composition of the products studied. Because of this limitation, the results of these studies can only provide general knowledge of the products studied.

The moisture content of the concrete at time of application can have a significant effect on the penetration depth of the sealant. Bush’s 1998 study indicated that the penetration depth of silane was reduced due to high levels of moisture in the concrete specimen. Basheer (1998) backs up these finding for multiple deck sealants (silanes, siloxanes, silane/siloxane mixture). Tests indicated that with increased moisture content, penetration depth of the sealant generally decreases. Typically a drying time of two days is used in practice following power washing (Kavanagh A.8). However, under certain conditions a longer drying time may be required. Alternatively, dry cleaning methods (e.g., shot-blasting) may be adopted to eliminate the delay associated with deck drying following power washing.

Little research has been conducted on how surface preparation affects the penetration depth of deck sealants. Soriano (2002) tested three forms of surface preparation: sandblasting, power broom/forced air, and no preparation. The study determined surface preparation did not seem to play an important role in deck sealer penetration depth. In fact, the sandblasted deck seemed to provide the least protection against water ingress, for which Soriano postulates that sandblasting the deck increased the size of the concrete pore openings, thus increasing concrete permeability.

Soriano recommends the “do nothing” approach for surface preparation due its economic and time benefit. This recommendation assumes that the deck is absent of excessive debris. In the case of excessive debris, a power broom/forced air surface preparation is recommended. This conclusion contradicts common practice as indicated by the survey noted all recipient states used some form of surface preparation prior to application of deck sealants.

5.2.1 Silanes

Information gathered from the survey indicates that silane is the most commonly used deck sealant in the mid-western United States. Silane has many positive attributes which contribute to its widespread use. Due to its small particle size (in comparison to siloxane), silane generally penetrates deeper into the concrete deck than siloxane. This larger depth of penetration is confirmed by many studies in the literature review (Pincheira 2005, Wright 1993, Whiting 2005). Silane products are also easy to apply to the bridge deck. There are some application stipulations, with respect to carrying agent, that are discussed in subsequent sections. Refer to Table 7 for silane depth of penetration and chloride resistance results.

(a) Solvent-Based Silanes
The carrying agent of silane products can have a significant effect on the performance of the sealant. According to the survey, solvent-based silanes are more commonly used than their water-based counterparts. This is due to the notion that solvent-based products penetrate deeper into the concrete bridge deck. Many studies in the literature review support this notion (Pincheira 2005, Whiting 2005). Additionally, some studies also indicate that a solvent carrier can have beneficial effects on the reduction of chloride ingress in concrete bridge decks (Pincheira 2005).

Solvent-based products have some stipulations that need to be considered during application. For example, solvent-based products should be used when reapplying a penetrating sealant to the bridge deck. This requirement is necessary due to the possibility that previous applications may repel a water-based sealant. Solvent-based sealants will not be repelled by previously applied sealants. A disadvantage of solvent-based sealants, however, is that they can be more harmful to the environment than water-based products. The potential for harmful environmental effects is measured by the volatile organics compound (VOC) content of a sealant. Usually, solvent-based sealants have considerably higher VOC content than water-based sealants. Because most states set limits on the allowable VOC content in penetrating sealants, solvent-based products may not be adequate for environmentally sensitive areas.

Little research has been conducted on solvent-based silanes with solids content below 40 percent. The only study discovered in the literature review to address these products was a chloride content study by Hagen (1995). This study did not observe a large difference in the chloride content of bridge decks sealed with products that contain 0 to 39 percent solids and 40 percent solids products. The chloride content after three years of S40Si sealants ranged from 1680 to 2560 PPM. The chloride contents of S20Si and S30Si products were 2280 and 2370 PPM, respectively.

Survey and literature review results indicate that sealants with 40 percent silane solids content are the most commonly used silane products. Pincheira (2005) studied four different S40Si sealants. These four products were the top performers (out of 13 products) in a chloride ingress test. The products received average ratios of sealed-to-unsealed chloride contents of 0.37, 0.46, 0.50, and 0.57. A S40Si product was also the top performer of a chloride study by Whiting (2002). Hagen's (1995) field chloride study yielded results for the sealant that were more variable, and the S40Si sealants ranked third (1680 PPM), seventh (2360 PPM), and ninth (2560 PPM) out of 17 products. However, taking all of these results into account, the S40Si products seem to perform very well in chloride ingress tests.

When testing penetration depth, Pincheira (2005) found that the four S40Si sealants had the largest penetration (out of 13 products). Their average penetration depths were 3.8, 3.1, 2.7, and 2.5 mm. Whiting's (2005) study had a S40Si sealant penetrate slightly less than a 100 percent solids silane sealant. These tests seem to indicate that the S40Si products achieve some of the largest penetration depths of all penetrating sealers considered in the literature survey.

(b) Water-Based Silanes

Water-based silanes are not as commonly used as solvent-based products. As previously mentioned, solvent-based products tend to penetrate more deeply into the bridge deck. They also have the ability to penetrate past previous sealant applications (which water-based products can not). However, due to lower VOC content, water-based products are more environmentally friendly than solvent-based products. Thus, they tend to be the product of choice for environmentally sensitive locations. Another advantage to water-based products is that they tend to evaporate more slowly than solvent-based products. This characteristic can be beneficial if the sealant is applied on a particularly hot or windy day. Recommendations indicate that most deck sealants should be applied between the temperatures of 40°F and 100°F (Pincheira 2005).

From the limited data available on the performance of water-based silanes with less than 40 percent solids content, few differences can be seen in comparison to the 40 percent solids counterpart. A laboratory study by Pincheira (2005) determined that the ratio of sealed to unsealed chloride contents for W40Si is slightly less than W20Si. The two 40 percent solids content products had ratios of 0.77 and 0.88, while the two 20 percent solids content products had ratios of 0.84 and 1.05. This would indicate that the products with lower solids content performed slightly worse that the products with more solids. However, the variation in the test data tends to obscure this observation.

The same study also investigated how well water-based products with less than 40 percent solids penetrated the bridge deck. The two products with 40 percent solids contents achieved 2.1 and 1.9 mm depths of penetration. The 20 percent solid content products penetrated the deck 2.0 and 1.4 mm. This would indicate that the water-based silane products with less than 40 percent solids do not penetrate as well into concrete as the water-based silanes with 40 percent solids content. However, there difference is not considerable between the two products (Pincheira 2005).

Three chloride ingress studies were conducted that included W40Si products. Pincheira's (2005) laboratory test included two sealants from this group. The sealants ranked fifth and ninth out of 13 products in terms of resistance to chloride ingress. The sealed-to-unsealed chloride content ratios were 0.77 and 0.88, respectively. Whiting's (2002) laboratory test ranked the W40Si second behind a S40Si. Hagen's (1995) field chloride ingress study ranked W40Si first (970 PPM) and 13th (2630 PPM) out of 17 products. These results indicate a highly variable performance for this group of products. Other than the top ranked sealant in Hagen's (1995) study, the water-based sealants seemed to offer a slightly inferior performance to that of their solvent-based counterparts.

Depth of penetration results from Pincheira's (2005) study showed W40Si to rank fifth and eighth out of 13 sealants. The penetration depths of the two sealants were 2.1 and 1.9 mm. These results are lower than the penetration depths for the S40Si products.

(c) Silanes with 100 Percent Solids Content
Products with 100 percent solids have no carrying agent. Tests conducted on these products indicate slight advantages associated with the use of an increased amount of solids. A test by Soriano (2002) indicated 100 percent silane absorbed slightly less water than the 40 percent silane products analyzed. Increased penetration was also noticed for products that contained an increased amount of silanes. Basheer (1998), Whiting (2005), and Soriano (2002) all demonstrated 100 percent silanes to penetrate slightly deeper than 40 percent silanes. However, Whiting (2006a) observed similar chloride concentrations among the 100 percent silane, S40Si, and W40Si. Thus, any benefit from a higher solids content was not observed in Whiting's chloride tests.

The environmental effects and product application can also be effected by the increase in solids. Products with 100 percent solids have little or no VOC content. This makes the 100 percent solids products ideal for environmentally sensitive areas. However, carrying agents are typically mixed with the sealant resin for ease of application. Because the resin is not mixed with a carrying agent, the sealant will be more viscous and less coatable. Depending on the particular sealant, this scenario may not be adequate for application.

5.2.2 Siloxanes

The survey conducted indicated that siloxane products are less commonly used than silane. This is most likely due to the reduced penetration depths when compared to silane products. However since both products are penetrating sealants, the application process for siloxane is very similar to that for silane. This similarity suggests that there is no advantage to either product when considering ease of application. Refer to Table 8 for siloxane depth of penetration and chloride resistance results.

(a) Solvent-Based Siloxanes
Similar to silane, the carrying agent can have an impact on the application and performance of siloxane deck sealants. Few studies have been conducted to define the differences between solvent and water-based siloxanes. Pincheira (2005) indicated that a S10Sx he sampled demonstrated a larger mean chloride content than the W10Sx that was included in his study. Thus, in this specific test, water-based siloxane products outperformed solvent-based siloxne products. This observation is contrary to Pincheira's results for solvent and water-based silanes. However, this discrepancy could have resulted solely from scatter in the chloride test data.

As mentioned in the solvent-based silane products section (3.2.1(b)), the carrying agent can affect the application process. Solvent-based products should be used for reapplication because water-based products can have problems penetrating through previously applied sealants. Also, solvent-based products can be harmful to the environment by virtue of higher VOC emissions. Thus, water-based products may be required in environmentally sensitive areas.

Little information could be gathered from the literature review on solvent-based siloxane products with a solids content of 10 percent or less. Pincheira's (2005) laboratory chloride ingress test indicated that a S10Sx product yielded the highest ratio of sealed-to-unsealed chloride contents (1.27). Thus, the sample that was sealed with a S10Sx product fared worse than an unsealed sample. Hagen's (1995) field test indicated that a S9.2Sx sealant had a chloride content of 2550 PPM after three years. This was the second highest chloride content for penetrating sealants and the worst result for siloxane sealants. Pincheira (2005) also determined that the average depth of penetration of the previously mentioned S10Sx product was 1.8 mm. The depth of penetration was higher than the water-based siloxane (1.4 mm) and the same as a siloxane product with higher percent solids. These results indicate that solvent-based siloxane products with 10 percent or less solids content are not adequate for resisting chloride ingress, and they offer an average performance (among other siloxanes) relative to depth of penetration.

Test results indicated a very slight improvement in resistance to chloride ingress for siloxane-based products with 11 to 20 percent solids content. Pincheira's (2005) laboratory chloride ingress test defined a sealed-to-unsealed ratio of 0.86 to a S12Sx product. This is an improvement over the rating given to the product with 10 percent solids (i.e., a sealed-to-unsealed chloride content ratio of 1.27). Whiting (2002) tested a 20 percent solids solvent-based siloxane. This product performed worse in a chloride ingress test than water and solvent-based silanes. No other siloxane products were considered in this test so a better comparison cannot be made. Hagen (1995) indicated that a S15Sx product accumulated a chloride content of 1920 PPM after three years. This was the fourth best rating out of 17 sealant products in Hagen's study.

Pincheira's (2005) study determined that a S12Sx product had a depth of penetration of 1.8 mm. This was the same as a S10Sx product. Whiting (2005) tested the depth of penetration of a S12Sx. This product, along with a water-based silane, had the shallowest depth of penetration of the products considered in Whiting's study.

(b) Water-Based Siloxanes

The application practices for water-based siloxane products are very similar to those for water-based silane products. Water-based carriers should not be used for reapplications. However, water-based products can be useful for application in environmental sensitive areas by virtue of their lower VOC emissions. Also due to slower evaporation rates for water-based products upon application, they can be useful for high temperature and wind conditions.

Only one water-based siloxane product was studied in the literature review. Pincheira (2005) found the sealed-to-unsealed chloride content ratio for a W10Sx product to be 1.11. This was third worst among all the sealants he tested. The same study showed that the W10Sx sealant had a penetration depth of 1.5 mm. This was second worst among the sealants tested. It is challenging to arrive at an accurate conclusion regarding the performance of water-based siloxanes sealants with 0 to 10 percent solids contents because only one water-based product was tested in a single study. However, the results of this study found that the W10Sx product performed poorly in comparison to the other sealants tested.

No tests of water-based siloxane products with solids content between 11 and 20 percent were found in the technical literature.

5.2.6 Testing of Deck Sealants

The selection and inspection processes for deck sealants relies on performance testing of the products. Different tests are used for each process. The selection process typically relies on acceptance tests to generate an approved products list. The inspection process uses quality assurance/quality control testing (QA/QC) to ensure the products offer adequate performance.

The NCHRP Report No. 244 (Series II) is commonly used to quatify performance of penetrating sealants in laboratory studies. This test method covers sealant penetration depth, absorption, and acid-soluable chloride ingress. The test requires the sealant to reduce water absorption and chloride intrusion by 75 percent, as well as provide 100 percent of the concrete's original vapor transmission. Bush (1998) discusses many advantages and disadvantages of the NCHRP 244 Series II test. Since the NCHRP 244 test has an initial moisture content at the time of sealant application, he concludes that this more closely matches field concrete conditions. Also for bridge decks in northern climates such as Minnesota, the presence of salt in ingress moisture better simulates field conditions. Bush also suggests that the NCHRP 244 test might be a better choice simply due to the time requirement to obtain chloride ingress results (100 days vs. 140 days for the AASHTO T259/T260 test). However, the initial moisture content of the concrete in the NCHRP 244 test cannot be controlled which is not a desirable feature for laboratory test methods.

A study conducted by Wenzlick (2007) discusses five acceptance tests that can be used in the selection process of deck sealant products. These tests include: AASHTO T259 (90-day ponding), ASTM C672 (scaling resistance to de-icing chemicals), AASHTO T277 (electrical induction of concrete's ability to resist chloride ion penetration), ASTM C642 (density, absorption, and voids), and AASHTO T259 modified (crack sealer test). The goal of the study was to determine which testing regimen should be used to classify the sealants used in Missouri. Wenzlick determined that the AASHTO T259 and ASTM C642 tests should be used. Specifically, the AASHTO T259 test states that all concrete samples (covered with a specific sealant) should contain chloride levels less than 1.00 pounds per cubic yard at a depth of ½ to 1 inch. Also, the ASTM C642 test more specifically states that sealed concrete samples should not have absorption levels more than 1 percent after 48 hours and 2 percent after 50 days (Wenzlick 2007).

Like Missouri, the state of North Dakota uses AASHTO T259 and ASTM C642 as acceptance test for concrete deck sealants. However, the acceptance restrictions on the AASHTO T259 test for North Dakota are more strenuous than those used in Missouri. North Dakota requires the chloride levels of the sealed specimen to remain below 0.75 pounds per cubic yard. The restrictions for the 90-day ponding (AASHTO T259) test remain the same as Missouri's tests (Schwartz A.13).

Wisconsin also has a specific test regimen required for penetrating sealants. For the penetrating sealants to be approved they all must pass the following acceptance tests: ASTM C672 (scaling resisance to de-icing chemicals), AASHTO T259 (90-day ponding), ASTM D5095 (determination of nonvolatile content), and EPA Method 24 (volatile organic compound content) (Karow A.18). The first two tests are discussed by Wenzlick (2007). The last two are required to maintain sufficient environmental standards.

Typically, depth of penetration and chloride content tests are the only QA/QC tests conducted (if any) after the deck sealant has been applied in the field. The inspection process for both silane and siloxane sealants are similar. The depth of penetration can be determined by applying water to a split core sample. The applied water will bead when in contact with concrete that contains the sealant, otherwise it will soak into the concrete. Using this method, an approximate value for the depth of penetration of the product can be determined. The chloride content tests are typically conducted using a vacuum drill to harvest samples from a bridge deck. The samples should be subdivided into two or three depths. After the concrete dust samples are gathered they can be brought to the laboratory for chloride analysis. Due to high variability and large scatter obtained from field results, it is challenging to place requirements on field performance. These tests are better suited to determine if the laboratory results can be duplicated in the field.

5.3. Crack Sealers

This section discusses the four classes of crack sealers discussed in the literature review and survey. These sealers are epoxy, high molecular weight methacrylates (HMWM), methacrylates, and polyurethane (Figure 3). This section compares the products using the performance measures discussed in the literature review as well as experiences collected in the survey. Little information was found on the final two sealants considered (i.e., methacrylates and polyurethanes). This lack of information is likely due to the scarcity within the use of these sealants. Refer to Table 10 for an overview of depth of penetration and bond strength results for the crack sealers studied.

The aspect of gel time is an important consideration for the application of all crack sealers. The time required for a crack sealer to gel is directly related to the temperature of the sealer. If the sealer is applied to a deck that is too hot, the sealer will cure too fast and not have enough time to effectively penetrate the deck. If the sealer is too cold, it will take longer to cure and this becomes a problem when the sealer seeps through the deck and drains out the bottom of the cracks. Such spillage can cause environmental problems when the resin drains into a river below the bridge deck. Studies typically recommend a gel time of approximately one hour for crack sealers (Meggers 1998). Sources suggest applying HMWM sealers on a mild day with the temperature between 45 and 90 °F (Krauss 1985). However, accelerators and retardants can be mixed with the sealers to better control gel time and account for extreme temperatures.

Due to thermal expansion, the cracks in the bridge deck vary in size throughout the day. This means that the higher temperatures and direct sunlight that occurs during the middle of the day cause the cracks to be smallest (during their daily cycle). The shift of live loads on the deck can also compound with thermal expansion and contraction of cracks. The expansion and contraction causes a problem because some crack sealers are not flexible enough to expand and contract constantly. Studies suggest it is more beneficial to seal a crack at night because that is when the crack is the largest. This means more resin will occupy (larger penetration depth and width) and cure in the cracks (Marks 1988, Sprinkel 1991). The bond strength of the resin will hypothetically last longer since the resin will be in compression during the day and neutral at night. When the resin is in tension, the bond between the resin and the crack wall tends to break down sooner.

The amount of moisture in the bridge deck during application is also an important parameter to consider. The presence of moisture can decrease the penetration depth and bond strength of the crack sealer. Moisture in the bridge deck can originate from many sources. The two more common sources are rainfall and surface cleaning methods with require water. A laboratory study conducted by Rodler (1989) suggests that a bridge deck be allowed to dry for three days after a rainfall or cleaning to retain 95 percent of the sealers dry bond strength. The study also mentions that a two day waiting period should be observed to retain 95 percent of the sealers dry penetration depth. One should note that since this study is done in a laboratory oven that drying times in the field will vary. The heat and humidity of the climate may prolong the time required for the cracks to dry; however, the test specimens in the lab were not subjected to direct sunlight which may speed up the drying process.

Although most literature points out the importance of surface preparation prior to application, only one study determined how it affects crack penetration depth. Soriano (2002) tested three types of surface preparation: sandblasting, power broom/forced air, and no preparation. The test concluded that the surface preparation method did not affect the penetration depth of the crack sealer. However, the bond strengths of the cracks were not measured. Although the penetration depth was not affected, one would assume that the additional contaminants lining the crack walls would interfere with the sealer's ability to develop adequate bond strength.

5.3.1 Epoxies

The survey found epoxies to be the most commonly used crack sealer throughout the Midwestern United States. Two laboratory studies indicated that the epoxy sealants could penetrate the entire depth of the crack (Pincheira 2005, Sprinkel 1995). However field studies demonstrated that the penetration depths of epoxy sealers were highly variable. Meggers (1998) found that two HMWM sealers penetrated deeper than the epoxy sealer studied. Krauss (1985) documented a case in which the epoxy sealers failed to adequately penetrate the cracks of a bridge deck. A HMWM sealer was used as a substitute due to its lower viscosity.

Laboratory tests indicated that epoxy sealers retained the highest bond strengths of the crack sealers considered when subjected to freeze-thaw effects (Pincheira 2005; Meggers 1998; Sprinkel 1995). Epoxy sealers were also to found to achieve the highest bond strength when not subjected to freeze-thaw conditions (Pincheira 2005). Through chloride ingress and corrosion laboratory testing on reinforced concrete samples, Meggers (1998) determined an epoxy crack sealers would protect the bridge with a cracked deck for approximately 15 years. The tests used to determine the protection rating were modeled from exposure conditions based on a typical Kansas climate (e.g., freeze/thaw, wet/dry, chloride pooling, and temperature conditions). This protection rating was better than the rating given to the HMWM sealers investigated in Meggers' study.

Pincheira (2005) also determined that an epoxy resin retained the highest bond strength for hairline (1/32 in.) and medium (1/8 in.) cracks. An epoxy and HMWM sealer performed the best for wide (1/5 in.) cracks. However, Pincheira noted that the epoxy and HMWM sealer exhibited poor freeze-thaw resistance. Because of this, he recommends using the epoxy resin (Sikadur 55 SLV) for all three crack sizes. Refer to Table 9 for Pincheira's results.

5.3.2 High Molecular Weight Methacrylates (HMWM)

The survey indicated that HMWM sealers were the second most common crack sealer used. A large reason for the sealer's use is that it has a very low viscosity which allows it to penetrate more deeply into cracks. Two laboratory tests determined the HMWM sealers were able to penetrate the entire depth of the crack (Pincheira 2005, Sprinkel 1995). Rodler (1989) also conducted penetration tests on three HMWM sealers. The products penetrated 92.0, 83.3, and 95.7 (90.3 average) percent of the cracks. Marks (1998) conducted a field study which determined that the HMWM sealer used penetrated the entire depth of the two inch core. Meggers (1998) determined that both HMWM sealers tested penetrated deeper into cracks than epoxy sealers. Whiting (2006c) did not observe any penetration deeper than 3/8 in. on the TH 100 Bridge. Most of these tests reaffirm the idea than HMWM sealers penetrate very well into concrete cracks.

When subjected to freeze-thaw conditions Meggers (1998) determined that HMWM sealers lost more of their original bond strength than epoxy sealers. However HMWM sealers performed better during freeze-thaw testing than polyurethanes sealers (Pincheira 2005). When not subjected to freeze-thaw testing, studies determined the bond strength of the sealer was highly variable. Rodler (1998) determined that slabs repaired with HMWM sealers retained 84 percent of their original uncracked strength. However, Sprinkel's (1991) field test indicated that repaired cracks only retained 11 percent of their original uncracked strength. This large drop in bond strength was attributed to contaminants lining the crack walls prior to sealer application.

Through chloride ingress and corrosion laboratory testing on reinforced concrete samples, Meggers (1998) determined the three HMWM sealers would protect the bridge for approximately eight, nine, and 11 years. These periods are shorter than that for the epoxy sealer tested (15 years). Additional studies also indicated that HMWM sealers could not stop the flow of water through the bridge deck, even though the sealers did slow the flow of water and chloride ions (Marks 1988, Whiting 2006c).

5.3.3 Methacrylates

Methacrylates have similar properties to those for HMWM sealers. Pincheira (2005) noted that these sealers were able to penetrate the entire depth of the crack (2.5 in.). Pincheira also determined that the sealer experienced a significant reduction in bond strength when subjected to freeze-thaw conditions. Methacrylate was also used to seal the TH 100 Bridge by Whiting (2006c). Three of the four total cores broke apart along the repaired crack during the coring process. This observation indicates that the methacrylate sealer did not repair the cracked bridge deck adequately.

5.3.4 Polyurethanes

Like methacrylates, there was little information found on the performance of polyurethane cracks sealers. Polyurethanes were found to penetrate the entire depth of a crack in Sprinkel's laboratory study (1995). However a study by Soriano (2002) indicated that polyurethane (along with epoxy) achieved the smallest penetration depths of the sealers he onsidered. Sprinkel's (1995) bond strength study indicated that the polyurethane repaired section retained 100 percent of its original uncracked strength. Despite this high rating in the bond strength study, the polyurethane sealer performed the worst in Sprinkel's freeze-thaw studies.

5.3.5 Testing of Crack Sealers

Many states do not conduct acceptance tests on crack sealing products to generate an approved products list. These states do, however, review previous literature in which a number of tests have been used to quantify the success of numerous crack sealing products. For example, Wisconsin bases the acceptance of crack sealer products on a laboratory study by Pincheira (2005). Other states, such as South Dakota, have determined which crack sealing products to use through field performance.

Some acceptance limits have been suggested by past literature, laboratory, and field studies. Meggers (1998) concluded that crack sealers should have a viscosity of less than 500 cP. This ensures the crack sealer will reach an adequate penetration depth. The study also states that a sealer should have a tensile strength of at least 8 MPa. This value ensures that the crack sealer creates an adequate bond with the crack wall. Lastly, he suggests that a crack sealer should have a tensile elongation of 10 percent. Large tensile elongation properties are desired because brittle sealers tend to fail prematurely. This should ensure a longer lifespan for the sealed cracks. Wenzlick (2007) suggests a maximum viscosity limit of 25 cP for HMWM crack sealers. It should be noted that this viscosity limit is unrealistic for most epoxy sealers and should only be applied to HMWM products.

Similar to deck sealants, depth of penetration and chloride content tests are the only QA/QC tests conducted after application of crack sealers. These penetration tests require cores to be taken over a sealed crack in a bridge deck. By visual inspection of the cross section which includes the sealed crack, the depth of penetration of the sealer can be determined. Occasionally the use of microscopes, florescent dye, and ultraviolet light may be needed to establish the penetration depth. As previously stated for deck sealants, chloride content tests are typically conducted using a vacuum drill to harvest samples from a bridge deck. The samples should be split up into two or three depths. After the concrete dust samples are gathered they can be brought to the laboratory for chloride analysis. Montana considers chloride levels of five pounds per cubic yard poor (Mends A.10). This would indicate that concrete bridge decks should maintain chloride levels significantly below this concentration.

Table 7: Performance of Silane Deck Sealants

Generic Sealer	Product Name	Reference Lab-[l], Field-[f]	Ave. Depth of Penetration (mm)	Sealed-to-Unsealed Chloride Content Ratio (%)
S40Si	Hydro Silane 40 VOC	Pinchiera (2005) [l]	3.8	0.37
S40Si	Sonneborn Penetrating Sealer 40 VOC	Pinchiera (2005) [l]	3.1	0.46
S40Si	Anuanil Plus 40	Pinchiera (2005) [l]	2.5	0.50
S40Si	Penseal 244	Pinchiera (2005) [l]	2.7	0.57
W40Si	Powerseal 40%	Pinchiera (2005) [l]	1.9	0.77
W20Si	Aqua- Trete BSM 20	Pinchiera (2005) [l]	2.0	0.84
W40Si	Hydrozo Enviroseal 40	Pinchiera (2005) [l]	2.1	0.88
W20Si	Hydrozo Enviroseal 20	Pinchiera (2005) [l]	1.4	1.05
100Si	Hydozo 100	Whiting (2005) [f]	4.1	-
S40Si	TK-590-40	Whiting (2005) [f]	3.7	-
W40Si	Enviroseal 40	Whiting (2005) [f]	2.3	-

Table 8: Performance of Siloxane Deck Sealants

Generic Sealer	Product Name	Reference Lab-[l], Field-[f]	Ave. Depth of Penetration (mm)	Sealed-to-Unsealed Chloride Content Ratio (%)
S12Sx	TK 290-WDOT	Pincheira (2005) [l]	1.8	0.86
W10Sx	TK 290-WB	Pincheira (2005) [l]	1.5	1.11
S10Sx	Eucoguard 100	Pincheira (2005) [l]	1.8	1.27
S12Sx	TK-290-12 TriSiloxane	Whiting (2005) [f]	2.3	-

Table 9: Bond Performance of Crack Sealers from Pincheira's (2005) Laboratory Study

Generic Sealer	Product Name	Crack Width (mm)	Average Bond Strength (lb)		
			not subjected to freeze-thaw cycles	subjected to freeze-thaw cycles	percent retained
Methacrylate	Degadeck Crack Sealer	< 1.5	5585	3902	69.9
		1.5-2.5	5680	3521	62.0
		2.5-5.1	4129	3625	87.8
		> 5.1	-	-	-
Methacrylate	Denedeck Crack Sealer	< 1.5	5191	4152	80.0
		1.5-2.5	5101	3695	72.4
		2.5-5.1	5257	2498	47.5
		> 5.1	-	-	-
Urethane Polyurea Hybrid	TK-9030	< 1.5	-	-	-
		1.5-2.5	-	-	-
		2.5-5.1	1227	620	50.5
		> 5.1	-	-	-
Epoxy	TK-9010	< 1.5	-	-	-
		1.5-2.5	2291	990	43.2
		2.5-5.1	-	-	-
		> 5.1	-	-	-
HMWM	SikaPronto 19	< 1.5	3637	2887	79.4
		1.5-2.5	3552	2210	62.2
		2.5-5.1	2772	2249	81.1
		> 5.1	-	-	-
Epoxy Resin	Sikadur 55 SLV	< 1.5	8560	6020	70.3
		1.5-2.5	7994	5876	73.5
		2.5-5.1	6321	5572	88.2
		> 5.1	-	-	-
Epoxy	Sikadur 52	< 1.5	7350	3845	52.3
		1.5-2.5	6140	4352	70.9
		2.5-5.1	6012	2463	41.0
		> 5.1	-	-	-
Epoxy	Dural 335	< 1.5	8329	6599	79.2
		1.5-2.5	-	-	-
		2.5-5.1	-	-	-
		> 5.1	-	-	-
Epoxy	TK-9000	< 1.5	-	-	-
		1.5-2.5	2955	1249	42.3
		2.5-5.1	2829	981	34.7
		> 5.1	1938	900	46.4
HMWM	Duraguard 401	< 1.5	3545	0	0.0
		1.5-2.5	3051	196	6.4
		2.5-5.1	4082	0	0.0
		> 5.1	3409	0	0.0

Table 10: Performance of Crack Sealers

Generic Sealer	Product Name	Reference Lab-[l], Field-[f]	Crack Width (mm)	Ave. Depth of Penetration (mm)	Repaired-to-Uncracked Strength Ratio (%)
HMWM	-	Lasa (1990) [f]	< 0.1	19.3	90.5
			0.1-0.3	23.7	
			> 0.3	24.1	
HMWM 1	-	Rodler (1989) [l]	-	92.0*	75.5
HMWM 2	-	Rodler (1989) [l]	-	88.3*	85.5
HMWM 3	-	Rodler (1989) [l]	-	95.7*	96.5
HMWM	T70M/T70X	Sprinkel (1991) [f]	-	-	11.1
Polyurethane	-	Sprinkel (1995) [l]	0.2		94
			0.5		114
			0.8		79
			1.0		118
Epoxy 1	-	Sprinkel (1995) [l]	0.2	-	110
			0.5		114
			0.8		119
			1.0		103
Epoxy 2	-	Sprinkel (1995) [l]	0.2	-	115
			0.5		123
			0.8		104
			1.0		114
Epoxy 3	-	Sprinkel (1995) [l]	0.2	-	118
			0.5		93
			0.8		95
			1.0		95
HMWM	-	Sprinkel (1995) [l]	0.2	-	131
			0.5		102
			0.8		128
			1.0		108
Epoxy	-	Meggers (1998) [f]	0.40†	34 (55*)	-
HMWM A	-	Meggers (1998) [f]	0.32†	40 (62*)	-
HMWM B	-	Meggers (1998) [f]	0.39†	32 (60*)	-

*- Results given in percent penetration of crack (%)

†-Average crack width

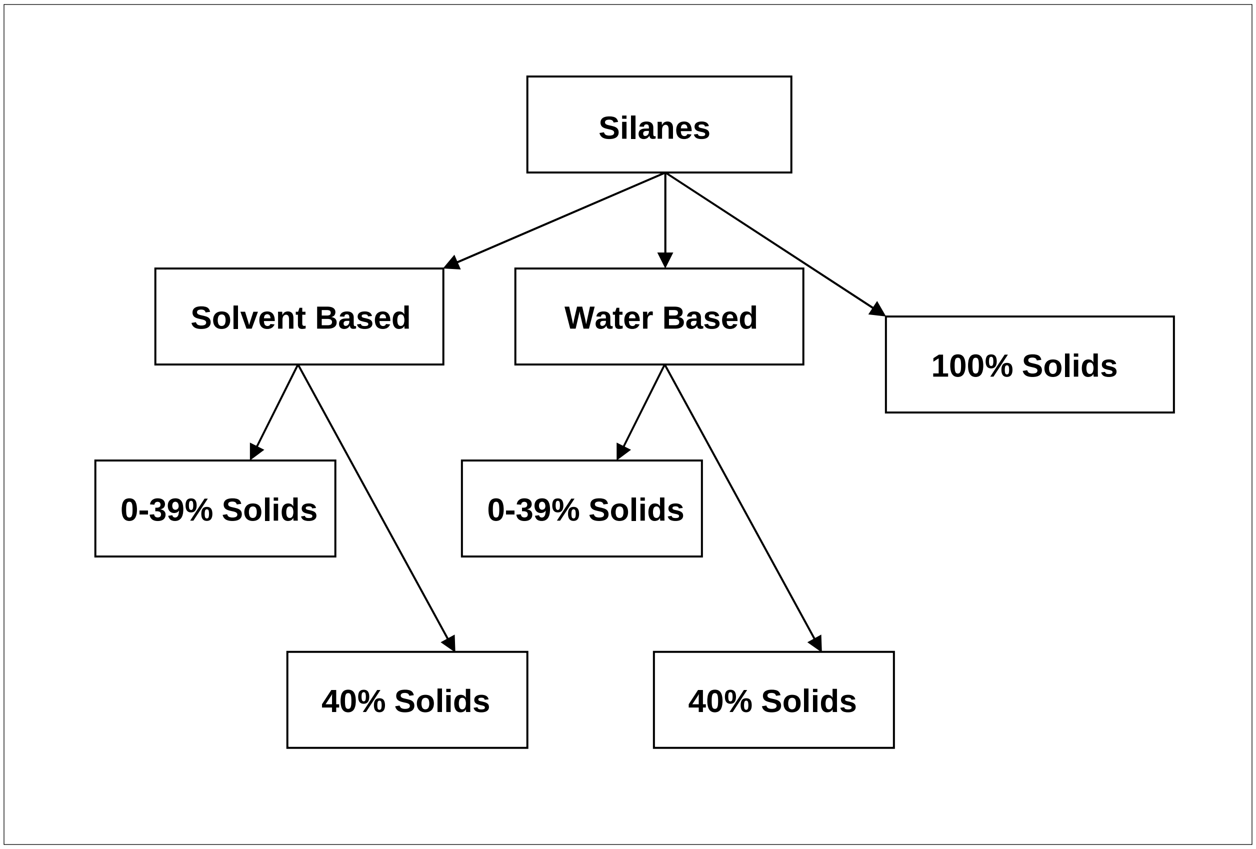

Figure 3. Classification of Silane Deck

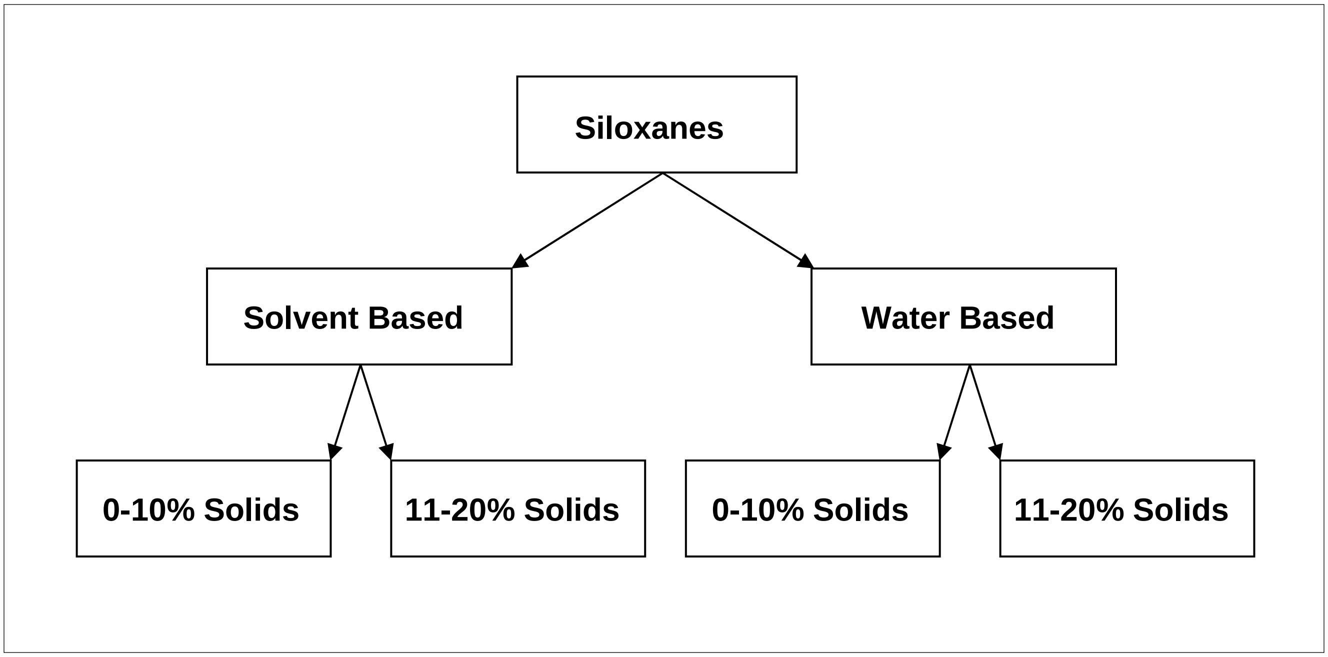

Figure 4. Classification of Siloxane Deck

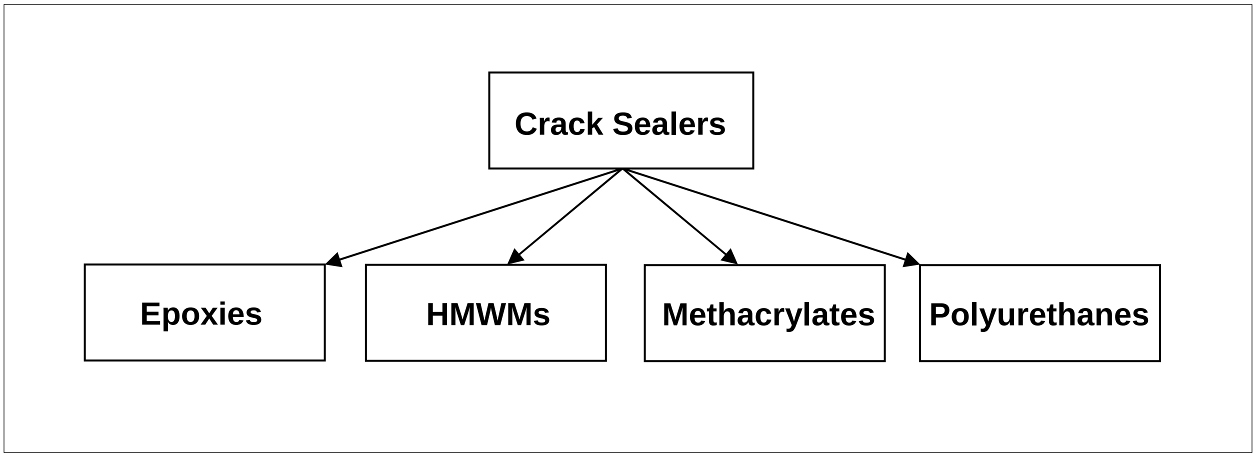

Figure 5. Classification of Crack

Chapter 6 – Summary, Conclusions and Recommendations

6.1. Deck Sealants

This chapter summarizes some of the main findings and conclusions discovered from the literature review and the survey. Recommendations are made to help improve deck repair and maintenance. Proper steps and procedures to achieve the greatest outcome are outlined.

6.1.1 Summary

The survey indicated that 90-day ponding (AASHTO T259) and absorption (ASTM C642) tests are commonly used acceptance tests. The literature also indicated that the NCHRP 244 Series II test is widely used to quantify sealant performance. The survey results showed that depth of penetration and chloride ion concentration tests were the only common QA/QC tests to be conducted on bridges. However, some states did not use any QA/QC testing.

Research suggests that there are a number of measures that can be taken prior to application to improve the effectiveness of the sealants applied. The initial moisture content should be as low as possible because a higher moisture content can hinder the ability of sealants to penetrate the bridge deck (Bush 1998; Basheer 1998). This means that the deck should be allowed to dry prior to application of the sealant if wet. Power washing and rainfall are common events that can cause moisture buildup in the deck. Research recommends that curing compounds be removed from the deck prior to application (Bush 1997). This is due to some curing compounds, such as a white pigmented membrane compound, hindering the penetration depth of sealers. Also due to the high volatility of some silane sealants, sealants should not be applied during high wind conditions because the sealant may evaporate too fast.

Due to the large scatter in the data and the varying effectiveness of each sealer relative to its particular application, it is impossible to predict which sealant will work the best in all situations. Typically silanes had a notably larger penetration depth than siloxane and linseed oil (Pincheira 2005; Basheer 1998; Weyers 1995; Whiting 2005). Also solvent-based silanes and siloxanes tended to penetrate deeper than their water-based counterparts with the same solids content. Basheer (1998), Whiting (2005), and Soriano (2002) all demonstrated that silanes with higher solids content (40% or higher) penetrated slightly deeper that the same sealants with lower solids content. Silanes also displaying the least amount of salt-water absorption of the sealants tested. A slight benefit in absorption performance was also seen by Soriano (2002) with silanes of higher solids content (100% vs. 40%). All of this data indicates that a high solids content, solvent-based silane should be chosen for use. Water-based silane may need to be used if environmental restrictions are present.

Whiting (2006b) resealed a bridge deck one, two, three, five, seven, and ten years after the initial application. The additional coats did not appear to lower chlorides any more significantly than a single application ten years prior to study. This is due to water-based products not being fit for reapplication. Weyers (1995) estimates the service life for silane and siloxane to be between one and eight years due to varying levels of traffic abrasion. This means the duration between applications should depend on the amount of traffic that uses the bridge. Reapplication of the sealant after it has abraded away should protect the deck against chloride ingress longer and prolong the service life of the deck.

6.1.2 Conclusions and Recommendations

Evaluation of the information compiled from the literature review and performance survey yields some trends. First, silane products seem to generally outperform siloxane products both in terms of resistance to chloride ingress as well as depth of penetration. This may be due to the smaller particle size of silanes relative to siloxanes which are able to more readily penetrate concrete. There are specific instances in which siloxanes have outperformed silanes, however this situation is not typical. Second, solvent-based products tend to outperform water-based products relative to both deeper penetration and better resistance to chloride ingress. Also, water-based sealants are not effective for reapplication. Finally, for a given type of carrying agent (i.e., either solvent or water), products with higher solids content tend to perform better in penetration and chloride ingress tests than products with lower solids contents. Products with 40 percent solids content also seem to be the most commonly used products in the survey and the literature review. These results indicate that S40Si deck sealant products are the best choice.

Sealants should be applied between the temperatures of 40 and 100 °F. Also, a drying period of at least two days should be allowed if there has been recent rainfall or if water was used to clean the deck. The AASHTO T259 and ASTM C642 tests are commonly used acceptance tests used by states surrounding Minnesota. However, the NCHRP 244 Series II test is commonly used in laboratory studies and offers advantages over the previous tests.

A special note is made regarding the large amount of variability that was present in the data collected for the deck sealants. Many times, observations made in the laboratory could not be reproduced in the field. Moreover, it was common for different laboratory studies to yield conflicting results. These discrepancies may have been due to differences in the test methods or laboratory conditions used to quantify the results or the inherent unpredictability of sealant performance. Nonetheless, given the information available at the time the present report was written, solvent-based silane deck sealers with high contents of solids appear to be the top performers.

More research is needed to clarify contradictory findings in some of the existing studies, including freeze-thaw effects, penetration depth, UV degradation, and chloride ingress prevention. The future research conducted on penetration depth and chloride ingress should include fieldwork that is closely coordinated with a laboratory study. This would help define the differences between field and laboratory conditions as well as field and laboratory sealant performance. Also additional research on freeze-thaw effects should control the total amount of moisture initial available to the concrete sample. By controlling the initial amount of moisture available to the concrete, more definite trends in sealant performance under freeze-thaw action may develop. Future research should also be focused on explaining which variables cause other sealant materials to outperform silane. Such research could also determine which other sealants may be more appropriate for specific conditions.

The following specific observations, conclusions and recommendations can be made on the basis of this study:

- 90-day ponding (AASHTO T259) and absorption (ASTM C642) tests are commonly used acceptance tests.
- NCHRP 244 Series II testing is widely used to quantify performance .
- NCHRP 244 Series II requires 75 percent reduction in water absorption and chloride intrusion while maintaining 100 percent vapor transmission.
- Depth of penetration and chloride content tests are the most common QA/QC tests conducted on bridge decks, if any are used, but the results are highly variable.
- Silane products typically outperform Siloxane products.
- Water-based products are not suitable for reapplication.
- Solvent-based products typically outperform water-based products.
- High solids content is typically desirable.
- S40Si is the commonly produced sealant that best fits the criteria above.
- Sealants should be applied between temperatures of 40 and 100°F.
- A drying period of at least two days should be enforced if the deck is moist.

6.2. Crack Sealers

6.2.1 Summary

The survey indicated that very little acceptance testing was done during the selection process of concrete crack sealers. Also, no ASTM were typically used for crack sealer testing. Most states selected crack sealing products by reviewing previous laboratory and field research. Others states simply used their own field experience when selecting a product. Similar to deck sealants, depth of penetration and chloride ion concentration tests were the only common QA/QC tests to be conducted on bridges. Typically, states did not consistently use any QA/QC testing.

Prior to application of the sealer, the cracks should be thoroughly cleaned at least once. Power washers and compressed air are common methods for cleaning the contaminants from cracks. Because contaminant levels play such a large role in the success of the sealer, removing as much as possible is desired. If power washers are used, or if rainfall is experienced, the deck must be given sufficient time to dry before application of the crack sealer. Rodler (1989) suggests the deck should be allowed to dry for two days prior to application to retain 95 percent of its dry penetration depth. He also suggests that a three day waiting period should be given after washing or rainfall for the deck to retain 95 percent of its dry bond strength.

The laboratory investigations into depth of penetration determined that that all sealers were successful in penetrating cracks in concrete. Field investigations into penetration depth indicate that methyl-methacrylate and HMWM sealers were the best performers. Krauss (1985) documented a case in which an epoxy sealer failed to penetrate the cracks of a bridge deck. After the epoxy's failure, a HMWM was used to successfully seal the same cracks. Meggers (1998) also conducted a study in which two HMWM sealers obtained a deeper penetration than an epoxy sealer. These results indicate that methyl-methacrylate and HMWM sealers have a distinct advantage over most epoxy sealers in penetration depth. The HMWM and methyl-methacrylates sealers successful penetration performance is likely due to their lower viscosity in comparison to the other sealers.

Laboratory studies into a sealer's bond strength indicate that epoxy sealers performed the best (Pinchiera 2005). The HMWM sealers also performed well but were second in comparison to the epoxy sealers. Very few sources could be found testing materials other than HMWM in the field. The HMWM sealers vary in their effectiveness depending on the study. Lasa (1990) states that the repaired cracks retained 90 percent of their original uncracked strength. Also, there was a very small drop in strength when the cores were tested again 15 years later. Sprinkel's 1991 study states the opposite. The repaired cracks retained only 11 percent of their original strength. These results indicate that despite epoxy's ability to yield a high bond strength in the laboratory, there is not enough information available to determine if it will perform the same in the field. Since there are many more variables in the field that contribute to a sealer's bond strength, epoxy would probably yield unpredictable results in the field (similar to HMWMs sealers).

6.2.2 Conclusions and Recommendations

The information collected in the literature review and performance survey indicates that the performance of two of the crack sealer products stand out. Epoxy crack sealers tend to have the highest bond strength as well as a good resistance to freeze-thaw effects. However, HMWM products are much less viscous which enables them to achieve a larger penetration depth. Because of this property, product selection may need to depend on project conditions. If very narrow cracks are present in the bridge deck, depth of penetration may be deemed more important than bond strength indicating that an HMWM product is the best choice. Crack sealers provide no benefit to a cracked bridge deck if they do not penetrate the cracks sufficiently. However if the bridge deck cracks are large, bond strength may become a more important criterion in the selection indicating that an epoxy crack sealer is the best choice. Additionally, HMWM products are typically applied in a flood coat and epoxy products are generally applied to individual cracks. This means the extent of cracking on the bridge deck may also be a factor in the decision. If there are numerous cracks throughout the bridge deck a flood coat may be more appropriate. If the number of cracks is minimal, application of a sealer to individual cracks is more cost effective.

Meggers (1998) suggests that crack sealers have a viscosity lower than 500 cP, tensile strength above eight MPa, and tensile elongation greater than 10 percent. Crack sealing products should be applied between the temperatures of 45 and 90 °F. This is to control the products gel time. If possible the cracks should also be sealed at night. Marks (1988) suggests application take place between 11:00 pm and 7:00 am. Although Soriano (2002) determined that surface preparation did not affect sealer penetration depth, the effect on bond strength was not discussed. Some form of surface preparation should be used to ensure an adequate bond between the sealer and crack wall. Also, a two to three day waiting period should be enforced if the deck has become moist from rainfall or surface preparation.

To better understand the selection and performance of crack sealers, more research is needed in several areas. First, most of the field research exclusively used HMWM sealers to repair cracks. Because of this limitation, it is difficult to determine how sealers such as epoxies (which were promising in laboratory tests) will perform in the field. Second, more research should also be conducted to determine which sealers stand up to the rigors of freeze-thaw testing, because sealers of the same generic family can have very different reactions when subjected to similar changes in temperature. Third, the lifespan of sealed cracks should be investigated further, as well as the age when a sealer should be reapplied to a previously sealed deck. The need for this line of research is the lack of information on the topic, much which has generated a lot of conflicting opinions. Fourth, the occurrence of re-cracking should be studied further because very little research effort has been dedicated to this issue. However, of the small amount of research found on this topic, re-cracking did not seem to be an issue. Lastly, field and laboratory studies should be closely coordinated to better understand how laboratory results can be extrapolated to field performance.

The following specific observations, conclusions and recommendations can be made on the basis of this study:

- Many states do not conduct acceptance tests to identify acceptable crack sealing products, and products are typically chosen based on well known research (e.g., Pincheira 2005).
- Depth of penetration and chloride content tests are the most common QA/QC tests conducted on bridge decks, if any are used, but the results are highly variable.
- HMWM products typically provide better penetration (suited for smaller cracks).
- Epoxy products typically provide higher bond strength.
- Although test results are variable, epoxy sealers tend to demonstrate good resistance to freeze-thaw effects.
- Crack sealers should be selected with:
    - viscosity less than 500 cP (or 25 cP for HMWM sealers),
    - tensile strength more than 8 MPa, and
    - tensile elongation larger than 10 percent.
- Crack sealers should be applied between the temperatures of 45 and 90°F.
- If possible, crack sealer should be applied between the 11:00 pm and 7:00 am.
- Some form of surface preparation should be used to clean the cracks.
- A drying period of two to three days should be enforced if the deck is moist.

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Appendix A:

Survey Summaries

A.1. Sample Survey Questions

A survey was conducted to identify and document the experience of bridge owners including the Minnesota Department of Transportation (Mn/DOT) with deck sealants and crack sealers. The topics considered in the survey are listed below as a series of questions and follow-up topics.

A.1.1 Deck Sealant Questions

(1) What type of experience do you have working with concrete deck sealants?
- Conducted studies/research (If studies conducted can they be sent to us?)
- Practical applications/field experience

(2) Which type deck sealant products are used in your state and why?
- How many
- Most common
- Penetrating (e.g., silane) or barrier (e.g., linseed oil)
- Approval process
- Important specifications (e.g., depth of penetration, absorption, vapor permeability, or chloride ingress)
- Any testing methods post application to ensure success (Which tests?)

(3) What application procedures are used to seal concrete bridge decks in your state?
- New/Old
- Noticed any difference
- Reapplication (schedule)
- Cleaning methods
- Moisture of deck when applied (drying time)

(4) Are there any particular problems that your state has noticed with the application process or the performance of the repaired bridge decks?

A.1.2 Crack Sealer Questions

(1) What experience do you have working with concrete crack sealers on bridge decks?
- Conducted studies/research (If studies conducted can they be sent to us?)
- Practical applications/field experience

(2) Which type of crack sealer products are used in your state and why?
- How many
- Most common (Any trends?)
- Approval process
- Important specifications (e.g., depth of penetration (viscosity), tensile strength, tensile elongation)
- Were different sealers used for cracks with varying widths or severity?
- Any testing methods post application to ensure success? Which tests? (e.g., cores for determining depth of penetration in comparison to crack width)
- Any debonding noticed?
- Were any parallel cracking observed next to previously repaired cracks?

(3) What application procedures are used to seal concrete bridge deck cracks in your state?

- Typically used to prevent corrosion or structurally repair bridge deck
- New/Old
- Noticed any difference
- Before of after deck sealer if both are used
- Reapplication schedule
- Cleaning methods
- Moisture of deck when applied (drying time)
- Any restrictions on when in the day application can occur?

(4) Are there any particular problems that your state has noticed with the application process or the performance of the repaired cracks in concrete bridge decks?

A.2. Individual Survey Summaries

Transcripts of the individual surveys are included in the following sections.

A.3. Mike Lee (California, CalTrans)

A.3.1 Experience

California used linseed oil to seal bridge decks in the 1950's and 1960's, however that practice has been discontinued. The state does not currently use any type of penetrating sealer on bridge decks. However, a 40 percent silane sealant is used on concrete barriers and the bridge substructure.

The state uses HMWM sealers to seal cracked bridge decks. Specifications are currently being prepared that would allow the use epoxy healer sealers as well. By allowing both sealers (HMWM and epoxy) the state can select whichever is priced more competitively. Roughly 80 percent of the bridge decks have been sealed. Most of the treatment has been on reinforced concrete bridges. Fewer cracking problems are experienced with prestressed concrete bridges. If early age cracking occurs, the contractor is required to seal the bridge deck cracks.

A.3.2 Materials Used

A 40 percent silane sealant is specified for sealing concrete barriers and the bridge substructure (no bridge decks). However some counties do not allow the application of the sealant due to VOC regulations. HMWM sealers are used exclusively in the state to seal cracked bridge decks.

A.3.3 Application Procedures

Before the crack sealant is applied the deck is shot blasted, blown, and swept. The HMWM sealer is applied using a flood coat over the entire deck. The sealer is applied at a coverage rate of 90 square feet per gallon and allowed to soak into the cracks. Sand is then broadcast over the deck to help promote friction. The industry now pre-promotes the HMWM sealer which means the three component (initiator, monomer, and promoter) sealer can no longer explode. In the past, mixing the components in an incorrect order caused a potentially violent reaction. The only drawback is that large batches of the sealer can not be mixed.

When using a HWMW sealer the gel time is important. If the temperature is too low the sealant will gel too fast and not penetrate the crack. If the temperature is too warm the sealant will take too long to cure. This can cause two undesirable effects: (1) the sealer can run out the bottom of the crack if it is not sealed, and (2) the applications may require longer bridge closures. California specifies that the temperature should be above 45°F and below 100°F. If the temperature is below 60°F a cold formulation for the HMWM must be used.

The state has experienced some problems during the application process. Decks that have been previously sealed with linseed oil contain residue that clogs the crack. Also some cracks run through the entire deck. To prevent the HMWM sealer from running right through the deck, the bottom of the cracks are sealed using a latex paint.

A.3.4 Other Information

The state of California is subdivided into three areas depending on environmental conditions. Area 1 has moderate to warm weather. Area 2 experiences some frost and deicing salts will occasionally be used. Area 2, with elevations greater than 3500 ft, often experiences snow and ice. Deicing salts are routinely used in the latter area. CalTrans takes a much more aggressive approach with crack sealing in Area 3. Area 3 is the only area in which epoxy coated rebar is used in bridge decks.

In the past, the state of California has not done any testing to ensure the HMWM crack sealer was effective. However, every bridge deck sealed this year will be cored for two years. The depth of penetration of the sealer will be determined from the cores. This practice should indicate the effectiveness of the crack sealers used.

California currently uses a seven day wet cure. Wet burlap is placed after the deck is finished. The deck is also fogged during the finishing process. After the wet cure concludes a curing compound is applied.

If 20 to 30 percent of the deck concrete is unsound, the bridge deck is overlaid. This is typically done with a ¾ in. polymer concrete overlay. A HMWM is used as a prime coat because the overlay can not be placed on bare concrete. If less than an inch of the deck is to be removed, the deck can be ground. If more than an inch is to be removed, hydro-demolition (i.e., with a high-pressure water stream) is used. If more than three inches must be removed the deck is simply replaced. This is due to problems with deck repair that extends below the top rebar mat.

A.3.5 Contacts

No contacts were provided.

A.4. Ali Harajli (Colorado, CDOT)

A.4.1 Experience

Silane penetrating sealants are used on all bare bridge decks. Silanes were chosen over siloxanes due to a history of better field performance judging by the depth of penetration. Epoxy sealers have also been used to seal bridge decks and cracks. The state does not reapply deck or crack sealers.

A.4.2 Materials Used

Silane sealants with 40 percent solids are used for sealing Colorado bridge decks. The state has also experimented with epoxy crack and deck sealers. To this point the state has not approved products list. Currently no QA/QC testing is used to quantify the performance of the sealants used.

A.4.3 Application Procedures

A dustless method of cleaning is required by specification to clean all bridge decks 48 hours prior to application. This does not preclude other methods such as sandblasting or power washing if approved. The application rate and method should follow manufacturer’s recommendations.

A.4.4 Other Information

The state of Colorado believes the largest problem with penetrating sealants such as silane is to establish the length of time over which the sealant is effective. Since it is believed that the sealant typically wears off in one to two years, repeated reapplication may be needed. In contrast, Wisconsin studies indicate penetrating silane sealants still have 85% of their original effectiveness after three years.

A.4.5 Contacts

No contacts were provided.

A.5. Carl Puzey (Illinois, IDOT)

A.5.1 Experience

Illinois does not typically seal decks with either penetrating sealants or crack sealers. Typically the bridges will only be sealed only if other types of maintenance are being performed on the bridge as well. Occasionally the state will seal major bridges. For example, the Clark Bridge was sealed in 2006 with both deck and crack sealers. Illinois does not regularly seal bridge decks and cracks because of the lack of knowledge on the subject as well as insufficient resources. They also feel the results are not always consistent. Carl Puzey estimates that less than five percent of the bridges have been sealed.

A.5.2 Materials Used

The states of Illinois typically does not call out specific products for use. The deck and crack sealants used to seal the Clark Bridge in 2006 were TK-290 and TK-9000, respectively (both produced by TK Products). TK-290 is a siloxane penetrating sealant, and TK-9000 is a two component epoxy crack sealer.

A.5.3 Application Procedures

Sand blasting is used to prepare the deck before deck and crack sealers are applied. Compressed air is also used to clean out cracks prior to application.

A.5.4 Other Information

The state of Illinois is currently conducting a research project on surface sealants. When this project is completed the state hopes to create a deck sealing program. This program will specify which sealant to use, when to first apply the sealant, and how often the sealant should be reapplied.

Because the state does not typically seal bridge decks and cracks, they used other methods, such as concrete patching and overlays, to repair the deck. The state uses 2½ in. thick latex micro silica overlays.

A.5.5 Contacts

No contacts were provided.

A.6. Jaffar G. Golkhajeh (Indiana, INDOT)

A.6.1 Experience

Material scientists for the state of Indiana have determined that the deck sealants used in the past (unaware which sealants) were not achieving the expected degree of preventative maintenance. This was due to the deck sealant being too watery and running off the deck before properly curing. The specifications for Indiana also indicate that sealants can be reapplied after two to five years (once the initial sealant has worn off). However, due to a small maintenance workforce, bridge decks are typically not resealed. Due to their past experiences with sealants and a small maintenance workforce, Indiana typically will seal a bridge deck only once right after construction with an epoxy deck sealant.

No crack sealing is done in the state of Indiana. It is common practice (not policy) to patch, overlay, or replace a deck when needed. A flow chart has been created (with the help of Purdue University) to show when decks will typically need to be patched, overlaid, or replaced. If less than ten percent of the deck has structural problems (cracks, potholes, etc.) the maintenance crews will patch the damaged portion of the deck. If ten to 30 percent of the deck is damaged, the state will apply an overlay to the bridge deck (typically a latex modified overlay). If over 30 percent of the deck is crack or damaged, the state will replace the deck. The aforementioned flow chart indicates that the first overlay will should be applied approximately 12 years after construction. After another ten to 12 years another overlay will typically be applied. After 35-40 years the deck may need to be replaced.

The flow chart is used as a guideline; however inspections of the bridge deck will first be conducted to determine if maintenance is needed. The state generally expects to apply two overlays to a concrete bridge prior to having to replace the deck. Steel bridge decks typically receive one overlay prior to being replaced.

A.6.2 Materials Used

Epoxy deck sealants and latex modified overlays are used.

A.6.3 Application Procedures

Sandblasting is used to clean decks prior to application of the sealer. The penetrating sealer is then applied at a rate of 90-110 square feet per gallon. The sealer can be applied using brush, roller, squeegee, or any other approved method. Sand is then broadcast over the surface to promote friction.

A.6.4 Other Information

In the past silica fume was used in the deck concrete. However due to improper curing by contractors this practice is no longer used.

The state of Indiana uses epoxy coated rebar in all bridge decks.

The state of Indiana uses a district wide bridge preventative reduction contract to perform maintenance on most of the bridges in the state. This entails bundling together numerous damaged bridge decks is the same area and contracting out the work.

A.6.5 Contacts

No contacts were provided.

A.7. David Meggers (Kansas, KDOT)

A.7.1 Experience

On the basis of Megger's 1998 crack sealing study, it was determined that cracks could not be adequately sealed in old bridge decks. This was due to the presence of contaminants in the crack making a successful sealing process challenging. Instead of crack sealing on older bridges, Kansas uses a two coat broom and seed overlay on cracked decks. A heavy shot blasting application is used prior to placement of the overlay. The state has yet to reapply the two coat broom and seed overlays. Overlay life expectancy is approximately 20 years. This information comes from similar overlays implemented by Sprinkel in Virginia. However new bridges that develop cracks will be sealed.

Another study also concluded that silane and siloxane sealants were not cost effective. Also linseed oil is typically not used because it is mixed with environmentally harmful materials like kerosene. Because of this Kansas looked to improve their concrete mix design for bridge decks and overlays. This new “performance based concrete” theoretically should decrease concrete permeability as well as number of cracks. The “performance based concrete” is created by providing a minimum amount of cement and a maximum water cement ratio. Using an optimized aggregate gradation, they can then formulate a concrete that cuts down on permeability and cracks. For bridges with an ADT higher than 6000, a 1½ inch high density silica fume overlay will be used. The mix for the overlay currently contains seven percent silica fume. However, Kansas is trying to reduce that percentage to five percent. The reduction in silica fume will hopefully reduce the amount of cracking experienced by the bridge deck overlays. Slag is allowed in the silica fume mix. Fly ash is not allowed due to inconsistent results noticed in the specimens containing the product.

A.7.2 Materials Used

Unitex Bridge Seal HS epoxy is used due to its price and close proximity of the supplier. The state has also experimented with methacrylate, HMWM, and polyesters materials. Due to inadequate durability and short lifespan, other products are preferred over polyester products. Methacrylates are occasionally used due to their ability to cure at low temperatures and low viscosity.

A.7.3 Application Procedures

When new bridges need to be sealed, an epoxy is used. The cracks are first allowed to dry and the deck will either be lightly shot or sand blasted prior to application. The epoxy is mixed in 30 gallon tubs (ten gallons at a time). The epoxy is then spread on the deck with notched squeegees. Lastly aggregate (1/4 inch) is broadcasted into the epoxy prior to curing. Most overlays cure in approximately four hours.

A.7.4 Other Information

In an effort to reduce cracking Kansas has specific regulations for curing of the bridge deck concrete. After the deck is poured, it is cured until the overlay is applied (typically seven days later). After the overlay is applied, it is tined and a curing compound is applied. The overlay is then allowed to cure for seven days using wet burlap. Fogging is also used until the wet burlap is placed. After evaluating the condition of 60-70 bridge decks with and without the new curing procedure, a large reduction in cracking was noticed.

A.7.5 Contacts

The following contacts were recommended:
Mike Sprinkel
Mike Stenkel
Dave Fowler
Nigel Mends

A.8. Larry Cooper (Minnesota, Mn/DOT) Dist. 7

A.8.1 Experience

Linseed oil was used in the 1980’s to protect bridge decks. The district has recently started using silane sealants. The district also uses two part epoxy sealers on cracked bridge decks.

A.8.2 Materials Used

A 40% silane sealant called PENSEAL 244 40% (made by VEXCON Chemicals) is used to seal bridge decks. A two part epoxy named 2501 Clear produced by Viking Paint is used to seal cracked bridge decks in the region.

A.8.3 Application Procedures

The decks must be flushed with high pressure water and allowed to dry before the silane can be applied to the deck. The silane sealant is applied using a spray bar apparatus that is mounted on the back of a tractor. The sealant is typically applied using two passes to prevent the product from running off the bridge deck.

Cracked bridge decks are either blown clean with compressed air or sand blasted prior to application. The two component epoxy is then mixed together on site (five minute stir process required). The epoxy mixture is then applied to the cracks with handheld bottles through a tapered nozzle.

A.8.4 Other Information

The district tries to reseal both the decks and cracks every five years. If this five year rotation is not met spalling and other structural problems arise.

A.8.5 Contacts

No contacts were provided.

A.9. Steve Kavanagh (Minnesota, Mn/DOT) Dist. 3

A.9.1 Experience

Originally linseed oil was used on bridge decks. However linseed oil does not typically last long on the bridge deck. His experience is that the linseed oils do not last for much longer than one summer season. This is due to traffic wearing the sealant away. Also linseed oil takes a long time to cure on the deck.

Because maintenance crews are not restricted by construction guidelines, Steve Kavanagh began using silane sealants in 1996. Originally a water based 40 percent solids silane was used. A water based silane was chosen for environmental reasons. In 2004 he switched to solvent based silanes due to the increase in penetration depth. Another reason for switching to a solvent based silane is that water based silanes will be repelled by the deck during reapplication. Typically the silane sealant should be reapplied every three to five years. However due to limited resources, reapplication typically happens every five to seven years. Reapplications of the solvent based silanes are scheduled to take place in the next year or two.

A.9.2 Materials Used

Solvent based Silane with 40 percent solids, and PaulCo TE-2501 two part epoxy are used.

A.9.3 Application Procedures

Prior to the application of deck sealers, a pump truck is used to power wash the deck. The deck is then allowed to dry for one to two days. No longer than two days are allowed to pass between washing and application. The time allowed for drying is controlled by the heat/humidity of the day and time constraints of the district. The drying time is used to allow the top ¼” to $^{3}/_{8}$” inch of the deck to dry out. The solvent is applied using vehicle with a farm-like sprayer on the back. The vehicle has a 12 foot width for application. Silanes typically require a 250-300 ft^2/gallon application rate. Since the silanes were taking too long to cure with this coverage rate, the district began using a double application with a coverage rate of 500-600 ft^2/gallon. The two applications take place one after the other. The double application allows the silane to penetrate faster into the deck. Traffic is allowed to travel on the bridge three hours after application. A case in Duluth was documented where a single application of silane did not cure for four days. If a curing compound is used on the deck (e.g., 25 percent solids acrylic) the deck will have a light sandblasting before the deck sealant is applied.

Steve Kavanagh uses 100 percent resin epoxy on cracked bridge decks in his district. The rapid set two part epoxy (PaulCo TE-2501) is manufactured by Viking Paints. Epoxies are used on cracks larger than $^{1}/_{32}$". The cracks originally sandblasted for the first 25 years. For the last five years the cracks have been cleaned using 110 psi air pressure. Typically a two-day (ideally three-day) waiting period will be used if the cracks are wet. This is due to the reduced ability of epoxies to stick to wet concrete. A three wheel cart is used to apply the epoxy. The cart has two containers and the two part system is mixed at the nozzle. Epoxies used primarily on reflection cracks (mainly transverse). More cracks were documented at mid-span of bridges. Silanes are typically used on the deck prior to crack sealing in an attempt to seal the vertical faces of the cracks. The epoxy typically gets brittle over time. This causes the concrete paste to pull away from the inflexible epoxy. Reapplication is suggested every three to five years. However like deck sealants, the application process typically happens every five to seven years. Prior to reapplication the excess epoxy is pulled from the cracks and the cracks are re-blown with 110 psi air pressure.

A.9.4 Other Information

Another product with which Steve Kavanagh has begun experimenting is Accuflex. This product is typically used to seal decks that have a large amount of very small shrinkage cracking. The product seals both the deck and very small cracks. This product is applied the same way the silane products are applied (sprayer on back of vehicle over two applications). The application rate for Accuflex is 150 ft^2/gallon (or 300 ft^2/gallon for double application). The product reacts with the free calcium in the cracks to form a water soluble barrier. After the product has cured the shrinkage cracks are no longer visible. District 1 is the leader in application of this product (Pat Houston). Steve is unsure if Accuflex can be reapplied. He also has very limited experience with siloxane. Canada and Wisconsin have been testing siloxanes. Due to the long curing process required to use the siloxane products Steve does not use them.

One case in which epoxies failed occurred when a sidewalk was sandblasted and a flood coat of epoxy was applied. Due to the use of a flood coat (not just applied to cracks), the concrete was not allowed to breathe. The surface then deteriorated (turned powdery). They have also experimented with other epoxy products. They used a TK epoxy in Duluth and cracks propagated up through the epoxy resin. Silicones are typically not used since they tend to harden from UV rays. District 1 now experimenting with urethanes.

A.9.5 Contacts

No contacts were provided.

A.10. John Wenzlick (Missouri, MoDOT)

A.10.1 Experience

Linseed oil is used to seal bridge decks in Missouri because of its ability to prevent surface scaling. Linseed oil was chosen after performing best in a 90-day ponding and freeze-thaw test. Also, Missouri has found linseed oil to be one of the most cost-effective options for sealing bridge decks. Originally the state of Missouri applied linseed oil after bridge construction, and then once a year for the next five years. During the late 1970's this practice was changed by applying linseed oil after construction of the bridge deck and then following up with one reapplication after the first year. This was done because the applications after the first year application were not deemed cost-effective.

Cracks sealers are primarily used for maintenance procedures. This means they are typically not applied to the deck until it experiences one decade of use. Occasionally Star Macro Deck has been applied to new decks that have experienced a large amount of cracking right after construction. Pavon INDeck has been the primary crack sealer since the middle 1990's. However other products, such as Star Macro Deck, are sometimes chosen for aesthetic reasons. Regular asphalt crack sealers were used on concrete bridge decks prior to the middle 1990's.

A.10.2 Materials Used

Missouri uses Linseed oil (50/50 mix with mineral spirits) to seal all bridge decks in the state.

Four products have been used to seal cracked bridge decks in Missouri. The most common material is called Pavon INDeck which is produced in Kansas City. The crack sealer is an emulsion which is placed over the entire deck. Electro-attraction helps the sealer penetrate further into the decks cracks. The sealer is black in color and costs approximately eight cents per square foot. Reports have shown that the sealer achieves between one and 1¼ inch depth of penetration. Friction problems, although rare, occurred in the past with this material. Because of this, sand tack is broadcast over the sealer prior to curing. The bridge is then typically opened within one hour of application. This crack sealer is typically reapplied every three years.

The second most common product used is called Star Macro Deck. This is a latex based emulsion that is also applied to the entire deck. The advantage that Star Macro Deck offers is that the sealer is white in color when it is applied and it turns clear after curing. The product costs approximately eight to 16 cents per square foot.

Occasionally, High Molecular Weight Methacrylates (HMWM) have been used in the past to seal cracked decks. Because these products were more expensive (40-45 cents per square ft) they are no longer used. Occasionally a two-part epoxy is applied only to the cracks on the bridge deck.

A.10.3 Application Procedures

After the curing process has concluded, crews wait two days for the concrete to dry. The linseed oil is then spread on the deck with an application rate of 0.05 gallons per square yard. Prior to the second application (one year after construction) the bridge is blown dry with compressed air. The sealant is then applied with the same application rate.

Before sealing cracks on a bridge deck the bridge is first flushed with water (not a high–pressure stream). After waiting two days for the bridge to dry, the cracks are then blown clean with compressed air. The crack sealer (typically either Pavon INDeck or Star Macro Deck) is applied over the entire deck and pushed into cracks with squeegees and brooms. While the crack sealer is curing sand tack is broadcast over the deck to promote friction.

A.10.4 Other Information

The state has been noticing more cracking of bridge decks in the past ten years. This is likely due to a stronger concrete mix which was implemented in 1977. This mix was originally formulated for lower chloride permeability.

A seven day wet burlap cure is used on all bridge decks in Missouri. Typically a dissipating curing compound is applied immediately after the bridge deck is tined. Then specifications allow 30 to 45 minutes to start the seven day wet cure. Occasionally the wet cure is implemented immediately after the deck finishing is completed and they diamond grind (process utilizing diamond blades to grind and texture concrete) the deck after it has cured.

The state of Missouri has also been experimenting with reactive silicates. These products react with the free calcium in the bridge deck to form a crystalline structure that fills small cracks.

Missouri uses a 8½ inch thick decks. Two mats of epoxy coated rebar with a three inch cover are used in the deck. Standard decks also include four inch thick precast post-tensioned panels. Epoxy coated rebar or mesh is also in the precast panels. However the post-tensioning is not epoxy coated.

A.10.5 Contacts

No contacts were provided.

A.11. Nigel Mends (Montana, MDT)

A.11.1 Experience

Silane is used to seal all bridge decks because of its favorable cost and ease of application. Montana also has been using High Molecular Weight Methacrylates (HMWM) since the 1990's to seal all bridge deck cracks.

A.11.2 Materials Used

Both the deck sealant (silane) and crack sealer (three component HMWM) were chosen after a review of previous studies. Either a water or alcohol based silane is used. When the temperature is high during the summer, alcohol based products tend to flash off the deck before penetration. Because of this, water based products are used in this situation. In most other situations, alcohol based silanes are used.

A.11.3 Application Procedures

Bridge decks are typically sealed 28 days after the deck is poured. A two-week wet cure is implemented immediately after the deck is poured (wet burlap). This is followed up by a dry cure for one week. After all of the water has evaporated from the deck (typically 28 after completion), hand sprayers are used to apply silane to the deck. Multiple passes are made until the deck refuses to absorb the additional deck sealant. The silane typically cures in a matter of minutes so traffic can traverse the bridge within one hour of completion. The deck sealants are typically reapplied every three to five years.

Prior to the application of the HMWM sealer, the deck is cleaned by shot blasting. The bridge deck is then flooded (100-150 square feet per gallon) with HMWM sealer. Sand is broadcast over the sealer by hand for traction. The sealer takes anywhere between two and 24 hours to cure. The curing time is greatly influenced by temperature and ratio of the three components. No respirators are needed during the application of the HMWM sealer. Reapplication of the HMWM sealers is set for approximately 15 years. This procedure is based on studies showing the life of similar sealers to last for 17 years. No bridge decks in Montana have had HMWM sealer reapplied to date.

A.11.4 Other Information

Montana has used polymer overlays instead of crack sealers in the past. Due to reoccurring implementation problems these overlays are no longer used.

Ten years ago, crack sealing became a priority after chloride tests indicated a spike in chloride contained in the bridge decks. Typically five pounds per cubic yard is considered a poor reading. Montana began noticing 25-50 pounds per cubic yard of chloride in their bridge deck concrete. This was attributed to Montana switching to a Magnesium Chloride de-icing material.

A.11.5 Contacts

The following contact was recommended:

Jim Wong, Alberta, Canada

A.12. Jim Laughlin (Nebraska, NDOR) Dist. 2

A.12.1 Experience

Nebraska has used polymer based sealants to seal all new bridge decks in the state for the past five years. The decks are typically sealed three to four months after construction. Also, all of the old bridge decks were sealed over a three year period. Currently there is no program for resealing bridge decks. Jim Laughlin feels the application of the polymer sealants have been beneficial to the service lives of the bridge decks.

A.12.2 Materials Used

The most common materials used to seal bridge decks are Sika Pronto 19 TF and STAR Macro-Deck. These sealants successfully fill cracks that are an 1/8th of an inch wide or less.

A.12.3 Application Procedures

If the curing compound is still present on the deck, the deck is power washed prior to application of the sealant. Older decks are subjected to compressed air prior to application. A flood coat is then poured on the deck and manipulated with brooms and squeegees.

A.12.4 Contacts

The following contact was recommended:
Dave Jochim 402-479-3874 – Materials and Research (NDOR)

A.13. Dan Holderman (North Carolina, NCDOT)

The North Carolina DOT typically does not seal decks or cracks. NCDOT has used some decks sealants but did not believe that the sealants produced good results. Twenty years ago linseed oil was used. That practice was discontinued due to unclear results and problems with application. These problems included having to stop traffic and needing to broadcast sand over the deck due to increased slipping of traffic.

A research project conducted approximately four years ago by North Carolina State University tested six or seven sealers. The test, which coated blocks and subjected them to a salt bath, did not product adequate results. Because of these results, the state of North Carolina feels that inhibiters and sealants are not worth the time or the trouble to apply them.

Calcium Nitrate is occasionally used as an admixture in deck concrete. However this is only used along the coastline and highly salted (urban) areas.

If a deck begins to deteriorate, typically a two-coat epoxy overlay with silica sand is used to prolong deck life. North Carolina also uses hydro-demolition to strip off deteriorating concrete and uses a latex modified concrete overlay. This practice has been done for 30 years with success. Epoxy or cementious patches have also been use on potholes.

A.14. Larry Schwartz (North Dakota, NDDOT)

A.14.1 Experience

North Dakota specifications call for a penetrating sealant to be applied to all new bridge decks. This penetrating water repellant is required to be either an Alkyl-Alkoxysilane or Oligomerous Alkyl-Alkoxysiloxane sealant. This practice has been used for approximately 20 years. North Dakota does not currently reapply penetrating deck sealants and does not have a crack sealing system in place.

A.14.2 Materials Used

The state requires the deck sealants to consist of an Organo Silicon compound which can be either Alkyl-Alkoxysilane or Oligomerous Alkyl-Alkoxysiloxane. Both sealants are dissolved in a solvent carrier and must have over 40% solids. The solvent is also required to leave less than one percent residue upon evaporation. All sealants used must pass both an absorption (ASTM C-642) and chloride ion penetration test (AASHTO T-259).

A.14.3 Application Procedures

Prior to application the deck surface is cleaned by power washing (1800 psi) or sandblasting. If the concrete surface is moist (either from rain or power washing) the deck will be allowed to dry. An airless spray bar (15 to 40 psi) is used to apply the penetrating sealant. The coverage rate is specified by the manufacturer.

A.14.4 Other Information

Tom Bold is conducting research for the state of North Dakota on several products that are used to seal cracked bridge decks. Depending on the results, the products may be used in the future to seal older cracked bridge decks.

The historical cost of applying penetrating deck sealants has been 2.82, 7.35, 3.51 dollars per square yard in 2007, 2006, and 2005 respectively.

A.14.5 Contacts

The following contact was recommended:
Tom Bold (701) 328-6921

A.15. Walter Peters (Oklahoma, ODOT)

A.15.1 Experience

The state of Oklahoma has been using silanes since the late 1970’s. The state waits 28 days after construction is finished to apply the silane sealant. If the bridge is built in the winter, the silane sealant will be applied the following summer. Generally the state tries to seal individual cracks. However if a bridge deck has extensive cracking a flood coat will be used. To this point no cracks have been resealed.

A.15.2 Materials Used

Silane sealants are used to seal the bridge deck. The state requires the silane to penetrate at least 0.15 in. Two different types of sealers are currently used to seal and mask cracks on bridge decks. High Molecular Weight Methacrylate (HMWM) sealers were used in the past, however epoxy sealers have produced comparable results and are much cheaper. The first sealer that is still in current use is SSI Deck Seal. This product is a low viscosity (less than 50 cps) sealer which is typically applied by flood coating the entire deck. The sealer’s primary use is to penetrate the cracked bridge deck. Due to poor penetration in older cracks (due to contaminant build up) this product is only used on newer bridge decks. The product costs approximately 17 dollars per square foot. The second sealer used is SSI ReDeck. This product is a thick epoxy (higher viscosity) used to create a barrier on the top of the deck. ReDeck is typically applied with multiple coats and is mixed with aggregate. This product costs approximately 40 to 50 dollars per square foot and is primarily used to extend the service life of older bridge decks.

A.15.3 Application Procedures

The surface preparation required for both deck and crack sealing are similar. Typically sandblasting or high pressure water is used to clean any remains of the curing compound as well as dirt, oil, or other contaminants. SSI Deck Seal is typically applied using a flood coat. Brooms and squeegees are then used to manipulate the product and direct it into cracks. Sand is broadcast over the deck afterwards to promote friction for traffic. SSI ReDeck is typically applied in two subsequent coats. Each coat consists of spreading the two component bonding agent on the deck and applying a coarse hard aggregate over it until it is no longer absorbed.

A.15.4 Other Information

A seven day wet cure is used for all newly constructed bridge decks that do not contain fly ash. A ten day wet cure is used on decks that contain fly ash. Specifications require the deck to be fogged while being finished and covered with wet mats within ten minutes of completion. After the seven to ten day cure, a curing membrane is applied to the deck. There are also environmental conditions that are added to the specification to prevent excessive cracking. These specifications are in place to prevent extreme weather conditions (such as temperature and wind) from causing more cracks.

A.15.5 Contacts

The following contact was recommended:
Dave Darwin

A.16. Tom Gilsrud (South Dakota, SDDOT)

A.16.1 Experience

The state of South Dakota has used linseed oil to seal bridge decks in the past. However recently (last three to four years) they have moved away from linseed oil and started applying silane. This change was made because of literature reviewed by the state. Also, applying linseed oil every other year was very labor intensive. New specifications indicate that silane should be applied to all new bridges in South Dakota.

Most of the crack sealing is done is the Southeast part of the state due to higher population density and traffic volumes.

A.16.2 Materials Used

Materials (both deck sealants and crack sealer) are primarily chosen by region. A solvent based silane called ChemTreat is used for most bridge decks. This specific sealant was decided upon after lab studies and field experience.

Unitex Bridge Sealer is the most common crack sealer used in South Dakota. An epoxy deck seal called Transpo T48 has also been used to seal cracked decks. The Transpo seal involves flooding the entire deck and adding aggregate. This product has been used for approximately ten to 12 years throughout the state. No reapplications have been made.

A.16.3 Application Procedures

Application and preparation procedures for both deck and crack sealants are primarily determined by region. Typically the decks are broom cleaned prior to the application of silane. No reapplications of silane have been made since the process is still relatively new.

A.16.4 Other Information

A 14 day wet burlap cure is used on all bridge decks. This was implemented because the state was seeing a large amount of early shrinkage cracks in bridge decks. Curing compounds have been used in the past, however they were phased out with the new 14 day wet cure. The state has seen some improvement in cracking after implementing the new curing specifications.

A.16.5 Contacts

The following contact was recommended:
Jay Larson – Region Bridge Specialist, (605) 995-8136 ext. 218

A.17. Jay Larson (South Dakota, SDDOT) Region Bridge Specialist

A.17.1 Experience

Jay Larson has held the Region Bridge Specialist position for approximately five years. It is common practice for all new bridge decks that are bare (no low-slump or other type of overlay) to be treated with silane. The decks are sealed just before they are opened to traffic by the contractor. His predecessor began an epoxy crack sealing program. The state of South Dakota tries to seal bridge deck cracks after one or two winter cycles.

A.17.2 Materials Used

The most common product used to seal bridge decks in South Dakota is Chem-Trete BSM40. The sealant is a solvent based silane. TK5090 Tri Silane was used in the past, however, due to the inconsistent size of the silane particles and varying solvent base used, use of the sealant was discontinued. Problems arose when the sealant took too long to dry and created a slick surface on the bridge deck. This required the bridges to be closed to traffic for most of the day.

The most common product used to seal cracks in bridge decks is Unitex Bridge Seal. This is a penetrating epoxy sealer with a viscosity of 50 cps. Conspec Spec-Seal was used in the past, however the sealer set up too fast which caused a large amount of wasted crack sealer.

A.17.3 Application Procedures

Bridge decks are flooded every spring (regardless if they will be sealed) to remove excess deicing products. The deck is also blown clean prior to application of a deck sealant or crack sealer. A six to eight foot spray bar mounted on the back of a truck is used for deck sealant application. A common agricultural pump is purchased to pump the sealant. The spray bar is set to give off a fine (but not too fine) mist. The sealant is applied with one pass of approximately 200 square feet per gallon. The goal is to reapply the silane deck sealant every five years. To this point Jay Larson has not resealed any decks.

The same deck preparation process is used for crack sealers. Due to the price of the selected crack sealer doubling in the last four years, the state tries to seal individual cracks instead of flood coating the entire deck. However if extensive cracking is present a flood coat may be used. The state plans on resealing the bridge deck cracks every five to eight years. To this point Jay Larson has not resealed any cracks.

A.17.4 Other Information

Most of the products chosen were based on a 2003 South Dakota laboratory and field study by Soriano. QA/QC core testing has been done by the state on epoxy sealed cracks to ensure sufficient penetration. Also water beading tests have been performed on decks sealed with penetrating sealants. This test is also to ensure a sufficient penetration depth is being met.

A.17.5 Contacts

No contacts were provided.

A.18. Bruce Thill (Washington, WSDOT)

A.18.1 Experience

The state of Washington at this point does not use any deck sealants (i.e., silanes, siloxanes, or linseed oil) on bridge decks. The state will seal cracks in a deck if they occur within three days after the decks construction. If a large amount of cracking (due to shrinkage, etc.) forms within the first three days after the construction the contractor is required to seal the deck with a flood coat of High Molecular Weight Methacrylate (HMWM). Typically extensive cracking only forms within the first three days if some specifications are not followed during the construction and curing process (i.e., rained during deck concrete pour). This practice of sealing bridge decks is implemented on less than five percent of the bridge decks in the state. Cracking that forms after the first three days will not be sealed during the life of the bridge. Moreover, the state of Washington does not overlay bridges as a measure to mitigate cracking. The state also does not have specified testing procedures implemented prior to application or after application to verify product effectiveness.

A.18.2 Materials Used

A High Molecular Weight Methacrylate is used for almost all crack sealing projects. This selection is used based on Washington’s experience and prior success with the product application procedures and performance (no approved product list). By the use of a single product, the state of Washington gets more consistent results and can diagnose problems if they arise. At this point the state of Washington does not have testing required for product approval or QA/QC testing.

A.18.3 Application Procedures

The manufacturer’s instructions are followed for all surface preparation and application rate. If the manufacturer recommends sand-basting, high pressure water, brooming, etc. these will be performed prior to application. Sand is typically broadcast over the top of the deck while the HMWM is curing to promote friction.

A.18.4 Other Information

Engineers in the state of Washington question whether repeated applications (which is recommended by manufacturers) of crack sealants are cost effective. Through existing literature and past experience they feel there is not enough evidence to indicate the positive effects of sealing cracks are enough to outweigh the cost. Also due to the varying types (Diagonal, Map, Longitudinal, Shrinkage, and Transverse) and sizes (small, large, deep, shallow, narrow, or wide) of cracks that occur, the state of Washington is unsure if consistent results can be achieved or predicted.

Washington does not use sealants (after construction) or overlays to seal bridge deck cracks. However, the state has had to replace only two decks in the past 20 years.

Washington uses the industry standard for curing of bridge decks. They are also in the process of conducting a study to reduce the amount of cement in their bridge deck concrete mix. This study hopes to create a concrete that produces less cracks.

A.18.5 Contacts

The following contact was recommended:
Paul Krauss (847) 272-7400 (In charge of NCHRP Research Project)

A.19. Bruce Karow (Wisconsin, WisDOT)

A.19.1 Experience

The use of deck sealers depends on which region the bridge is located. The state of Wisconsin is moving towards producing better quality concrete (with less permeability) so that deck sealants will not be needed. Materials specialists as well as field personnel have not seen a large difference in performance of the different types of high-performance concrete. The state is placing a larger emphasis on crack sealing.

A.19.2 Materials Used

A products list of deck sealants has been established by the state. Wisconsin is still working towards establishing a product list for crack sealers. These lists are formulated by material lab specialists and previous studies of the products (Pincheira 2005). The specific material used to seal bridge decks and cracks are determined by the county where the bridge is located. The selection of the material is typically based on its cost and the region's experience with the product.

A.19.3 Application Procedures

The application rate for concrete deck sealants is 200 square feet per gallon (or as recommended by manufacturer). Bridge decks are to be resealed every three years. Specific application procedures (deck preparation, application method, drying time, etc.) are dictated by the region.

The state of Wisconsin attempts to seal bridges with cracks larger than 0.02 inches in width. Cracked bridge decks are to be resealed every four years (or as needed). Specific application procedures (deck preparation, application method, drying time, etc.) are dictated by the region.

A.19.4 Other Information

Wisconsin uses the following tests to determine which products should be allowed for use:

1. ASTM C672 - Standard Test Method for Scaling Resistance of Concrete Surfaces Exposed to De-icing Chemicals
    - WisDOT Spec - Test blocks must rate at least at least one full visual rating unit better than control blocks, and in no case shall exceed a rating of "2".
2. AASHTO T259 - Resistance of Concrete to Chloride Ion Penetration
   (Test blocks are abraded 1/8" prior to ponding)

WisDOT Spec - Difference in total chloride content between test blocks and unponded control blocks shall not exceed 50% of the difference between the ponded and unponded control blocks, and in no case shall exceed 2.0 pounds per cubic yard.

3. ASTM D5095 – Determination of Nonvolatile Content in Silanes, Siloxanes and Silane-Siloxane Blends

    WisDOT Spec – Product as designed should be nominally a 40% Silane product. Field samples of production product must have D5095 results within the range of 40 +/- 5% non-volatile content.

4. EPA Method 24 - Volatile Organic Compound (VOC) Content

    WisDOT Spec – Must not exceed maximum allowable VOC of 600 g/L for Waterproofing Sealers category per U.S. EPA requirements.

A.19.5 Contacts

The following contact was recommended:
Tom Hardinger, thomas.hardinger@dot.state.wi.us (715) 421-8323
Matthew Murphy, matthew.murphy@dot.state.wi.us (608) 246-3250
John Bolka, john.bolka@dot.state.wi.us (262) 548-6711
Dale Weber, dale.weber@dot.state.wi.us (920) 492-7161
Dave Bohnsack, david.bohnsack@dot.state.wi.us (608) 785-9781
Greg Haig, gregory.haig@dot.state.wi.us (715) 577-0646
Brock Gehrig, brock.gehrig@dot.state.wi.us (715) 365-5799
Allan Bjorklund, allan.bjorklund@dot.state.wi.us (715) 225-9308

Appendix B:

Literature Review Summaries

B.1. Format of Literature Review Summaries

The summary of previous research is broken down into two categories for user ease, concrete sealant research and crack sealant research. In the event that relevant research did not fit either category, a third category was created defined as “other.” If a certain report or paper investigated concrete and crack sealers, 2 summaries were written, one for the concrete and one for the crack sealant category. If this were the case, both summaries for the report or paper made note of this.

Summaries in the concrete sealant research, crack sealant research, or “other” categories can be traced back to the references section by the last name of the first author presented and the date of publication at the respective summary’s heading. The table of contents lists the page number for each reference to enable quick and easy access to the summaries in the relevant categories.

Concrete and crack sealant summaries are primarily broken down according to concrete or crack sealers tested respectively, aspects of performance investigated, and main findings and conclusions from the report or paper. Following the section, concrete or crack sealers tested respectively, a table is presented to allow the user to quickly see the number and the generic chemical composition of the sealers studied. For concrete sealant reports and papers the solids content by percent weight and if the sealer was solvent or water-based was reported if given by the researcher/s. It should be known that solvent-based refers to a carrier for the active sealing product other than water (i.e. alcohol or petroleum). Water-based implies that the active ingredient is water-soluble or dissolves in water. The solids content and the respective “carrier” for the sealer were reported in concrete sealer summaries to see the effect on silane and siloxane performance. A table was also presented for concrete and crack sealant summaries after the section, aspects of performance investigated, to allow the user to quickly identify performance characteristics analyzed by the researcher/s. For reports and papers of the “other” category, the breakdown of their summaries did not follow a consistent structure.

B.2. Concrete Sealant Research

B.2.1 Attanayake (2006)

“Penetrating Sealants for Concrete Bridge Decks-Selection Procedure”

<u>Description</u>

The study cited the depth of penetration of a sealant as an important criterion for the sealer’s performance. Properties of the sealer and the concrete that affect depth of penetration were investigated and presented through literature review. Two test procedures used to determine sealer performance: the NCHRP Series II test and the effective depth of penetration test developed by Alberta Transportation and Utilities were presented and discussed. Assuming steady-state flow for the sealer through the capillary structure of the concrete, a theoretical expression for a sealant’s depth of penetration vs. ponding time of the sealant was presented using Darcy’s Law. Lastly, a flow chart for selection of a sealer was presented.

Main Findings and Conclusions

Attanayake noted that two classifications of penetrating sealants exist, pore blockers and water-repellents (hydrophobic agents). Water-repellents were mentioned as the preferred type of sealant for bridge decks due to their larger penetration depths (molecular size of water-repellents is smaller than that of pore blockers) and thus their greater resistance to vehicle abrasion and ultraviolet light degradation. Also, water-repellents were noted as allowing the concrete to breathe, thus not encapsulating moisture within the concrete pore structure and affecting durability. Water-repellents (silanes and siloxanes) have molecular structures that are comprised of alkyl and alkoxy groups. The size of the alkyl and alkoxy groups determines the water-repellency of the sealer. Sealers with larger alkyl and alkoxy groups provide a greater degree of water-repellency but their penetration depths are reduced to their increased molecular size. Sealers with smaller alkyl and alkoxy groups and thus smaller molecules penetrate deeper into the pore structure of the concrete but provide a less degree of water repellency. In comparing silanes vs. siloxanes, it was noted that silanes have smaller molecules and thus larger penetration depths.

Attanayake cites that the deck should reach its nominal 28 day strength before sealer application. Surface prep methods before sealer application were also recommended to rid the deck surface of any contaminants that may block the capillary pore structure of the concrete. Two common surface prep methods were identified in the article: power washing and dustless abrasive shot blasting. If power washing were employed, Attanayake mentions that most manufacturer’s recommend at least a 2 day drying period before sealer application. The amount of moisture in the concrete is known to affect a sealer’s penetration depth. Moisture loss was noted to occur primarily through the deck surface by drying under ambient temperature. Under constant ambient conditions, 2 drying phases are exhibited: constant-rate and falling-rate period. It is during the constant-rate period where most of the moisture is removed. Assuming constant-rate drying, Attanayake presents an analytical expression (dependent on ambient conditions and porosity of the deck) to determine the time requirement to reduce the concrete to a desired moisture content after power washing. Attanayake employed the drying rate expression for 5 decks in Michigan just subjected to power washing for a typical summer day in Michigan. It was shown that after a 2-day drying period over 30% free moisture remained in the concrete. This observation demonstrates that a 2 day drying period may not be long enough after power washing decks.

A theoretical expression for the depth of penetration of a sealant vs. ponding time of the sealant was presented using Darcy’s Law. The expression was a function of the concrete’s porosity and mean pore radius and the sealant’s viscosity, surface tension, and contact angle. Factors such as the moisture state of the concrete, molecular size and weight of the sealer, reactivity of the sealer with the substrate, and ambient conditions are not considered in the penetration depth estimate.

Attanayake mentions two tests commonly used to evaluate sealer performance: the NCHRP Report 244 test (Series II) and Alberta Transportation and Utilities (AT&U) test. The NCHRP Test determines the salt water absorption and total chloride content for sealed vs. unsealed cubic specimens. The AT&U Test accounts for abrasion effects by measuring weight gain of immersed abraded, sealed specimens.

A proposed flow chart for sealant selection was given by Attanayake. From samples cores of a bridge deck (to obtain permeability measurements), a depth of penetration vs. ponding time of sealant profile is generated using the theoretical expression. If the depth of penetration for the sealant is greater than 6mm for a required application ponding time, the sealant performance is then tested via NCHRP Report 244 Test (Series – II) for salt water absorption and total chloride content. If the sealant reduces the salt water absorption and total chloride content of unsealed specimens by 75 and 80% respectively, the sealant is then tested for salt water absorption and total chloride content via AT&U Abrasion Test. If the abraded sealant reduces salt water absorption and total chloride ion by 80 and 75% respectively, the sealant can be used for the bridge deck. If any of the requirements of the flow chart are not met at any step, a new sealant must be evaluated.

Concrete Sealers Tested

In this study no explicit deck sealers were tested.

Aspects of Performance Investigated

	performance measures						factors affecting performance										
	depth of penetration	chloride content	absorption	vapor transmission	surface scaling resistance	electical resistance	reapplication period	abrasion	freeze-thaw exposure	concrete permeability	concrete's moisture state	surface-cleaning	presence of curing compounds/ film formers	concrete's surface finish	sealer's coverage rate	sealer's method of application	ultraviolet light exposure
laboratory investigation																	
field investigation																	
theoretical investigation	i																

i = investigated

B.2.2 Ballew (1989)

"Evaluation of Protective Coatings to Reduce Chloride Penetration of Bridge Surfaces"

<u>Description</u>

Laboratory Investigation:
The preliminary laboratory investigation consisted of testing the chloride repellency of treated test blocks according to the provisions of AASHTO T259/T260; testing including abrasion of the sealed face before subsequent ponding of three percent sodium chloride solution for 90 days. Two specimens were cast from the same batch of concrete; one of these test blocks was sealed with linseed oil, the other with one of the sealers in question (only comparison results given for test nos. 2, 3, 4, 5, and 6). Linseed oil was used as the control specimen for each sealer to see how the performance of each treatment compared to that of linseed oil. Chloride contents for the six sealers (test nos. 1, 2, 3, 4, 5, and 6) were also checked against the maximum recommended chloride contents given in Report No. FHWA/ RD-78/ 35, 12.16 and 2.43 pounds per cubic yard for depth intervals of 1/16 to 1/2 in. and 1/2 to 1 in. respectively.

Field Investigation:
For the field investigation, nine test sections were established on a bridge deck in northern Pennsylvania. Linseed oil was applied to two of these test sections, each of the six remaining sealers were assigned to individual test sections. One untreated test area of the bridge deck was also established. After discussion with the manufacturer, test no. 6 was not applied to its designated test area on the deck due to a high likelihood of skid problems; this area of the deck did not receive any type of coring or testing during the duration of the field evaluation.

The annual average daily traffic (AADT) and the average daily truck traffic (ADTT) for the bridge was reported as 3680 and 232 respectively in 1985. The deck consisted of Class AAA concrete with a water to cement ratio of 0.44 and a tine finish. Designated test areas of the deck were treated after its construction in 1984; sealers were either applied with a low pressure sprayer apparatus, squeegee, broom, or a roller. Application rate adhered to the manufacturers' recommendations. No mention of surface preparation before subsequent treatment was given in the report.

Two cores were extracted from each test area of the deck (except section designated for test no. 6) approximately one month, one year, two years, and four years after the application of the sealants. Cores were tested for rapid chloride permeability and chloride content at a depth of two inches according to the procedures outlined in Report No. FHWA/ RD-81/ 119 and AASHTO T260-84 respectively. For each section of the deck, cores were generally extracted in the wheel path area; coring operations over time were relatively close to one another to help reduce variability in results due to sample location.

Additional chloride analysis was conducted approximately 4.5 years after sealer application; the number of samples per test section was increased from 2 to 5 to help reduce variability in results due to sample location. Chloride testing was performed according to the PTM No. 414 procedure. Using a rotary hammer drill, small holes (5 per test section) were drilled into the concrete to a nominal depth of 2 inches. For each test section, the resulting concrete dust samples were collected from each hole and analyzed for chloride content; the average chloride content of the 5 dust samples was then reported.

Main Findings and Conclusions

Laboratory Investigation:

Chloride contents for the linseed oil control specimens varied substantially (five comparison sealers tested therefore five linseed oil control slabs). Test nos. 2 and 3 were the only comparison sealers that exhibited chloride contents less than their respective linseed oil control slabs. However, the great variability in chloride results for the linseed oil specimens could certainly be responsible for the above observation. The author suggests the inconsistencies in the abrading techniques as a possible reason for the scatter in chloride data noticed for the linseed oil slabs.

All sealers tested (including linseed oil control slabs) exhibited chloride contents much less than the criteria suggested in Report No. FHWA/ RD-78/ 35. Also, all sealers displayed a trend of decreasing chlorides with depth. As far as best performers goes, the following performance in descending order was noted as: test no. 2, 3, 6, 5, and 4 (seen in both depth intervals). If one averages the chloride contents of the linseed oil specimens in the 1/16 to 1/2 in. depth interval, linseed oil's performance would be between that of test nos. 3 and 6.

Field Investigation:

Results of the chloride analysis using extracted cores did not always yield a trend of increasing chloride accumulation with exposure time for the test sections. The author suggests a possible reason for the inconsistencies in the chloride data as the deck being sloped 2.7 percent from the South to North. Thus, the northern end of each test section would have received more deicer runoff during thawing. However, the author notes that the coring operations over time were conducted relatively close to one another so variability due to sampling location should have been minimized. The author also suggests the possibility of the sealer's performance not being uniform throughout the test section; again though, chloride sampling in relatively the same location every test period should have minimized this possibility. What the author does not consider though is the increased possibility of scatter due to sampling and measurement techniques at much lower chloride values. Chlorides accumulation was analyzed at a depth of 2 inches, even after 4 years of exposure, chlorides at this depth ranged from 0.2 to 1.3 pounds per cubic yard for the test sections. For comparison, laboratory results for the sealers yielded chloride accumulations in the 1/16 to 1/2 in. depth interval that ranged from 3.54 to 9.73 pounds per cubic yard.

After 4 years of exposure, using the chloride data from the extracted cores, test no. 5 clearly provided the best protection. Linseed oil provided slightly less protection against chloride ingress than test no. 5; linseed oil (test no. 1) and test no. 5 were the only two sealers that allowed less chloride penetration than that of the untreated section. Test no. 4 (water-based epoxy) provided similar protection as the untreated section. The high molecular weight methacrylate and solvent-based epoxy (test nos. 7 and 3 respectively) provided similar protection that was slightly worse than that of the untreated concrete. Test no. 2 (water-based sodium silicate product) clearly provided the worst protection against chloride ingress demonstrating chloride values much higher than that of the untreated section. (After 4 years of exposure in order of descending performance: test nos. 5, 1, 4 = untreated, 7 = 3, and 2.)

Rapid permeability test data did not parallel very well with the chloride data from the cores. (i.e. after 4 years, the section treated with test no. 5 appeared as permeable or more permeable than the other treated and untreated sections). The untreated section did however exhibit permeability measurements (coulombs) that were as large as or larger than those exhibited by the majority of the sealed sections.

Results from the PTM No. 414 testing indicated the following performance in descending order: test nos. 1, 3, 2, 7, 4, 5, and the untreated section. The relative results for test nos. 2 and 5 in comparison to the other treated and untreated sections were not the same in the PTM No. 414 and AASHTO T260-84 procedures. In the PTM procedure, test no. 5 was clearly the worst performer whereas in the AASHTO procedure test no. 5 was clearly the best performer. In the AASHTO test procedure, test no. 2 was clearly the worst performer but offered comparable performance to the top performing products in the PTM test procedure. The author describes how the PTM procedure analyzed chlorides in the top 2 inches of pavement whereas the AASHTO procedure only looked at chloride accumulation at a depth of 2 inches. Thus, chloride results of the two procedures can not be compared. The author implies that chloride results from the cores (AASHTO) hold more weight; the ability of the sealer to prevent chloride accumulation at a depth close to the depth of reinforcement is being analyzed. However, the author does not point out the value of measuring chloride accumulation in the top 2 inches of pavement (PTM); the ability of the sealer in preventing chloride penetration into the deck at all is being analyzed. Also, chloride levels for the sealers as a result of the PTM procedure (2.0 to 6.0 pounds per cubic yard) were much larger than those from the AASHTO procedure (0.2 to 1.3 pounds per cubic yard). Thus, with the larger chloride levels, the likelihood that minor variances in collecting and analyzing the samples affected the results was minimized.

In either case, both chloride analyses demonstrated linseed oil as one of the most effective products analyzed. In comparing the relative performance of the other products, the author neglects the results of the PTM procedure completely. Whether the author’s decision was right is hard to say.

Concrete Sealers Tested

	penetrating sealers					film formers				
test no.	silane	siloxane	siloxane/ silane mixture	silconate	silicate	linseed oil	epoxy	polyster resin	high molecular weight methacrylate	proprietary blend
1						x, x				
2					w/ 9					
3							*s/ 21			
4							w/ 35-40			
5										s/ 40-60
6								s/ x		
7									100	
s, w, or x = solvent-based, water-based, or not stated respectively / ## or x = percent solids by weight or not stated respectively										

*Two component system. "B" component as listed in table. "A" component consists of epoxy resin material.

The performance of six sealers was compared to that of linseed oil. For the proprietary blend, since the active ingredient was not given by the manufacturer, the designation of the product being a penetrating sealer or a film former was not made.

Aspects of Performance Investigated

	performance measures					factors affecting performance										
	depth of penetration	chloride content	rapid chloride permeability	absorption	vapor transmission	reapplication period	abrasion	freeze-thaw exposure	concrete permeability	concrete's moisture state	surface-cleaning	presence of curing compounds/ film formers	concrete's surface finish	sealer's coverage rate	sealer's method of application	ultraviolet light exposure
laboratory investigation		i														
field investigation		i	i													
theoretical investigation																
i = investigated																

B.2.3 Basheer (1998)

"Protection Provided by Surface Treatments against Chloride Induced Corrosion"

Description

Slab specimens, 300 x 300 x 150 mm (11.81 x 11.81 x 5.91 in.) in size were cast; a dike, 12 mm (.47 in.) deep, was created around the perimeter of the 300 x 300 mm test face. Test specimens contained upper reinforcement at 25 and 40 mm (0.98 and 1.57 in.) from the test face and lower reinforcement at 125 mm (4.92 in.) from the test face. Test specimens implemented three mixes of varying water to cement ratio (0.45, 0.55, and 0.65) to study the effect of concrete permeability on sealer performance.

Three different moisture conditions were also created for the concrete specimens of varying permeability by the manner in which they were cured. Thus, researchers analyzed the effect of concrete permeability and moisture state on sealer performance.

All specimens were wet cured in water for two weeks and then allowed to dry for two weeks at 20^{o}C and 55 ± 5% relative humidity. The three exposure conditions, representing a wet, dry, and very dry environment were simulated by submerging the slab specimens in water for three days following the two week drying period. The saturated specimens were then exposed to the three different environments to yield concretes of three different moisture levels before subsequent sealer application. Thus, for each treatment, nine different concrete slabs were created (three moisture conditions per water to cement ratio). Nine control, untreated slabs were also created three moisture conditions per water to cement ratio)

The wet environment was simulated by allowing the concrete to dry only three days at 20^{o}C and 55 ± 5% relative humidity following the three day immersion period; sealer application followed the three days of drying. The dry environment allowed for four weeks of air drying at 20^{o}C and 55 ± 5% relative humidity before sealer application. To simulate the very dry environment, specimens were allowed to dry at 40^{o}C and 12% relative humidity for two weeks before sealer application.

The treated and untreated wet, dry, and very dry concretes of varying permeability were subjected to cyclic salt-water ponding and subsequent drying for 44 weeks. Specimens were ponded with 15% sodium chloride solution for three days and then were allowed to dry four days at 20^{o}C and 55 ± 5% relative humidity. The weekly cycle repeated itself for the 44 week test period.

Water-soluble (free) chloride ingress was measured throughout the 44 week test period at the 25 and 40 mm depths of upper reinforcement. Half-cell potential and macro cell corrosion current measurements were also taken throughout the course of the 44 week test period to monitor the corrosion activity of the upper reinforcement. At the conclusion of the chloride exposure period, the upper steel was extracted and inspected for corrosion. The mean depth of penetration of the sealers was also measured at the conclusion of the investigation; each slab was fractured in two and the depth of the visible non-wetting band was measured in six locations.

Main Findings and Conclusions

Impact of Water to Cement Ratio and Cover Depth:

Chloride results with exposure time for the control concretes followed the trend one would expect to see with increasing water to cement (w/c) ratio. As the w/c ratio increased, or as the concrete's permeability increased, chloride ingress over time was observed to be larger for both the 25 and 40 mm depths. Also, for the 25mm depth, chloride ingress over time was observed to asymptotically approach a limiting value for all three control concretes of varying w/c ratio. At the 40 mm depth, this asymptotical characteristic was not seen in the chloride ingress verse exposure time plots for the three control concretes. Also, the chloride ingress values at the 40 mm depth proved to be much less than those at the 25 mm depth.

The chloride ingress with exposure time plots for the control concretes indicated a clear benefit of a greater cover depth. Also, the results clearly indicate the benefit of a lower water-cement ratio. Chloride ingress data at the end of the 44 week test period for the treated specimens did not indicate the water to cement ratio of the concrete to impact sealer performance. Thus, the higher w/c ratio concrete received a much larger benefit from treatment than the lower w/c ratio concrete. Chloride accumulation at the end of the investigation also indicated a clear benefit of treated concrete over untreated concrete. Treated concretes did not completely prevent chloride ingress though.

Impact of Moisture State of Concrete:

Increased moisture content of concretes with the same w/c ratio generally caused the depth of penetration of each sealer to decrease. Varying water to cement ratio of concretes with the same moisture condition did indicate the w/c ratio to impact a sealer's depth of penetration.

The chloride ingress data at the end of the 44 week test period was plotted against the sealers' depth of penetration. Since depth of penetration was found to be hindered by an increased moisture state of the concrete; the plot qualitatively measured the effect of moisture content on chloride ingress. No correlation was found between a sealer's depth of penetration and respective chloride ingress. Beyond the fact all sealers penetrated a minimum of 1.0 mm, a sealer's depth of penetration, did not appear to affect its subsequent chloride repellency. It should be noted that freeze-thaw exposure and abrasion were not included in the testing which may have drastically affected these observations.

Half-cell potential and macro cell corrosion measurements indicated treated slabs to combat corrosion much more effectively than that of the control concretes. Also, treated "wet" concretes offered less corrosion resistance than treated "dryer" concretes. Thus, the moisture content of the concrete at time of sealer application appeared to affect how well the sealer protects the reinforcement from corroding.

Best Performers:

Chloride ingress data at the end of the 44 weeks did not clearly indicate a best performer among the sealers. Concentrations fluctuated in such a manner with varying water to cement ratio and moisture state of the concrete that relative performance could not be distinguished. However, depth of penetration results indicated the 100% silane to generally be the best penetrating product with varying w/c ratio and moisture state of the concrete.

Concrete Sealers Tested

	penetrating sealers					film formers
test no.	silane	siloxane	siloxane/ silane mixture	silconate	silicate	epoxy
1	x/ 40					
2	100					
3			x/ x			
4	x/ x					
s, w, or x = solvent-based, water-based, or not stated respectively / ## or x = percent solids by weight or not stated respectively						

Four concrete sealers were analyzed as indicated by the above table. For test no. 4, the sealer consisted of a two part system: a silane primer and an acrylic top coat.

Aspects of Performance Investigated

	performance measures						factors affecting performance										
	depth of penetration	chloride content	absorption	vapor transmission	surface scaling resistance	electical resistance	reapplication period	abrasion	freeze-thaw exposure	concrete permeability	concrete's moisture state	surface-cleaning	presence of curing compounds/ film formers	concrete's surface finish	sealer's coverage rate	sealer's method of application	ultraviolet light exposure
laboratory investigation	i	i								i	i						
field investigation																	
theoretical investigation																	
i = investigated																	

B.2.4 Bush (1998)

“Laboratory Test Procedures for Evaluating Concrete Treated with Sealers”

Description

Two test methods quantifying similar performance measures yielded different results. Performance characteristics of a single 40% solvent-based silane were measured using the NCHRP 244 Series II test and a test series developed by the Oklahoma DOT. In each test series, the following performance criteria of the silane were measured: depth of penetration, absorption, and acid-soluble chloride ingress. Concrete permeability was taken into effect by performing the 2 test series on Class A, AA, and HD concrete. Class A, AA, and HD concrete have water to cement (w/c) ratios of 0.49, 0.44, and 0.33 respectively. NCHRP 244 Series II tests and the Oklahoma DOT test series implemented in the study will now be described to familiarize the reader with the differences in the test sequence procedures.

Oklahoma Dot Series:
Depth of Penetration:

1. 2 specimens (8” x 8” x 2”) per mix class (6 total) were wet cured for 1 week
2. specimens were **oven dried** at 110+-5C(230+-9F) to a constant weight
3. specimens were allowed to cool
4. silane was applied to one face of specimens
5. silane was allowed to adequately cure
6. each block specimen was broken into 4 pieces
7. pieces were wetted
8. visible penetration depth was measured at 12 random locations per specimen
9. average visible penetration depth was obtained

Water Absorption (modified version of ASTM C642):

1. 24 specimens (8” x 8” x 2”) per mix class (72 total) were wet cured for 28 days
2. specimens were **oven dried** at 110+-5C(230+-9F) to a constant weight
3. specimens were allowed to cool
4. silane was applied to one face of designated specimens
5. 5 remaining unsealed faces were waxed to ensure water absorption occurred solely through the sealed face
6. specimens were immersed in deionized water
7. absorption was measured after 2 and 50 days (absorption of specimens not sealed with silane were also measured)

Acid-Soluble Chloride Ingress (AASHTO T259/T260):

1. 7 specimens (12” x 12” x 3”) per mix class (21 total) were wet cured for 14 days (note: 3 specimens were sealed with silane on the horizontal surface, 3 specimens were not sealed, and one specimen was used as the control so the background chloride content could be determined)
2. specimens were stored in a climate controlled chamber at 23^{o} C and 50% RH
    a. at 21 days of age designated specimens were sealed

   - b. at 35 days of age specimens were removed and the top surface of the specimens were ponded with 3% NaCl for 90 days (except control)
3. powdered samples were taken using a rotary drill in depth ranges 1/16" – ½" and ½" – 1"
4. the total acid soluble chloride content was measured from the powdered samples and the background chloride content was subtracted from these values to determine the chloride ingress

NCHRP Series II:
Salt Water Absorption/ Vapor Transmission (weight gain during immersion/drying):

1. 12 specimens (4" x 4" x 4") per mix class (36 total) were moist cured in plastic bags for 21 days
2. at 7days of age, specimens were lightly sandblasted to remove surface laitance
3. after curing, specimens were air dried for 5 days in an environmental chamber at 23^o C and 50% RH
4. all six faces of specified specimens were sealed with silane
5. specimens were air dried for another 26 days in the environmental chamber
6. specimens were immersed in 15% NaCl for 21 days
7. specimens were removed and air dried for 21 days
8. weight measurements were taken every 3 days during the immersion and drying process

*For the acid soluble chloride ingress, the NCHRP Series II test calls for the specimen to be crushed into powder form and for chloride measurements to be taken from the resultant powder. In this study the methods of AASHTO T259/T260 were employed. Powdered samples were taken from 3 faces of each specimen using a rotary drill at the depth intervals described above. The baseline chloride content was subtracted to determine chloride ingress measurements.

*For the visible depth of penetration, the same process that the Oklahoma Series test used to determine penetration depth was implemented. The penetration depth was only determined for the Class AA concrete. This will be discussed in the conclusions section of this summary.

Main Findings and Conclusions

From the results of the Oklahoma DOT test series, visible penetration depth in descending order for the mix classes were class HD (w/c = 0.33), A (w/c = 0.49), and AA (w/c = 0.44). Thus, penetration depth measurements did not follow the expected trend with water to cement (w/c) ratio. One would expect that as w/c increases, or as the concrete becomes more permeable (less dense), greater penetration depths would occur. As previously mentioned for the NCHRP Series II procedure, penetration depth was only measured for class AA concrete. The results indicated that the penetration depth measured according to the NCHRP Series II procedure was approximately 60% of that measured for class AA concrete according to the Oklahoma DOT test series. The smaller penetration depth produced from the results of the NCHRP procedure was a result of initial moisture in the concrete (~3%) when the silane was applied. For the Oklahoma DOT test series, the specimens were oven dried to remove all moisture after wet curing. Thus, at the time of silane application, the moisture content in the concrete was zero. A control study was performed on class AA concrete to determine the effect of moisture content within the concrete at the time of silane application. For moisture contents of 1, 2, and 3%; the measured depths of penetration were found to be 90, 70, and 40% respectively of the measured depth of penetration for class AA concrete using the Oklahoma DOT test series. Silane's penetration depth was obviously negatively affected by higher moisture contents within the concrete at the time of application.

Bush mentions that penetration depth of a sealer is an easy performance characteristic to measure and can be used to indicate the life of a sealer based on traffic abrasion. He stresses that caution should be taken when using visible penetration depth as a selection criteria for a sealant because the penetration depth can be easily affected by the moisture content within the concrete (as indicated above), mix design (as indicated above), and the molecular size of the sealer. The molecular size of the sealer did not affect the visible penetration depth in this case because the same sealer was used for all concrete mix classes. Bush also distinguishes the difference between visible penetration depth and effective penetration depth. The effective penetration depth is a measure of well the sealer repels water throughout its penetration depth. A test procedure was developed by Alberta Transportation and Utilities that measures an effective penetration depth by measuring absorption before and after abrasion. Bush cautions that just because a sealer has a large visible penetration depth, the sealer may not perform very well in repelling the ingress of water. Thus, the sealer may not have a very large effective penetration depth. In summary, visible and effective penetration depth do not necessarily have to correlate with one another. For all the reasons mentioned above, care should be given when selecting a sealer on the basis of its visible penetration depth.

The modified ASTM C642 test (corresponds to the Oklahoma DOT test series) demonstrated the mix classes in order of highest to lowest percent absorption (for sealed and unsealed specimens) to be class A (w/c = 0.49), AA (w/c = 0.44), and HD (w/c = 0.33). Note that this overall trend should be expected for the varying w/c ratios. As the w/c ratio decreases, the concrete becomes more dense (less permeable) and smaller degrees of absorption occur for the concrete. For the NCHRP Series II tests, the mix classes in order of highest to lowest % weight change for treated and untreated specimens were found to be class AA, A, and HD. Thus, the expected trend for decreasing w/c ratio was not observed.

Differences in the ASTM C642 (Oklahoma DOT test series) and the NCHRP Series II test procedures were materialized to evaluate reasons for the discrepancies in the absorption results between the two procedures. The following comparison list summarizes the differences.

1. For the ASTM C642 procedure, specimens were oven dried before immersion, thus absorption equaled the moisture content because the initial moisture content was zero. For the NCHRP Series II procedure, specimens were not oven dried before immersion, they were air dried. Thus, the initial moisture contents for the NCHRP specimens could not be controlled.

2. For the ASTM C642 procedure, specimens were immersed in deionized water. The NCHRP Series II procedure immersed the specimens in 15% NaCl.

3. For the ASTM C642 procedure, the rate of initial moisture content increase (0-2 day immersion period) was 3-6 times larger for sealed mix classes and at least 10 time larger

for unsealed mix classes when compared to the rate of initial moisture content increase (0-3 day immersion period) for the NCHRP Series II specimens. The greater initial rate of moisture content increase for the ASTM C642 specimens was a result of the moisture content of the concrete equaling zero before immersion. The rate of moisture increases for longer periods (2-50 days for the ASTM C642 procedure and 3-21 days for the NCHRP Series II specimens) were much more similar for the two tests.

4. For the ASTM C642 procedure, five of the faces were waxed for sealed specimens. Thus, absorption occurred though the sealed 8” x 8” face resulting in an exposed surface area to volume ratio of 0.5. For the sealed NCHRP specimens, absorption occurred through all of the sealed six faces resulting in an exposed surface area to volume ratio of 1.5.

5. For the ASTM C642 procedure, the moisture content was 0% at the time of silane application, thus the depth of silane penetration was much greater for the ASTM C642 specimens than the NCHRP Series II specimens.

No specific difference between the tests could be attributed to the reason for the discrepancy in absorption results. The question of which test to use then becomes the question. Bush brings up the point that field concrete will likely have a certain amount of moisture at the time of sealer application and the NCHRP 244 test may better simulate these field conditions. Also for bridge decks in northern climates such as Minnesota, the presence of salt in ingress moisture better simulates field conditions. However, the initial moisture content of the concrete in the NCHRP 244 test can not be controlled which is not a desirable quality of laboratory test methods.

The decision to measure chloride ingress by obtaining powdered samples through drilling and not crushing of the cube for the NCHRP Series II test was based on the results of a pilot study. In the pilot study, a cube was sealed and immersed according to the NCHRP Series II test’s provisions. The cube was then split in half and chloride content was measured using 2 methods. Powdered samples were obtained for one-half of the cube by using a rotary drill as in AASHTO T259. The other half of the cube was crushed according to NCHRP provisions. From the results of the chloride analyses, the chloride contents found from crushing the cube were observed to be twice as high as the chloride content found from powdered drill samples. A possible reason for this occurrence was given as crushing the samples incorporates a higher mortar content into the powdered samples because aggregate does not crush as easily as mortar. Another possible reason was given as drilled samples exclude the top 1/16” of the surface from analysis; the top 1/16” is the most chloride contaminated. Due to the extreme labor and time requirements and concerns of contamination, obtaining powdered samples by crushing of the specimens was decided to be abolished for this study. Another reason for the decided abolishment of crushing the specimens was the desire to obtain more closely related chloride contents from the NCHRP and Oklahoma DOT tests for comparison purposes. Thus, the decision to use a rotary drill for obtaining powdered samples in the NCHRP Series II test was made.

Results of the chloride analysis showed that mix AA had slightly higher chloride ingress measurements than mix A for the Oklahoma DOT series test. This observation contradicts the results of the absorption analysis (Mix A had a higher percent absorption than Mix AA). The results of the chloride analysis correlated well with the absorption results for the NCHRP Series

II test. The results of the chloride analysis demonstrated large degrees of scatter for both tests; standard deviations were similar or larger than the mean chloride ingress values. Bush suggests careful consideration when choosing a sealer based on the chloride ingress results due to the large degree of scatter observed within the measurements. Bush also suggests the chloride ingress results for the first depth interval (1/16” – 1/2”) be used to evaluate sealer performance because the chloride ingress measurements for the second depth interval (1/2”- 1”) were very small. Thus, difference in sealers’ performance would be very hard to determine in the second depth interval due to the magnitude of the chloride ingress and the scatter of the chloride measurements. Finally, no specific recommendation is given on which test produces a better estimate of sealer performance based on the chloride ingress results. If chloride ingress measurements are desired, Bush suggests that the NCHRP Series II test might be a better choice simply due to the time requirement to obtain chloride ingress results (100 days vs. 140 days for the AASHTO T259/T260 test).

Concrete Sealers Tested

	penetrating sealers					film formers
test no.	silane	siloxane	siloxane/ silane mixture	silconate	silicate	epoxy
1	s/ 40					

s, w, or x = solvent-based, water-based, or not stated respectively /
or x = percent solids by weight or not stated respectively

One 40% solvent-based silane was analyzed as indicated by the above table.

Aspects of Performance Investigated

	performance measures						factors affecting performance										
	depth of penetration	chloride content	absorption	vapor transmission	surface scaling resistance	electical resistance	reapplication period	abrasion	freeze-thaw exposure	concrete permeability	concrete's moisture state	surface-cleaning	presence of curing compounds/ film formers	concrete's surface finish	sealer's coverage rate	sealer's method of application	ultraviolet light exposure
laboratory investigation	i	i	i	i						i	i						i
field investigation																	
theoretical investigation																	

i = investigated

B.2.5 Bush (1997)

“Influence of Field Variables on Laboratory Performance of Silane-Treated Concrete”

Description

The following study by Bush preceded his 1998 investigation (see Appendix A.1). The same research analyzing the effects of water to cement ratio (0.49, 0.44, and 0.33) and testing procedure (NCHRP 244 Series II verse Oklahoma DOT series testing) on silane performance was discussed and those specifics of the investigation will not be repeated. However, the 1997 paper made note of additional elements of the research not discussed in the 1998 paper, and these elaborations will be summarized below.

Test specimens for the Oklahoma DOT series tests received a tine or broom finish; only mix class AA (w/c = 0.44) and HD (w/c = 0.33) received the tine finish. Depth of penetration, absorption, and chloride ingress were subsequently measured for treated and untreated sections. All test specimens for the NCHRP Series II testing received a smooth finish. However, some of these NCHRP cube specimens had curing compounds applied to their surfaces immediately after removal from their forms. NCHRP treated and untreated test specimens were then analyzed for depth of penetration, absorption (weight gain during immersion), vapor transmission (weight loss during drying), and chloride ingress. Bush’s 1998 paper inspects the effect of test procedure and mix design on silane performance only for the Oklahoma DOT and NCHRP test specimens subjected to a broom finish and no curing compounds respectively. The 1997 paper also addresses these factors in addition to the effect of surface finish and the use of curing compounds; this new information will be subsequently summarized below.

Slabs for the Oklahoma DOT series testing were a given a tine finish; depth of penetration, absorption, and chloride ingress were subsequently measured. These results for the tine finished specimens were then compared to that of the broom finished specimens to evaluate the effect of surface finish on silane performance. It should be noted that the application rate (gallon per square foot) of the silane was not increased from the broom to tine finished specimens to account for the increase in surface area.

Cubes for the NCHRP Series II testing either had a linseed oil emulsion, pigmented membrane, or no curing compound applied to their surfaces immediately after removal from their forms. (Curing compounds were applied to top surface of the cubes immediately after casting, not just after the forms were stripped). Cubes were then allowed to cure 21 days in either plastic bags or an environmentally controlled chamber (specimens with no curing compounds were moist cured in the plastic bags). After curing, the surfaces of the cubes were prepared for silane application either by dry shot-blasting, power washing, or no cleaning method at all. It should be noted that the application rate of silane was not increased to counteract the presence of the curing compounds. The effect of curing compounds and subsequent cleaning method on silane performance was only examined for mix class AA (w/c = 0.44) using the NCHRP Series II testing. The performance parameters investigated included depth of penetration and absorption and vapor transmission (percent weight gain and loss during immersion and drying respectively).

Main Findings and Conclusions

Tine vs. Broom Finish:

The depth of the visible non-wetting band followed the topography of the tine finish; depth of penetration was measured normal to the surface in question. Results indicated the tine finish did not notably affect the depth of penetration of the silane when compared to that of the broom finished specimens.

Absorption results indicated the broom finished, treated specimens to reduce water absorption more effectively than the tine finished, treated specimens. This trend was especially evident with long term water absorption results.

Mean chloride results substantiated the trend seen in absorption data. The tine finished treated specimens exhibited larger mean chloride values than that of the broom finished treated specimens for both the first and second depth intervals (1/16” to ½” and ½” to 1” respectively). (AASHTO T259/T260 stipulates dust samples to be taken and analyzed for total chloride content at these depth intervals). However, a statistical analysis performed on mean chloride values indicated no statistical difference between surface treatments for the treated specimens at either depth.

Effect of Curing and Subsequent Cleaning Methods:

Depth of penetration results from the uncleaned cubes indicated the pigmented membrane to greatly inhibit silane’s penetration into the concrete substrate. The linseed oil emulsion did not appear to affect silane’s depth of penetration. Regardless, the author recommends complete removal of all curing compounds from the concrete surface before sealer application; shot and water blasted specimens always produced depths of penetration similar to that of control specimens (no curing compounds applied before sealer application).

Surface cleaning (dry shot-blasting or power washing) before sealer application produced absorption and vapor transmission results closer to that of the control specimens (no curing compounds used before sealer application).

In isolating the difference between the two cleaning methods, shot-blasted specimens demonstrated slightly better absorption characteristics. The author brings up the point that shot blasting may be preferred over water blasting; power washing raises the moisture state of the concrete and impedes sealer penetration if adequate drying time is not allowed.

Concrete Sealers Tested

	penetrating sealers					film formers
test no.	silane	siloxane	siloxane/ silane mixture	silconate	silicate	epoxy
1	s/ 40					

s, w, or x = solvent-based, water-based, or not stated respectively /
or x = percent solids by weight or not stated respectively

A solvent-based 40% silane was analyzed as indicated by the above table.

Aspects of Performance Investigated

	performance measures						factors affecting performance										
	depth of penetration	chloride content	absorption	vapor transmission	surface scaling resistance	electical resistance	reapplication period	abrasion	freeze-thaw exposure	concrete permeability	concrete's moisture state	surface-cleaning	presence of curing compounds/ film formers	concrete's surface finish	sealer's coverage rate	sealer's method of application	ultraviolet light exposure
laboratory investigation	i	i	i	i						i	i	i	i	i			
field investigation																	
theoretical investigation																	

i = investigated

B.2.6 Carter (1986)

“Comparative Evaluation of the Waterproofing and Durability of Concrete Sealers”

Description

Phase 1 Laboratory Testing:

Four inch cube specimens were cast from a chloride free concrete mix with a water to cement ratio of 0.46; the mix design followed that of Alberta Transportation’s Class D concrete used in the construction of Alberta Bridges. Cubes underwent 21 days of moist curing; after moist curing their surfaces were lightly sandblasted to remove surface laitance. Following sandblasting, cubes were allowed to air dry for 14 days; sealer application succeeded the drying period. Sealers were applied according to the manufacturers’ recommendations; each sealer (57 total) was applied to three blocks to obtain a more representative measure of its performance. Sealers were allowed to cure a minimum of 7 days following application.

After curing, treated and untreated specimens were immersed in 15 percent sodium chloride solution for 14 days. Weight gain of the treated cubes was measured at selected intervals throughout the immersion process and compared to that of the control specimens; reduction of weight gain as a resultant of treatment was reported for each sealer. Sealers were considered acceptable if they reduced absorption at the end of the immersion period by at least 75 percent (recommended in NCHRP Report No. 244). Following the immersion period, cubes were removed and air dried for 14 days at 35 percent relative humidity. Weight loss due to vapor transmission was measured every 3 days. At the end of the drying period, vapor permeability of the sealers was deemed acceptable if respective treated cubes lost at least 125 percent of the weight gained during immersion. This was of course if sealers first met the absorption criteria. Following vapor transmission testing, depth of penetration of the treatments was also measured. Cubes were split in half; red water dye was applied to the fractured surface. Penetration of the sealers was determined by measuring the depth of the visible non-wetting band (i.e., portion of fractured surface that did not absorb the dye and turn red).

Phase 2 Laboratory Testing:

The top 28 performers from the absorption and vapor transmission testing in phase 1 were chosen for phase 2 laboratory testing. In addition to the top 28 performers, the mixture of linseed oil and kerosene was also chosen for testing even though its absorption and vapor transmission characteristics were not up to par with the other 28 sealers.

Slab specimens, 11.8 inches x 11.8 inches x 4.9 inches in size, were cast from the same batch of concrete used to construct the cube samples in phase 1 testing. Slabs were moist cured for 28 days; following moist curing, the top surfaces of the slab specimens were lightly sandblasted to remove surface laitance. Respective sealers were then applied to the top surface of designated slabs; each sealer was applied to two slabs. Sealers were applied according to the manufacturers’ recommendations; after application a 7 day curing period was allowed for the products.

After treated specimens were allowed to cure, both sealed and unsealed specimens were subjected to 200 cycles of weathering. Each 24 cycle consisted of ponding the top surface of the specimens with 15 percent sodium chloride solution for 4 hours in the morning. The salt-water solution was then removed and the slabs were stored in a freeze-chamber for 6 hours. Following the afternoon freezing, the specimens were removed and subjected to 14 hours of overnight ultraviolet light exposure. Weathering cycles were conducted and controlled in the laboratory; the intensity of the ultraviolet exposure was 469 watt-hours per square meter per 14 hour cycle.

Acid-soluble chloride content of the slabs was determined after every 50 cycles. The author decided the best method for chloride sampling was to drill six evenly spaced 10 mm (0.39 in.) holes into each slab. At the location of each hole, prior to drilling, the slab face was ground to remove the sealer and precipitated chlorides. Holes were drilled to a depth of 56 mm (2.20 in.); for each slab, the six dust samples were collected as one and mixed thoroughly. Representative portions of these composite samples were then analyzed for total (acid-soluble) chloride content.

It should also be noted that slabs were visually inspected each week for blemishes, blisters, and scaling.

Main Findings and Conclusions

Phase 1 Laboratory Testing:

It should be noted that the control cubes gained an average mass of 40.6 grams during the 14 day immersion period. A weight gain of 10.2 grams corresponds to the maximum amount of water a treated cube could absorb with the respective sealer still meeting the 75 percent reduction criteria.

In averaging the weight gains among generic groups of sealers, epoxies proved to be the most effective product. Out of the 57 products studied, the 8 concrete sealers demonstrating the lowest weight gains were all epoxies. Average weight gains for the top six generic performers: epoxies, chlorinated rubbers, acrylics, silanes, siloxanes, and methacrylates were 5.4, 7.0, 7.3, 7.5, 8.2, and 8.6 grams respectively. Keep in mind though that abrasion was not included in the absorption analysis which surely might have affected relative results for the silanes and siloxanes in comparison to the other sealers.

It should be noted that within sealers of a generic composition, weight gain varied substantially; this was especially evident for the epoxies. As mentioned previously, 8 of the epoxies provided the best water repelling performance of the 57 products analyzed. However, one of the epoxy products ranked only 51st place when analyzing absorption results.. Siloxanes were the only group of sealers whose water repelling performance was relatively consistent. The range of weight gain values (grams) for epoxies, chlorinated rubbers, acrylics, silanes, siloxanes, and methacrylates were 2.2 – 11.6, 4.8 – 10.5, 5.1 – 10.1, 5.3 – 10.7, 7.8 – 8.4, and 5.3 – 14.3 respectively. Thus, it becomes obvious that water repelling capability was not consistent among sealers of a generic composition.

One possible reason for the variance in water repellency among sealers of a generic composition was the difference in recommended coverage rates. For example, recommended coverage rates for the epoxy, silane, siloxane, chlorinated rubber, acrylic, and methacrylate products ranged from 75 – 200, 80 – 245, 125 – 350, 125 – 325, 80 – 325, and 125 – 160 square feet per gallon respectively. For each of these generic sealers, coverage rate was plotted as a function of moisture gained upon completion of the immersion process. For the epoxies, significant scatter existed in the data plot and no trend of moisture ingress with coverage rate could be distinguished. For the silane and acrylic sealers, a clear trend of increased moisture gain with increasing coverage rate (i.e., a lighter application) existed. As with the case for the epoxies, it was difficult to see any correlation between coverage rate and moisture gain for the chlorinated rubbers, methacrylates, and siloxanes. A general observation noticed in the coverage rate verse absorption plots for the generic sealers was that products who failed the NCHRP criteria exhibited coverage rates larger than 140 square feet per gallon. It should be noted however that the author is not isolating the effect of coverage rate in the above analyses. Among a generic group of sealer, solids content and the carrier may not have been the same. Thus, minor differences in composition could also explain the reason for variance in water repelling performance among sealers of a generic composition.

In analyzing weight gain performance of one verse two coat systems; two coat systems appeared to provide better water repellency. When looking at pigmented verse clear products, clear sealers appeared to provide better water repelling performance. Only 7 of the 17 pigmented sealers passed the NCHRP criteria but 34 of the 40 clear sealers reduced absorption by at least 75 percent.

In evaluating the water repelling effectiveness of linseed oil, the product did not pass the NCHRP absorption criteria. The linseed oil treated cube exhibited a weight gain of 15.3 grams thus only reducing water absorption by 62.3 percent. Linseed oil was the 50th best performer when analyzing absorption results; no silane or siloxane treated cubes demonstrated larger weight gains than that of linseed oil.

Results of the vapor transmission analysis yielded silanes on average as the best performers. Vapor transmission for each product was reported as a percentage of the weight lost upon drying to the weight gained during immersion. Average percent moisture loss for the silanes, acrylics, siloxanes, methacrylates, chlorinated rubbers, and epoxies were reported as 187, 171, 167, 151, 133, and 113 respectively. As noted with absorption results, large variation in performance was noted among sealers of a generic composition. For example, vapor transmission percentages for the silanes, acrylics, siloxanes, methacrylates, chlorinated rubbers, and epoxies ranged from 145 – 238, 99 – 217, 158 – 173, 103 – 255, 112 – 165, and 38 – 193 respectively.

Coverage rate verse percent moisture loss was plotted for generic groups of sealers. Results indicated that silanes, siloxanes, and acrylics demonstrated the highest vapor transmission percentages over a large range of coverage rates. Methacrylates and chlorinated rubbers exhibited slightly lower vapor transmission percentages than the silanes, siloxanes, and acrylics. The majority of these percent moisture losses were still larger than the criteria of 125 percent though. Also, the range of coverage rates at which these vapor transmission percentages were exhibited was notably smaller than that of the silanes, siloxanes, and acrylics. From the above discussion it appears that coverage rate did not notably impact the vapor permeability characteristics of silanes, siloxanes, acrylics, methacrylates, and chlorinated rubbers. For the epoxies, considerable scatter existed in the data plot and no clear trends could be distinguished. It should be noted that of the 11 sealers that did not meet the vapor percentage criteria of 125 percent, 6 were epoxies with coverage rates below 150 square feet per gallon (i.e., heavier application than 150 square feet per gallon).

In analyzing the vapor permeability of clear verse pigmented coatings, clear sealers appeared to be the better performers. Only 2 out of the 17 pigmented sealers met or exceeded the vapor percentage criteria of 125 percent; clear sealers had a much higher acceptance rate with 32 out of the 40 products meeting or exceeding the permeability stipulation.

In analyzing penetration depth results of the 57 products, linseed oil penetrated the deepest (2.3 mm). Two silane products exhibited the next best performance with penetration depths of 2.0 and 1.0 mm respectively. Following the two silanes, the silicone product penetrated to a depth of 0.8 mm. There were two siloxanes, a mineral gum wax, two silanes, and an epoxy sealer that exhibited a penetration depth of 0.5 mm. Succeeding the performance of these sealers, a silane and a chlorinated rubber product penetrated to a depth of 0.2 and 0.1 mm respectively. Beyond this, the rest of the sealers exhibited no measurable penetration into the cube specimens.

Phase 2 Laboratory Testing:
From the results of phase 1 testing, a total of 29 sealers were chosen for phase 2 chloride testing. These 29 sealers consisted of 10 epoxies, 8 acrylics, 1 chlorinated rubber, 2 methacrylates, 1 mineral gum, 1 linseed oil, 4 silanes, 1 siloxane, and 1 silicone.

Chloride sampling yielded the following general trends: i) chloride accumulation increased with exposure time; ii) treated concretes allowed less chloride ingress than that of uncoated slabs. Also evident from the chloride analysis was that effectiveness of sealers generally decreased over time. Finally, chloride repellency among sealers of a generic composition varied substantially.

Results of the visual inspections of the treated slabs after 200 cycles of weathering revealed the following:

1. Epoxies – only two products did not exhibit blemishes, blisters, or scaling
2. Silanes – one sample was scaling, two samples had soft aggregate eroding, one sample still in good condition
3. Acrylics – all but one sample was scaling and/or blistering

Concrete Sealers Tested

It should be noted that the solids content (i.e., the percent active ingredient) or the carrier (i.e., solvent or water) was not given for any of the sealers below. Also, products were distinguished as one or two coat systems and clear or pigmented because Carter makes note of these differences in his research.

penetrating sealers - one coat systems			
	no. of products tested with generic compostion		
generic composition	clear product	pigmented product	total
silane	5	0	5
siloxane	3	0	3
silicone	1	0	1
penetrating sealers - two coat systems			
	no. of products tested with generic compostion		
generic composition	clear product	pigmented product	total
silicate	1	1	2
film formers - one coat systems			
	no. of products tested with generic compostion		
generic composition	clear product	pigmented product	total
epoxy	2	3	5
acrylic	4	0	4
methacrylate	2	1	3
chlorinated rubber	2	0	2
latex	0	2	2
mineral gum	1	0	1
cementitious polymer	0	1	1
film formers - two coat systems			
	no. of products tested with generic compostion		
generic composition	clear product	pigmented product	total
epoxy	11	2	13
acrylic	4	3	7
methacrylate	1	2	3
chlorinated rubber	1	0	1
cement-latex	0	1	1
aluminum stearate	1	0	1
asphalt emulsion	0	1	1
mixture of kerosene and linseed oil	1	0	1
total no. of sealers analyzed			57

Aspects of Performance Investigated

	performance measures						factors affecting performance										
	depth of penetration	chloride content	absorption	vapor transmission	surface scaling resistance	electical resistance	reapplication period	abrasion	freeze-thaw exposure	concrete permeability	concrete's moisture state	surface-cleaning	presence of curing compounds/ film formers	concrete's surface finish	sealer's coverage rate	sealer's method of application	ultraviolet light exposure
laboratory investigation	i	i	i	i					i								i
field investigation																	
theoretical investigation																	

i = investigated

B.2.7 Hagen (1995)

"Field Performance of Penetrating Sealers for Concrete Bridge Decks: Final Report"

Description

A three-year field investigation of sixteen different concrete sealers was conducted on the Western-Avenue Bridge in St. Paul. The bridge was constructed in 1991 and consisted of a low slump overlay. The sixteen different concrete sealers were applied to their respective test sections on the deck surface when the concrete was slightly over its nominal 28 day strength. In addition, an untreated area of the deck was established so that chloride reduction relative to uncoated concrete could be calculated for the sealers each year.

Prior to application of the sealers, the deck surface was sandblasted to remove curing compounds and other contaminants. Sealer application adhered to manufacturers recommended coverage rate and application method. Repeated "lighter" coats were needed for most of the products in order to avoid runoff of the sealers and to obtain the recommended coverage rate. The author suggests the low permeability of the deck as a possible reason why runoff was a problem for most of the sealers in obtaining the appropriate dosage rate.

Three drill dust samples per each treated and untreated section of the deck were obtained on an annual basis for three years. Each dust sample was produced in half inch increments to a depth of one and one-half inches below the pavement surface. In the first half inch increment, the top one-sixteenth inch of the pavement surface was discarded due to possible chloride precipitation on the deck. Dust samples were then analyzed to produce total (acid-soluble) chloride concentration with depth. The three chloride concentration with depth samples for each treated and untreated section of the deck were then averaged to produce mean chloride concentration with depth. The baseline chloride content of the concrete was subtracted from the mean chloride concentration with depth data so only chloride ingress through the deck was measured. From this mean chloride ingress with depth data, the percent chloride reduction relative to uncoated concrete was calculated for each sealer. The reduction of chlorides in the one to one and one-half depth interval was discarded due to the negligible accumulation of chlorides at this depth in the time frame of the study.

In addition to the field testing, the author evaluated chloride reduction relative to uncoated concrete for eleven of the sixteen sealers using a laboratory test procedure based on the NCHRP 244 Series II tests (see Appendix A.1). The concrete sealers evaluated in the laboratory investigation included test no. 1, 2, 3, 4, 8, 9, 11, 12, 13, 14, and 15.

The NCHRP 244 Series II testing does not incorporate abrasion or freeze-thaw exposure which the sealers were obviously subjected to in the three year field test. Also to be mentioned, the author gives no mention of the water to cement ratio used for the laboratory concrete. If standard laboratory concrete were used, the differences in water to cement ratio between the laboratory and field concrete would be substantial.

Main Findings and Conclusions

Field Results:

Field results indicated silanes and siloxanes as a group reduced chloride ingress much more effectively than the thermoplastic resins, sodium silicate, and epoxy film formers. These film formers generally did not impart any added chloride protection to the uncoated concrete after the first year. Epoxy performed slightly better than the thermoplastic resins and sodium silicate but still only reduced chloride ingress as effectively as the worst performing silanes and siloxanes in the last year of the field study.

Field results generally indicated sealers experienced a reduction in effectiveness from year to year, thus suggesting the negative effects that freeze-thaw exposure and abrasion have on a sealer's performance. For silanes of a specific composition (i.e. water-based 40% silanes, solvent-based 40% silanes) the reduction in chloride performance from year to year was not consistent across the group. For example, some water-based 40% silanes experienced much larger reductions in chloride effectiveness than others; this observation also holds true for the solvent-based 40% silanes. Thus, not all silanes of a specific composition can be expected to exhibit the same initial or long term performance. A possible explanation for this substantial variation in performance observed could be that not all silanes of a specific composition are affected the same by freeze-thaw exposure and abrasion. Scatter in chloride measurements alone cannot explain the deviations in performance.

No clear trend could be seen as far as solvent-based 40% silanes outperforming water-based 40% silanes or vice versa. Thus, the benefit of solvent or water-based could not be seen. Also, the benefit of higher solids content could not be seen in the solvent-based 40, 30, and 20% silanes. The benefit of higher solids content could be seen in the solvent-based 15% and 9.2 % siloxane though. As far as silanes verse siloxanes, as a whole no group distinctly peformed better than the other. The four best sealers at reducing chloride ingress after three years of exposure to deicing chemicals proved to be a water-based 40% silane, the solvent-based 40% siloxane/silane mixture, a solvent-based 40% silane, and the solvent-based 15% siloxane. It should be noted that the water-based 40% silane product provided notably higher long term chloride effectiveness than that of the other three sealers.

Laboratory Results:

Laboratory results indicated the sealers to be much more effective at reducing chloride ingress than field results demonstrated. For example, chloride reductions relative to uncoated concrete for sealers ranged from 83 to 94% from laboratory results. Field results, for the same sealers studied in the laboratory, indicated chloride reductions between 3 and 67% after the third year. Thus, the NCHRP 244 Series II tests did not yield a good indication of long term performance most likely due to not including abrasion and freeze-thaw exposure. Also, performance on a relative scale did not correlate between laboratory and field results for the eleven sealers analyzed in both cases. Thus, the NCHRP Series II tests could not have been used to predict best and worst performers in the field. Finally, laboratory results indicated no trends of performance as far as silanes verse siloxanes, solvent verse water-based products, and the effect of higher solids content. Finally, laboratory results did not indicate a large variation in performance among silanes of specific composition (i.e. solvent-based 40% silanes, water-based 40% silanes) or among the eleven sealers in general as field results demonstrated. The lack of freeze-thaw exposure and abrasion in the laboratory investigation most likely accounts for this discrepancy.

<u>Concrete Sealers Tested</u>

	penetrating sealers					film formers	
test no.	silane	siloxane	siloxane/ silane mixture	silconate	silicate	epoxy	thermoplastic resins
1	s/ 20						
2	s/ 30						
3			s/ 40				
4	w/ x						
5							w/ 25
6							s/ 16
7							s/ 21
8						w/ x	
9	w/ 40						
10	s/ 40						
11		s/ 15					
12		s/ 9.2					
13	s/ 40						
14	w/ 40						
15	s/ 40						
16					x/ x		
s, w, or x = solvent-based, water-based, or not stated respectively / ## or x = percent solids by weight or not stated respectively							

Sixteen different concrete sealers were analyzed as indicated by the above table. It should be noted that for test no. 4, the sealer consisted of a two part system: a water-based silane primer and an acrylic top coat.

Aspects of Performance Investigated

	performance measures						factors affecting performance										
	depth of penetration	chloride content	absorption	vapor transmission	surface scaling resistance	electical resistance	reapplication period	abrasion	freeze-thaw exposure	concrete permeability	concrete's moisture state	surface-cleaning	presence of curing compounds/ film formers	concrete's surface finish	sealer's coverage rate	sealer's method of application	ultraviolet light exposure
laboratory investigation		i															
field investigation		i															
theoretical investigation																	

i = investigated

B.2.8 Kottke (1987)

"Evaluation of Sealers for Concrete Bridge Elements"

Description

Alberta Department of Transportation and Utilities devised a laboratory test procedure based on the NCHRP Report 244 test methods as a screening method for the above sealers. Cube specimens, 100 x 100 x 100 mm, were cast for the "Alberta Department of Transportation Test Procedure." The water to cement ratio of the concrete used was 0.50. After casting, cube specimens underwent 21 days of fog curing followed by 14 days of air drying. Following air drying, the surfaces of the cubes were lightly sandblasted to remove surface laitance (including untreated cubes). The total amount of material removed from each cube was 20 ± 2 grams; this removal of mass was evenly distributed between all six sides.

Following curing and surface preparation, designated cube specimens were treated with their respective products. Sealers were applied according to the manufacturers' recommended coverage rate with a brush; for low viscosity sealers, several light coats were needed to achieve the recommended coverage rate. After application, sealers were allowed to cure for 7 days before proceeding with the absorption test.

Absorption testing consisted of immersing treated and untreated cube specimens in deionized water for 5 days. Weight gain of the treated and untreated specimens was then compared after the immersion process; the percent reduction of weight gain caused by treatment was then reported for each sealer.

Immediately following absorption testing, the treated and untreated cubes were allowed to dry for 14 days to determine vapor permeability. For each specimen, the amount of weight lost during the drying process was reported as a percentage of the weight gained during the immersion process. The author refers to this value as the vapor transmission percentage.

Following vapor transmission testing, the effect of abrasion was investigated for penetrating sealers only. Film formers were not subjected to abrasion testing since they were not to be applied to bridge surfaces exposed to vehicular wear (i.e., decks). For cubes treated with a penetrating sealer, their surfaces were sandblasted to remove a nominal depth of 1 mm from each of their six sides. This abrasion depth was quantified by removing 70 ± 2 grams of total material from each treated cube; mass removal was evenly distributed between the six sides. After the faces of the treated cubes were subjected to abrasion, these specimens underwent a second cycle of absorption testing. The procedure for the second cycle of absorption testing did not differ from the first. Uncoated control cubes did not undergo the abrasion and second cycle of absorption testing as did the cubes treated with the penetrating sealers. Instead, the weight gained by each treated, abraded specimen after the second absorption cycle was compared to that gained by respective control specimens in the first absorption cycle. The percent reduction of weight gain as a resultant of treatment and subsequent abrasion was reported for each penetrating sealer.

In evaluating how well penetrating sealers reduced water ingress after being subjected to abrasion, there was a reason why the comparison untreated cubes did not undergo abrasion and the subsequent second absorption cycle. After the first absorption cycle and following drying period, control cubes and untreated cubes had much different moisture contents. For example, after the drying period following the first absorption cycle, the average percent vapor transmission of the cubes treated with penetrating sealers was found to be 150 percent. For the control specimens, average percent vapor transmission was only 84 percent. Thus, at the start of the second absorption cycle, moisture content of the control cubes proved to larger than that of the treated specimens; the control cubes did not lose all the water they gained during the first immersion period. Therefore, absorption values for treated, abraded specimens were compared to absorption values of control specimens subjected to the first immersion cycle.

Each of the sealer's water proofing performance was then ranked according to the following categories: A, B, C, and D for reduction of weight gain of greater than 90, 82.5 – 90, 75 – 82.5, and less than 75 percent respectively. Alberta Department of Transportation and Utilities 1987 water proofing acceptance criteria for film formers was stated as an initial rating of at least "C". For penetrating sealers, an initial rating of at least "B" and final rating after abrasion of at least "C" was required to use the product in the field.

Main Findings and Conclusions

In evaluating absorption results for the film formers, reduction of weight gain ranged from 95.6 to 29.7 percent. No generic type of sealer proved to be the best performer. Furthermore, water repelling performance was found to vary among film formers of a generic composition. It was noted however that the combined 2 product systems were consistently among the top performing products.

Reduction of weight gained before abrasion ranged from 93.6 to 67.6 percent for the penetrating sealers. After abrasion, reduction of weight gain ranged from 87.8 to 10.6 percent; the effect of abrasion was clear on the water repelling performance of the penetrating sealers. Also evident was that abrasion seemed more detrimental for some of these sealers than others.

In looking at absorption results before and after abrasion, performance among the silanes and among the siloxanes varied greatly. However, silanes were the only products to demonstrate an absorption rating of "B" after abrasion (no product received a rating of "A" after abrasion). Siloxanes exhibited absorption ratings of "C" or "D" after abrasion though many silanes were ranked the same after abrasion also.

Concrete Sealers Tested

Due to the number of concrete sealers tested, a table of previous format was not used in depicting the number and composition of the sealers analyzed. Instead, the following table was used to display the number and generic type of products studied.

penetrating sealers - 1 product systerms	
generic composition	no. of products tested with generic compostion
silane	19
siloxane	14
epoxy	1
MMA*	1
acrylic	1
film formers - combined 2 product systems	
generic composition	no. of products tested with generic compostion
1. epoxy 2. urethane	2
1. epoxy 2. epoxy	2
1. silane 2. MMA*	2
1. copolymer 2. copolymer	2
1. MMA* 2. MMA*	1
film formers - 1 product systems	
generic composition	no. of products tested with generic compostion
MMA*	6
polyurethane	4
aliphatic urethane	1
epoxy	5
copolymer	2
acrylic	9
chlorinated rubber	1
*Note: MMA = methylmethacrylate	

It should be noted that the author split the groups of sealers studied into two groups: penetrating sealers and coating sealers (film formers). Within the film formers, certain sealers were a combined 2 product system and hence the further designation in the above table. The author classified one epoxy, MMA, and acrylic sealer as “penetrating” as indicated by the above table. The percent solids content or the carrier was not noted for any of the products analyzed.

Aspects of Performance Investigated

	depth of penetration	chloride content	absorption	vapor transmission	surface scaling resistance	electical resistance	reapplication period	abrasion	freeze-thaw exposure	concrete permeability	concrete's moisture state	surface-cleaning	presence of curing compounds/ film formers	concrete's surface finish	sealer's coverage rate	sealer's method of application	ultraviolet light exposure
	performance measures						factors affecting performance										
laboratory investigation		i	i	i				i									
field investigation																	
theoretical investigation																	

i = investigated

B.2.9 Pfeifer (1981)

“Concrete Sealers for Protection of Bridge Structures”

Description

NCHRP Report 244 was the first major study to investigate sealer/ surface coating performance through means of laboratory analysis. The objective of the project aimed to determine the best performing sealer/ surface coatings for bridge components excluding bridge decks because abrasion resistance was not a performance criterion measured. The investigation consisted of four series of tests: Series I, Series II, Series III, and Series IV laboratory tests. The major reason for including this summary is the fact that many manufacturers of concrete sealers rate the effectiveness of their sealers using the test procedures developed in the Series II tests.

Series I Tests:

Series I tests served as a screening method for the twenty-one sealers/ surface coatings analyzed. Parameters investigated were salt-water absorption, vapor transmission during drying, and chloride ion penetration. Also, dual specimens were pretreated with linseed oil and then sealed with each of the 21 sealers/ surface coatings to evaluate the effect that bridge components previously treated with linseed oil had on the performance characteristics of the sealers/ surface coatings. After 24 hours of initial curing in forms, four inch prismatic cubes were cured in water for six days and lightly sandblasted at seven days of age to remove surface laitance. After lightly sandblasting their surfaces, the cubes were allowed to air dry for 21 days in an environmentally controlled chamber. After the 21 days of air drying the cubes were split into two groups. One group was sealed with the 21 selected sealers/ surface coatings at 28 days of age according to the manufacturers’ recommendations. The other group was sealed with single coats of boiled linseed oil and mineral spirits at 28 and 29 days of age respectively. The pretreated linseed oil specimens were then exposed to ultraviolet light for aging purposes. At 35 days of age, the 21 sealers/ surface coatings were applied to these specimens pretreated with linseed oil using the manufacturers’ recommendations. Both groups of specimens were then cured for 14 days in an environmentally controlled chamber after the 21 sealers/ surface coatings were applied. After the 14 day curing period both groups of specimens were immersed in 15% NaCl solution for 21 days, where the weight gain was measured every 3 days. Following immersion, the cubes were air dried in the environmentally controlled chamber for 24 days where weight loss was measured every 3 days until day 21 and every day for the last 3 days. After the 24 days of air drying, each cube was split in half where one of the halves was crushed in order to measure acid soluble (total) chloride content using an acid digestion potentiometric titration procedure. The background chloride content of the concrete mix used to construct the specimens was subtracted in order to measure chloride ingress during the salt-water soaking process.

Series II Tests:

Series II tests served as a means to further evaluate the top 5 performers from the Series I screening tests (test no. 4, 6, 8, 10, and 16). Thus, Series I tests demonstrated a polyurethane, silane, two methacrylates, and an epoxy as the best performers according to salt-water absorption, vapor transmission, and chloride ingress results for specimens not pretreated with linseed oil. It should be noted that these 5 sealers/ surface coatings were also evaluated in the Series III and IV tests. Series II and III tests did not analyze specimens pretreated with linseed oil as did the Series I tests. Series IV tests analyzed the effect of pretreatment with linseed oil as did the Series I tests.

Series II tests followed virtually the same procedure as the Series I tests with the following exceptions. The stripped specimens were moist cured in plastic bags for 21 days instead of the six days of being submerged in water as in the Series I tests. Thus, the presence of saturated specimens as in the Series I tests was eliminated. The authors of the report felt this non-saturated condition more accurately represented field conditions. Another change was in the amount of drying time after moist curing. Series II tests allowed for drying times of 1, 5, and 21 days in an environmentally controlled chamber before sealing the specimens. Thus, the effect of the moisture state of the concrete upon sealer/surface coating application was investigated. It should be noted that sealers/surface coatings were applied using the manufacturers' recommended "normal" application rate. This "normal" application rate should be assumed to be in the middle of the recommended application rate for each sealer/surface coating. After sealer application, specimens were allowed to air dry in an environmentally controlled chamber. After 31 days had passed since the removal of specimens from the plastic bags, all cubes were immersed in 15% NaCl solution. Absorption, vapor transmission, and chloride ingress were then measured as in the Series I tests. The only deviation in the Series II tests was the length of time used to determine the vapor transmission characteristics of the sealers/ surface coatings (21 days instead of 24 days as in the Series I tests).

Series III Tests:
While the purpose of the Series II tests was to investigate the effect of the concrete's moisture state upon sealer/surface coating application, Series III tests determined the effect of a varying application rate on the sealer/ surface coating's absorption, vapor transmission, and chloride ingress characteristics. Series III tests analyzed the five best performers from the Series I tests (test no. 4, 6, 8, 10, and 16) as mentioned above. Series III tests followed the same procedure as the Series II tests with the following exceptions. After moist curing in bags for 21 days, the drying time in the environmentally controlled chamber before sealer/ surface coating application was held constant at 5 days. Also, the application rates were varied as mentioned before. The manufacturers chose application rates above and below the "normal" application rates.

Series IV Tests:
The purpose of the Series IV laboratory tests was to investigate the performance of the five selected sealers/ surface coatings from the Series I tests under 24 weeks of accelerated weathering. A northern climate and southern climate was simulated. The northern climate simulation will only be discussed due to the current deck and crack sealant research only pertaining to bridge decks in Minnesota.

For the Series IV laboratory tests, 12" x 12" x 5" cracked reinforced and unreinforced slab specimens were constructed. The reinforced slabs consisted of bare no. 4 bars spanning in one of the 12" directions with a clear cover of 1". The reinforced slabs were cracked at midspan in the longitudinal direction of the reinforcement using a flexure inducing apparatus to obtain an average crack width of 0.10". Each of the five selected sealers/ surface coatings from the results of the Series I tests were applied to cracked reinforced and unreinforced slabs. Unsealed cracked, reinforced and unreinforced slabs were also constructed as control specimens. In addition, unreinforced slabs treated and pretreated with boiled linseed oil were also constructed. The only two sealers/ surface coatings applied to the pretreated specimens were sealer/ surface coatings no. 10 and 16 (methacrylate and epoxy respectively). These unreinforced slabs treated and pretreated with boiled linseed oil were allowed to age for seven days by being subjected to ultraviolet light. In the case of the pretreated slabs, after 7 days of ultraviolet aging, sealers/ surface coatings no. 10 and 16 were applied.

It should be noted that concrete mix design used to construct the cracked, reinforced and unreinforced concrete slabs was the same mix design implemented to construct the Series I, II, and III test specimens. After stripping the slabs from their forms, the slabs were covered and allowed to moist cure for 21 days. After moist curing, the slabs were allowed to air dry in an environmentally controlled chamber for 5 days. The cracked, reinforced and unreinforced slabs were then sealed at 26 days of age with the 5 selected sealers/ surface coatings from the Series I tests. The application rate used adhered to the manufacturers' recommended normal rates. Cracked, reinforced and unreinforced slabs subjected to no linseed oil treatment started accelerated weathering tests at 42 days of age.

The unreinforced slabs treated and pretreated with linseed oil underwent single coats of boiled linseed oil at 26 and 27 days of age. As mentioned previously, the pretreated and treated linseed oil slabs then underwent 7 days of aging by ultraviolet light. The designated pretreated slabs were then sealed with test no. 10 and 16 according to manufacturers' normal coverage rates at 34 days of age. At 50 days of age, the unreinforced slabs treated and pretreated with linseed started accelerated weathering tests at 50 days of age.

For the simulated northern climate, the cracked reinforced and unreinforced concrete slabs were subjected a daily cycle that consisted of freezing and thawing, ultraviolet radiation and infrared heat exposure, salt and acid water ponding, and fresh water rinsing. The acid water solution was meant to simulate acid rain encountered in northern climates. The daily cycle was repeated each day during the work week for the 24 week accelerated weathering period. During the weekend, the reinforced and cracked, reinforced slab specimens were not subjected to the accelerated weathering tests and were stored in a thawed condition. To assess the performance of the five selected sealers, chloride ion ingress for the unreinforced concrete slabs was measured at the end of the 24 weeks of accelerated weather testing using powdered samples from a rotary drill. Also, copper-copper sulfate half cell corrosion potential readings were taken on the cracked reinforced slabs. Lastly, the surface condition of each of the slabs was evaluated.

Main Findings and Conclusions

Series I Tests:

For specimens not pretreated with linseed oil, the five best performers with respect to the salt-water absorption, vapor transmission, and chloride ingress measurements were always test no. 16, 15, 8, 4, and 6 (two epoxies, methacrylate, urethane, and silane respectively). The spread in absorption, vapor transmission, and chloride ingress values demonstrated a large range in the performances of the 21 selected sealers/ surface coatings. Thus, the five best performing sealers/ surface coatings were easily distinguishable in each performance category. Interestingly, siloxane generally exhibited the poorest absorption, vapor transmission, and chloride ingress characteristics of the 21 tested sealers/ surface coatings. In comparison to uncoated concrete, siloxane was found to provide no added protection. The low solids content of the siloxane, 6.5%, could be hypothesized to be responsible for its poor performance.

When comparing the performance of specimens treated solely with linseed oil and specimens treated solely with the five best performing sealers/ surface coatings, linseed oil's effectiveness came short. Salt-water absorption for linseed oil specimens was only 20% less than that of unsealed concrete; chloride ingress was reduced only by 11%. The five best performers (test no. 16, 15, 8, 4, and 6) reduced salt-water absorption and chloride ingress by 90-70% and 97-79% respectively when compared to uncoated concrete.

Pretreatment with linseed oil reduced salt-water absorption and chloride ingress of all of the tested sealers/ surface coatings, all except one. Silane was the only sealer of the 21 materials tested where salt-water absorption and chloride ingress increased as a result of pretreatement; the increase was quite substantial. The author suggests that the reduction in performance for silane pretreated with linseed oil resulted from the linseed oil blocking the pore walls of the concrete's capillary structure. Thus, the silane was unable to react with the pore walls and render them hydrophobic. Since siloxane is also a hydrophobic agent, an increase in absorption and chloride ingress should have also occurred for siloxane specimens pretreated with linseed oil. Since this increase in absorption and chloride ingress did not happen, one may hypothesize this was a result of the low solids content of the siloxane (6.5%).

Although salt-water absorption and chloride ingress characteristics benefited for most of the 21 sealers/ surface coatings as a result of linseed oil pretreatment, vapor transmission decreased for 18 of the materials (including silane). This suggests linseed oil does not allow the concrete to breathe.

For both specimens pretreated and not pretreated with linseed oil, the researchers found a very strong, direct relationship between salt-water absorption and chloride ingress. It should be noted that the strength of the correlation was slightly less for the pretreated specimens. The above observations suggest the validity of salt-water absorption as a performance criterion for sealers/ surface coatings.

Based on the similar composition of test no. 16 and no. 15 (two epoxy formulations), test no. 15 was not recommended for Series II, III, and IV tests. Test no. 10, a methacrylate material which was consistently the next best performer for specimens not pretreated with linseed oil, was recommended instead. Thus, the sealers analyzed in the Series II, III, and IV tests were test no. 16 (epoxy), 8 (methacrylate), 4 (urethane), 6 (silane), and 10 (methacrylate).

Series II Tests:
As indicated earlier, Series II tests did not evaluate the effect of pretreatment with linseed oil. Series II tests evaluated the effect that varying drying time (1, 5, or 21 days) had on the five selected sealer/ surface coatings' performances. Water absorption for test no. 4, 6, and 8 (urethane, silane, and methacrylate respectively) were not significantly affected by the moisture state of the concrete. For test no. 10 and 16 (methacrylate and epoxy respectively), significantly lower water absorption occurred when the two surface coatings were applied after 1 or 5 day of

air drying. The authors mention the fact that a greater potential for absorption occurs after longer drying periods due to the lower moisture state of the concrete. The authors suggest this phenomenon as the reason for test no. 10 and 16 decreased absorption values at higher concrete moisture states.

A good correlation existed between salt-water absorption and chloride ingress values. Choride contents were not found to be influenced by drying time for test no. 6, 8, and 16. Vapor transmission characteristics of test no. 4, 6, 8, and 10 were not found to negatively impacted by various moisture states of the concrete. It should be noted that in evaluating salt-water absorption, vapor transmission, and chloride ingress characteristics of silane, drying time did not significantly affect its performance.

Series III Tests:
As in the case of the Series II tests, the effects of pretreatment with linseed oil on the five selected sealers/ surface coatings was not evaluated. The Series III tests differentiated the effect that coverage rate had on sealer/ surface coating performance. Drying time after moist curing was held constant at 5 days. Results of the Series III tests indicated that water absorption for test no. 4, 6, and 16 was not affected by coverage rate. Both test no. 8 and 10 exhibited decreased absorption with increased coverage rate.

Chloride content again correlated well with salt-water absorption. Chloride content seemed to be affected by coverage rate for all of the sealers/ surface coatings, all except test no. 4 (urethane material). The optimal coverage rate for silane's best performance with respect to salt water absorption and chloride ingress was found to be 50-100 ft^2/gal. With respect to vapor transmission, varying the coverage rate only significantly affected the performance of sealer no. 16 (epoxy formulation).

Series IV Tests:
As mentioned previously, the purpose of the Series IV tests was to evaluate the performance of unreinforced and cracked, reinforced slabs exposed to accelerated weathering. Unreinforced and cracked, reinforced slab specimens were treated with the five selected sealers/ surface coatings from the results of the Series I tests. In addition, pretreatment with linseed oil was investigated for unreinforced slabs for sealers no. 10 and 16 (urethane and epoxy respectively). Also, unreinforced slabs coated solely with linseed oil were investigated as control specimens for the pretreated slabs.

Chloride content results for the unreinforced slabs indicated that test no. 16, 8, and 6 (epoxy, methacrylate, and silane respectively) still performed very well in the northern climate simulation. Test no. 16, 8, and 6 reduced chloride ingress by 97, 87, and 76% respectively when compared to uncoated control concrete. Test no. 4 and 5 performed rather poorly with chloride reductions of 52 and 43% respectively. Test no.16, 8, and 6 provided consistently good performance in all four series of tests, where test no. 4 and 5 only performed very well in the first three series of tests. From this observation, the authors imply the salt water soaking procedures implemented in first three series of tests cannot be the only method used to evaluate sealer/ surface coating performance.

In analyzing the chloride contents for the unreinforced slabs, the performance of the specimens treated solely with linseed oil was especially interesting to note. Specimens only coated with linseed oil exhibited the lowest chloride contents out of all the unreinforced slab specimens for the northern climate simulation. In comparing the results of the Series I tests that did not undergo pretreatment, linseed oil performed very poorly with respect to the 21 sealers/ surface coatings analyzed. The authors believe the sharp contrasting performance of the linseed oil specimens in the Series IV and Series I tests was due to the amount of ultraviolet exposure used to age the linseed oil. Series IV specimens treated and pretreated with linseed oil underwent 5000 watt-hours/sq meter of ultraviolet light exposure during the 1 week aging process before being subjected to the weathering tests. Series I specimens subjected to only one treatment of linseed oil (no pretreatment took place) were exposed to zero ultraviolet light radiation prior to salt-water immersion.

Concrete Sealers Tested

	penetrating sealers					film formers						
test no.	silane	siloxane	silane/ siloxane mixture	silconate	silicate	epoxy	methacryalate	urethane	material based on butadiene	chlorinated rubber	material based on isobutyleneand aluminum stearate	boiled linseed oil with mineral spirits
1		x / 6.5										
2												s / 50
3				x / 30								
4								x / 60				
5										x / 20		
6	x / 40											
7									x / 41			
8							x / 20					
9					x / 31.4							
10							x / 36					
11									x / 64			
12											x / 9.97	
13							x / 15					
14								x / 20				
15						x / 100						
16						x / 50						
17						x / 25						
18						x / 17						
19						x / 20						
20						x / 50						
21						x / 30						

s, w, or x = solvent-based, water-based, or not stated respectively / ## or x = percent solids by weight or not stated respectively

Twenty-one different sealers/ surface coatings were analyzed through means of laboratory analysis. The sealers/ surface coatings investigated can be seen in the above table.

Aspects of Performance Investigated

	depth of penetration	chloride content	absorption	vapor transmission	surface scaling resistance	electical resistance	reapplication period	abrasion	freeze-thaw exposure	concrete permeability	concrete's moisture state	surface-cleaning	presence of curing compounds/ film formers	concrete's surface finish	sealer's coverage rate	sealer's method of application	ultraviolet light exposure
	performance measures						factors affecting performance										
laboratory investigation		i	i	i													i
field investigation																	
theoretical investigation																	

i = investigated

B.2.10 Pincheira (2005)

“Evaluation of Concrete Deck and Crack Sealers”

Description

Two sets of specimens were created, one set for determining the sealants’ depth of penetration and the other set for determining total chloride ion content after ponding the sealed specimens for 90 days with sodium chloride solution. Sealant application was performed with a low pressure sprayer and adhered to the manufacturer’s coverage rate recommendations. The depth of penetration of the sealants was measured by splitting the sealed concrete specimens at 1/8, 3/8, 5/8, and 7/8 spans and using a dye to distinguish the sealed vs. unsealed concrete. 8 depth of penetration measurements were recorded per split section for a total of 32 measurements per sealed specimen. The average depth of penetration of the sealer was then recorded. The total (acid soluble) chloride content was determined according to AASHTO T259 and AASHTO T260 Procedure A.

AASHTO T259 lays out a process of abrading and then ponding the specimen’s sealed surface with sodium chloride solution for 90 days. The abrasion depth required by AASHTO T259 is 3.2mm+/-1.6mm (1/8”+/1/16”) and was obtained by sandblasting the specimens. During the sandblasting process for each sealed specimen, a specially created measuring device was used to ensure that the abrasion depth fell within the AASHTO T259 tolerances. This tolerable range of abrasion depth was then verified at a minimum of six random locations after sand blasting. After sealing and abrading the specimens, the specimens were subjected to sodium chloride ponding.

To investigate the sealers’ durability, duplicate sealed and abraded specimens for each sealer were created. One set of specimens were subjected to 90 day ponding under no freeze-thaw cycles and the other set was subjected to 90 day ponding under freeze-thaw cycles. After ponding, the total chloride content was determined according to AASHTO T260 Procedure A. AASHTO T260 Procedure A lays out a procedure for determining the total (acid soluble) chloride content via potentiometric titration. For specimens not subjected to freeze-thaw cycles, chloride ion repellency was measured as a ratio of the chloride ion content of the sealed to unsealed specimen. For specimens subjected to freeze-thaw, the ratio was reported as the chloride ion content of the sealed specimen subjected to freeze-thaw to the unsealed specimen not subjected to freeze-thaw. Chloride repellency and the durability of the sealers were measured this way. Comparison of the two ratios revealed the sealers’ degradation under freeze-thaw.

Main Findings and Conclusions

It was noticed that considerable scatter existed within the penetration depth profile of each sealant. It was also noticed that the larger the average penetration depth of a sealant, the better chloride ion repellency the sealant provided. A direct, but not perfect relationship existed between penetration depth and chloride ion protection. It was also noticed that substantial variance existed within the chloride ion measurements taken from a single sealed specimen. This variance in chloride content could somewhat be due to variations in the tolerable sandblasting depth, but was more related to the vast variance in the penetration depth of the sealant. When more chloride ion content samples were taken, the average chloride content for the specimen became a more reliable indicator of the true chloride content. These observations should be taken into account when different studies produce vastly different penetration depths and total chloride ion contents for the same sealants.

Further expanding on the relationship between penetration depth and protection against chloride ion ingress, it was noticed that abrasion depth required by AASHTO T259 may have been too large to simulate actual vehicular abrasion that occurs on bridge decks. Only one sealant, Hydrozo Silane 40 VOC (40% solvent-based silane product) was able to penetrate beyond the average depth of 3.2 mm required by AASHTO T259. When 3 sealants with penetration depths around 1.9 mm were subjected to chloride ponding and no abrasion, their ability to deter chloride ions vastly increased, thus strengthening the relation between depth of penetration and chloride repellency. This vast reduction in chloride ion content makes sense because with penetration depths around 1.9mm and abrasion depths around 3.2mm and the substantial variance in penetration depth, portions of exposed, unprotected concrete were inevitable.

Trends were also noticed in the results of the acid soluble chloride ion content in specimens not subjected to freeze-thaw. When not subjected to freeze-thaw, solvent-based silane products were the most effective at reducing chloride ion ingress when compared to water-based silane and solvent and water-based siloxane products. It should also be noted that these solvent-based silane products exhibited the greatest depths of penetration among the 13 deck sealants. In general, under no freeze-thaw, sovent-based silanes provided greater chloride repellency than their water-based counterparts and solvent and water-based siloxanes followed the same trend. These solvent-based products also had larger depths of penetration than their water-based counterparts. In considering silane vs. siloxane, generally silane products provided greater chloride protection than solvent and water-based siloxane products under no freeze-thaw. Silane products were also generally exhibited greater depths of penetration than solvent and water-based siloxane products. This trend is reasonable because siloxane molecules are larger than silane molecules.

For sealers subjected to freeze-thaw, trends were also noticed. No distinction between solvent-based outperforming water-based products and vice versa could be made. As far as silane vs. siloxane, many silane products provided around the same or less chloride protection than the siloxanes did, while products with the greatest protection were all silanes. Exposure to freeze-thaw cycles decreased the ability of nearly all the sealers' ability to deter chloride ion ingress. This trend shows that freeze-thaw testing is an important test in evaluating the performance of a sealer for selection criteria.

Evaluation of the results of the of the depth of penetration and the total chloride content under freeze-thaw and no freeze-thaw revealed Sonneborn Penetrating Sealer 40 VOC and Hydrozo Silane 40 VOC (both solvent-based, 40% silane products) as the best performers. However, mention is given that the abrasion depth and the freeze-thaw cycles administered modeled worst case scenarios. Thus, a sealer should be chosen that meets the needs of the specific project. Also, care should be taken when accepting manufacturers' claims concerning the depth of penetration of their product. In the case of the 13 penetrating sealers analyzed, none reached the penetration depths as stated by the manufacturer.

Concrete Sealers Tested

	penetrating sealers					film formers
test no.	silane	siloxane	siloxane/ silane mixture	silconate	silicate	epoxy
1	s/ 40					
2				x/ x		
3	w/ 20					
4		s/ 80				
5		w/ 10				
6			w/ x			
7	s/ 40					
8	w/ 20					
9	w/ 40					
10	s/ 40					
11	s/ 40					
12	w/ 40					
13		s/ 10				
s, w, or x = solvent-based, water-based, or not stated respectively / ## or x = percent solids by weight or not stated respectively						

Thirteen penetrating sealants were analyzed and compared as seen in the above table. Pincheira also analyzed and compared the performance of ten crack sealants. The crack sealant summary of the study can be found in Appedix B9.

Aspects of Performance Investigated

	performance measures						factors affecting performance										
	depth of penetration	chloride content	absorption	vapor transmission	surface scaling resistance	electical resistance	reapplication period	abrasion	freeze-thaw exposure	concrete permeability	concrete's moisture state	surface-cleaning	presence of curing compounds/ film formers	concrete's surface finish	sealer's coverage rate	sealer's method of application	ultraviolet light exposure
laboratory investigation	i	i						i	i								
field investigation																	
theoretical investigation																	

i = investigated

B.2.11 Rasoulian (1988)

"Evaluation of Experimental Installation of Silane Treatment on Bridges"

<u>Description</u>

Laboratory Investigation:
The laboratory investigation examined the performance of the above silane before deciding to undergo the field study. Treated and untreated laboratory specimens underwent freeze-thaw durability (ASTM C-666, Procedure B), 90-day chloride ponding (FWHA procedures), absorption (ASTM C642), and skid resistance testing (British Portable Skid Resistance Tester). Type 1 Portland Cement was used for all laboratory specimens with a standard water to cement ratio of 0.50. Specimens moist cured for 28 days followed by 7 days of air drying at 50 percent relative humidity before subsequent sealer application. Silane was applied to the specimens with a brush and coverage rate adhered to the manufacturer's recommendations. Once treated, specimens were allowed to cure for 24 hours before undergoing testing.

Field Investigation:
The field investigation consisted of monitoring the performance of five bridge decks sealed with the solvent-based 40% silane product. Application rate adhered to the manufacturer's recommended coverage rate; the silane was applied with a low pressure sprayer apparatus. Deck surfaces were either cleaned by power-washing or sandblasting prior to silane application. A designated treated and untreated area was established for each bridge deck so the silane's effectiveness with respect to reference concrete could be established. All bridges were sealed during 1981; their performance was monitored up until 1985. The following captions for each bridge describes its age prior to the silane application:

1. Corey Overpass: 45 year old deck at time of silane application
2. Missouri Pacific Overpass: 3 month old deck at time of silane application
3. I-10 Bridge over Lake Pontchartrain: 20 year old deck at time of silane application
4. Caminada Bay Bridge: 22 year old deck at time of silane application
5. Bayou Lafourche Bridge: 15 year old deck at time of silane application

Absorption, chloride ingress, and half-cell corrosion measurements were taken throughout the course of the study for the treated and untreated sections of the bridge decks. To determine absorption, four inch diameter cores were extracted from treated and untreated areas of each deck. All of but their top surfaces were coated with wax and the cores were subsequently immersed in water; percent absorption by weight was recorded after 1, 2, and 28 days of being submersed. Chloride contents were measured by obtaining and analyzing dust samples in the depth intervals 1/16 to 1/2 inch and 1/2 to 1 inch. Corrosion measurements were obtained in accordance with ASTM C876 "Half Cell Potentials of Reinforcing Steel in Concrete."

Depth of penetration of the silane into the treated area of the decks was also determined. Four inch diameter cores were extracted from the bridges and the depth of the visible non-wetting band was determined.

Infrared spectroscopy was also performed on the cores to determine the depth of silane penetration. Small cubes (1/2 in. x 1/2 in. x 2 in.) were extracted from the center of the top surface of the depth of penetration cores. These extracted cubes were then cut into 0.5 inch thick layers; each layer was crushed and mixed with potassium bromide. The infrared spectrum of each "layered sample" was then produced. It should be noted that in analyzing the infrared spectra of these layered samples, there is a certain absorption band caused by the silane bonding to the concrete substrate. Counting the number of layers that revealed this specific absorption band in its spectrum until it was no longer evident yielded the silane's depth of penetration.

Main Findings and Conclusions

Laboratory Investigation:

Results of the freeze-thaw durability testing indicated the durability factor of silane-treated concrete to be roughly three times of that of untreated concrete (treated and untreated concrete air-entrained). Thus, freeze-thaw durability of uncoated concrete appeared to be improved by the silane treatment.

Chloride measurements were not given for the control specimens so the relative benefit of silane treatment could not be seen. On the other hand, absorption measurements for the control and treated specimens demonstrated the benefit of silane treatment; silane coated concrete showed much less percent absorption by weight values than uncoated concrete (i.e. after 28 days of immersion, silane coated specimens reduced absorption values by 84 percent in comparison to control concrete). In evaluating skid resistance, silane treatment did not affect the skid characteristics of uncoated concrete. The benefit of silane treatment was deemed satisfactory enough to proceed with the field investigation.

Field Investigation:

Results from the absorption analysis demonstrated the effectiveness of the silane to generally decrease over time (cores from treated area of decks displayed higher absorption measurements over time). Also, the newly constructed bridge, the Missouri Pacific Overpass, exhibited the highest absorption values for both treated and untreated concrete than any other bridge deck. One would expect to see the trend of fresh concrete displaying larger absorption values than much older concrete.

It should be noted that the reduction in water absorption that occurs as a result of silane treatment over time could not be determined (untreated cores for bridge decks were only analyzed once throughout the time frame of the study where treated cores were analyzed several times). Given the one time after sealer application that treated cores and untreated cores were extracted, results generally indicated that silane treated concrete allowed less water ingress than control concrete. The reduction in water treatment that occurred as a result of silane application was never as great as seen in laboratory results. However, the time frame for when treated and untreated cores were extracted from a deck was at least two years after silane application. Thus, the observed trend of decreasing silane effectiveness with time could help explain the discrepancy seen in the benefit of silane treatment between laboratory and field results. Also, the difference in concrete age between laboratory and field specimens at the time of testing could help explain the discrepancy seen in the benefit of silane treatment. For instance, in the laboratory, roughly 36 day old treated and control concretes were tested whereas in the field the youngest treated and untreated concrete tested was roughly 2 years old (Missouri Pacific Overpass). Thus, the benefit of silane application might be more pronounced in fresh laboratory concrete where control specimens exhibit higher absorption values.

Chloride results from the treated and untreated area of the test bridges did not indicate a clear benefit of silane treatment. Also, chloride levels for treated and untreated concretes were not notably elevated in the top half inch of pavement. A general trend of increased chlorides with exposure time was also not seen in the chloride data from the test bridges. The author attributes the lack of distinguishable trends seen in the chloride data to the mild winters in Louisiana and thus very little deicer applications seen by the test bridges.

Mean half-cell potential readings indicated no corrosion activity taking place in any of the test bridges; average readings for the treated and untreated area of the decks were well below the corrosion threshold of 0.35 VCSE (considered active corrosion level by ASTM C876). Also, mean corrosion measurements for the treated and control section of the decks were not significantly different; a clear benefit of silane treatment was not seen. Once again, the author suggests infrequent deicer applications and the relatively short time frame of the study (4 years) as reasons why the benefit of silane application was not seen.

Depth of penetration measurements indicated the depth of the visible non-wetting band for the cores ranged from 0.0 to 0.1 inches (0.0 to 2.5 mm). Comparison of the infrared spectroscopy results for the cores with the visual measurements showed evidence of the silane at greater depths than the visible depth of the hydrophobic layer. The author also noted that depth of penetration results from infrared analysis yielded a general decrease in the concentration of silane with depth. This observation was concluded from the decreasing intensity of the absorption band until it was no longer evident (decreasing intensity indicates decreasing amount of silane bonded to the substrate). The above observations imply that beyond the depth of the visible non-wetting band, the percentage of the silane solids is too low for the product to exhibit notable hydrophobic characteristics.

Concrete Sealers Tested

	penetrating sealers					film formers
test no.	silane	siloxane	siloxane/ silane mixture	silconate	silicate	epoxy
1	s/ 40					
s, w, or x = solvent-based, water-based, or not stated respectively / ## or x = percent solids by weight or not stated respectively						

A solvent-based 40% silane was analyzed as indicated by the above table.

Aspects of Performance Investigated

	performance measures							factors affecting performance									
	depth of penetration	chloride content	absorption	vapor transmission	corrosion measurements	surface scaling resistance	skid resistance	abrasion	freeze-thaw	concrete's permeability	concrete's moisture state	concrete's surface finish	presence of curing compounds/ film formers	surface-cleaning	sealer's method of application	sealer's coverage rate	ultraviolet light exposure
laboratory investigation		i	i				i		i								
field investigation	i	i	i		i												
theoretical investigation																	
i = investigated																	

B.2.12 Smith (1986)

"Silane Chemical Protection of Bridge Decks"

<u>Description</u>

Laboratory and Preliminary Field Tests:
Depth of penetration testing was conducted according to ODOT test procedure L-34 by measuring the depth of the visible wetting band. Both Class A concrete [water to cement (w/c) ratio of 0.49] laboratory specimens and Class AA concrete (w/c ratio of 0.44) cores from a treated deck were analyzed; the deck had been cured with a linseed oil emulsion prior to silane treatment.

The effect of the moisture state of the concrete on silane's penetration was also investigated though laboratory analysis. A single untreated block specimen was split in half; one of the halves was sprayed with water prior to silane application. The other half was allowed to dry prior to treatment.

Absorption tests were conducted according to the ASTM C-642 provisions on Class A laboratory specimens and cores from a treated bridge deck constructed with Class AA concrete.

Vapor permeability analysis on a laboratory test specimen was performed according to OHD L-35 test procedures. The untreated block was immersed in water for 24 hours and its percent absorption was recorded. The surfaces of the block were then towel dried and all six sides of the specimen were subsequently treated with silane. The wet coated block was then oven dried and its dry weight was recorded. After oven drying the specimen was again immersed in water for 24 hours and its percent absorption was determined.

90 day chloride ponding tests were performed on laboratory block specimens according to the provisions of AASHTO T259/T260. Treated specimens were not abraded before subsequent chloride ponding. (AASHTO T259/T260 specifies treated specimens shall be abraded 3.2 mm ± 1.6 mm if the sealer shall be applied to surfaces exposed to traffic abrasion). Dust samples were taken at four depth intervals: 1/16 to 1/2 in., 3/16 to 1/2 in., 3/16 to 11/16 in., and 1/2 to 1 in; dust samples were analyzed for total chlorides. The baseline chloride content of the concrete at each depth interval was subtracted from each value and chloride ingress with depth was reported. Chloride ingress through the treated specimens were then compared with Oklahoma Department of Transportation (ODOT) requirements of maximum chloride absorptions of 1.50 and 0.75 pounds per cubic yard at depth intervals of 1/16 to 1/2 in. and 1/2 to 1 in. respectively.

Chloride analysis was also performed according to the FHWA (Federal Highway Administration) 450 day ponding test. Three differently cured treated concretes and three control concretes (method of curing not stated) were analyzed. Methods for curing the concrete before subsequent silane treatment either consisted of 35 days of fog curing, 28 days of fog curing followed by 7 days of air drying, or 28 days of fog curing followed by oven drying for 8 to hours. After preparation of the treated samples, specimens underwent 450 days of ponding with a three percent sodium chloride solution. Acid-soluble (total) chloride absorption was then measured at depth intervals of 1/16 to 1/2 in., 1/2 to 1 in., 1 to 1-1/2 in., and 1-1/2 to 2 in.

A preliminary long term field investigation was also conducted on the Bird Creek Bridge deck in Rogers County, Oklahoma (not the same deck as described above). The deck was constructed in 1974 and sealed with silane three years later in 1977. Absorption testing (ASTM C-642) was performed on extracted cores from 1977 to 1984. Half cell corrosion tests (ASTM C-876) were conducted in 1985, 8 years after sealing and 11 years after construction. Chloride concentrations, for depth intervals of 1/2 inch above and 1/2 inch below the rebar, were reported in 1978, 1979, and 1985 (AASHTO T260).

Skid resistance testing on a newly constructed bridge deck was also conducted according to ASTM E 303 provisions using the British Pendulum Tester; an untreated and treated area of the deck was tested. Friction numbers referred to as British Pendulum Numbers were reported from the results of the test procedure. For all tests, silane was applied according to the manufacturer's recommended coverage rate.

Oklahoma Field Evaluation Program:

Nine silane coated bridges and one control bridge were analyzed. Surface preparation for silane application included sandblasting, shot blasting, water blasting, or steam cleaning. In the event that water washing methods were implemented, the concrete deck was given ample time to dry so the concrete would be substantially dry upon silane application. (Laboratory tests demonstrated an increased moisture state of the concrete impedes silane penetration.) In the event that the bridge deck was newly constructed, the concrete was allowed to cure to its nominal 28 day strength before silane treatment. Application rate for the silane adhered to 1 gallon per 125 square feet; silane was applied with a low pressure sprayer apparatus. After application and allowing the silane sufficient time to penetrate into the concrete, the deck was lightly misted with water. The intent was to provide enough moisture for the silane to undergo hydrolysis and subsequent bonding to the substrate.

Bridge structure no.	Year of treatment	Age of deck at time of silane application (yrs.)	No. of years after treatment chloride sampling took place	No. of years after treatment corrosion measurements taken	Use of deicers on deck	AADT (annual average daily traffic)
1039ex	1982	14	3	4	mod./heavy	14100
1039wx	1982	14	3	4	mod./heavy	14100
0281wx	1977	3	8		mod./heavy	2900
0038sx	1981	1	4	4	mod./light	3300
0038nx	N/A - control		5*	5*	mod./light	3300
0292nx	1983	11	2	2	mod./light	19400
0233nx	1985	0	0	1	mod./heavy	9500
0080x	1984	0	0	1	mod./light	400
0570nx	1983	5	2	2	heavy	50000
0541nx	1983	10	1	2	heavy	54000

* No. of years after constuction

Half cell potentials were taken on the treated and untreated bridge decks using the ASTM C876 test procedure. Chloride sampling at depth intervals 1/2 inch above and 1/2 below the depth of the reinforcement was also performed for the treated and untreated bridge decks (AASHTO T260). The following table summarizes the age of the deck at treatment, number of years after treatment that corrosion and chloride measurements took place, use of deicers on the deck, and the annual average daily traffic (AADT).

In 1987, a visual condition survey of the above bridges was performed to evaluate post treatment spalling and scaling.

<u>Main Findings and Conclusions</u>

Laboratory and Preliminary Field Tests:

Mean penetration for the Class A laboratory concrete revealed a minimum penetration of 0.15 inches and a mean penetration of 0.25 inches; penetration results for the Class AA field concrete cured with linseed oil revealed a mean penetration of 0.19 inches. Whether the difference in water to cement ratios of the two concretes (0.49 and 0.44 for Class A and Class AA concrete respectively) was the reason for the difference in mean penetration results is hard to say. It should be noted that the mean penetration results do follow the trend one would expect to see with decreasing w/c ratio or concrete permeability. The linseed oil pretreatment could also explain the lower mean penetration depth witnessed in the field specimens.

Mean penetration results for the “wet” and “dry” concretes demonstrated silane’s penetration to be greatly affected by the moisture state of the concrete. Treated dry concrete exhibited an average penetration depth roughly twice that of treated wet concrete.

Absorption testing proved treated Class A and Class AA concretes to exhibit percent absorption by weight values less than 1 percent. Results for the untreated concretes yielded absorptions by weight that were much higher (5.5 to 6.0 percent by weight). Thus, the benefit of silane treatment was clearly seen.

Results of the vapor permeability analysis proved silane treatment to reduce water absorption from 4.85 to 0.70 percent. Also, the silane coating released 86 percent of the moisture gained by the untreated block.

AASHTO T259/T260 ninety day ponding results revealed chlorides were notably more elevated in the top half inch (1/16 to 1/2 in. depth interval) compared to the 1/2 to 1 in. depth interval. Also, chloride accumulation in the top half inch for the treated specimens was greater than ODOT criteria of 1.50 pounds per cubic yard; chloride ingress in the 1/2 to 1 in. depth interval was well below the ODOT stipulation of 0.75 pounds per cubic yard.

Chloride accumulation with depth for the treated specimens proved to be much less than that for the control specimens. Mean chloride accumulation with depth results for the three treated and control specimens revealed silane treatment reduced chloride ingress by 78, 86, 93, and 92 percent at depth intervals 1/16 to 1/2 in., 1/2 to 1 in., 1 to 1-1/2 in., and 1-1/2 to 2 in. respectively. The general trend of decreasing chloride accumulation with depth was also noticed in the results from the treated and untreated specimens. In analyzing the effect of curing method for the treated specimens, the moisture state of the concrete at the time of silane application appeared to affect the chloride repelling capability of the sealer. Mean chloride absorption with depth values clearly decreased with decreasing concrete moisture state (descending average chloride absorption with depth values: fog cured, air-dried, and oven-dried concrete). Thus, it appeared the drier the concrete before silane application, the better the chloride repellency of the product.

Results from absorption testing with time for the Bird Creek Bridge deck did not show the effectiveness of the silane to increase or decrease; results were relatively similar from year to year. Also, silane proved to be very effective at repelling water ingress compared to untreated concrete; the average 24 hour absorption of the treated cores taken over time proved to be 0.70 percent by weight compared to 6.0 percent by weight for the untreated cores. In analyzing the half cell corrosion measurements, results indicated that 98.3 percent of the test potentials were well below the corrosion threshold of -0.35 V CSE (copper/copper sulphate electrodes) as designated by ASTM C-876. The 1.7 percent of the potential readings that indicated corrosion of the reinforcement consisted of 2 measurements taken 6 to 9 inches from a corroded armor joint. Chloride ingress with depth testing for the treated cores showed chloride accumulation to increase with exposure time; chlorides were also noted to decrease with depth. Also, chloride levels over time for the treated cores were well below the chloride tolerance level of 2.5 pounds per cubic yard (chloride ingress over time was no greater than ~1.0 pound per cubic yard for a half inch above and below the reinforcement).

In evaluating the skid resistance of the newly constructed deck, the silane application only reduced the average British Pendulum Number by 1.4 percent; this difference was deemed insignificant by the researcher.

Oklahoma Field Evaluation Program:

Potential readings for the treated and untreated bridge decks remained below the corrosion indicator of -0.35 V CSE (ASTM C876). The majority of the readings for each bridge deck were well below the corrosion indicator; a small percentage of the corrosion measurements for a few bridge decks displayed readings that were at or close to the corrosion potential. One of the decks that displayed the highest percentage of readings (~10 percent) near the corrosion threshold was Bridge structure no. 0233 NX. This is interesting to note since this particular deck had a very short exposure time to deicing chemicals relative to the older decks. Also interesting to note is that the oldest decks (Bridge structure nos. 1039ex and 1039wx) displayed the lowest corrosion potentials out of all the decks analyzed. In analyzing the benefit of silane application, an advantage of treatment could not be seen in corrosion readings for the nine treated and one untreated bridge deck. It should be noted that to better evaluate the effectiveness of the silane treatment for each deck, control sections should have been established. Corrosion measurements for the treated and untreated section of each deck could have been compared; variables such as deck permeability and age, deicer exposure, and AADT would have been eliminated when analyzing the benefit of silane application with nine treated decks and one untreated deck.

Chloride concentrations for the treated and untreated decks revealed that chloride accumulation was well below the chloride tolerance level of 2.5 pounds per cubic yard at the depth of reinforcement for the majority of the decks. Bridge structure no. 0292 was the only deck that displayed chloride levels at the depth of reinforcement greater than 2.5 pounds per cubic yard; chloride accumulation in this structure was by far greater than in any other deck. Also interesting to note, chloride accumulation at the depth of reinforcement was very similar for the new decks (Bridge structure nos. 0233nx and 0080nx) and the oldest decks (Bridge structure nos. 1039ex and 1039wx).

Once again it is difficult to evaluate the effectiveness of the silane treatment relative to uncoated concrete due to the fact that a treated and untreated test section was not established for each bridge deck. Too many variables such as concrete permeability and age, deicer exposure, and AADT come into play when comparing the chloride results of the treated and untreated decks.

It should be noted that chloride sampling at the depth intervals 1/2 inch above and 1/2 inch below the reinforcement was also performed for the treated decks prior to silane application (only for decks that had been in service prior to silane application). (If the chloride values at the depth of reinforcement would have been greater than the chloride tolerance level of 2.5 pounds per cubic yard, the deck would have been scheduled for rehabilitation rather than silane treatment.) The average rate of chloride accumulation per year for the decks was calculated and proved to low (0.054 pounds per cubic yard increase per year). The author recommends continued monitoring of the decks to see if a similarly low accumulation rate is experienced over a longer term.

Results of the 1987 condition survey for the bridges revealed no post treatment spalling or scaling present in any of the treated decks.

Concrete Sealers Tested

	penetrating sealers					film formers
test no.	silane	siloxane	siloxane/ silane mixture	silconate	silicate	epoxy
1	s/ 40					
s, w, or x = solvent-based, water-based, or not stated respectively / ## or x = percent solids by weight or not stated respectively						

Aspects of Performance Investigated

	performance measures							factors affecting performance									
	depth of penetration	chloride content	absorption	vapor transmission	corrosion measurements	surface scaling resistance	skid resistance	abrasion	freeze-thaw	concrete's permeability	concrete's moisture state	concrete's surface finish	presence of curing compounds/ film formers	surface-cleaning	sealer's method of application	sealer's coverage rate	ultraviolet light exposure
laboratory investigation	I	I	I	I							I						
field investigation	i	I	i		I		I										
theoretical investigation																	
i = investigated																	

B.2.13 Smutzer (1993)

“Field Test of Resistance to Chloride Ion Penetration on Sealed Concrete Pavements”

Description

A three year field investigation was conducted on a newly constructed concrete pavement in Indiana that evaluated the chloride repellency of the seven concrete sealers noted above. Each sealer was assigned to a test section of the concete’s surface; three untreated areas of the pavement surface were also established so that percent chloride reduction relative to uncoated concrete could be calculated for the sealers each year. Three control sections were established so chloride reduction relative to uncoated concrete for the each sealer could be calculated with nearby untreated concrete. Sealers were applied according to the manufacturers’ recommendations when the concrete reached its nominal 28 day strength; the pavement surface was sandblasted and swept clean before the sealers were subsequently applied.

Chloride sampling was performed according to AASHTO T260. Four dust samples from each treated and untreated test section were obtained each year of the three year field study; samples were taken in the corners of each test section, just outside the wheel paths. Dust samples were produced with a rotary hammer drill in half inch increments to a total depth of three inches below the pavement surface. The top one-sixteenth inch of the pavement surface for the first depth interval was discarded due to possible chloride precipitation on the pavement surface. The dust samples were then analyzed for total chloride concentration with depth. The four chloride concentrations with depth samples were averaged to produce mean chloride concentration with depth for each test section of the deck. From the chloride concentration with depth data, chloride accumulation in the two to three inch depth interval was observed to be insignificant for all the test sections (treated and untreated). Thus, the chloride concentrations at these depths were discarded. For each test section, the mean chloride concentrations for the half depth intervals were averaged to produce the mean chloride concentration in the upper two inches of the pavement surface. From this mean chloride accumulation in the upper two inches data, the percent chloride reduction relative to uncoated concrete was calculated for each sealer.

In addition to the field study, a laboratory study based on the NCHRP 244 Series IV tests – Southern Climate Exposure (see Appendix A.3) was conducted to determine the percent chloride reduction relative to uncoated control concrete for the sealers. It should be noted that the epoxies were not evaluated in the laboratory investigation. The simulated southern exposure subjected laboratory specimens to acid, salt-water ponding, thermal heat, ultraviolet exposure, and drying. Abrasion was not accounted for in the laboratory testing. It is strange that the author simulated a southern exposure to compare the results of the laboratory investigation with that of the field investigation. In the field investigation the sealers were subjected to freeze-thaw exposure; the author should have implemented the simulated northern exposure procedure for the NCHRP 244 Series IV tests, which includes freezing and thawing, to more accurately represent the field environment.

The percent chloride reductions from the laboratory and field results were compared to each other as previously mentioned. The NCHRP 244 Series IV testing produced a mean chloride reduction for a depth interval of 0.25 to 1.25 inches below the pavement surface (total chlorides were measured in treated and untreated specimens to obtain chloride reduction relative to uncoated concrete for the sealers analyzed). To better compare field and laboratory results, chloride reductions from the field for the first three half increments were averaged to obtain the mean chloride ingress in the top 1.5 inches of the pavement.

Main Findings and Conclusions

Field Results:

Chloride reduction data from the field indicated the effectiveness of the silane and the epoxies increased each year. This interesting to note because one would think the effectiveness of a sealer would typically decrease each year. The above observation could imply that freeze-thaw degradation affected the untreated concrete each year much more drastically than that of the silane and epoxy treated concrete. For the two siloxanes, the siloxane/silane mixture, and the modified aluminum siloxane, a decrease in effectiveness was noted in the first two years of chloride reduction data. However, the subsequent third year indicated an increase in effectiveness for these sealers; the chloride reduction for the third year was smaller than that observed in the first year though. The two siloxanes experienced a much smaller loss in effectiveness from year one to year three than that of the the siloxane/silane mixture and the modified aluminum siloxane.

The chloride reduction data indicated silane to notably be the most effective product for all three years. Also, the data each year demonstrated the modified aluminum siloxane to be by far the worst product; the siloxane/silane mixture was not that much more effective than the modified aluminum siloxane. The siloxanes and the epoxies proved to be the intermediate performers but relative performance among these sealers individually could not be seen from the data.

A statistical grouping analysis was performed on the mean chloride concentration in the upper two inches of pavement for each treated and untreated concrete. This mean value averaged each treated and untreated concrete's chloride content in the upper two inches of pavement for all three years of exposure. Mean chlorides indicated the following performance for the test sections in ascending order: the three control concretes, modified aluminum siloxane, siloxane/silane mixture, the two siloxanes, the two epoxies, and the silane. The three control concretes exhibited mean chlorides that were much higher than any of the treated concretes. Also, the mean chlorides for the untreated concretes proved to be statistically similar (the three control concretes were identical as group at a 99.9 confidence interval). All the sealers proved to demonstrate mean chlorides that were statistically different from that of the control concretes and each other except the two epoxies and two siloxanes. These two generic types of sealers showed some intertwining because the two siloxanes and one of the epoxies were labeled as an identical group while the two epoxies and one of the siloxanes was labeled as another identical of better performance. The silane followed as another distinct group of with the best performace.

This statistical grouping corroborated the trends witnessed in percent chloride reduction data for the sealers for the three years. Silane clearly demonstrated the largest chloride reductions out of all the sealers for each year. The two epoxies and siloxanes were clearly the next best performers but chloride reductions fluctuated in such a manner from year to year that relative performance between the two groups could not be seen. Chloride reduction data for each year clearly indicated the siloxane/silane mixture and the modified aluminum siloxane as the next least performing products respectively.

Laboratory Results:
Laboratory results did not correlate with field results. Chloride reductions for the sealers seen in the laboratory proved to be much larger than that witnessed in the field. The lack of freeze-thaw exposure and abrasion in the laboratory tests might explain the much larger effectiveness of the sealers seen in laboratory results compared to of that seen in the field. Also, field results showed a much larger range in performance among the sealers (chloride reductions ranged from 10 to 64% after the third year) than that demonstrated by laboratory results (chloride reductions for the sealers ranged from 89.3 to 98.7%). Finally, relative performance of the sealers seen in laboratory results did not parallel with relative performance seen in the field results. For instance, chloride reductions of the modified aluminum siloxane and the siloxane/silane mixture proved these sealers to be more effective than the two siloxanes in the laboratory, but field tests demonstrated these two sealers to perform much worse than that of the two siloxanes. Thus, even for a relative performance indication for the field, the NCHRP Series IV – Southern Exposure testing was not valid.

Concrete Sealers Tested

	penetrating sealers					film formers
test no.	silane	siloxane	siloxane/ silane mixture	silconate	silicate	epoxy
1	x/ x					
2		x/ x				
3		x/ x				
4			x/ x			
5		x/ x				
6						x/ x
7						x/ x

s, w, or x = solvent-based, water-based, or not stated respectively /
or x = percent solids by weight or not stated respectively

Seven concrete sealers were analyzed as indicated by the above table. For test no. 5, the sealer was a modified aluminum siloxane.

Aspects of Performance Investigated

	performance measures						factors affecting performance										
	depth of penetration	chloride content	absorption	vapor transmission	surface scaling resistance	electical resistance	reapplication period	abrasion	freeze-thaw exposure	concrete permeability	concrete's moisture state	surface-cleaning	presence of curing compounds/ film formers	concrete's surface finish	sealer's coverage rate	sealer's method of application	ultraviolet light exposure
laboratory investigation		i															
field investigation		i															
theoretical investigation																	

i = investigated

B.2.14 Soriano (2002)

“Alternative Sealants for Bridge Decks: Final Report”

Description

The study consisted of a literature review, a survey of other states’ and provinces’ concrete deck and crack sealing strategies, and a field and laboratory analysis.

The survey investigated trends in concrete deck and crack sealing strategies of northern states and Canadian provinces. 40 states and provinces were sent the survey and of the 40 questioned, 25 replied. Questions were worded for simple yes/ no answers. Individual state and province answers were not given but rather the number and percentage of states and provinces answering yes and no to individual questions. The portion of the survey concerning crack sealant use will be discussed in the summary of the crack sealant portion of the Soriano report found in Appendix B10. The deck sealant portion of the survey investigated if the states and provinces that responded used penetrating, barrier, other, or no deck sealing product at all. No questions were asked to specify differences or commonalities among the types of penetrating and barrier sealers used by the states and provinces surveyed.

For the field investigation, 3 different bridges were used for sealant application. The surface of the bridge decks were either prepared for sealant application in one of three ways: i) sandblasting; ii) power broom/ forced air; or iii) do nothing. Cracks were mapped and their widths were recorded for each bridge deck. Six test sections were defined per bridge. Based on ACI 201 definitions of crack widths (fine: < 0.04 in, medium: 0.04 to 0.08 in, wide: > 0.08 in), the six test sections were categorized as medium or low crack density areas. No, clear distinction on the characteristics of each classification is given in the report. Note that surface prep was performed after classification of the test sections was performed. Based on the classification of each test section, either a crack or deck sealer was applied. Deck sealers were applied to low crack density areas and crack sealers were applied to medium crack density areas. Further description on the crack sealers portion of Soriano’s report can be seen in Appendix B10. The three silane products were applied using a low pressure sprayer. After application and adequate drying time, three cores from each test section were extracted. This produced a total of 54 cores (3 cores x 6 test sections x 3 bridges). Of these 54 cores, only 30 were able to be tested due to 24 of the cores containing surface cracks and breaking during transport and laboratory preparation. To measure the depth of sealant penetration and water penetration, a 56 day ponding test with a fluorescence day was performed. Note that this was performed for the deck and crack sealants. The cores were not ponded with sodium chloride due to concerns of the samples breaking upon determining the chloride content. The depth of water penetration was stated as a qualitative indicator of the chloride repellency of the crack and deck sealants.

Representative cores from each bridge deck were taken to determine concrete properties such as the water-cement ratio and paste hardness. Differences in concrete permeability among the three bridge decks were accounted for this way. Large variations in concrete permeability could then help explain any major deviations in the depth of penetration for a certain deck sealant.

Main Findings and Conclusions

11 of the 25 surveyed states and provinces (44%) reported using penetrating sealers, 4 out of the 25 (16%) reported using barrier sealants, 1 out of the 25 (4%) reported using other, while 13 of the 25 states (52%) reported using no type of deck sealer at all. This trend showed the preference of penetrating sealants among the states and provinces surveyed and corroborated the investigation of penetrating sealants in Soriano's study as an alternative to linseed oil.

Soriano recommends SDDOT to discontinue use of linseed oil as a penetrating deck sealer. He goes on further to recommend to not classify linseed oil as a true penetrating sealer at all due to its high viscosity and its molecular size being larger than that of the concrete pores. Soriano recommends linseed oil to be classified as more of a membrane sealer due it being easily abraded off by traffic. Further corroborating linseed oil as an inferior penetrating sealer, Soriano references NDOT as describing silanes as the best performers out of all the sealers they have used (linseed oil being on of the sealers used by NDOT). Soriano further goes on to validate the superior performance of silanes by citing other suppliers and users stating silanes are the "best overall penetrating sealer for the following reasons: i) low viscosity (10-50 cps); ii) low molecular size (2-4 x 10^{-5} in.) vs. concrete pore size (5-50 x 10^{-5} in.); iii) resistance to alkaline environments (depending on chemistry)."

The results of Soriano's field study indicated that the 100% silane product exhibited slightly better penetration and water repellency than the 40% silane products. This should be expected because 100% silane products have more reactive material that interacts with the concrete, thus providing better water repellency. The results of the concrete permeability analysis from the 3 different decks revealed that all had similar permeability characteristics. Also, no major differences in depth or penetration were observed for the same sealant from deck to deck. Thus, slight differences in concrete permeability did not likely play a role in the performance of the deck sealers.

Further expanding on similar depths of penetration noticed for each sealant for the 3 different bridge decks, surface preparation did not seem to play an important role in a deck sealer's depth of penetration. This phenomenon was noticed for the crack sealers also. In fact, the sandblasted deck seemed to provide the least protection against water ingress. Soriano postulates the reason for this as sandblasting the deck increased the size of the concrete pore openings, thus increasing concrete permeability. Soriano recommends the do nothing approach for surface preparation due its economic and time benefit. This is of course assuming the deck is absent of excessive debris. In the case of excessive debris, a power broom/ forced air surface preparation is recommended.

Soriano's recommendations for SDDOT include replacing the use of linseed oil for a deck sealer with the silanes incorporated in the study or "functional equivalents with large molecular weight alkyl groups." Silanes and siloxanes with larger molecular weight alkyl groups will exhibit better water repellency, thus better chloride repellency. Care should be taken selection though because although silanes and siloxanes with larger molecular weight alkyl groups provide better water and chloride repellency, depth of penetration is limited by the size of the alkyl group. Soriano also provides recommendations for SDDOT in optimum timing and reapplication of penetrating sealers. Using the logic that the sooner newly constructed bridge decks are protected the better, Soriano recommends sealing bridge decks within 3 to 6 months after construction and in 5 year intervals. The five year interval recommendation comes from literature review (McGettigan, E., “Silicon-Based Weatherproofing Materials”) describing sealants ability to withstand 7 years of simulated traffic abrasion. No mention of what sealants were analyzed is mentioned by Soriano. Soriano reduces the interval to 5 years to account for variability in sealant application, concrete permeability, and traffic density.

Concrete Sealers Tested

	penetrating sealers					film formers
test no.	silane	siloxane	siloxane/ silane mixture	silconate	silicate	epoxy
1	x/ 40					
2	x/ 40					
3	100					
s, w, or x = solvent-based, water-based, or not stated respectively / ## or x = percent solids by weight or not stated respectively						

This study compared and contrasted the performance of penetrating deck sealers (as seen in table above) and crack sealants. The crack sealant portion of Soriano’s study can be seen in Appendix B10.

Aspects of Performance Investigated

	depth of penetration	chloride content	absorption	vapor transmission	surface scaling resistance	electical resistance	reapplication period	abrasion	freeze-thaw exposure	concrete permeability	concrete's moisture state	surface-cleaning	presence of curing compounds/ film formers	concrete's surface finish	sealer's coverage rate	sealer's method of application	ultraviolet light exposure
	performance measures						factors affecting performance										
laboratory investigation																	
field investigation	i									i		i					
theoretical investigation																	
i = investigated																	

B.2.15 Wenzlick (2007)

“Bridge Deck Concrete Sealers”

Description

This report considers five selection tests and five deck sealants. The selection tests are as follows: AASHTO T259 (90-day ponding), ASTM C672 (scaling resistance to de-icing), AASHTO T277 (electrical induction or resistance to chloride penetration), ASTM C642 (density, absorption, voids), and Ohio Modified T259 (crack sealer test). The sealers tested were as follows: Linseed oil, reactive silicate one (Chem Tee One), reactive silicate two (Radon #7), water soluble sealer (Star Macro-Deck), and Silane 55 (Sil-Act AST-55).

MoDOT conducted these tests because they have not found any sealant to outperform linseed oil. They also wanted to select a certain number of tests to classify deck sealants.

Main Findings and Conclusions

MoDOT chose not to use the following selection tests: ASTM C672, AASHTO T277, and the Ohio Modified T259. The state did decide to use AASHTO T259 and ASTM C642 as selection tests.

None of the penetrating sealers tested could pass both chosen procedures (AASHTO T259 and ASTM C642). Linseed oil performed the best in selected tests.

Concrete Sealers Tested

	penetrating sealers					film formers
test no.	silane	siloxane	siloxane/ silane mixture	other	silicate	linseed oil
1						x/x
2					x/x	
3					x/x	
4				x/x		
5	x/x					

Aspects of Performance Investigated

	depth of penetration	chloride content	absorption	vapor transmission	surface scaling resistance	electical resistance	reapplication period	abrasion	freeze-thaw exposure	concrete permeability	presence of cracks	concrete's moisture state	surface-cleaning	presence of curing compounds/ film formers	concrete's surface finish	sealer's coverage rate	sealer's method of application	ultraviolet light exposure
	performance measures						factors affecting performance											
laboratory investigation		i	i		i													
field investigation																		
theoretical investigation																		

i = investigated

B.2.16 Weyers (1995)

"Service Lives of Concrete Sealers"

Background (Weyers, 1994; Weyers, 1993)

Fick's second law describes non-steady state diffusion (the concentration within the diffusion volume changes with respect to time). Fick's second law can be used to model chloride diffusion through concrete bridge decks:

$$C_{(x,t)} = C_0\left(1 - erf\,\frac{X}{2\sqrt{D_c t}}\right) \qquad (1)$$

Where:

$C_{(x,t)} =$ Chloride concentration at depth X after time t for an equilibrium chloride concentration C_0 at the surface

$erf =$ Error function

$D_c =$ Chloride diffusion constant for bare decks

For bridge decks, the equilibrium chloride concentration at the surface, C_0, or the driving chloride content causing the diffusion of chlorides was taken at ½" (1.3 cm) below the concrete surface. This depth was taken due to the many variations in chloride content that occur at the bridge deck surface. To determine the chloride diffusion constant (D_c) and driving chloride content (C_0) for a certain bridge deck in service, one must take a set of acid soluble chloride content measurements in the ranges of ¼"-¾ ", ¾"-1¼", 1¼"-1¾", 1¾"-2¼", 2¼"– 2¾", 3¾"-4¼". This gives acid soluble chloride contents at the mean depths of ½", 1", 1½", 2", 2½" and 4". This set of chloride contents should be performed every 600 ft^2 of bridge deck and at a minimum of 3 sets per bridge deck. The background chloride content of the bridge deck is considered to be the chloride content at the mean depth of 4 in. The background chloride content should be subtracted from the chloride measurements at the mean depths to determine the chloride ingress at these depths. The chloride diffusion constant for the original concrete is determined from a least squares fit to the above field data (background chloride content is subtracted to yield chloride ingress at each depth). The driving chloride concentration is nothing more than the chloride ingress at the ½" depth. Using a process similar to the one described, an analysis was performed on over 2700 powdered samples from 321 bridges across 16 states, Minnesota being one of them. From the results of this analysis, the 16 states were grouped according to four different chloride exposure environments based on the driving chloride concentration: low$\left(0 < C_0 < 4\right)$, moderate$\left(4 < C_0 < 8\right)$, high$\left(8 < C_0 < 10\right)$, and severe$\left(10 < C_0 < 15\right)$. (All C_0 values are in $\frac{lbs}{yd^3}$.) These chloride corrosion environments seemed to agree with the states' salt usage history and a map of vehicle corrosion potential in the U.S. Minnesota fell within the moderate chloride exposure environment with a mean driving chloride concentration of $6.54\frac{lbs}{yd^3}$. Also, for each state analyzed, their representative chloride diffusion constant (D_c) was presented. For the state of Minnesota, the mean value of D_c presented was $0.05\frac{in^2}{yr}$. In the absence of a calculated D_c and C_0 from field analysis, the mean values presented may be used.

In defining D_c and C_0, an effective time to corrosion initiation of a certain percentage of the reinforcement can be deduced using Fick's Second Law (for untreated deck with bare steel). The corrosion threshold for bare steel was presented as 1.2 lb of acid soluble chloride per cubic yard of concrete (the background chloride content has already been subtracted). The reinforcement cover is assumed to be normally distributed. The typical value for X is such that 2.5% of the reinforcing steel experiences corrosion initiation (2.5% of the reinforcement has cover depth equal or less than X). Thus, in order to obtain X, the mean and standard deviation for cover depth must be determined. To determine the time to initial corrosion of 2.5% of the reinforcing steel; D_c, C_0, X, and $C_{(x,t)} = 1.2\text{lb/yd}^3$ are inputted into (1) and t is solved for.

Using Fick's Second Law, a computer analysis was performed using a finite difference model to simulate the effects of sealed decks. In the analysis it was assumed that the sealer did not allow any chloride ingress to occur through the deck's surface. To evaluate the effect of sealing a deck after chloride exposure, finite difference models based on the occurrence of chloride ingress through the deck's surface (i.e., an unsealed deck) were first performed to obtain a chloride concentration vs. depth profile for an unsealed deck being exposed to chlorides for a certain number of years. In each analysis, a certain chloride diffusion constant (D_c) and driving chloride content causing the diffusion (C_0) was chosen to be inputted into the model. Then, using the assumption that sealers prevent chloride ingress through the deck's surface, the concentration of chloride ingress vs. depth was generated for a deck after such a number of years after sealer application. To clarify, an unsealed deck with a chosen D_c and C_0 was modeled for a certain time period prior to sealer application (20 yrs) to obtain a chloride ingress vs. depth profile. Then this deck's chloride ingress vs. depth profile was modeled for certain time periods after sealer application (5, 10, and 20 yrs). The resultant chloride ingress concentration vs. depth profiles for 5, 10, and 20 yrs. after sealer application were analyzed and compared to that of the unsealed deck. Results showed that for a certain cover depth (which represents a certain percentage of the reinforcement) and D_c and C_0 value, a chloride ingress concentration which was below the threshold value of 1.2lb/yd^3 for 20 years of unprotected chloride exposure did not mean the chloride ingress concentration at this depth would remain below the corrosion threshold value after being sealed. The models showed that when the chloride ingress concentrations were below the corrosion threshold value at a representative cover depth for a certain percentage of reinforcement, sealing the decks and preventing further chloride ingress through the concretes' surface did not inhibit the representative reinforcement from corroding. Thus, sealing a deck which is contaminated with chlorides should be done with caution; the reinforcement (assuming bare, exposed steel) may still corrode long after the deck is protected from further chloride ingress through its surface.

From the results of the finite difference models, the chloride ingress concentrations vs. depth profiles were found to be reasonably approximated by straight lines. Methods for estimating the linear profiles for 10, 20, and 40 years after sealer application were presented. Thus, from a chloride ingress concentration vs. depth profile for an unprotected, in-service bridge deck, one can estimate if a certain percentage of the reinforcement (assuming bare, or exposed steel) will experience corrosion after 10, 20, and 40 years of sealer applications. Thus, after sealing of a chloride contaminated bridge deck, an approximation of how many years to corrosion initiation can be made (assuming original chloride contamination at the selected reinforcement depth was below the corrosion threshold). This time to corrosion approximation assumes sealers completely prevent chloride ingress at the concrete's surface, which is not true. Thus, leakage of chlorides through a sealed surface will lower the time estimate to initiation of corrosion.

Concrete Sealers Tested

	penetrating sealers					film formers
test no.	silane	siloxane	siloxane/ silane mixture	silconate	silicate	epoxy
1	x/ x					
2		x/ x				
3						s/ x
						w/ x
s, w, or x = solvent-based, water-based, or not stated respectively / ## or x = percent solids by weight or not stated respectively						

4 types of sealers were analyzed in this study: a silane, siloxane, and a water and solvent-based epoxy. Note that epoxy is considered a surface coating/crack sealer, and in this study was used as a surface coating.

Aspects of Performance Investigated

	performance measures						factors affecting performance										
	depth of penetration	chloride content	absorption	vapor transmission	surface scaling resistance	electrical resistance	reapplication period	abrasion	freeze-thaw exposure	concrete permeability	concrete's moisture state	surface-cleaning	presence of curing compounds/ film formers	concrete's surface finish	sealer's coverage rate	sealer's method of application	ultraviolet light exposure
laboratory investigation		i															i
field investigation							i	i									i
theoretical investigation							i										
i = investigated																	

This study consisted of a laboratory and field investigation. The laboratory analysis consisted of constructing fifteen 91 x 91 x 10 cm horizontal slabs and one 30 cm thick, 1.83 m high, 4.88 m long wall. The horizontal slabs were met to simulate bridge decks, and the wall was met to simulate the vertical surfaces of abutments, pier caps, and piers. Concrete variability was not an issue because the slabs and wall came from the same batch of redi-mix concrete. 1.3 cm diameter shrinkage and temperature steel was placed in the slabs and the wall to control cracking; the depth of cover for the steel was 5.1 cm. Each sealer was applied to three slabs thus allowing for 3 control (un-sealed) specimens. The wall was broken down into five 70 cm wide vertical test strips; each test strip was separated by 10 cm wide vertical test strips painted red. Each sealer was assigned to a test section on the wall, thus allowing for one control (un-sealed) section. The field investigation consisted of analyzing a high-traffic volume bridge (HTVB) and a low-traffic volume bridge (LTVB). The HTVB and LTVB had respective annual average daily traffic counts (AADT) of 24,270 and 12,430 in 1990. The HTVB and LTVB were 27 and 2 years old respectively at the time of the field investigation and no mention of the bridges ever being sealed before was given. The decks of these two bridges were broken down into 90 cm wide test strips that extended from the edge of the breakdown lane to the median. Each sealer was assigned to a test section; 10 cm wide separation strips were placed between the test sections to avoid cross contamination.

Before sealer application for the slabs, wall, and bridge decks, their concrete surfaces were lightly grit blasted. (The control specimens were lightly sandblasted too.) Laboratory specimens were allowed to cure to their nominal 28 day strength before being lightly grit blasted and sealed. Sealer application coverage rates fell within the middle to high end range of the manufacturers' recommendations and method of application fell within manufacturers' recommendations as well.

After sealer application, the slabs, wall, and bridge decks were subjected to the outside environment for a 30 week monitoring program which consisted of one winter, a spring, and a summer. The slabs and bridge decks were subjected to full direct sunlight and the wall was subjected to partial direct sunlight. The total direct sunlight exposure hours was recorded for the slabs, wall and bridge decks over the course of the 30 week period.

In addition to outside exposure, the slabs, wall, and bridge decks were subjected to some type of chloride contact. For the slabs, this consisted of 3 days of continuous sodium chloride ponding followed by 4 days of air drying. The cycle then repeated itself over the course of the 30 weeks. For the wall, sodium chloride solution was pumped over the sealed surface of the wall for 3 consecutive 8 hour days. A 4 day period of air drying followed the 3 days of chloride exposure and this cycle too was continued over the course of the 30 weeks. Bridge decks were mentioned to be subjected to deicer applications but no specifics are given how many times this occurred over the course of the winter in the 30 week test period.

The average acid soluble chloride content was determined via ASTM C-114, Section 19 at depths of 1.3 cm (.5 in), 2.5 (1 in), and 3.8 cm (1.5 in) for each slab and wall test section at the end of 10, 20, and 30 weeks. The chloride ingress through each sealed and control slab and wall section was determined by subtracting the baseline chloride content of the concrete which the slab and wall were constructed from. The acid soluble chloride content was not determined for the test sections for the 2 bridge decks because there was no way to determine the baseline chloride contents of the 2 concretes from which the bridge decks were constructed from. Thus, chloride ingress through each test section could not be measured directly. It should be noted that choride ingress on a relative scale could have been measured. For each bridge deck the baseline chloride content is the same, thus comparison of the chloride contents of the test sections for the same bridge would have yielded chloride ingress through the test sections on a relative scale.

Vehicle abrasion was accounted for in the 2 bridge decks by extending a 3 m straightedge transversely across the traffic lane (3.65m wide) in which the test sections were located. Using a

.01 mm precision ruler, the abrasion depth was measured in 15 cm intervals along the length of the straight edge. An average wear rate in mm/year was then calculated based on the bridge's number of years in service. Note that for the LVTB (2 years old), the vehicle abrasion was too small to determine an average wear rate. The average wear rate for the HVTB was then used to calculate an estimate for the service life of a deck sealer under similar traffic demand (20,000 - 30,000 AADT). By service life, it was meant the time it takes until the sealer is completely abraded off. It should be noted that this service life assumes the sealer's depth of penetration is around 1.5 mm to 3.0 mm. (Weyers reports this range of depths being typical of hydrophobic sealers. No further explanation is given.)

An analytical expression for the service life of a sealer was presented in the report on the basis of Fick's Second Law and the concept of laboratory and allowable leakage factors. It should be noted that a 50 year desired corrosion protection period was assumed and the depth of 2.5% of the reinforcement used in the calculations (1.6 in. or 4.1 cm) was calculated from the laboratory specimens. Essentially, the allowed leakage factor accounted for how much chloride could pass through an unsealed deck's surface in a certain period of time such that in 50 years the chloride concentration at the depth of 2.5% of the reinforcement was at or below the corrosion threshold value. The laboratory leakage factor accounted for how much chloride leakage occurred through the sealed specimens using the results of the 30 week analysis. For the term service life, here it was meant the time to reapplication of the sealer was necessary. Thus, in a 50 year desired corrosion protection period, if the sealer was reapplied at the calculated service life for the duration of the 50 year period, 2.5% of the reinforcement in a sealed concrete bridge component (deck, abutment, pier, etc…) would be at or below the corrosion threshold. It should be noted that since the chloride ingress measurements taken from the laboratory analysis were used to calculate the laboratory leakage factors, the effects of UV degradation and other weathering damage on sealers were accounted in the service life estimates. Service lives for the silane, siloxane, and water and solvent-based epoxy were presented in the report for the four chloride exposure environments presented in the background section of this summary. For each exposure condition, three different diffusion constants were analyzed: 0.05, 0.09, and 0.13 in^2/yr. Thus, for a specific chloride environment and diffusion constant, a service life based on chloride diffusion through concrete was calculated for each sealer/ surface coating. Two of these service life matrixes were computed, one from the laboratory results of the horizontal slabs and one from the laboratory results of the wall section.

Main Findings and Conclusions

Since the purpose of this study is to investigate optimum deck and crack sealing strategies for bridge decks, analysis of the wall section (simulating vertical surfaces of abutments, pier caps, and piers) will not be discussed.

Service life estimates of sealers/ surface coatings were conducted in two fashions. The field analysis estimated a service life for the sealer/ surface coating in the amount of time it took the sealer/surface coating to be abraded off and thus become ineffective. The combined laboratory and analytical analysis estimated the service life of a sealer/surface coating as the amount of time it took before the sealer/surface coating needed to be reapplied such that in a period of 50 years, 2.5% of the reinforcement just reaches corrosion initiation.

The abrasion service life estimate was found to be 9-10 years for the 27 year old HVTB analyzed. The wear rate of the bridge and the depth of penetration of the sealer used to determine the service life estimate was 0.17mm/yr and 1.5 to 3.0mm respectively. Thus, this service life is applicable to similar decks of the same age and traffic demand (20,000-30,000 AADT) with sealer depth of penetration between 1.5 and 3.0mm. Weyers recommends reducing the service life down to 8 years to give a conservative estimate for the service life of a sealer on a bridge deck with 20,000-30,000 AADT. Once again, this may only be conservative if the sealer's depth of penetration is in the range of 1.5-3.0mm. For silanes and siloxanes, this should not be a problem. (Note that for decks with lower traffic demands the wear rate should presumably be less, and thus Weyers applies the 8 year service life cap due to abrasion on LVTB's as well.) In analyzing the service life of the surface coatings (water and solvent-based epoxy), the service life due to abrasion was found to be around one year. Both the water and solvent-based epoxy were observed to be abraded off the HVTB and LVTB in less than one year. This observation corroborates the recommendation that surface coatings are not applicable for bridge decks due to easily being abraded off because of their shallow depths of penetration.

The service life estimate for the sealers/surface coatings based on chloride diffusion and chloride leakage through a sealed surface was calculated in the terms of a reapplication period for a desired corrosion protection period of 50 years. For a newly constructed bridge deck, it was determined when the sealer/surface coating would have to be reapplied to keep the chloride ingress through the sealed deck's surface at such a level that in 50 years, only 2.5% of the reinforcement would reach its corrosion threshold. This reapplication period accounts for UV and other weather degradation on the sealers/surface coatings since the laboratory leakage factors were incorporated into the service life estimate. Also, the reapplication periods presented in this study assume an average cover depth of 2.0 in. with a standard deviation of .20 in. Water and solvent-based epoxy reapplication periods were not included in the results for the horizontal slabs because the slabs were supposed to simulate bridge decks. Therefore since bridge decks are subjected to abrasion, and the water and solvent-based epoxy were observed to be worn off in less than one year in the field studies, they were not included. For the state of Minnesota, the mean diffusion constant and driving chloride concentration for bare concrete decks was found to be $0.05\frac{in^2}{yr}$ $\left(0.32\frac{cm^2}{yr}\right)$and $6.54\frac{lbs}{yd^3}\left(3.86\frac{kg}{m^3}\right)$ respectively. Inputting these values into the reapplication matrix computed for the horizontal slabs, one finds reapplication periods of 8 years for the silane and siloxane sealer respectively. The 8 year cap comes from the service life of the sealers due to abrasion. Thus, abrasion controlled the reapplication periods. It should be noted that the leakage factors did not account for the simultaneous effects of abrasion. If the simultaneous effect of abrasion would have been accounted for in the service life estimates based on chloride leakage, the service life estimates based on chloride leakage may have controlled.

The service life estimates provided assumed that the bridge deck was not contaminated with chlorides before sealer application. For a deck that is already chloride contaminated, the same concept of allowable and laboratory leakage factors can be employed to determine the sealer's necessary reapplication period to be prevent corrosion of a certain percentage of the reinforcement for a certain desired corrosion protection period. It should be noted that the corrosion threshold value would have to be reduced to account for the current presence of chlorides; most likely the desired corrosion protection period of the deck will be less than 50 years too.

B.2.17 Whiting (1992)

"Condition Evaluation of Concrete Bridges Relative to Reinforcement Corrosion, Volume 5: Methods for Evaluating the Effectiveness of Penetrating Sealers"

Description

The laboratory investigation implemented both the NCHRP Series II and AASHTO T259/T260 test procedures to analyze chloride repellency of the five above sealers.

Type 1 Cement (low alkali) and chloride-free sand and gravel were used in all mixes; the water to cement ratio was that of standard laboratory concrete, 0.50. Concretes of two different moisture conditions, dry and moist, were created from the curing methods. NCHRP 244 Series II testing implemented both treated and untreated concretes of the two different moisture conditions. The AASHTO T259/T260 procedure tested only treated and untreated dry concretes.

Concrete specimens for the NCHRP and AASHTO test procedures were cast (4 x 4 x 4 inches and 12 x 12 x 3 inches respectively). All cast specimens were covered with wet burlap and polyethylene sheeting and underwent one day of curing before forms were stripped. After stripping the forms, specimens cured in heavy duty plastic bags for 28 days. Designated NCHRP and AASHTO specimens were removed from the plastic bags at the end of the 28 days and were placed in an environmentally controlled chamber at 73^{o} F ± 3^{o} F and 50% ± 5% relative humidity. These specimens represented the dry concretes and were removed after 21 days of drying in the chamber. After the 21 day drying period, concrete specimens were removed and either sealed or left untreated as control specimens. Both NCHRP 244 Series II and AASHTO T259/T260 testing initiated for the treated and untreated dry concretes 10 days after sealer application.

Moist concretes for the NCHRP testing were also created by subjecting designated cubes to moisture cycles after curing in the plastic bags for 28 days. Concretes were sealed after being subjected to 15 weeks of these moisture cycles; respective sealer coverage rate and application method did not vary from moist to dry concrete for NCHRP testing. Treated and untreated specimens underwent an additional five moisture cycles before NCHRP 244 Series II testing initiated.

AASHTO T259/T260 test procedures were employed on the treated and untreated dry concretes by first ponding the 12 x 12 inch test faces of the specimens with three percent sodium chloride solution at a constant depth of one-half inch. Foam polystyrene dikes were created around the perimeter of the test specimens as a reservoir for the salt-water solution. Also, the solution was covered to retard evaporation. After 90 days of salt-water ponding, the solution was removed and the surface was allowed to dry and brushed clean of precipitates. Powdered drill samples were subsequently taken at depth intervals of 1/16 to ½ inch and ½ to 1 inch and analyzed for total chloride content via AASHTO T260 procedures.

Treated and untreated concrete cubes, both moist and dry, underwent the NCHRP 244 Series II test procedure. Specimens were immersed in a 15 percent sodium chloride solution for 21 days and allowed to dry upon removal for 21 days at 73^{o} F ± 3^{o} F and 50% ± 5% relative humidity. At the conclusion of the drying period, cubes were split in half; one of the halves of each cube was crushed and analyzed for total (acid-soluble) chloride content (powder analyzed for total AASHTO T260 potentiometric titration procedure).

Main Findings and Conclusions

The AASHTO T259/T260 procedure (dry concretes) indicated much larger mean chlorides at both depth intervals for the control specimen than that of the treated concretes. Also, chloride ingress in the 1/16 to ½ inch depth interval proved to be much larger than that in the ½ to 1 inch depth interval for all samples. With the extremely small chloride measurements in the second depth interval (0.046 to 0.007 percent chloride by mass of concrete), one can only question the accuracy of the sampling and testing methods at such small values.

As far as sealers with the best performance, mean chlorides for the first depth interval in ascending order were as follows: test no. 1, 3, 2, 5, 4, and finally the control specimen. The epoxy and the sodium-silicate sealer (test no. 5 and 4 respectively) were by far the worst performing sealers in comparison to the silanes and siloxane (test no. 1, 2, and 3 respectively). The solvent-based 40% silane product roughly exhibited 10.5% and 38% lower mean chlorides in the first depth interval than the water-based 40% silane and solvent-based 20% siloxane product respectively.

Scatter in the AASHTO chloride data indicated standard deviations ranged from 7 to 29 percent of respective mean chloride values for the first depth interval. The second depth interval demonstrated much larger scatter in the chloride data exhibiting standard deviations that ranged from 9 to 71 percent of the mean.

NCHRP mean chloride data for the dry concrete specimens yielded values that were relatively similar to the AASHTO mean chloride data for the first depth interval (also analyzed dry concrete). However, performance on a relative scale was not the same. Mean chloride results from the NCHRP dry concrete specimens yielded the following performance of the sealers in descending order: test no. 2, 1, 3, 5, 4, and the control specimens. The control concretes again allowed much more chlorides to permeate into their surfaces than that of the treated concretes. Again, the sodium silicate sealer was noticed to be the worst performing treatment with the epoxy performing somewhat more effectively. The solvent-based 20% siloxane exhibited roughly 20 percent and 49 percent lower mean chlorides than the solvent-based and water-based 40% silane respectively. Whether the deviations in siloxane's relative performance from the AASHTO to the NCHRP test sequence for dry concrete was due to difference in test procedure or simply scatter in the data is hard to say.

NCHRP mean chloride data for the moist concrete was somewhat similar to that of the dry concrete analyzed under the NCHRP Series II procedure. Relative performance for the treated and untreated concretes in descending order proved to test no. 1, 3, 2, 5, 4, and the control concrete. Untreated concrete again allowed the most chloride ingress into its surface. The sodium silicate was again the worst performing sealer with epoxy's mean chloride data exhibiting better performance. The silanes and siloxane products by far allowed the least mean chloride once again but relative performance varied among the three from that of the dry concretes analyzed under the NCHRP procedure. The solvent-based 40% silane allowed roughly 9 percent and 32 percent less mean chloride ingress than that of the water-based 40% silane and solvent-based 20% siloxane respectively.

Scatter in the NCHRP chloride data yielded standard deviations that ranged from 8 to 30 percent of the mean for the dry concretes. Standard deviations for the moist concretes ranged anywhere from 6 to 44 percent of the respective mean values.

Concrete Sealers Tested

	penetrating sealers					film formers
test no.	silane	siloxane	siloxane/ silane mixture	silconate	silicate	epoxy
1	s/ 40					
2		s/ 20				
3	w/ 40					
4					w/ x	
5						s/ x
s, w, or x = solvent-based, water-based, or not stated respectively / ## or x = percent solids by weight or not stated respectively						

Five sealers were analyzed as indicated by the above table.

Aspects of Performance Investigated

	performance measures						factors affecting performance										
	depth of penetration	chloride content	absorption	vapor transmission	surface scaling resistance	electical resistance	reapplication period	abrasion	freeze-thaw exposure	concrete permeability	concrete's moisture state	surface-cleaning	presence of curing compounds/ film formers	concrete's surface finish	sealer's coverage rate	sealer's method of application	ultraviolet light exposure
laboratory investigation		i															
field investigation																	
theoretical investigation																	
i = investigated																	

B.2.18 Whiting (May 23, 2006)

“Technical Memorandum: Chloride Concentrations in Stillwater Bridge (#4654) Deck”

Description

The May 23, 2006 technical memorandum summarizes a follow-up investigation on the Stillwater Bridge (#4654). (See summary in Appendix A.1) One year after the application of the three silanes and one siloxane on the newly replaced Stillwater Bridge deck, chloride ingress through the treated deck sections was analyzed by drilling a total of ten 1 inch cores. For each of the four test sections of the deck where respective sealers were applied over the sodium-silicate curing compound, two cores were drilled. For each test section, one of the two cores was taken in the wheel-path and the other core was taken in mid-lane. As indicated in Appendix A.1, these sealers were applied according to the manufacturer’s recommended coverage rate. Two additional 1 inch cores were also taken, one in a control section of the deck (no sealer applied) and one in the section of the deck where 100% silane was applied solely over the linseed oil emulsion at a coverage rate three times smaller than recommended. (A smaller coverage rate equals more of the product applied to the deck surface.) Both of these cores were taken in mid-lane of the test sections.

Disks cut from the cores that were one-half inches in depth, were ground up and analyzed for acid soluble (total) chloride content by Mn/DOT’s Chemistry lab. Chloride contents were analyzed for each one-half inch depth interval of the cores to a total depth of two and one-half inches. The top one-sixteenth of each of the cores was cut off and discarded due to possible chloride precipitation on the deck’s surface.

It should also be noted that before chloride exposure, one of the depth of penetration cores (see Appendix A.1) was ground up to determine the base chloride content of the concrete deck.

Main Findings and Conclusions

Chlorides were found to be noticeably elevated in the top one-half inch compared to the other depth intervals. Beyond the 1.0 to 1.5 inch depth interval, the benefit of a sealer or a particular sealer could not be distinguished among chloride results. Also, at these greater depths, chloride levels for sealed and unsealed concrete were only slightly above the baseline level.

In the first half inch depth interval, certain trends were noticed. First, all treated concretes had much lower chloride contents than the untreated core indicating the benefit of water-repellents in general. Second, the chloride content of the concrete treated with siloxane for both the wheel-path and mid-lane sample had noticeably higher chloride levels than concrete wheel-path and mid-lane samples treated with silane products. Third, all three silane products and the triple dose of 100% silane over the linseed emulsion performed similarly. It should be noted that this study only compares performance after one-year of exposure to deicing chemicals; long term performance of the products was not investigated. Finally, wheel-path cores exhibited higher chloride contents than mid-lane cores of concrete treated with the same sealer.

A plot was constructed that compared chloride contents in the first half inch of the treated cores to that of the sealer's respective depth of penetration into the new concrete (Appendix A.1). Results indicated little to no correlation between the sealers' depth of penetration and chloride repellency for both wheel-path and mid-lane samples. The author did observe though that all sealers penetrated at least 1mm in into the concrete and to a mean value no less than 2.3 mm. The author implies sealers with these minimum penetration criteria can repel chlorides as effectively as sealers with larger penetration depths.

Concrete Sealers Tested

	penetrating sealers					film formers
test no.	silane	siloxane	siloxane/ silane mixture	silconate	silicate	epoxy
1	s/ 40					
2	w/ 40					
3	100					
4		s/ 12				
s, w, or x = solvent-based, water-based, or not stated respectively / ## or x = percent solids by weight or not stated respectively						

The concrete sealers analyzed include a solvent-based 40% silane, water-based 40% silane, 100% silane, and a solvent-based 12% siloxane as indicated by the above table.

Aspects of Performance Investigated

	performance measures						factors affecting performance										
	depth of penetration	chloride content	absorption	vapor transmission	surface scaling resistance	electical resistance	reapplication period	abrasion	freeze-thaw exposure	concrete permeability	concrete's moisture state	surface-cleaning	presence of curing compounds/ film formers	concrete's surface finish	sealer's coverage rate	sealer's method of application	ultraviolet light exposure
laboratory investigation																	
field investigation		i											i				
theoretical investigation																	
i = investigated																	

B.2.19 Whiting (November 7, 2006)

"Technical Memorandum: Bridge of Hope #05011 – Sealing and Chloride Intrusion"

Description

In 1995 the Bridge of Hope (#05011) was constructed over the Mississippi River; the deck consists of a two inch low slump overlay on top of the underlying concrete. Steel is embedded at a nominal depth of 3 inches below the deck surface.

The deck was sealed with the water-based 40% silane in both the north-bound (NB) and south-bound (SB) lanes prior to being opened up to traffic in 1995. The SB lanes were recoated with the silane product in 1996, 1997, 1998, 2000, 2002, and in August 2005. Coverage rates needed to be increased (less product applied to deck surface) upon subsequent applications due to sealer runoff and ponding; the initial coverage rate was the same for both the NB and SB lanes in the 1995 application. Before initial application and reapplication of the silane, the deck was power-washed and allowed to dry for two days; the silane was applied by spraying the product on the deck surface. As mentioned before, NB lanes were only subjected to initial silane treatment in 1995. It should also be noted that in 2005, surface cracks were sandblasted; cracks were then subsequently blown clean and sealed with epoxy. No tests were performed on the epoxy crack sealers so no summary is given in Appendix B of this report. However, the effect of cracks on the silane's ability to repel chlorides was investigated and will be discussed below.

In 1996, 1997, and 1998 eight representative drill dust samples were taken from the NB lanes and three from the SB lanes. Drill dust samples were produced in one-half increments to a total depth of two inches; the top one-sixteenth inch was discarded due to possible chloride precipitation on the pavement surface. These drill dust samples were then analyzed for acid soluble (total) chloride content verse depth by the Mn/DOT Chemistry Lab.

After the 2005 application, ten cores were also taken and analyzed for chloride content vs. depth and the depth of penetration of the sealer. One set of four, 1 inch cores were taken from both the NB and SB lanes; these cores were only analyzed for chloride content verse depth. (Cores were sliced into disks of one-half inch depth until the nominal depth of reinforcement, 3 inches; the top one-sixteenth inch of the cores was discarded due to possible chloride precipitation on the deck surface. These disks were then sent to the Mn/DOT Chemistry Lab where they pulverized and analyzed for total chloride content.) In addition, one 4 inch core was taken from both the NB and SB lanes. These two 4 inch cores were drilled in such a manner that a crack traversed the width of the cores to the depth of the reinforcement (3 inches nominally below pavement surface). These 4 inch cores were then analyzed to plot total chlorides as a function of lateral distance away from the crack and depth. This chloride analysis was performed by cross sectioning the center portion of the cores into a grid like pattern, both in the plane of the crack and pavement surface, to create 0.5 x 0.5 x 1.5 inch cubes approximately. These cubic sections were then pulverized and analyzed for total chloride content by the Mn/DOT Chemistry Lab. The reinforcement from these 4 inch cores was then removed and inspected for corrosion.

The remaining sections of the 4 inch cores were used to determine the penetration depth of the water-based 40% silane into the concrete surface and into the crack walls. Penetration depth was determined by wetting the fractured surface of interest and measuring the depth of the visible non-wetting band.

Main Findings and Conclusions

Chloride Concentrations with Depth vs. Time:

Chloride concentrations with depth verse time for the NB and SB lanes did not reveal a distinct advantage of reapplication over a single treatment of the water-based 40% silane. Chloride concentrations with depth verse time yielded a general trend of chloride accumulation in the deck with time. A notable difference in this trend occurred in the NB and SB lanes where chloride contents decreased rather substantially in the first half inch from 1998 to 2005. Another general trend seen in the data was chloride concentration decreased with depth and chlorides were much higher in the top half inch.

Notable scatter in chloride measurements was noticed in both the NB and SB lanes for all depths; the scatter in chloride measurements was generally more pronounced in the NB lanes, especially for 1996.

An interesting deviation between the chloride levels of the NB and SB lanes was observed after the first year of chloride exposure, 1996. The NB lanes exhibited substantially higher chlorides than that of the SB lanes. For example, the mean chloride content of the NB lanes was roughly 2.3 times the mean chloride content of the SB lanes in the one-sixteenth to one-half inch depth interval. This difference in performance is difficult to explain since at the time, both the NB and SB lanes theoretically underwent the same chloride exposure and a single application of silane. As mentioned previously though, in subsequent years when silane had been applied repeatedly to the SB lanes, chloride contents for the NB and SB lanes were much more comparable. A distinct advantage of reapplication could not be seen in the chloride results.

Depth of Penetration of Silane into Concrete Surface:

Depth of penetration of the silane into the concrete surfaced yielded a mean penetration depth of 3 mm for the NB lanes and 3.7 mm for the SB lanes. In the SB lanes where silane was applied repeatedly, the visible wetting non-wetting band was much more distinct than in the NB lanes where only a single application of silane was applied. Thus, a larger degree of water-repellency was noted in the SB lanes than in the NB lanes. It should be noted however that only a small representative portion of the deck was used to measure penetration depth (2 and 2.8 inches for the NB and SB lanes respectively). Also, a large degree of variability in penetration depth measurements was noticed for the small representative portions of the deck. For example, in the NB lanes penetration depth measurements ranged from 0.0 – 4.0 mm. In the SB lanes, penetration depth measurements ranged from 0.0 – 7.0 mm. From, the above observations, repeated applications of the silane did not appear to yield a distinctly deeper non-wetting band.

Chloride Concentration with Depth vs. Lateral Distance from Crack:

For the cracked NB and SB lane core, notable observations included chlorides were generally more elevated as one moved closer to the crack. Also, chloride contents near the crack were much higher than chloride contents obtained from uncracked cores for each respective traffic lane, thus suggesting the negative impact cracks have on chloride ingress through a deck. Although reinforcement was much more susceptible to corrosion near the cracks, the extracted, epoxy coated rebar indicated no signs of corrosion after 10 years.

Penetration of Silane into Surface of Crack Walls:
Penetration results indicated the silane did not substantially penetrate into the surface of the crack walls. In the NB lanes, little to no evidence of the silane existed on the surface of the crack walls for an analyzed depth of 1 inch below the pavement surface. In the SB lanes, the mean penetration of the silane into the surface of the crack walls was 5.0 mm for a depth of 0.5 inches below the pavement surface. Beyond the half inch depth, little to no penetration of the silane into the crack walls was observed. From the above observations, silane did not appear to significantly penetrate into the deep open cracks of the cores. Also, little correlation was observed between the silane’s penetration into the crack walls and respective chloride contents near the crack for the cracked NB and SB lane core.

Concrete Sealers Tested

	penetrating sealers					film formers
test no.	silane	siloxane	siloxane/ silane mixture	silconate	silicate	epoxy
1	w/ 40					
s, w, or x = solvent-based, water-based, or not stated respectively / ## or x = percent solids by weight or not stated respectively						

A water-based 40% silane was analyzed as indicated by the above table.

Aspects of Performance Investigated

	performance measures						factors affecting performance											
	depth of penetration	chloride content	absorption	vapor transmission	surface scaling resistance	electical resistance	reapplication period	abrasion	freeze-thaw exposure	concrete permeability	presence of cracks	concrete's moisture state	surface-cleaning	presence of curing compounds/ film formers	concrete's surface finish	sealer's coverage rate	sealer's method of application	ultraviolet light exposure
laboratory investigation																		
field investigation	i	i					i				i							
theoretical investigation																		
i = investigated																		

B.2.20 Whiting (October 25, 2005)

"Technical Memorandum: Field Application of Bridge Deck Sealers – Stillwater Bridge #4654"

Description

A field investigation was conducted on the newly replaced Mn/DOT Stillwater Bridge (#4654) deck that analyzed depth of penetration for the four sealers studied; the mix used consisted of a 30% fly ash concentration. A sodium-silicate curing compound was placed on the deck initially after construction. Also, a portion of the deck was treated with an emulsion of boiled linseed oil, but no sodium-silicate, initially after casting. To study the effect of curing compounds and film formers on sealer penetration, the three silanes and one siloxane were applied over the sodium-silicate at the manufacturer's recommended coverage rate. In addition, the 100% silane was applied over the concrete treated solely with the linseed oil emulsion at three times its recommended coverage rate. Three, 2 in. cores were taken from each test section treated with sodium-silicate and the respective water-repellent applied at its recommended coverage rate. Only one 2 in. core was taken from the test section treated with the linseed oil emulsion and the triple dose of 100% silane. Cores were fractured perpendicular to the plane of the treated surface, the fractured surface was wetted, and the mean depth of the visible non-wetting band of the water-repellents was measured.

Main Findings and Conclusions

Depth of penetration results revealed all four sealers applied at their recommended coverage rate penetrated past the sodium-silicate compound. The same can be said for the triple dose of the 100% silane applied over the boiled linseed emulsion.

Mean penetration results for the four sealers applied at their recommended coverage rates over sodium silicate proved to be 4.1, 3.7, 2.3, and 2.3 mm for the 100% silane, solvent-based 40% silane, water-based 40% silane, and the solvent-based 12% siloxane respectively. Thus, a slight benefit of higher solids content was seen in the mean penetration results of the 100% silane and the two 40% silane products. Also, the solvent-based 40% silane penetrated substantially deeper than the water-based 40% silane (by ~60%), thus indicating solvent-based silanes may be better penetrating products than water-based silanes of the same solids content. It should also be pointed out that the three silane products penetrated as deep as or deeper than the solvent-based 12% siloxane. This observation coincides with the fact that silanes are smaller molecules than siloxanes.

The triple dose of 100% silane over the linseed oil emulsion exhibited a mean penetration similar to that of the single dose of 100% silane over the sodium-silicate (4.3 mm compared to 4.1 mm). One cannot say if the 100% silane penetrated through these two curing compounds in a similar fashion since the coverage rate was varied; the lower coverage rate of the 100% silane over the linseed emulsion may or may not have been needed to exhibit similar performance.

It should be noted that the penetration depth measurements varied substantially when obtaining the mean penetration of each sealer. For the sealers applied at their recommended coverage rate, penetration depth measurements ranged as much as 2-8mm for a particular sealer. This range of penetration was observed only on a 5.3 in. representative piece of bridge deck for each sealer. Also to be noted, aggregates appeared to block sealer penetration suggesting permeability of the deck affects sealer penetration.

Concrete Sealers Tested

	penetrating sealers					film formers
test no.	silane	siloxane	siloxane/ silane mixture	silconate	silicate	epoxy
1	s/ 40					
2	w/ 40					
3	100					
4		s/ 12				
s, w, or x = solvent-based, water-based, or not stated respectively / ## or x = percent solids by weight or not stated respectively						

The concrete sealers analyzed include a solvent-based 40% silane, water-based 40% silane, 100% silane, and a solvent-based 12% siloxane as indicated by the above table.

Aspects of Performance Investigated

	performance measures						factors affecting performance											
	depth of penetration	chloride content	absorption	vapor transmission	surface scaling resistance	electical resistance	reapplication period	abrasion	freeze-thaw exposure	concrete permeability	presence of cracks	concrete's moisture state	surface-cleaning	presence of curing compounds/ film formers	concrete's surface finish	sealer's coverage rate	sealer's method of application	ultraviolet light exposure
laboratory investigation																		
field investigation	i													i				
theoretical investigation																		
i = investigated																		

B.2.21 Wiss, Janney, Elstner, and Associates (1984)

"Investigation of the Use of Silane-Siloxane Penetrating Sealers (Water-Repellents) on Portland Cement Concrete"

Description

Four inch cube specimens were cast from a concrete mix with a water to cement ratio of 0.50; chloride free sand and aggregate were used in the mix design. After specimens were cast, they were covered and allowed to cure in their forms for 24 hours. Forms were subsequently stripped and the cubes underwent 21 days of moist curing in plastic bags. Following moist curing, specimens were allowed to air dry for 5 days; proceeding this drying/ curing period, cubes were sealed. Each treatment was applied to two cubes; coverage rate adhered to 125 square feet per gallon for all the sealers. Following sealer application, treatments were either allowed to cure/air dry for 14 or 21 days before cubes were subjected to absorption testing. The author wanted to see if the curing time of the sealer had any effect on its performance.

After the sealers were allowed to cure, treated cubes were immersed in 15 percent sodium chloride solution for 21 days. Weight gain measurements were conducted after 1, 3, 7, and 21 days of immersion. Specimens were removed from the salt-water solution after the submersion period and allowed to air dry for 21 days. Weight loss measurements due to vapor transmission through the treated surface were taken after 1, 3, 7, 14 and 21 days of drying.

After determining vapor permeability, chloride permeation as a function of depth was determined for the treated cubes (only for sealers that cured 14 days prior to absorption testing). Concrete dust samples were collected at depth intervals of 0 to 1/2 in., 1/2 to 1 in., 1 to 1-1/2 in., and 1-1/2 to 2 in. A total of six of these 2 inch deep holes were drilled into each cube. For each depth interval, the six respective dust samples were combined and these composite samples were analyzed for acid soluble chloride content. Following the sampling for chloride penetration, cube specimens were fractured in two. One of the halves was used to determine depth of penetration of the sealers by measuring the thickness of the visible non-wetting band. The second half of each cube was crushed and analyzed for acid soluble chloride content.

It should be noted that two control (i.e., unsealed) cubes were subjected to the above testing procedures; this way, the effectiveness of the sealers relative to untreated concrete could be established.

Main Findings and Conclusions

Absorption results revealed that the seven sealers reduced final moisture gain by 74 to 86 percent when compared to untreated concrete. The suggested criteria of at least 75 percent reduction in weight gain as by NCHRP Report No. 244 was met by virtually all of the sealers. Also, the length of the curing time (i.e., 14 or 21 days) did not notably affect absorption results for the sealers.

Vapor transmission testing proved that all seven sealers were able to lose more water in the final drying period than they gained during salt-water soaking. The average residual weight change for cubes treated with the seven sealers ranged from -0.03 to -0.24 percent (compares weight of cube after final drying period to initial weight before immersion). As noted with absorption results, the length of curing time of the sealer did not appear to affect its vapor permeability.

Chloride penetration analysis revealed that significant chloride accumulation was only noted in the top half inch. Chloride contents of the half-cubes proved the sealers to reduce chloride ingress by 75 to 89 percent when compared to uncoated concrete. Thus, all the sealers met or exceeded the 75 percent chloride reduction criteria as suggested by NCHRP Report No. 244. The chloride contents of the treated half-cubes and respective final weight gains were compared; a very strong, direct relationship between the two was observed. One would expect that if a cube absorbed more salt-water, respective chloride accumulation would be larger. Also to be noted, the length of the curing time for the sealer did not appear to affect chloride content results for the half-cubes.

In analyzing penetration depth data, penetration of individual sealers varied substantially. For one product, penetration varied from 2 mm (0.08 in.) to 11 mm (0.44 in.) across the two cubes treated with this sealer. On the other hand, some of the products exhibited very uniform depths of penetration. Mean penetration of the products ranged from less than 1 mm (0.04 in.) to 7 mm (.27 in.). Even though penetration was found to be highly variable among individual sealers and across the seven products, all sealers achieved satisfactory average weight gain and chloride reductions as stipulated by NCHRP Report No. 244. However, abrasion of the sealed surfaces of the cubes was not implemented; performance of the sealers could have changed drastically if abrasion was included.

Concrete Sealers Tested

	penetrating sealers					film formers
test no.	silane	siloxane	siloxane/ silane mixture	silconate	silicate	linseed oil
1			x/ x			
2			x/ x			
3			x/ x			
4			x/ x			
5			x/ x			
6			x/ x			
7			x/ x			
s, w, or x = solvent-based, water-based, or not stated respectively / ## or x = percent solids by weight or not stated respectively						

Seven siloxane/ silane mixtures were analyzed as indicated by the above table; solids content or carrier for the sealers was not distinguished.

Aspects of Performance Investigated

	depth of penetration	chloride content	absorption	vapor transmission	surface scaling resistance	reapplication period	abrasion	freeze-thaw exposure	concrete permeability	presence of cracks	concrete's moisture state	surface-cleaning	presence of curing compounds/ film formers	concrete's surface finish	sealer's coverage rate	sealer's method of application	sealer's curing time
	performance measures					factors affecting performance											
laboratory investigation	i	i	i	i													i
field investigation																	
theoretical investigation																	
i = investigated																	

B.2.22 Wright (1993)

"A Three-Year Field and Laboratory Evaluation of Linseed Oil as a Concrete Sealer"

<u>*Description*</u>

Field Investigation:

For the field investigation the sealers were applied to a seven day old concrete city street and highway and to a seven year old concrete airport apron in Winnipeg, Manitoba. Surface preparation and subsequent sealer application adhered to the manufacturers' recommendations. Designated test sections were established for each sealer at each site; in addition, one test section at each site was left untreated for comparison purposes.

At each site, two cores were extracted from every test section for three years on an annual basis. For the first year (seven days after sealer application), one set of cores was subjected to depth of penetration testing while the second set underwent salt-water ponding to measure absorption. The subsequent two years cores were either subjected to salt-water absorption or chloride ingress testing.

Mean depth of penetration was determined by fracturing respective cores perpendicular to the pavement surface, wetting the fractured surface, and subsequently measuring the depth of the visible non-wetting band in three locations. Quantifying salt-water absorption involved creating dikes around the perimeter of the top surface of the designated cores. The reservoir was kept full with a 15 percent solution of sodium chloride solution for 21 days and final weight gain of the cores was measured. At each site, salt-water absorption of the treated cores was reported relative to that of the control concrete. To measure chloride ingress, designated cores had the top 2 mm ground off so results would not be contaminated by possible chloride precipitation on the concrete's surface. A 6 mm disc was then sliced off the top of each core and analyzed for total chlorides (acid-soluble) by an external source.

Laboratory Investigation:

Concrete cubes (3 x 3 x 3 in.), prisms (3 x 3 x 14 in.), and slabs (10 x 10 x 3 in.) were constructed for the laboratory tests. The water to cement ratio for the cubes and prisms (0.58) and for the slabs (0.59) proved to be higher than that of standard laboratory concrete. After the forms were stripped (one day after casting), all specimens underwent moist curing in plastic bags that contained a small amount of water for 14 days at 23^o C and 100% relative humidity. After the moist curing period, specimens were removed and allowed to dry at 23^o C and 50% relative humidity; drying time before and after sealer application varied depending on the test procedure. Designated surfaces to be sealed were lightly sandblasted before the application of the sealers. Sealer application rate and method did not vary per sealer or per test. All tests were repeated on duplicate specimens.

Mean depth of penetration testing was performed by fracturing cube specimens, wetting the fractured face, and measuring the depth of the visible non-wetting band. Specified cube specimens also underwent salt-water absorption and vapor transmission tests that were based on those developed in the NCHRP Report 244 (see Appendix A.1). Treated and untreated cubes were immersed in 15 percent sodium chloride solution for 90 days; weight gain was measured throughout the immersion process do to determine reduction in total water content relative to control specimens. The drying time before and after coating were varied individually to isolate the effect either parameter had on absorption characteristics. After the 90 day immersion period, treated and untreated cube specimens were allowed to air dry for 90 days to determine vapor transmission characteristics. Weight loss was measured frequently throughout the drying period and reported relative to the final weight of the specimen after the immersion process.

The effects of abrasion were qualitatively measured by comparing absorption results before and after abrasion. Treated and untreated cubes were immersed in 15 percent sodium chloride solution for 45 days and weight change of the cubes was recorded. Duplicate treated and untreated specimens that had the top 0.5 mm ground off one of their faces underwent the same immersion process. Absorption results before and after abrasion was then compared.

Chloride ingress measurements were conducted on respective treated and untreated slab specimens according to the provisions of AASHTO T259-80. Slab specimens were ponded with 4 percent sodium chloride solution for 90 days; a dike was created around the periphery of the top surface of the slabs as a reservoir for the salt-water solution. At the conclusion of the 90 day ponding period, the top 2mm of the slabs' surfaces were ground off due to possible chloride precipitation. Using a dry friction saw, 6 mm thick samples were then cut off the top surface of the slabs and analyzed for total chlorides. Chloride contents for the treated specimens were reported relative to the chloride content of the uncoated concrete.

Surface scaling resistance of designated treated and control slabs was measured according to ASTM C672-84. Slabs were ponded with 4 percent sodium chloride solution and subjected to 60 daily cycles that consisted of 16 hours of freezing and 8 hours of thawing. Scaling was collected from the specimens every five cycles.

Rapid freeze-thaw testing of the treated and untreated prism specimens was conducted according to the provisions of ASTM C666-84 Procedure A. Prism specimens were soaked in water for 2 days and subsequently placed in a chest freezer. Specimens were frequently removed and their reduction in stiffness and mass were recorded.

Main Findings and Conclusions

Field Investigation:

Penetration depths were found to be immeasurable at the seven year old airport apron; the author suggests the age and low permeability of the concrete as possible explanations for this phenomenon. At the city street, penetration depths proved to be roughly 1.0 mm, 1.75 mm, and 1.2 mm for linseed oil, silane, and siloxane respectively. At the highway, linseed oil, silane, and siloxane exhibited mean penetration depths of 1.3 mm, 1.0 mm, and 1.3 mm. The author suggests that silane's dramatic decrease in penetration from the street to the highway site could be due to the very windy conditions at the highway location at the time of sealer application. Silane's higher volatility rate than siloxane or linseed oil greatly supports the author's suggestion.

Absorption results from the street and highway site revealed linseed oil was much more effective than silane or siloxane at reducing water ingress; siloxane demonstrated slightly more effectiveness than silane. Also, the effectiveness of silane and siloxane at reducing water ingress substantially decreased from year to year at the street and highway site; linseed oil's effectiveness stayed relatively the same. Absorption trends from the airport site could not be clearly seen; possibly the negligible penetration of all three sealers at the airport site are responsible for the inconsistency in results.

Results from the chloride analysis revealed linseed oil reduced chloride ingress much more effectively than the silane or siloxane; this trend was seen at both the street and highway site for both years of chloride data. (The airport site was not exposed to deicer solutions and thus not considered in the chloride analysis). The silane, siloxane, and linseed oil sealers demonstrated a general trend of decreasing chloride effectiveness from the second to third year; their ability to repel chlorides decreased with time. As far as silane verse siloxane performance, the two sealers exhibited similar relative chloride levels at the city street for both years of data. However, at the highway silane performed notably worse than siloxane for the second and third year. Silane's higher chloride levels at the highway could possibly be attributed to its notably shallower penetration at this location.

Laboratory Investigation:
Depth of penetration results from the laboratory analysis showed a much larger mean penetration for linseed oil than field results indicated. Mean penetration results for linseed oil, silane, and siloxane proved to be 4.62, 2.29, and 1.48 mm respectively. In the laboratory linseed oil by far was the best performer, in the field, linseed's oil penetration compared much closer to that of silane and siloxane. The high water to cement ratio of the laboratory concrete (thus increased porosity) might explain linseed oil's substantial increase in mean penetration.

Salt-water absorption analysis proved linseed oil to be notably more effective at reducing water ingress when the concrete was allowed to dry/cure for a longer period before subsequent linseed oil application. The salt-water absorption characteristics of silane or siloxane did not appear to benefit as greatly as that of linseed oil by letting the concrete reach its nominal 28 day strength before subsequent sealer application. In evaluating relative performance of the sealers when the concrete had adequately cured, siloxane proved to be by far the most effective sealer at reducing water ingress. Silane demonstrated initial effectiveness over linseed oil but linseed oil reduced water ingress more effectively than silane after a longer immersion period. In analyzing the effect of increasing the drying time after coating, all sealers were better able to reduce water ingress when the drying time after coating was increased. This trend was especially evident with the linseed oil coated specimens.

Vapor transmission results indicated siloxane to be the worst performer. The author warns though that vapor transmission results were expressed as a ratio of weight lost during drying to the final of the weight of the respective specimen after immersion. Siloxane proved to gain the least amount of water during the immersion process; the final moisture content of the siloxane specimen was much smaller than that of the other treated and untreated cubes. Thus, the siloxane treated cubes naturally exhibited the smallest weight loss relative to weight gain due to their smaller moisture contents. On that same note, silane and linseed oil proved to have similar final moisture contents after immersion but silane demonstrated far more relative weight loss during the drying period than linseed oil. Keeping the author's caution in mind, silane appeared to exhibit better vapor transmission characteristics than linseed oil.

Abrasion results indicated siloxane and silane were much more affected by abrasion than that of linseed oil; siloxane was affected the most. The author suggests that the greater penetration depth of linseed oil could be responsible for its better performance.

Results from the chloride analysis clearly indicated silane to be the least effective sealer at reducing chloride ingress. Performance between the linseed oil and the siloxane treated slabs could not be distinguished due to fluctuations in chloride levels from the duplicate specimens.

Results of the scaling resistance test proved siloxane and linseed oil to be the most effective at reducing surface scaling for concretes with and without air-entrainment. Silane was the worst performing product offering less protection against surface scaling than that of uncoated concrete.

Rapid freeze-thaw testing indicated silane and siloxane prisms experienced a notably larger reduction in stiffness than that of control and linseed oil specimens for concretes cast with and without air-entrainment. The recorded amounts of mass loss during the cycling process confirmed the trends seen in the stiffness results. The authors do not recommend the ASTM C666-84 procedure as an appropriate method for evaluating sealer effectiveness due to the very poor behavior of the silane and the siloxane.

Concrete Sealers Tested

	penetrating sealers					film formers
test no.	silane	siloxane	siloxane/ silane mixture	silconate	silicate	linseed oil
1	x/ x					
2		x/ x				
3						x/ x
s, w, or x = solvent-based, water-based, or not stated respectively / ## or x = percent solids by weight or not stated respectively						

The performances of a silane, siloxane, and a boiled linseed and mineral spirits (1:1 ratio) concrete sealer were compared and contrasted. The boiled linseed and mineral spirits is referred to as linseed oil for the remainder of the summary.

Aspects of Performance Investigated

	depth of penetration	chloride content	absorption	vapor transmission	surface scaling resistance	electical resistance	reapplication period	abrasion	freeze-thaw exposure	concrete permeability	presence of cracks	concrete's moisture state	surface-cleaning	presence of curing compounds/ film formers	concrete's surface finish	sealer's coverage rate	sealer's method of application	ultraviolet light exposure
	performance measures						factors affecting performance											
laboratory investigation	i	i	i	i	i			i	i									
field investigation	i	i	i															
theoretical investigation																		
i = investigated																		

B.3. Crack Sealant Research

B.3.1 Engstrom (1994)

“Field Performance of High Molecular Weight Methacrylate Monomers and Silanes on a D-Cracked, Joint Reinforced Concrete Pavement”

Description

This study determined if HMWM sealants could repair D-cracking on concrete pavements in Southern Minnesota. A silane sealant was also used to coat test section of the deck. These techniques for repairing and slowing the damage of D-cracking were tested on a 41 mile stretch of I-90 that contains a D-cracking susceptible aggregate. The silane sealant was applied using a spray application and the HMWM was applied using squeegees. Both test sections were cleaned before the sealants were applied. The silane section was shot blasted and the HMWM section was cleaned with compressed air. Sand was also spread over the HMWM resin as it cured to promote friction. The application rate for the silane solution was 125 feet squared per gallon. The application rate for the HMWM resin was 100 ft per gallon. Due to the fact that D-cracking starts at the bottom of the pavement where moisture is present, the engineers felt the silane would have little effect on the concrete. This is because silane sealers are typically used to block moisture from infiltrating the top of the pavement and would have no effect on the bottom.

Before application of both sealers the roads were visually inspected to determine the existing damage. The classifications of cracks were low, medium, high, and severe. Cores were also taken from the road. All of the cores were positioned over a cracked area. Each core was tested for the presence of alkali-silica reactivity (ASR). Also uranyl acetate was applied to the crack face. When looking at the cracks under Ultraviolet light the depth of penetration could be determined.

Main Findings and Conclusions

Based on the visual inspection prior to application and after application a few conclusions could be made. Engstrom questioned silane’s ability to repair or slow the deterioration of the pavement. This was due to the fact that two of the three silane sections experienced a faster rate of deterioration than the control section. Due to this acceleration in cracking it can be assumed that the silane solution did not help repair or prevent any D-cracking on I-90. However, the section treated with HMWM preformed better than the control section. A 40 percent reduction in cracking was experienced over 22 months. The cores showed that the HMWM penetrated the cracks between 0 and 3 inches. The depth of penetration was closely linked with the size and width of the crack. No additional information was given on depth of penetration.

Engstrom concluded that the effectiveness of the HMWM resin wore away after 18 months. This was due to the dramatic increase in rate of cracking 18 months after application. He suggests that, depending on traffic levels, a reapplication period ever 18 months could dramatically extend the service life of the road. He also concluded that the Transpo T70X and the 3M 4R Concrete Restorer provided the best performance. This was surprising due to the fact that the T70X was half the price of the Sika sealant (which did not perform as well).

Crack Sealers Tested

test no.	high-molecular weight methacrylate (HMWM)	reactive methyl methacrylate (MMA)	methacrylate	polyurethane	urethane polurea hybrid	epoxy	epoxy resin	silicon joint sealer
1	i							
i = investigated								

A high-molecular weight methacrylate (HMWM) flood coat and squeeze bottle application was implemented in the study.

Aspects of Performance Investigated

	depth of penetration	bond strength	seepage rate	freeze-thaw exposure	temperature	surface cleaning
	performance criteria			factors affecting performance		
laboratory investigation						
field investigation	i					
i = investigated						

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B.3.2 Krauss (1985)

"New Materials and Techniques for the Rehabilitation of Portland Cement Concrete"

Description

Krauss' study first offers some background on the formation, mixture, and application of HMWM crack sealants. The process consists of catalyzing the HMWM with a metallic drier (normally cobalt naphthenate) and an organic peroxide. The metallic drier reduces the activation energy required to produce the polymerization reaction and the organic peroxide initiates the hardening process. HMWM resins are known for their low viscosity, low volatility (in comparison to reactive methyl metharylate), and low initial shrinkage. The low viscosity and vapor pressure allow the resin to penetrate very narrow cracks that sealants like epoxy can not. A high solvency allows the sealant to bond through light oil or grease stains that may be present on the deck. Also, HMWM typically has a bonding strength equal to or exceeding the shear strength of concrete.

Krauss also explains some methods for applying the sealant to the bridge deck. The resin can be swept, squeegeed, or sprayed onto a deck with an approximate cover rate of one gallon to 100 square feet. The surface and cracks should be cleaned prior to application to enhance the bond between the sealer and substrate. Cleaning methods include sweeping, power washing, or spraying compressed air. If water is used during the cleaning process sufficient time should be allowed for the concrete and cracks to dry.

An important idea to consider during application of the crack sealer is gel time. The gel time for a HMWM crack sealer can vary greatly due to the percent initiator in the mixture and temperature of the deck. If the deck temperature is too low, the resin will cure slowly and may seep through the bottom of the deck. If the temperature is too high, the gel time will be to fast and the sealant will not have sufficient time to penetrate the cracks. According to Krauss, a temperature between 45 and 90 degrees Fahrenheit is preferred. A gel time of one hour is optimal for the sealant's penetration of cracks. Accelerators and retardants can be used to adjust the gel time to the desired length. Manufacturers should be consulted for the gel time verses temperature for specific sealants.

Krauss also summarizes his observations from four bridge sites in which HMWM sealants were used. These sites include the Hallelujah Junction Bridges, Rio Vista Lift Span, Richmond-San Rafael Bridge, and Feather River Bridge. Very minimal testing was conducted on these bridges, aside from visual inspections, to determine the success of the crack sealers. The tests included coring taken from the Hallelujah Junction Bridges to determine penetration depth and skid tests on all four bridge sites.

Individual Application Processes and Main Findings

There are two bridge decks on the Hallelujah Junction Bridges site that are made from experimental wax-bead entrained Portland Cement Concrete (PCC) and methyl methacrylate polymer impregnated PCC. Both decks were initially scheduled to be sealed with an epoxy sealant due to cracking at a width of 0.008 inches. However after the epoxy failed to penetrate the cracks, more research was conducted that determined the cracks had a width of 0.002 inches just below the deck surface. Due to this significant reduction in crack width, a sealant with a lower viscosity was needed.

HMWM was chosen to seal the cracks on the two bridge decks. The sealant was applied using squeeze bottles and had a gel time of 45 minutes. Three total treatments were needed to seal the larger cracks. A total of ten gallons of resin was used to cover the 6,300 square foot deck which had 12,000 linear feet of cracks. Four two inch diameter cores were taken from the two bridge decks. The coring areas were selected so that a crack would be running through the center of the core. It was determined that the HMWM sealant fully penetrated all of the cracks to the steel reinforcing bars.

The Rio Vista Lift Span bridge deck was made out of light weight concrete and had significant cracking. During the rainy season the bridge deck would gain weight due to the light weight concrete absorbing water through the cracks. Large weights were added to the counter weights every winter to counteract the weight gained by the deck. After the application of the HMWM sealant, the bridge deck has not needed the weight to be added and subtracted annually. A replacement deck was estimated to cost $223,000. The sealing procedure (including labor, materials, and traffic control) cost $6,850. Also cracking did not develop next to the old repaired cracks like the engineers expected.

No information on the Richmond-San Rafael and Feather River Bridges was given aside from the fact that they were sealed with a HMWM resin and the project was deemed a success. Skid tests were performed on all four sites bridge decks. Due to the application of sand during the gel time of the HMWM resin, all of the skid tests were deemed satisfactory. Some of the bridge decks even experienced an increase in friction due to the applied sand. It was later found that the resin eventually wore away from all of the decks leaving the original concrete exposed. However, the cracks still remained sealed despite the resin on the surface wearing away.

Crack Sealers Tested

test no.	high-molecular weight methacrylate (HMWM)	reactive methyl methacrylate (MMA)	methacrylate	polyurethane	urethane polurea hybrid	epoxy	epoxy resin	silicon joint sealer
1	i							
i = investigated								

A high-molecular weight methacrylate (HMWM) flood coat and squeeze bottle application was implemented in the study.

Aspects of Performance Investigated

	depth of penetration	bond strength	seepage rate	freeze-thaw exposure	temperature	surface cleaning
	performance criteria			factors affecting performance		
laboratory investigation						
field investigation	i					
i = investigated						

B.3.3 Lasa (1990)

"Evaluation of Rohm and Haas, High Molecular Weight Methacrylate Monomer as a Crack Sealer on the Seven Mile Bridge in Florida One Year after Application"

Description

After the construction of Seven Mile Bridge, which is located on Florida State Road No. 5, engineers noticed a large amount of longitudinal cracking running down both sides of the deck. These areas coincided with where the webs connected to the deck (or flange). A study determined that the corrosion threshold of the reinforcement bars would be reached around 1992 if nothing was done. The Florida Department of Transportation suggested sealing the entire length of the bridge with a low viscosity high molecular weight methacrylate (HMWM). Before application, the resin was mixed with a cobalt naphthenate drier and a cumene hydroperoxide initiator. Using an airless two bar spraying system, the mixture was applied to the deck and spread using brooms. Lastly a silica sand cover was spread over the curing deck to promote friction. Traffic was allowed to drive on the bridge four hours after application.

Depth of penetration and bond strength tests were conducted 11.5 months and 16 years after the application of the HMWM resin. This was done by removing cores from the bridge deck. During the first test (11.5 months), the locations of 64 two inch diameter cores were chosen at random along the bridge deck (the number of cores for the 16 year test is unknown). Fifty one of the cores selected from the bridge deck had a crack running through the middle. Nine of the cores that were taken contained a segment joint. Since the final six cores were of selected from solid concrete, they acted as controls. After the cores were harvested they were brought back to the lab for tests.

The cracks were split up into three different size groups before tested for depth of penetration. Group one consisted of crack widths smaller than 0.005 inches. Group two consisted of cracks between the width of 0.005 and 0.010 inches. The final group (group three) contained all of the cracks wider than 0.010 inches. The width of the crack at either side of the core was averaged to determine the cores grouping. The percentage of cores in each group for the first test (11.5 months) is as follows: 46.9 percent were included in group one, 51.0 percent were included in group two, and 2.1 percent were included in group three. The percentage of cores in each group for the second test (16 years) was also recorded and is as follows: 12.9 percent were included in group one, 58.1 percent were included in group two, and 29.1 percent were included in group three. A microscope was used to measure the depth of penetration at each side of the core. These two measurements were then averaged to get the recorded penetration for each core.

The 16 year old cores were also split apart and were inspected visually to determine the degradation of the HMWM resin. Water droplets were dropped on the split core to see if they formed a bead or were absorbed into the concrete. If the water was absorbed into the concrete, it was clear that the HMWM resin had worn away from that section.

The bond strength of the sealant for both tests (11.5 months and 16 years) were measured by cutting off the top one inch of the core and subjecting it to a tensile splitting test. The disks were placed in an electrohydrolic compression testing machine on their side with the crack running parallel with the applied compressive force. If this setup is followed correctly a tensile force will form in the crack. The maximum tensile force achieved prior to failure was then recorded. This value was then compared to the maximum tensile force achieved from a one inch disk cut from a core with no crack.

The last type of test preformed on the sealed bridge deck was a friction test. The test was preformed in accordance with ASTM E274-90. The friction value was tested fourteen times at random places along the seven mile deck. For traffic traveling at 55 mph, a test result of 35 or higher is considered satisfactory.

Main Findings and Conclusions

The average depth of penetration results for the first test (11.5 months) is as follows: 0.760 inches for group one, 0.934 inches for group two, and 0.950 inches for group three. The average depth of penetration results for the second test (16 years) is as follows: 0.241 inches for group one, 0.349 inches for group two, and 0.417 inches for group three. According to the results, the depth of penetration in the cores has gotten smaller over 15 year; however, Lasa suggests the discrepancy is due to the HMWM resin dulling over time and becoming harder to see. Also, Lasa states that since less cores were taken during the second test they may not have been an accurate representation of the actually penetration depth.

The average load applied to the first set (11.5 months) of core disks with a repaired crack was 972.67 pounds. The uncracked disks had an average load of 1074.95 pounds applied to them at failure. This means that the 11.5 month old repaired cracks maintained 90.5 percent of the uncracked specimen's strength. The average allowable load applied to the second set (16 years) of core disks with a repaired crack was 872 pounds. The uncracked disks had an average load of 1225 pounds applied to them at failure. This means that the 16 year old repaired cracks maintained 70.4 percent of the uncracked specimen's strength. However, it should be noted that the 16 year old uncracked cores were stronger than the 11.5 month old cores. If the 16 year old *cracked* cores are compared to the 11.5 month of *uncracked* cores there is only an 87.5 percent strength loss. This means that the HMWM sealant lost between three and 20 percent of its bond strength between the two tests. In 2002, the engineers estimated the sealant would successfully seal the cracks from corrosion for another 10 to 15 years. This sets the corrosion life span to between 2012 and 2017.

The skid tests (conducted in accordance with ASTM E274-90) yielded an average coefficient of friction of 45.5 on the bridge deck. The coefficient of friction of the concrete prior to the application of the sealant was 52.8. Although there was a 14 percent decrease in friction, the level was still above the minimum safety value (35). Also, the sealant eventually wore off the deck raising the friction levels back to the value prior to application.

Crack Sealers Tested

test no.	high-molecular weight methacrylate (HMWM)	reactive methyl methacrylate (MMA)	methacrylate	polyurethane	urethane polurea hybrid	epoxy	epoxy resin	silicon joint sealer
1	i							
i = investigated								

A high-molecular weight methacrylate (HMWM) flood coat was implemented in the study.

Aspects of Performance Investigated

	depth of penetration	bond strength	seepage rate	freeze-thaw exposure	temperature	surface cleaning
	performance criteria			factors affecting performance		
laboratory investigation						
field investigation	i	i				
i = investigated						

Properties of Sealant

Viscosity	15-20 cps Brookfield RVT w/UL adaptor 50 RPM at 77°F
Density	8.5-9.0 lbs/gal at 77°F
Vapor Pressure	less than 1mm Hg at 77°F
Cure Speed	Bulk Cure 3 hours at 73°F Surface Cure 8 hours at 73°F
Gel Time	50 +/- 10 minutes
Tack-Free Time	5 hours

B.3.4 Marks (1988)

"High Molecular Weight Methacrylate Sealing of a Bridge Deck: Final Report"

Description

The US 136 bridge which passes over the Mississippi River in Iowa experienced transverse cracking soon after construction. The cracks were later found to penetrate the entire depth of the deck. This was discovered by observing rain water drip through the bottom of the deck during stormy weather. Engineers hypothesized that the cracking was due to shrinkage of the concrete and change in moment of the deck. Originally it was determined that at least 215 cracks were allowing water to pass through the deck.

Due to the corrosion problem this would create with the reinforcement bars that were placed within the bridge deck, engineers determined some sort of sealing processes would be needed to seal the cracks. Initially three unidentified sealants were used to seal small test sections on the bridge. Two of these sealants were very fluid and one was not. The low viscosity sealants were applied by spraying or brooming while the viscous fluid was applied using a squeeze bottle. It was determined that all three sealants penetrated the cracks; however, none of the sealants prevented the flow of water through the concrete deck.

After the unsuccessful test using the three unidentified sealants, the Iowa Department of Transportation decided to try a HMWM resin on a small test section of deck. The decision to use a HMWM sealant was based off of success documented by the California Department of Transportation. The sealant was applied on three 50 ft test sections of the deck. After application, it was determined that the cracks leaked in the morning but not in the afternoon. Engineers hypothesized this was due to thermal expansion from higher temperatures during the middle of the day. Even though there was still some leaking in the morning, it was determined that the leaking was far less than the three unidentified sealants.

Due to these findings, a HMWM resin (RPM-2000W produced by Revolan Systems) was applied to the entire 15 spans of the bridge. Due to the idea of thermal expansion, the sealants were applied between the hours of 11:00 pm and 7:00 am. The deck was first swept with brooms and then the cracks were cleaned with high amounts of air pressure. The concrete was allowed the sit for 24 hours after the air cleaning and was visually inspected to determine if it was dry. The rate of application was approximately one gallon of sealant per 100 square feet of deck. The deck and sidewalk were sprayed with a two parallel spray bar application. Then brooms were used to move the excess sealant to heavily cracked areas.

Sand was applied after the application of the sealant to create friction on the driving surface. Friction tests were conducted before and after the application of the sealant. ASTM E-274 was used as a guideline for conducting the friction test.

Lastly, six two inch diameter cores were taken to determine the penetration depth of the sealant. All cores were centered on an apparent crack. The cores were only drilled two inches deep so that they would not damage the epoxy coated rebar. The rebar had a two inch cover. The extracted cores were then split to determine the depth of penetration. It was noted that the split did not always follow the crack, which would suggest the HMWM sealant had a strong bonding strength; however, no test was conducted to measure the bonding strength of the sealant. The split cores were then treated with a solution that consisted of half concentrated sulfuric acid and half water. Heating the split cores in the oven at 140 degrees Fahrenheit for two hours caused the organic compounds (HMWM sealant) to turn black.

Main Findings and Conclusions

After conducting tests in accordance to ASTM E-274, it was determined that the friction on the sealant covered bridge ranged between 27 and 39 with an average of 33 for treaded tires. This compares to an average of 36 prior to the application of the sealer. Both of these friction values are well within specified limits.

The depth of penetration tests showed that the HMWM sealant penetrated the entire depth of the two inch cores. It should be noted that since the cores were only two inches deep the actual penetration depth of the sealant was not determined. It is only known that the depth of penetration for this HMWM was greater than two inches.

To determine if the HMWM crack sealant had successfully sealed the bridge, the underside of the deck was observed during rainfalls to document leaking. The first observation was in October of 1986 during a 0.25 inch rain. It was observed that five cracks leaked between pier seven and eight. Another inspection in March of 1987 with a light rain showed no sign of leaking. Yet another inspection in April of the same year with steady rains showed no signs of leakage. The last inspection in August of the same year with similar rains to the April check showed substantial leakage in all spans of the bridge. There were over 300 cracks on the eastbound side of the bridge and 400 cracks on the westbound side of the bridge that were leaking. The leakage however was at a much lower rate in comparison to the unsealed bridge.

Due to this observation, the engineers determined to apply a second coat of the same sealer to half of the bridge. The friction testing after the second application showed that the bridge had more friction than before either coat of the sealer was applied to the bridge. This was due to crushed quartz that was mixed in with the sealant (something that was not done in the first application). However, it was determined that the sealer eventually wore away and the normal friction of the concrete controlled.

The penetration depth of the second sealant coat could not be determined using the same method. So instead of using another method to determine the depth of penetration for the second coat, it was simply not tested.

It was observed during June of 1988 with 0.6 inches of rainfall that 50 cracks leaked between piers four and five, and 16 cracks leaked between five and six. Both of these sections had only been subject to one coat of HMWM sealant. The sections with two coats of the sealant between piers six and seven, and seven and eight, had 14 and 47 leaking cracks respectively.

It was determined that the HMWM sealant was not successful in preventing leaks in the deck with one or two coats. However it did reduce the amount of leaks that the deck experienced in comparison to when it was untreated. The friction tests showed that as long as sand was applied to the deck or crushed quartz was mixed with the sealer that the friction would meet specifications. However, the sealant was eventually worn off the deck and the friction levels went back to where they were prior to application of the sealer.

Crack Sealers Tested

test no.	high-molecular weight methacrylate (HMWM)	reactive methyl methacrylate (MMA)	methacrylate	polyurethane	urethane polurea hybrid	epoxy	epoxy resin	silicon joint sealer
1	i							
i = investigated								

A high-molecular weight methacrylate (HMWM) flood coat was implemented in the study.

Aspects of Performance Investigated

	depth of penetration	bond strength	seepage rate	freeze-thaw exposure	temperature	surface cleaning
	performance criteria			factors affecting performance		
laboratory investigation						
field investigation	i		i			
i = investigated						

B.3.5 Meggers (1998)

"Crack Sealing and Repair of Older Serviceable Bridge Using Polymer Sealers”

Description

This report consisted of a literature review of previous findings as well as a laboratory and field study which focused on the four crack sealants.

For the field investigation, eight bridges throughout Kansas were used for sealant application. The bridges used for the project varied from 2 to 29 years in age. Previous to application of the sealants, a power washer was used to clean the cracks of all possible debris. Four test sections were developed on each bridge. The first section would act as a control section and would have no sealants applied to the cracks. The other three section had a specific sealant (HMWM A, HMWM B, or Epoxy) applied to all of the cracks within the corresponding sections area. Samples were removed using a vacuum drill at three different depths: between 0 and 19 mm, 19 mm and 38 mm, and 38 mm and 57 mm. To eliminate as much variability as possible, the samples were removed at four specific places in the test section: one at the curb line, one in each wheel path, and one directly between the wheel paths. The first samples were removed prior to the sealant application (1992) and the last samples were removed in 1995. After the application of the sealants, multiple 50 mm cores were also extracted to determine the effective penetration of the sealer. Additional cores were removes once each year for the next three years to determine the sealants’ ability to resist the environmental effects. Using a microscope and Ultraviolet light, the penetration of each crack was recorded.

For the laboratory investigation, 30 test beams with dimensions measuring 75 mm by 100 mm by 400 mm were cast. One 356 mm long number 13 reinforcing bar was placed in the center of each beam. Epoxy coated chairs were used to support the bar while the concrete dried. A copper wire used to determine the corrosion potential and the corrosion rate was also connected to the reinforcing bar. To create a crack to the depth of the reinforcement bar the beam was subjected to a three-point loading condition. Due to an average crack width of 0.3 mm found in the field test, stainless steel shims were placed in the cracked beams to maintain this average crack width value. The cracks were then sealed with the appropriate sealant (HMWM A, HMWM B, HMWM C, or Epoxy) and the other sides of the beam (excluding the top) were waterproofed. The beam was then subjected to continuous cycles that simulated the freeze/thaw, wet/dry, chloride pooling, and temperature conditions of the Kansas state area. After each cycle, the corrosion characteristics were found by applying a voltage to the reinforcing bar and measuring the current. The beams were tested during the wet state in order to obtain consistent results. Details on this method can be found on page 19 of Meggers. After the experiment concluded the beams were saw-cut in order to determine the sealants’ penetration.

Main Findings and Conclusions

The results of Meggers’ field study on chloride levels in the eight bridges throughout Kansas were inconclusive. Due to the results for chloride concentration being so random, it was impossible to determine which sealant performed the best. One would assume that the chloride concentration in the unsealed portion of the deck would significantly increase compared to the sealed portions. However, in many cased the unsealed deck performed better than the sealed deck section. This may suggest that since the sealants were applied to older bridges that the chloride concentration may have been trapped in by the sealants. If this is the case, the sealants would be doing more harm than good. The following table shows the percent of samples increase or decrease over the three year span.

Test		Increase	Decrease	No Change
Control		59	38	3
EPOXY		58	41	1
HMWM A		54	44	2
HMWM B		58	41	1
All Sealers		57	42	1

No correlation in the data was found to show that any sealer worked better than the other. However, it was determined that the bridges in the northern region of the state had higher chloride contents than bridges in the southern regions of the states. This can be explained by the harsher winter weather in the upper half of Kansas. Due to this colder weather, more de-icing products are used on the roads which cause higher chloride levels.

The depth of penetration in the 50 mm cores that were taken from the field also produced similar inconclusive results. The penetration data varied greatly with little correlation. However, when looking at percent penetration of the crack, more sense could be made. For example, if a sealant penetrates 10 mm into a crack this does not tell the full story. However, if it were stated that a sealant penetrated 10 mm into a 15 mm crack this would be more significant than a sealant that penetrated 10 mm into a 100 mm crack. Relationships between crack widths vs. crack depths, penetration vs. crack depths, penetration vs. crack width, and percent penetration vs. bridge age were considered. After reviewing all of the data a few slight trends were recognized in relation to percent penetration. Average percent penetration followed this decending order (greater percent penetration first): HMWM A, HMWM B, and EPOXY. Another conclusion that could be made from this experiment was that after cracks became too wide they were much harder to penetrate. The reason for this is likely that wider cracks more easily collect contaminants that hinder penetration. Also newer bridges had better percent penetration values than older bridges. This can again be attributed to the contaminant build up in older cracks.

The laboratory results for this experiment yielded much more conclusive results. A corrosion rate of 1.0μA/cm^2 was used as a maximum rate. This is due to that fact that when the corrosion rate gets to1.0μA/cm^2, damage from the corrosion begins to take palace. The days it took for the beam to reach this rate of corrosion was then input into an equation to determine the lifespan of the bridge. The unsealed cracked beam reached the corrosion rate of 1.0μA/cm^2 in 50 days. After plugging this into the equation, it was determined that the unsealed crack could keep corrosion below 1.0μA/cm^2 in an actual bridge for approximately four to five years. The EPOXY sealed beams lasted 271 days. The equation gave the bridge a minimal corrosion lifespan of 15 years or more. The HMWM A sealed beams lasted 156 days. This yielded a time of nine years of protection for the bridge. HMWM B sealed beams lasted 170 days, which meant the bridge should be protected for up to 11 years. The final sealant (HMWM C) which was only used in the laboratory experiment lasted 110 days. This would protect the structure from corrosion for approximately eight years.

The laboratory tests concluded that the EPOXY and HMWM B sealants protected the beams the longest. HMWM B provided slightly less protection and HMWM C provided the worst protection. The varying protection was attributed to three basic properties of the sealants. These properties are viscosity, tensile strength, and tensile elongation. The viscosity affects the sealants ability to penetrate the cracks and the tensile strength and tensile elongation affect the ability of the sealant to stand up to weathering and abuse. EPOXY had a higher viscosity which hindered its penetration; however, its tensile strength was the highest of the four sealants and its tensile elongation was relatively high. HMWM B had similar characteristics to EPOXY which was the reason why it was nearly as effective. The main difference was that HMWM B had a slightly smaller tensile strength. Since HMWM A and C had significantly lower tensile strengths they could not compete with EPOXY and HMWM B. Meggers concludes that, "most effective sealers would be one with a relatively low viscosity, a tensile strength of at least eight (8) MPa, and a tensile elongation of at least 10 percent." He also stated that a tensile elongation of greater than ten would be preferred if the tensile strength was not reduced.

Crack Sealers Tested

test no.	high-molecular weight methacrylate (HMWM)	reactive methyl methacrylate (MMA)	methacrylate	polyurethane	urethane polurea hybrid	epoxy	epoxy resin	silicon joint sealer
1						i		
2	i							
3	i							
4	i							
i = investigated								

This 1998 study investigated the performance characteristics of 4 crack sealants as seen in the above table. One epoxy and two HMWM sealants were used in the field portion of this experiment. One additional HMWM was added to the laboratory tests to obtain more conclusive results. All of the sealers tested were gravity or flood sealers.

Aspects of Performance Investigated

	depth of penetration	Chloride Concentration	freeze-thaw exposure	temperature	surface-prep methods
	performance criteria		factors affecting performance		
laboratory investigation	?	i	i		
field investigation	i	i	i		

i = investigated

Properties of Epoxy

Viscosity	0.3 - 0.5 Pa.s
Density	1078.4 kg/m3
Compressive Strength	35.6 MPa
ASTM D659	
Tensile Strength	29.3 MPa
ASTM D638	
Flexural Modulus	1.4 GPa
ASTM D 790	
Elongation	9.9%
ASTM D 638	
Gel Time	60 min
Tack-Free Time	3 hours

Properties of HMWM A

Viscosity	0.01 - 0.025 Pa.s
Density	994.6 kg/m3
Compressive Strength	23.4 MPa
ASTM D659	
Tensile Strength	2.8 MPa
ASTM D638	
Flexural Modulus	N/A
ASTM D 790	
Elongation	30%
ASTM D 638	
Gel Time	30 min
Tack-Free Time	4 hours

Properties of HMWM B

Viscosity	0.07 - 0.15 Pa.s
Density	994.6 kg/m3
Compressive Strength ASTM D659	44.8 MPa
Tensile Strength ASTM D638	8.3 MPa
Flexural Modulus ASTM D 790	N/A
Elongation ASTM D 638	10%
Gel Time	80 min
Tack-Free Time	4 hours

Properties of HMWM C

Viscosity	0.025 Pa.s
Density	1068.9 kg/m3
Compressive Strength ASTM D659	29.6 MPa
Tensile Strength ASTM D638	2.8 MPa
Flexural Modulus ASTM D 790	17.2 MPa
Elongation ASTM D 638	1.9%
Gel Time	20 min
Tack-Free Time	6 hours

B.3.6 Pincheira (2005)

“Evaluation of Concrete Deck and Crack Sealers”

Description

To test the bond strength and freeze-thaw durability of the sealants, 3"x4"x16" prisms were constructed. These prisms were then cut in half to yield 3"x4"x8" prisms that were tested for bond strength and freeze-thaw durability respectively. 4 prescribed crack widths: hairline (1/32"), narrow (1/16"), medium (1/8"), and wide (1/5") were constructed in order to determine the effect crack width had on sealer bond strength and durability. In order to construct the cracks, prisms were first split following a process similar to that used to measure the splitting tensile strength of concrete. Splitting the specimens this way created realistic cracks patterns encountered in the field. After specimens were split, the prescribed crack widths were constructed. After crack widths were constructed, sealers were gravity fed into the cracks. Sealers were only applied to crack width ranges as recommended by the manufacturers. Not all sealers were applicable for every prescribed crack width. The bond strength and the durability of the sealers were then measured after the sealers were allowed to adequately cure (at least 14 days). Note that two 2" sections were cut from the ends of the prism to visually evaluate the depth of penetration of the sealant. The remaining 3"x4"x4" sections were used to evaluate the bond strength of the sealants. The bond strength of the sealant was measured according to the process used to crack the original concrete specimens. The failed, sealed prisms were then evaluated to see if the failure plane was a result of concrete, bond, or sealant failures or any combination of the three. Durability of the sealers was measured by subjecting companion prisms (3"x4"x8") to freeze-thaw cycles immediately after the sealants adequately cured. The bond strength of the sealant was then measured after being subjected to freeze-thaw to determine if degradation of the sealant's bond strength occurred.

Main Findings and Conclusions

All 10 sealers penetrated the full depth of the 2-½” crack (3” minus 2, ¼” saw notches) for all applicable crack widths. Thus, being able to adequately to penetrate any of the crack widths was not an issue for any sealer.

Trends were noticed within individual crack widths when subjected and not subjected to freeze-thaw. Primarily concrete failure within the failure plane was generally associated with sealants with the highest bond strengths. Transition to bond failure and sealant failure within the failure plane were generally associated with sealants with intermediate and the lowest bond strengths respectively. This observation makes sense. When a tested, sealed specimen failed primarily due to the concrete, the sealant was able to provide as much strength as the concrete, thus higher bond strength was achieved. When bond and sealant failure became more prevalent, the resultant meant that the sealant was weaker, or less stiff than the concrete, thus bond strength decreased.

Certain trends were noticed as crack width increased. As crack width increased, bond strength generally decreased for sealants subjected and not subjected to freeze-thaw. This decrease in bond strength was generally associated with a decrease in the prevalence of concrete failure within the failure plane and an increase in the percentage of bond and sealant failure. This observation coincides with the trend seen in the above paragraph.

Sealants subjected to freeze-thaw cycles experienced substantial reduction in bond strength. This percent reduction varied among sealants within a certain crack width and for each sealant from crack width to crack width. The reduction in bond strength was generally associated with a transition from higher to lower strength failures. (The presence of concrete failure diminished and bond and sealant failure became more prevalent or the presence of bond failure diminished and the percentage of sealer failure increased within the failure plane.) The performance of some sealers drastically decreased after being subjected to freeze-thaw for certain crack widths even though these sealers had more than adequate bond strength and concrete failure in a range of crack widths under no freeze-thaw. Thus, the importance of testing the durability of crack sealers should be emphasized when selecting a certain sealer for projects in northern climates.

In evaluating the bond strength and freeze thaw durability of the 10 crack sealants in the hairline (1/32”) to wide (1/5”) crack range, Sikadur 55 SLV and Dural 335 (epoxy resin and expoxy respectively) were found to have the best performance characteristics for hairline cracks. For narrow (1/16”) and medium (1/8”) cracks, Sikadur 55 SLV was found once again the best performer. Two sealants were applicable for wide cracks, Duraguard 401 and TK-9000 (HMWM and epoxy respectively). Of these two sealants, none were found to have adequate bond strength and freeze-thaw durability for the wide cracks. In fact, Duraguard 401 essentially exhibited zero bond strength after freeze-thaw for hairline, narrow, medium, and wide cracks. The report suggests that Sikadur 55 SLV would perform well in wide cracks due to it exhibiting excellent bond strength and freeze-thaw durability in the hairline, narrow, and medium cracks.

The report notes however that all characteristics of the sealer and the needs of the project should be evaluated when selecting a sealer for a specific project. Sealer characteristics such as time to open traffic or project needs such as the duration of required chloride protection should all be considered. (If the deck is scheduled for an overlay relatively soon, the needed freeze-thaw durability of the sealant would be less.)

Crack Sealers Tested

test no.	high-molecular weight methacrylate (HMWM)	reactive methyl methacrylate (MMA)	methacrylate	polyurethane	urethane polurea hybrid	epoxy	epoxy resin	silicon joint sealer
1			i					
2			i					
3	i							
4						i		
5					i			
6						i		
7							i	
8						i		
9						i		
10	i							
i = investigated								

The study investigated the performance characteristics of 10 crack sealants as seen in the above table. All the sealers tested were gravity or flood sealers. Pincheira also evaluated deck sealers which can be seen in Appendix A9.

Aspects of Performance Investigated

	depth of penetration	bond strength	freeze-thaw exposure	temperature	surface-prep methods
	performance criteria		factors affecting performance		
laboratory investigation	i	i	i		
field investigation					
i = investigated					

B.3.7 Rodler (1989)

"Repair of Cracked Concrete with High Molecular Weight Methacrylate Monomers"

<u>*Description*</u>

As stated previously three different HMWM resins were used in the laboratory version of this experiment. The study refers to the sealers as system 1, system 2, and system 3. All of the sealants used were made up of 100 parts monomer, four parts initiator, and 2 parts cobalt naphthenate promoter. The initiator for system 1 and 2 were made from benzoyl peroxide, and the initiator for system 3 was contained cumene hydroperoxide. Due to these differences in mixing, the properties of the three systems varied greatly.

The laboratory portion of this study tested six different aspects of the three sealant systems. These aspects were strain capability of resin, bond strength, depth of penetration, effect of varying moisture levels, effect of varying temperatures, and deflection of repaired beams.

The first test performed measured the strain capability of the three different sealant systems. To test this, one inch diameter repaired cylinders were subjected to tension loading. The cylinders were fixed to the loading plates using an epoxy adhesive and were loaded perpendicular to the repaired crack. Two different size cracks were tested in this experiment (0.4mm and 1.0mm). After the test was completed, the strain purely across the crack (or the resin) was found. This means that the strains experienced by the mortar cylinders were subtracted from the total strain.

The sealants bond strength (or to be more accurate the ability for the sealant to repair a slab) and depth of penetration were tested by cracking a 4 in. by 6 in. by 12 in. slab under a flexural load and repairing it with the three sealant systems. Light gauge wire was used in the slab for reinforcement. The repaired slab would then be saw-cut in half. One half of the slab was then subjected to the same flexural loading as before and the other half was used for penetration tests. The ratio of strength between the uncracked and repaired beam was then determined by simply dividing the two values. To determine the depth of penetration, the slab was cut into sections and the penetration was visually inspected and recorded.

The ratio of repaired to uncracked strength and depth of penetration were also tested under different moisture and temperature conditions. In the temperature test, the same slab setup as mentioned before was repaired outside during a hot afternoon. The air temperature during that day was 95 degrees Fahrenheit, and the top of the slab reached temperatures of 110 to 120 degrees Fahrenheit. The moisture test used the same slab setup as well. However, this test required placing the cracked slabs into a moisture room. Once the cracks became saturated with water the slabs were allowed to dry for 4, 8, 16, 24, 48, and 72 hours. After this drying time, the cracks were sealed with the three systems using the same procedure as before. Both the temperature and moisture effected slabs then saw-cut to determine the strength ratio and depth of penetration.

The last section of the laboratory tests used 6 in. by 6in. by 36 in. concrete specimens to measure the deflection of repaired beams. The beams contained one number four bar for reinforcement.

Using a three point bending system, the beams were loaded to determine the affect of the different sealers on their deflection.

The field portion of this study focuses on the repair of a bridge deck in San Antonio, Texas. The 56,000 square foot deck of the Loop 1604 had experienced a large amount of shrinkage cracking. The sealant referred to as “system 3” in the laboratory tests was used to seal the cracks on the entire bridge deck. Seven days prior to application, a high pressure washing system was used to clean the cracks and the bridge deck. After the deck dried for seven days the cracks were again blown clean with compressed air. System 3 was then poured on the deck and brooms were used to move the resin to highly cracked areas. Cores were then extracted from the bridge deck to determine the sealants depth of penetration and bond strength. A tensile splitting test (ASTM C496-85) was used to determine the bond strength of the resin. The top section (2” or less) of the core was cut off so that the crack contained in the core ran through the entire disk.

Main Findings and Conclusions

In the strain test, it was determined that the wider cracks developed higher strains across the crack before failure. The lowest modulus system showed the greatest increase in ultimate strain with the increase in crack size. After looking at the results, it can be seen that system 3 is much more rigid in comparison to systems 1 and 2. This test is important because it gives an indication of how much strength the sealants will have. Materials that have smaller strains tend to have higher tensile strengths than materials with larger strains.

The depth of penetration for the three systems was actually recorded in percent penetration. The percent penetrations for systems 1, 2, and 3 for the standard laboratory test (no temperature or moisture affects) were 92.0, 83.3, and 95.7 percent respectively. The percent penetrations for the temperature affected test were 76.4, 73.1, and 91.0 percent. Lastly, the number our hours the beam dried to retain 95 percent of the percent penetration from the standard laboratory test was recorded. The required times for the three systems were 14, 32, and 50 hours. It can be seen from these tests that system 3 penetrated the cracks better than systems 1 and 2. System 2 performed the worst. Also a great reduction in percent penetration can be seen from the elevated temperature test. This is due to the high temperatures and UV radiation causes the HMWM resin to gel much faster. Due to the accelerated gel time, the resin has less time to seep into the cracks of the slab. It should also be noted that systems 1 and 2 lost a considerable amount of penetration due to higher temperatures and system 3 only lost 4.7 percent. The last observation worth noting is that the most drying time is required for system 3 (the best performing system so far). Rodler determines that an average two days of drying are required for 95 percent of the original penetration to be reached.

The ratio of cracked strength to uncracked strength was also discovered for the three tests (standard, temperature, and moisture). The strength ratio in the standard test for system 1, 2, and 3 were found to be 75.5, 80.5, and 96.5 percent. The ratios were again found for the elevated temperature test. The results for the three systems showed ratios of 72.8, 85.8, and 93.4 percent. Again the drying time required to reach 95 percent of the original cracking ratio was determined. Systems 1, 2, and 3 required 64, 37, and 62 hours to dry. The results show that system 3 regains most of its original strength when repaired. Also, systems 1 and 2 lose a great amount of strength when subjected to high temperatures when system 3 only loses 3.1 percent. Rodler determines that an average three days of drying are required for 95 percent of the original strength ratio to be reached.

The reinforced beams were loaded to 4850 pounds with an ultimate load factor of 1.5. The percent increase in stiffness was determined to rate the different systems. This percentage was determined by taking the difference of the repaired beam stiffness and the cracked beam stiffness and dividing it by the cracked beam stiffness. The average percent increase in stiffness for systems 1, 2, and 3 are 121.0, 136.0, and 112.3 percent respectively. This shows that the most flexible sealant is system 2 and the least flexible stiffness is system 3. Because higher amounts of flexibility are desired for flexural members, system 2 preformed the best. Due to the small amount of flexibility in system three, numerous cracks developed and the beam failed before it reached service loads.

Due to the performance of system 3 in all of the initial laboratory tests, it was chosen to seal the Loop 1604 bridge in Texas. The extracted cores showed a 60-80 percent penetration of the cracks. Also, all of the tensile splitting tests showed that the repaired cracks retained at least 80 percent of the original uncracked concrete. Both the penetration and bond strength findings were deemed acceptable.

Rodler gives some final conclusion pertaining to the entire study. In the direct tension and modulus of rupture tests the most rigid system preformed the best. In the flexural tests the most flexible system preformed the best. He also concludes that the systems using benzoyl peroxide are more sensitive to sunlight than the cumene hydroperoxide systems. Moisture in the cracks was found to greatly reduce strength of repair. Three days of drying should be good to retain 95 percent of the bond strength, and two days of drying should be sufficient to retain 95 percent of penetration depth.

Crack Sealers Tested

test no.	high-molecular weight methacrylate (HMWM)	reactive methyl methacrylate (MMA)	methacrylate	polyurethane	urethane polurea hybrid	epoxy	epoxy resin	silicon joint sealer
1	i							
2	i							
3	i							
i = investigated								

Three different high molecular weight methacrylates (HMWM) were used in Rodlers's study. The characteristics of these three HMWM resins were distinctly different due to their mix procedure. Due to the various different cracks being sealed in this experiment, Rodler states that all of the repaired cracks were filled with resin until penetration into the crack stopped. Most experiments used a gravity or flood application; however, variations were made during the strain test due to its setup making gravity of flood application challenging.

Aspects of Performance Investigated

	depth of penetration	bond strength	moisture exposure	temperature	surface-prep methods
	performance criteria		factors affecting performance		
laboratory investigation	i	i	i	i	
field investigation	i	i			
i = investigated					

B.3.8 Soriano (2002)

"Alternative Sealants for Bridge Decks: Final Report"

Description

As with the deck sealant portion of the Soriano study, the crack sealant portion consisted of a literature review, a survey of other states' and provinces' concrete deck and crack sealing strategies, and a field and laboratory analysis.

The survey investigated trends in concrete deck and crack sealing strategies of northern states and Canadian provinces. 40 states and provinces were sent the survey and of the 40 questioned, 25 replied. Questions were worded for simple yes/ no answers. Individual state and province answers were not given but rather the number and percentage of states and provinces answering yes and no to individual questions. The portion of the survey concerning deck sealant use can be found in the summary of the deck sealant portion of this study in Appendix A10. The crack sealant portion of the survey investigated if the states and provinces that responded employed crack sealing strategies on concrete bridge decks. If yes, trends toward the use of methacraylates, epoxies, and polysters among the respondent states were investigated. Further specification, such as the use of high molecular weight methacrylates was not asked. Tolerable crack width and crack density before beginning crack repair was also investigated among the 25 states and provinces.

For the field investigation, 3 different bridges were used for sealant application. The surface of the bridge decks were either prepared for sealant application in one of three ways: i) sandblasting; ii) power broom/ forced air; or iii) do nothing. Cracks were mapped and their widths were recorded for each bridge deck. Six test sections were defined per bridge. Based on ACI 201 definitions of crack widths (fine: < 0.04 in, medium: 0.04 to 0.08 in, wide: > 0.08 in), the six test sections were categorized as medium or low crack density areas. No, clear distinction on the characteristics of each classification is given in the report. Note that surface prep was performed after classification of the test sections was performed. Based on the classification of each test section, either a crack or deck sealer was applied (3 deck sealers and 4 crack sealers). (The silicon joint sealer was substituted for epoxy on 2 of the 3 bridge decks.) Deck sealers were applied to low crack density areas and crack sealers were applied to medium crack density areas. Further description on the deck sealers portion of Soriano's report can be seen in Appendix A10.The MMA was applied via roller application, the MPU and silicon joint sealer were applied via cartridge injection, and the epoxy was applied via a low pressure sprayer. After application and adequate drying time, three cores from each test section were extracted. This produced a total of 54 cores (3 cores x 6 test sections x 3 bridges). Of these 54 cores, only 30 were able to be tested due to 24 of the cores containing surface cracks and breaking during transport and laboratory preparation. To measure the depth of sealant penetration and water penetration, a 56 day ponding test with a fluorescence day was performed. Note that this was performed for the deck and crack sealants. The cores were not ponded with sodium chloride due to concerns of the samples breaking upon determining the chloride content with a vacuum drill. This would have prevented a future saw cut to determine the depth of penetration of the sealant. The depth of water penetration was stated as a qualitative indicator of the chloride repellency of the crack and deck sealants.

Main Findings and Conclusions

Epoxy and methacrylates received the highest consensus among the 25 states and provinces for types of crack sealers employed. 6 out the 25 states and provinces (24%) responded yes to the use of epoxies and to the use of methacraylates for sealing cracks. None of the survey responses indicated the use of polyesters for crack repair. 15 out of the 25 states and provinces (60%) indicated that they do not employ a crack sealing program for concrete bridge decks. No clear consensus could be deduced from the states' and provinces' responses as to when they initiated their crack sealing program

The results of Soriano's field study indicated that surface preparation did not seem to play an important role in a crack sealer's depth of penetration; the same crack sealers similar depths of penetration among all 3 bridge decks. The fact that the sealed, sandblasted deck exhibited the largest degree of water permeability as mentioned in the summary of the deck sealant portion of Soriano's study bears little importance to the crack sealant portion. Crack sealants only seal the crack and not the concrete, thus an increase or decrease in sealed concrete permeability should only be considered when evaluating how and what to seal a deck with, not when sealing cracks.

In the 56 day ponding test, water migration still occurred through the unsealed concrete. Thus, the importance of a crack and deck sealing program is emphasized in decks with substantial cracking. Soriano recommends sealing the cracks before the deck.

In evaluating the statement that surface preparation did not seem to affect a crack sealer's depth of penetration, care should be given. Soriano mentions that some of the cores broke due to surface cracks during transport and laboratory preparation. This suggests one of two things. Either the broken cores were taken solely from test sections sealed with penetrating deck sealers or from a combination of deck and crack sealant test sections. If the latter is true, the crack sealants must have debonded from the surface of the crack walls, most likely indicating that dirt and debris resulted in poor adhesion between the concrete and sealer. Thus, surface prep may indeed play a role, not necessarily in depth of penetration, but possibly in bond strength; this is only a hypothesis though. Interestingly, Soriano mentions that in the cores analyzed, the crack sealants appeared to exhibit adequate adhesion to crack walls.

In comparing the depths of penetration of the 4 types of crack sealers, MMA is cited as exhibiting the largest penetration depth (~0.010 in). Soriano suggests that is possibly due to MMA's roller application. In comparing labor and time requirement for application, silicone joint sealer is not recommended due to its extensive requirements.

Soriano recommends that SDDOT seals cracks with the sealants analyzed in his report (excluding the silicon joint sealer) or equivalent crack sealants with viscosities less than or equal to 15 cp. This recommendation stems from, although not stated directly, the crack sealants studied in his report exhibited good penetration into the cracks and had viscosities less than or equal to 15 cp. Soriano further distinguishes his recommendation for individual crack widths. Using ACI 201 for definitions of fine, medium, and wide cracks: epoxy, MMA, and MPU with viscosities less than or equal to 15 cp are recommended for fine and medium cracks. For wide cracks (> 0.08 in.), epoxy is excluded from the 3 recommended crack sealants due to Soriano citing epoxies as "generally more rigid than the other two materials." The probability of brittle fracture under concrete expansion is then increased for epoxies. If the crack density is severe, Soriano recommends SDDOT use an epoxy chip seal.

For optimum application, Soriano recommends sealing cracks within 3 to 6 months after bridge deck construction. This recommendation stems from literature review of NCHRP Report 380 “Transverse Cracking in Newly Constructed Bridge Decks.” The report describes cracks as small as 0.002 in. displaying water transmission. Using the report and the recognition of the early onsought of cracking in bridge decks, Soriano describes his recommendation as a reasonable one.

Crack Sealers Tested

test no.	high-molecular weight methacrylate (HMWM)	reactive methyl methacrylate (MMA)	methacrylate	polyurethane	urethane polurea hybrid	epoxy	epoxy resin	silicon joint sealer
1						i		
2		i						
3				i				
4								i
i = investigated								

The crack sealer portion of the Soriano study investigated the performance characteristics of 4 crack sealants as seen in the above table. All the sealers tested were gravity, or flood, sealers except that of the silicon joint sealer and modified polyurethane (MPU) which were cartridge injected.

Aspects of Performance Investigated

	depth of penetration	bond strength	freeze-thaw exposure	temperature	surface-prep methods
	performance criteria		factors affecting performance		
laboratory investigation					
field investigation	i				i
i = investigated					

B.3.9 Sprinkel (1991)

"Evaluation of the Use of High Molecular Weight Methacrylate Monomers to Seal Cracks on I-81 over the New River"

Description

Due to cracks forming after construction, the I-81 Bridge over New River needed maintenance to prevent the corrosion of reinforcing steel in the deck. The plate girder bridge had a prestressed concrete sub-deck with a cast-in-place deck laid over the top. Transverse cracks began to form above the joints between the sub-deck panels and longitudinal cracking appeared above the girders. Due to the fact that epoxy injection was deemed too expensive ($20/ft), it was determined that a HMWM resin would be used to seal the transverse and longitudinal cracks in the bridge deck ($1/ft). Due to the history of HMWM resins seeping through the bridge deck, a tarp was placed under the deck to prevent the resin from draining into the river. This caused the expense of using HMWM resin to raise a small amount. The other option was to seal the bottom of the cracks; however, this was also deemed too expensive.

Prior to application of the crack sealants, the deck was sprayed with oil free compressed air. Also in order to minimize the expansion of crack widths, the sealants were applied between the hours of 1 am and 11 am. Also the deck temperature needed to be between 55 and 70 degrees Fahrenheit. By following these processes it should ensure that the crack is at its largest width when the resin is applied. The resin was applied with two gallon spray cans at an approximate rate of 200 ft per gallon. The engineers originally called for three applications to the crack. However due to the fast gel time of the resin on top of the cracks, only the wider cracks accepted more than one application of resin. After all the cracks were sealed a coat of resin was sprayed across the entire bridge deck. The application took 17 days and cost $271,496.

Two different HMWM resins were selected to seal the bridge decks. They were both manufactured by Transpo Industries, Inc. The T70M was a high modulus monomer and the T70X was a low modulus monomer. By applying each of these sealants on half of the bridge deck, they hoped a comparison could be developed. During the application, two inch cubes containing the sealants and concrete sand were molded in accordance with ASTM C33. The tensile strength, elongation at break, and modulus of elasticity was determined from these cubes. The two sealants would also be evaluated based on the following tests: skid tests, chloride permeability of cores, petrographic examination of the cores, tensile splitting tests, flexural loading tests, and on site inspections of the bottom of the bridge deck.

Cores with the diameter of four inches and depth of 5.5 inches were extracted from the bridge deck. Both the T70M and T70X sections were sampled at two different times: June 2, 1988 and July 11, 1989. Workers removed 24 cores the first year and 14 cores the second year from transverse cracked, longitudinal cracked, and uncracked sections. Two disks were cut from each of the cores, each being 2 inches thick. The first slice was cut off the top of the core and the second slice was cut at a depth of 2.125 to 4.125 inches from the top. Due to the fact that the cores were taken in pairs (two cores were taken close to each other on the same crack), one core's slices were used for the rapid permeability test and the others slices were used for tensile splitting purposes. After the rapid permeability test, a 0.75 in. by 2 in. by 4 in. slice was cut from each disk perpendicular to the crack. This slice was then analyzed under a microscope to determine the percent penetration of the crack. The two segments left from the disk after the slice was removed were subjected to a three-point bending flexural test (done in accordance with ASTM C293). This test was used to determine the modulus of rupture of the concrete specimens. The disks taken from the pairs other core were subjected to a tensile splitting test (done in accordance with ASTM C496). A loading rate of 2,000 lb/min was used during the tests. Lastly, skid tests at 40 mph with bald (ASTM E524) and treaded tires (ASTM E501) were run on the bridge deck. These tests were used to discover if the coefficient of friction on the bridge deck met safety regulations.

Main Findings and Conclusions

The tests on the cast cubes as was well as on site inspections showed that that brittle resins, such as T70M, began to crack much sooner than flexible resins. According to inspection of the bridge in June of 1988, the cracks sealed with T70M had extensive cracking in the resin. The cracks sealed with T70X (a more flexible resin) had very few cracks in the resin. However, a second inspection was done a year later which revealed extensive cracking in the T70X repaired cracks. This shows that even though the T70X resin is more flexible than T70M, it still was not flexible enough to stand up to the environment for 15 months. It was later determined more flexible polymers such as RPM1100V would have performed better.

The permeability to chloride ion test was conducted in accordance with AASHTO T277. The 1988 test data showed that the top two inch slab had an average permeability of 44 percent in comparison to the base slab. The following years test data revealed that the top two inch slab had an average permeability of 52 percent in comparison to the base slab. It can be concluded that the increase in permeability over the year was due to the resin cracking. This allowed fluid to pass through the cores with greater ease. The tests also showed that the permeability increase in cracks sealed with T70M. This is due to the early cracking that occurred in the resin. Also the permeability increased more in the transverse crack in comparison to the longitudinal cracks. One unexplained occurrence was that the uncracked base concrete had a higher permeability that the cracked concrete. Since the resin did not penetrate far enough to reach the base concrete Sprinkel felt that the sealant played no part in the unorthodox readings.

The petrographic examinations showed that the cracks were much wider on the surface of the concrete. The cracks below the surface got very narrow (less than 0.2 mm). The transverse cracks were on average larger than longitudinal cracks. There seemed to be no significant difference in penetration when comparing the T70M and T70X resins. However, neither resin penetrated well below a depth of 0.5 in. The surface cracks of all sizes were found to be 95 percent filled. Cracks larger and smaller than 0.15 mm at a depth of 0.25 inches were found to be 92 and 44 percent filled respectively. Cracks larger and smaller than 0.15 mm at a depth of 0.5 inches were found to be 57 and 35 percent filled. All cracks at depths greater than 0.5 inches were less than 20 percent filled.

As stated previously, a three-point bending flexural test was conducted to determine the repaired concrete’s modulus of rupture. The average modulus of rupture for cracked specimens was 110 psi. The average modulus of rupture for uncracked specimens was 990 psi. It was determined that the reason for the significant drop off in strength was due to the resin not penetrating the crack efficiently enough. This was due to the dust, dirt, and carbonation that had infiltrated the crack. The test showed that 40 percent of the top disk failed specimens were coated with polymer and 60 percent were coated with dust, dirt, and carbonation. All of the failed specimens in the bottom slice were coated with contaminants. Flexural tests in the lab (clean cracks) showed a significant increase in flexural strength of the resin. This study shows why it is extremely important to clean the cracks as much as possible before application of the sealant. However, no cleaning method has been found to remove all of the contaminants from cracks.

The tensile splitting tests showed very similar results for cracked and uncracked specimens in 1998 and 1989. Due to this information, Sprinkel suggests that the resin preformed satisfactory in restoring the tensile strength to the cracked concrete. However, it was noted that 30 percent of the failures occurred through the original concrete. The rest of the failures occurred through the crack. When analyzing the crack, an excess of dust, dirt, and carbonation was found. So the cleanliness of the cracks again affected the tensile strength of the repaired cracks.

The skid tests found that the coefficient of friction present on the bridge deck was satisfactory for both bald and treaded tires. All tests (both bald and treaded) yielded results over 35 which are considered safe. A separate experiment performed on I-64 also showed that the more sand placed on the curing resin, the large amount of friction is achieved. It was also determined that if no sand was applied to the resin an unsatisfactory friction factor would be obtained. This shows the importance of applying sand to the bridge deck when the sealant is curing.

A final visual inspection was done one year after the application of the sealer. The inspector said that leaks were observed between spans six and nine. However, he attributed the leaks to the holes created from the cores taken from the bridge deck.

Crack Sealers Tested

test no.	high-molecular weight methacrylate (HMWM)	reactive methyl methacrylate (MMA)	methacrylate	polyurethane	urethane polurea hybrid	epoxy	epoxy resin	silicon joint sealer
1	i							
2	i							
i = investigated								

The performances of two high molecular weight methacrylates (HMWM) were tested in Sprinkel's field study. All of the cracks were gravity fed.

Aspects of Performance Investigated

	depth of penetration	bond strength	Permeability of Chloride ions	temperature	surface-prep methods
	performance criteria			factors affecting performance	
laboratory investigation					
field investigation	i	i	i		
i = investigated					

B.3.10 Sprinkel (1995)

"Gravity-Fill Polymer Crack Sealers. Transportation Research Record"

Description

Test beams were constructed to quantitatively measure the bond strength of the sealants using the flexural strength as the indicator. The test beams were broken under third-point bending and the beams' original flexural strength was recorded. From the broken beams, 4 prescribed crack widths were constructed to test the bond strength of the crack sealants not subjected to freeze thaw cycles and 3 prescribed crack widths were constructed to measure the bond strength of the sealants after being subjected to freeze-thaw cycles (freeze-thaw cycles according to ASTM C666 Procedure A). These crack widths being 0.2, 0.5, 0.8, and 1.0 mm for sealants not subjected to freeze-thaw and 0.2, 0.5, and 1.0 mm for sealants subjected to freeze-thaw cycles. Visual inspection of the sealed cracks was performed to determine if the crack sealant penetrated the crack fully. The ratio of the flexural strength of the repaired beam to that of the original beam was found to determine the effect that crack width and freeze-thaw cycles (durability) had on each of the five sealants' bond strength. The failed repaired beams were then inspected and the percentage of the crack failing due to concrete, bond, and sealant was reported.

The effects of temperature on gel times and penetration ability of the sealants was also investigated. Gel time indicates the workability and final cure time of the sealant, the lower the gel time, the less working time and final cure time of the sealant. Gel time was measured as the time it took the sealant to reach a Jell-O like consistency and not slide down the side of the cup of sealant when tipped. Penetration ability (percent penetration) for varying temperatures was found by pouring the sealants over 3 different gradations of sand and measuring the weight of sand not penetrated by the sealant.

Main Findings and Conclusions

All the sealers were able to completely fill the prescribed crack widths. For each crack width of repaired beams subjected to no freeze-thaw cycles, virtually all of the sealants restored 100% of the original flexural strength and the failure plane exhibited primarily concrete failures. Note that this restoration of original flexural strength is for ideal conditions where no dirt and debris exists within the crack. As crack width increased for sealants subjected and not subjected to freeze-thaw cycles, the ratio of the flexural strength of the repaired beam to the initial flexural strength decreased. Thus, bond strength of the sealants decreased as crack width increased. This trend was more pronounced for sealants subjected to freeze-thaw cycles. Repaired beams subjected to freeze-thaw cycles generally exhibited much smaller flexural strengths than that of repaired beams not subjected to freeze-thaw cycles. Repaired beams subjected to freeze-thaw cycles also exhibited higher percentages of bond failures in the failure plane than that of repaired beams not subjected to freeze-thaw cycles. HWMW and E2 were an exception to this rule exhibiting no increase in percent bond failure when subjected to freeze-thaw cycles. Note that this general increase in percent bond failure in the failure plane and reduction of flexural strength when being subjected to freeze-thaw cycles indicates that the sealant was affected by freeze-thaw cycles and not just the concrete.

For the temperature tests, an indirect relationship was noticed in gel time vs. temperature for all 5 sealants; gel time decreased as temperature increased for all 5 sealants. Thus, the sealants working time and cure time decreased as temperature increased. HMWM was the only sealant whose depth of penetration (percent penetration) into all three gradations of sand was completely unaffected by temperature change.

From the performance characteristics measured for each of the sealants in the tests described in section 1.3, HMWM was found to be the best performer. HMWM consistently outperformed or performed just as well the other sealers in the flexural strength, freeze-thaw, gel-time, and percent-penetration tests. However, HMWM emits a nauseating smell and if mixed improperly can explode. U was determined to be the worst performer considering the results of the tests described in section 1.3. If considering ease of mix ability, odor, safety, and cost as important as the performance characteristics measured in section 1.3 such as cure time (gel time), flexural strength (bond strength), freeze-thaw (durability), and penetration ability (percent penetration) for low range and high range temperatures, E1 was found to be the best sealer of choice and HMWM was found to the 3rd best. U and E3 were ranked last.

<u>Crack Sealers Tested</u>

test no.	high-molecular weight methacrylate (HMWM)	reactive methyl methacrylate (MMA)	methacrylate	polyurethane	urethane polurea hybrid	epoxy	epoxy resin	silicon joint sealer
1						i		
2						i		
3						i		
4	i							
5				i				
i = investigated								

The performance of 3, two-component epoxies (abbreviated E1, E2, and E3 in report); 1, three-component high molecular weight methacrylate (abbreviated HMWM); and 1, two-component polyurethane (abbreviate U) was compared and contrasted. All crack sealers were gravity fed (flood sealers). Viscosities (reported in centipoises) of the sealers at 23^0 C were found to be the following: (U = 12-16, E1 = 175 – 250, E2 = 200 – 230, E3 = 300 – 500, HMWM = <100).

Aspects of Performance Investigated

	depth of penetration	bond strength	freeze-thaw exposure	temperature	surface-prep methods
	performance criteria		factors affecting performance		
laboratory investigation	i	i	i	i	
field investigation					

i = investigated

B.3.11 Tsiatas (2002)

"Durability Evaluation of Concrete Crack Repair Systems"

Description

Test beams were constructed to determine a cracks sealants resistance to freeze/thaw temperature changes and cyclic loading (or fatigue). The beams were cast from a concrete mix that Rhode Island Department of Transportation classifies as X ¾ in. AE. This mixture is typically used for structural members in bridges. The beams dimensions were 101.6 mm by 76.2 mm by 406.4 mm. Before the concrete hardened, varying thickness of crack inserts were placed in the middle of the beam that penetrated half the depth of the beam. The crack widths investigated in this experiment were 0.51 mm, 6.35 mm, and 12.70 mm. The crack inserts were used instead of bending the beam to form an actual crack so that the crack width could be uniform. Due to this the crack will act slightly different than a real crack. For example the sealant will be bonding to a smooth flat surface instead of a jagged rough surface. Each crack was cleaned with a pressure washer (20670 kPa).

The six sealant materials were applied in accordance with the manufacturers' directions. The manufacturers stated that some of the resinous materials could not be applied to the wider cracks and that the CEM and MC1 could not be applied to very narrow cracks. Also one of the HMWMs had to be applied by an independent firm using a vacuum injection process.

When testing for the freeze/thaw effects on the beam, the experiment followed a modified ASTM C666 procedure (*Standard Test Method for Resistance of Concrete to a Rapid Freezing and Thawing*). This was achieved by recording the weight and the transverse frequency of the specimen every 30 to 36 cycles. The beams were subjected to 300 cycles total. The loss of weight and decay in the transverse frequency indicated that the sealant was failing.

Different samples were also tested for fatigue at the Infrastructure Laboratory of the University of Rhode Island. The fatigue testing of the beams was done in accordance with a modified ASTM C78 procedure (*Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Bending)*). The frequency used for loading the repaired beams was 10 Hz (10 cycles/s). The loading commenced until the beam either failed or the beam received 10,000 cycles.

Main Findings and Conclusions

According to the freeze/thaw testing, all of the sealant performed well. The durability factor for each of the sealants was determined from ASTM C666. With a slight improvement in fundamental transverse frequency, the two HMWM sealants performed the best (+4.31 and +1.37). The two epoxy sealants also performed well with only a slight loss in fundamental transverse frequency (-1.36 and -5.01). The MC1 performed slightly worse than the epoxy (-6.37), and the CEM performed the worst of all of the sealants used. The CEM products were the only sealant that lost a large fraction of its fundamental transverse frequency (-28.11 and -133.4).

After the fatigue testing was concluded it was apparent that the control beams performed the best. The control beams lasted an average of 154,200 cycles. The two epoxy sealants performed the best of the repaired beams. The epoxy sealed beams lasted for 130,800 and 100,600 cycles. One of the HMWM preformed almost as well as the epoxy repaired beams with 99,900 cycles. The other HMWM failed during the first cycle which would suggest that the beam was improperly repaired or that there was a major flaw in the beam. The MC1 sample sustained an average of 67,700 cycles. Lastly, the CEM sample performed the worst (similar to the freeze/thaw tests) with 410 cycles.

In conclusion, all sealants besides CEM preformed well during the freeze/thaw testing. The two HMWM sealants performed the best, followed closely by the epoxy sealants. The epoxy sealants performed the best in the fatigue analysis, and were followed closely by one of the HMWMs. In the smaller cracks the epoxies seemed to edge over the HMWMs, but in the larger cracks it was the opposite. Due to this, it is challenging to pick the best performing sealant between the HMWMs and the epoxies; however, it was clear that the HMWMs and epoxies outperformed the other two materials.

Crack Sealers Tested

test no.	high-molecular weight methacrylate (HMWM)	reactive methyl methacrylate (MMA)	methacrylate	polyurethane	urethane polurea hybrid	epoxy	Cementitious System	Modified Cementitious System
1	i							
2	i							
3						i		
4						i		
5							i	
6								i
i = investigated								

There were six crack sealers tested in Tsiatas and Robinson's 2002 study. The performance of two epoxies (abbreviated E1and E2 in report), two high-molecular weight methacrylate (MA1 and MA2), one cementitious material (CEM), and one modified cementitious material (MC1) were compared and contrasted in this report.

Aspects of Performance Investigated

	performance criteria		factors affecting performance		
	depth of penetration	bond strength	freeze-thaw exposure	temperature	Fatigue
laboratory investigation			i		i
field investigation					
i = investigated					

B.3.12 Whiting (September 13, 2006)

“Technical Memorandum: TH 100 Bridge #27254 – Sealing and Chloride Intrusion”

Description

The TH 100 Bridge (#27254) was constructed in 2004 and experienced substantial cracking during the curing process. A high-molecular weight methacrylate (HMWM) flood coat was immediately applied to the deck to help alleviate problems associated with cracking. In 2006, after 2 years of exposure to freeze-thaw, weathering, abrasion, and deicing salts, eight cores were taken from the deck. Four of the cores (4 inches in diameter) were taken in such a manner that a crack ran transversely across their diameter; the four remaining cores (2 inches in diameter) were drilled within 6 to 10 inches of the 4 inch cores. No cracks intersected the 2 inch cores.

Whiting initially tried to measure the bond strength of the HMWM with the 4 inch cores, but three of the four cores either broke upon coring or test set-up. With only one intact core remaining, a test that measured the seepage rate of water into the cores was performed instead. The seepage test was conducted on the intact core with the apparent “sealed crack”, a core with “no crack”, and a core with an “open crack”; the open crack core was held together with tape. The seepage rate test was performed by first placing the respective core in a beaker. Then, a 1 inch diameter water reservoir was attached to the top surface of the cores with a silicon seal. For the cracked cores, the water reservoir was attached over a portion of the crack in question. The water reservoir was then filled with 2.75 inches of water; water drop was timed to determine the seepage rate into the cracks or uncracked concrete respectively.

Acid-soluble (total) chloride concentration with depth was performed on one of the 2 inch diameter uncracked cores. Also, total chloride concentration as a function of depth and lateral distance from the crack was performed on the sealed and one of the open crack cores. See Appendix A.1 for a description of how the chloride analysis was performed on the cracked and uncracked cores.

Depth of penetration of the HMWM into the cracks was also measured from the 4 inch cracked cores. Crack face walls were examined at magnifications up to 150 times; the presence of the HMWM on the crack walls with depth was noted.

Main Findings and Conclusions

The uncracked concrete exhibited a seepage rate roughly three orders of magnitude smaller than that of the crack which still appeared to be sealed. This “sealed” crack proved to demonstrate a seepage rate roughly two orders of magnitude smaller than that of the “open” crack. The benefit of a sealed crack over an open crack was clearly seen in the water seepage results. Also, uncracked concrete proved to exhibit much lower permeability than the cracked concretes.

Chloride results for the uncracked, sealed crack, and open crack cores corroborated the water seepage results. Within one inch of the cracks, chloride concentrations with depth were notably higher in the cracked cores than in the uncracked core. Between the sealed crack and open crack cores, the open crack core exhibited higher chloride concentrations with depth than the sealed crack core. Beyond one inch from the cracks, chloride concentrations with depth were very similar for all three cores.

Depth of penetration results indicated the presence of the HMWM could not be seen any deeper than three-eighths of an inch on the crack face walls. Whiting points out the crack face walls were coated with dirt and silt and that could have been shadowing the presence of the sealer. Whiting also notes that wetting the crack face walls did not aid in spotting signs of the sealer.

Crack Sealers Tested

test no.	high-molecular weight methacrylate (HMWM)	reactive methyl methacrylate (MMA)	methacrylate	polyurethane	urethane polurea hybrid	epoxy	epoxy resin	silicon joint sealer
1	i							
i = investigated								

A high-molecular weight methacrylate (HMWM) flood coat was implemented in the study.

Aspects of Performance Investigated

	depth of penetration	bond strength	seepage rate	freeze-thaw exposure	temperature	surface cleaning
	performance criteria			factors affecting performance		
laboratory investigation						
field investigation	i	i	i			
i = investigated						

B.3.13 Wiss, Janney, Elstner, and Associates (2000)

"Evaluation of Cracked Bridge Decks Treated with Various High Molecular Weight Methacrylate Resins for the Montana Department of Transportation"

Description

This study looks at 26 different bridges that were sealed using HMWM resin in Montana. The cracks on these bridges were caused by plastic shrinkage, drying shrinkage, thermal effects, loads, reactive aggregate and freeze/thaw damage. HMWM resins were chosen due to there low viscosities. Low viscosity resins are beneficial because they can penetrate very narrow cracks in the bridge deck. Also HMWM resins were chosen because of their low volatility. Materials such as methyl methacrylates are considerably more volatile and can evaporate too quickly. The sealants were applied between temperatures of 55 and 90 degrees Fahrenheit to control their gel times.

Two to four cores were taken from each of the 26 bridges to test for depth of penetration. The core locations were chosen so that they contained a "typical" type of crack for the particular bridge. Most cracks in the 26 bridge decks were transverse, diagonal, or longitudinal. Due to a heavy layer of resin on some of the bridge decks, the bottom of the bridge was checked to determine where the cracks occurred. This needed to be done because the cracks could not be seen from the top of the deck. However, the resin from the older applications (1996 or before) had worn away from the bridge deck and the cracks could easily be seen. The depth of penetration was checked using stereo microscopes. Florescent and long-wave UV lighting was used to see the resin depth more easily. The penetration depth of each sealant was determined and compared to one another. Also the penetration depths of the high (30 percent) and low (10 percent) elongation sealants were compared. Lastly, the bridge decks were inspected to determine if any new cracks formed near the newly repaired cracks.

Main Findings and Conclusions

Each sealant except Sika Pronto 19 had an average maximum penetration depth of 14 mm or more: American Concrete Systems – 14.1 mm, Harris Specialty Chemicals – 14.5 mm, and Transpo – 14.7 mm. The Sika Pronto 19 had an average maximum penetration depth of 2.8 mm. Although there was a wide range of results, no significant difference was detected in penetration among high and low elongation sealers. One observation proved that penetration tended to be deeper in crack widths of 0.4 mm or less.

Visual inspection of the 26 decks showed that very few new cracks appeared after the old cracks were repaired. This was due to the stress transferring to the steel after the concrete cracked initially. Also most of the decks do not leak during rainfall. Engineers determined that structural bonding of the cracks was not achieved due to the large amounts of dirt and contaminants in the cracks. This large amount of dirt also hindered the penetration depth of the resin. However, engineers did determine that protection against chloride ions was achieved in numerous part of the bridge decks. Engineers suggest a reapplication of the HMWM resin in four to five years to prevent new leaking that occurs from moving cracks and failed sealant bonds. Also the application of a silane deck sealer was suggested because it could penetrate past the contaminants more easily.

Crack Sealers Tested

test no.	high-molecular weight methacrylate (HMWM)	reactive methyl methacrylate (MMA)	methacrylate	polyurethane	urethane polurea hybrid	epoxy	epoxy resin	silicon joint sealer
1	i							
2	i							
3	i							
4	i							
5	i							
6	i							
7	i							
8	i							
i = investigated								

Eight high molecular weight methacrylates (HMWM) were used in this study. All eight sealants were gravity fed.

Aspects of Performance Investigated

	depth of penetration	bond strength	freeze-thaw exposure	temperature	surface-prep methods
	performance criteria		factors affecting performance		
laboratory investigation					
field investigation	i				
i = investigated					

B.4. “Other” Research

B.4.1 McGettigan (1992)

“Silicon-Based Weatherproofing Materials”

Summary

How Silanes and Siloxanes Function:
The molecular structure of silanes and siloxanes consists of alkyl and alkoxy groups bounded to a centrally located silicon atom. The alkyl and alkoxy groups are known as “organofunctional” and “silicon functional” groups respectively. The alkyl group is nothing more than a hydrocarbon group (carbon and hydrogen atoms arranged in some structure), and the alkoxy group is nothing more than a hydrocarbon group attached to oxygen. The alkoxy groups undergo hydrolysis in the presence of moisture in the substrate to yield unstable silanol molecules. These unstable silanol molecules then undergo condensation in which they bond together to form a continuous network of protection against water intrusion. The silanol “network” then penetrates into the capillary structure of the concrete and bonds to available hydroxyl groups connected to the silicate structure of the concrete substrate. The bonded silanol “network” leaves exposed alkyl groups to repel water and consequently chloride intrusion. These exposed alkyl groups, bonded to the concrete substrate through the silanol network, lower the surface tension of the substrate to less than that of water, thus creating a water-repellent surface. In summary, the alkyl group is responsible for the silane’s or siloxane’s degree of hydrophobicity while the alkoxy group is responsible for binding the silane or siloxane to the silicate structure of the concrete substrate.

Composition - Factors Affecting Water and Chloride Repellency and Alkali Resistance:
The size of the alkyl group corresponds to the surface tension reduction or degree of water-repellency imparted onto the concrete substrate by the silane or siloxane. Higher molecular weight alkyl groups such as iso-butyl and n-octyl provide a larger hydrophobic effect than lower molecular weight alkyl groups such as methyl and ethyl. Also, the structure of the molecule of the alkyl group affects how well the silane or the siloxane repels water. For instance, a branched alkyl group repels water more effectively than a straight chained alkyl group; a cyclic structured alkyl group performs the worst of the three molecular orientations. The author brings up the point that chlorides permeate into the concrete in their hydrated form; thus, the size and structure of the alkyl group is also responsible for the degree of chloride repellency imparted onto the substrate by the silane or siloxane. The author also describes the benefit of higher solids content on water and chloride repellency; enough of the silane or siloxane “active ingredient” is needed to provide a continuous, bonded network of protection throughout the substrate.

The size and structure of the alkyl group is also responsible for the silane or siloxane’s long term alkali resistance. Concrete is a naturally alkaline (basic) environment; hydroxide ions can penetrate past the alkyl group barrier and break apart the linkage between the silanol molecules and their bond to the substrate. This broken up network allows more water and subsequent chloride ingress into the substrate. Higher molecular weight alkyl groups with branched structures offer the best resistance to the intrusion of hydroxide ions.

The author addresses siloxanes as generally having lower alkali resistance and water and chloride repellency than silanes because siloxanes usually incorporate a greater fraction of low molecular weight alkyl groups (i.e. methyl).

Composition – Factors Affecting Visible and "Working" Depth of Penetration:
The alkoxy group of a silane or siloxane determines the respective sealer's depth of penetration. The author distinguishes between visible and working penetration though; the degree of water and subsequent chloride repellency may not be consistent throughout the silane or siloxane's visible depth of penetration. Thus, only a portion of the visible penetration, or the working penetration, of the sealer remains effective at repelling water and chloride ingress. McGettigan then describes uniform gradient permeation (UGP) which expresses how consistent the silane or siloxane is able to repel water and subsequently chloride ingress throughout its visible depth of penetration. McGettigan mentions a test developed by Alberta Transportation and Utilities which qualitatively measures this UGP of a silane or siloxane; the absorption of treated concrete is measured before and after abrading 1 mm of the sealed surfaces of the specimens.

McGettigan describes how the alkoxy group controls the rate of hydrolysis and condensation for the silane or siloxane. For example, ethoxy reacts much more slowly than that of methoxy. Alkoxy groups that hydrolyze and condense more quickly than others before bonding to the substrate will produce a greater degree of UGP due to a more continuous network of protection throughout the depth of the substrate. However, faster reacting alkoxy groups such as methoxy cause the silane or siloxane molecules to grow as much in four times in size as a result of hydrolysis and condensation before bonding to the substrate. The resultant ends up hindering the penetration of the silane or siloxane into the capillary structure of the concrete. Slower reacting alkoxy groups such as ethoxy theoretically allow the silane or siloxane to penetrate deeper into the substrate while the alkoxy group undergoes hydrolysis and condensation before bonding to the substrate.

Silanes are smaller molecules than siloxanes (10 to 15 verse 25 to 75 Angstrom units respectively). So, theoretically, silanes penetrate deeper into the pore openings (20 to 200 Angstrom units) than siloxanes with similar characteristics.

McGettigan also mentions that higher solids content increase the degree of UGP and visible depth of penetration for silanes or siloxanes. The more active ingredient applied to the surface, the more likely enough material is present to form a continuous network of protection throughout the depth of the substrate.

The effect of the carrier used for the silane or siloxane is also discussed; the carrier stabilizes the silane or siloxane active ingredient and disperses it throughout the surface of the concrete medium. Alcohol solvents are often preferred over petroleum-based solvents due to alcohol being able to mix with water and petroleum not possessing this quality. Thus, concretes with high moisture contents impede penetration of a silane or siloxane with a petroleum-based carrier. McGettigan cites 100% silanes (no carrier, all active ingredient) as the best penetrating products due to optimization of physical and chemical properties.

Composition – Factors Affecting VOC Content:

The volatile organic compound (VOC) content of silanes or siloxanes is embedded in their solvent carrier, if not a water-based product, and the alcohol released by their alkoxy groups during hydrolysis. McGettigan describes manufacturers of silanes and siloxanes creating products with higher solids content and thus lower solvent content in order to meet VOC emission rate legislature. The increased production of water-based products was also noted. The author mentions solvent-based products as better performers than water-based products. However, improvements in water-based product technology are noted as limiting the variation in performance between the two groups.

B.4.2 McGettigan (1995)

“Factors Affecting the Selection of Water-Repellent Treatments”

Summary

McGettigan describes the difference between film formers and penetrants. Film formers, such as acrylics, stearates, mineral gum waxes, and silicone resins, do not penetrate into the capillary structure of the concrete. These types of sealers deposit their active ingredient on the concrete’s surface to create a barrier against subsequent chloride and water ingress. The effectiveness of film formers against water and chloride intrusion is hence determined by the porosity of the “film barrier”. Sealers commonly marketed as penetrants: silicates, siliconates, silanes, and siloxanes, penetrate into the pore structure of the concrete. Siliconates, silanes, and siloxanes function in a different manner than silicates; these three type of penetrating sealers impart water-repellency onto the concrete substrate by lowering its surface tension to less than that of water. Water vapor can still freely pass through the silane or siloxane treated concrete though since water vapor does not have a surface tension. Silicates repel water and subsequent chloride ingress by filling the pore structure of the concrete with precipitated silicon dioxide.

The molecular structure of silanes and siloxanes consists of alkyl and alkoxy groups (organofunctional and silicon functional groups respectively) bonded to a centrally located silicon atom. The alkyl group is responsible for the degree of surface tension reduction or water-repellency; a silane or siloxane’s alkoxy group controls the bonding of the sealer to the substrate. McGettigan cautions the type of alkyl and alkoxy group comprising the silane or siloxane contribute to the final performance of the product.

Silanes or siloxanes contain either a solvent or water carrier; typical solvents include alcohols and mineral spirits. McGettigan points out that the specific type of carrier can affect silane or siloxane performance, especially with a solvent vs. water-based product.

Silanes or siloxanes do not always exhibit uniform water repellent characteristics throughout their depth of penetration. A majority of the silane or siloxane solids can be concentrated in the upper depths of the visible non-wetting band. The “active ingredient” and thus water and chloride repellency is not consistent throughout the product’s depth of penetration.

McGettigan also stresses the importance of testing the silane or siloxane’s water-repellency on a substrate of the same composition the sealer will be applied to. McGettigan warns subtle changes in a substrate’s composition can affect the water-repellency of a silane or siloxane.

B.4.3 Oh (2004)

“Chloride Diffusion and Corrosion Initiation Time of Reinforced Concrete Structures”

Summary

The chloride binding capacity was defined as the ratio of free chlorides to total chlorides within the concrete, where total chloride concentration equals the free plus bound chloride concentration. Free chlorides contribute to reinforcement corrosion where bound chlorides do not. Thus, the larger the free chloride content, the less bound chlorides and the smaller the chloride binding capacity of the concrete. Through a theoretical model using Fick’s second law, the chloride binding capacity of concrete was predicted. Type 1 cement with w/c ratios of 0.4 and 0.6 and type 3 cement with a w/c ratio of 0.4 were inputted into the model to help distinguish the effect that water to cement ratio and cement type has on the presence of free and bound chloride ions within the concrete. From the results of the investigation it was found that the free chloride content increases as the w/c ratio increases. Thus, the amount of chlorides able to directly initiate corrosion of the reinforcement increases with increasing w/c ratio. Type 1 cement was found to have a higher free chloride content, thus smaller binding capacity, than type 3 cement (both had the same w/c ratio of 0.4).

Chloride diffusion modeled by Fick’s second law was expanded to predict the effect that rebar has on chloride diffusion through reinforced concrete structures. In this model variables were reinforcement or no reinforcement, the diameter of the reinforcing steel, and the cover depth. The results showed that the presence of reinforcement caused a build up of chlorides. Further characterizing the results, the larger the diameter of the reinforcing steel, the more pronounced the accumulation of chlorides was. Increasing the cover depth negated the chloride accumulation in front of the reinforcing bar somewhat. The reinforcement blocked the chlorides from diffusing further into the concrete and thus caused chloride accumulation. The author warns that this chloride build will lead to a shorter time to corrosion initiation of the reinforcement. Using a chloride corrosion threshold value of 1 percent total chlorides by cement weight, time to corrosion initiation of the reinforcement was computed for the different concretes modeled. The results indicated that including the presence of reinforcement in the chloride diffusion model reduced the calculated corrosion initiation time by roughly 20-30 percent. These results suggest that cores taken from the field where reinforcement is present may potentially give much larger chloride concentrations than cores taken where reinforcement is not present or laboratory samples. In analyzing the effectiveness of sealers by chloride ingress, the above realization may help explain discrepancies between field and laboratory results.

The study concluded with a laboratory analysis to investigate chloride binding for concretes with varying cement types, w/c ratios, mineral admixture, and total chloride addition (sodium chloride used). The cement was either type 1 ordinary Portland cement (OPC) or type 5 sulfate resisting Portland cement (SRPC). Water to cement ratios evaluated were one of the following: 0.55, 0.45, or 0.35. Percent fly ash, percent slag, or none were the mineral admixture variables. The total chloride addition ranged from 0 to 2 percent total chlorides by cement weight.

Prismatic samples with a centrally located reinforcing bar were constructed for each concrete studied. Free chloride content and OH^- concentration were measured at the end of 30 days. The rebar was extracted from each sample at the end of 30 days and the percent corroded area was determined. General trends were seen from the results of the analysis. Type 1 OPC had a greater chloride binding capacity than type V SCRP; thus OPC had a smaller free chloride content for the same total chloride addition. The author tributes the greater chloride binding capacity of OPC to its higher C_3A content which is one of the parameters directly responsible for chloride binding. Another trend witnessed, as in the theoretical study, was the increase in free chloride content, or decrease in chloride binding capacity as the w/c ratio increased.

Free and total chloride threshold values (percent total and free chloride by cement weight respectively) were also determined as a result of the laboratory study. Analysis indicated that corrosion initiation of the reinforcement occurred anywhere between 0.45 and 0.97 percent total chlorides by cement weight for the concretes evaluated. In the case of free chloride content, corrosion initiation occurred anywhere between 0.07 and 0.013 percent by cement weight. Three implications are suggested by this data. Number one, a large fraction of the total chlorides was bound for each concrete and thus only a small percentage of the total chlorides was contributing to reinforcement corrosion. Number two, the binding capacity of concrete varies for the cement type and chemical composition, mineral admixtures, and w/c ratio used. Lastly, the data suggests that the free chloride content is a more reliable indicator for addressing whether or not corrosion initiation of reinforcement has occurred in reinforced concrete structures.

B.4.4 Whiting (1990)

"Penetrating Sealers for Concrete: Survey of Highway Agencies"

<u>*Summary*</u>

Whiting surveyed 50 U.S. state highway agencies (SHAs) and 11 Canadian provincial highway agencies (PHAs) in 1989 to determine:

1. Commonality of use of penetrating sealers (i.e. silanes, siloxanes)
2. Most frequent application area for sealers
3. Screening methods used to delineate sealer performance
4. Problem areas in application and performance of sealers

All 61 agencies replied; though four of the U.S. and two of the Canadian agencies indicated they did not make use sealers. The data base for the survey responses summarized below thus only contained information on sealer use for 46 U.S. and 9 Canadian agencies.

Commonality of Use of Penetrating Sealers (i.e. Silanes, Siloxanes):
Agencies were asked to categorize their use of penetrating sealers and linseed oil as extensive, moderate, limited, and experimental. These categories simply represented the agencies perceived use of the product in the field. Results indicated linseed oil was used more extensively than penetrating sealers among the agencies. However, a large majority of the agencies indicated using penetrating sealers on a limited or experimental basis suggesting a trend to the increased implementation of penetrating sealers.

Most Frequent Application Area for Sealers:
Responses indicated sealers were applied most frequently on the surface of bridge decks; thus deck deterioration due to chloride ingress and subsequent corrosion of the reinforcement appeared to be the primary concern among the highway agencies. Application of sealers to substructural elements such as piers, pier caps, and beams was far less common among the respondents.

Screening Methods Used to Delineate Sealer Performance:
The most common screening methods used to differentiate sealer performance among the agencies included relying on vendor data and conducting internal testing within their own laboratories. Agencies that relied on internal testing were asked to identify the laboratory test procedure/s they used to differentiate sealer performance; the AASHTO T259/T260 procedure and the NCHRP 244 Series II tests proved to be by far the most frequently cited among the agencies. The NCHRP test procedure resulted from the first major laboratory investigation of sealer performance; thus the test sequence is not standardized and variation in testing procedure and results is possible. Performance measures quantified by the NCHRP 244 Series II test procedure include salt-water absorption, vapor permeability, and chloride ingress. The AASHTO T259/T260 procedure solely evaluates chloride ingress through a sealed concrete's surface by ponding the top surface of the specimen with salt-water.

ASTM C642 (measures absorption through sealed face) and other non-standardized absorption tests proved to be the next most common laboratory test procedures used among the agencies.

Penetration depth and vapor permeability tests developed by the Oklahoma DOT followed close behind. Only one or two agencies reported using tests for deicer scaling resistance (ASTM C672), freeze-thaw resistance (ASTM C666), rapid chloride permeability (AASHTO T277), and skid resistance testing.

Whiting also questioned the agencies in how they evaluate/ differentiate sealer performance through their field testing. Most agencies did not indicate use of field testing; for those that did, the majority evaluated sealer performance by chloride sampling either with cores or drill dust samples. A small percentage of the agencies specified to qualitatively measure sealer performance by flooding the treated areas of the deck with water and seeing if the water "beads".

Problem Areas in Application and Performance of Sealers:
Problem areas noted in the application of penetrating sealers included "drifting and evaporation in hot and windy conditions, difficulty in obtaining specified coverage on newly placed concrete, slippery surfaces when linseed oil or other more viscous sealers were used, runoff during application, discoloration of concrete, flammability, non-uniform application, and little or no apparent penetration."

Problem areas were also noted in the performance of penetrating sealers. Agencies reported penetrating sealers were not effective as claimed or ineffective at reducing chloride ingress. Also, the effectiveness of penetrating sealers at reducing chloride ingress was noted to decrease from year to year; after 3 years penetrating sealers were generally deemed ineffective. "Other performance problems included reduction of skid resistance (for sealers that left a surface residue), failure to improve freeze-thaw and scaling resistance in non-air-entrained concretes, and failure to halt corrosion of reinforcing steel (as measured by half-cell potential surveys.)"