Crack and Concrete Deck Sealant Performance

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Executive Summary

The research objective of this 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 reinforcing steel bars. The prevention of corrosion is important because corrosion produces expansion and local tensile forces in the concrete deck. Due to the weakness of concrete to carry tensile forces, the deck will begin to spall and deteriorate.

The report includes the information generated from a literature review and survey. The literature review focused 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. There are many issues regarding this practice that are considered. The report discusses how solids content of a penetrating sealer affects its penetration depth and effectiveness. A discussion is included regarding the potential negative effects to rebar 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 discussed. Also the report determines the number of coats before reapplication becomes ineffective. These important issues as well as others regarding the performance of deck sealants will be discussed throughout the report.

Because chloride ions can penetrate the cracks much faster than solid concrete, cracks pose a more immediate danger to the rebar. By preventing this fast-tracking of chloride

ion ingress, 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 on whether new cracks form near repaired cracks are collected. The length of time crack sealing products must be allowed to cure before normal traffic is allowed to traverse the bridge deck will be documented. Finally questions regarding which crack sealants have performed best in the past will also be answered.

The report consists of four sections. Section I provides a synthesis of the literature review on the background, application, and performance of concrete deck sealants and crack sealers. Section II 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 United States. Section III combines the information gathered from Section I and II to create an assessment of all selection criteria, materials, application practices, and performance. Finally Section IV draws some conclusions from the previous sections and develops some recommendations. In addition, the areas which could benefit from further research will be identified.

Section I (literature review) first gives a background of 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 quantify the test results obtained from the source literature. The performance measures used for concrete deck sealants are chloride ingress, absorption, depth of penetration, and vapor permeability. The NCHRP 244

Series II procedure can be used to quantify all of these performance measures. Other tests like the AASHTO T259/T260, ASTM C642, and Oklahoma DOT Test No. OHD L-35 can be used to test one or more of these performance measures. Laboratory and field testing indicates silane generally outperforms the other deck sealants tested. Also, the literature review shows that solvent based products typically performed better than water based products at preventing chloride ingress. Deck sealing products with higher solids contents also performed better than similar products with lower solids contents. On rare occasion, field tests indicated linseed oil to outperform silane and siloxane in chloride prevention and penetration depth.

A number of variables that affect the performance of deck sealants are discussed in the report. Concrete parameters such as moisture content at time of application and water cement ratio of concrete substrate are covered. A higher moisture content in the concrete at time of application reduces the penetration depth of most penetrating sealants (e.g., silane, siloxane, etc.). The increased moisture content did not have a significant effect on the water absorption of penetrating sealants. However, a higher initial moisture did negatively affect the water absorption of linseed oil barrier sealants. The water cement ratios of concrete test specimens did not seem to have an impact on depth of penetration of the sealant. However, the water cement ratio does affect the water absorption of unsealed concrete. Unsealed concrete specimens with higher water cement ratios absorbed more water in laboratory tests that specimens with lower water cement ratios. This would indicate that concrete with a higher water cement ratios would receive a greater benefit from a penetrating deck sealant.

Concrete parameters such as finishing and curing, surface preparation, coverage rate, abrasion, and freeze-thaw exposure are also discussed in the report. Research showed that smooth (as opposed to tined) concrete had a slight advantage in absorption and chloride ingress prevention. However, concrete finish did not have an effect on the sealants depth of penetration. Also, applying deck sealants over curing compounds can significantly reduce the depth of penetration of penetrating sealants. It is often recommended that curing compounds be removed prior to deck sealant application to maximize their effectiveness. Different studies gave mixed results on whether surface preparation (e.g., shot/sand blasting, power washing, etc.) is necessary prior to deck sealant application. A higher coverage rate of the material does reduce the amount of chlorides present in the concrete, however, it did not effect absorption and vapor transmission. Both laboratory (modified NCHRP 244 Series II) and field tests were conducted to determine the effect of abrasion on chloride intrusion. The field specimens performed much better than those in the laboratory. Differences in test methods and environmental effects are likely to blame for the discrepancy. Testing indicated that freeze-thaw effects lowered the effectiveness of all sealants to deter chloride ions.

The environmental conditions at the time of application can have a direct effect on the performance of the sealant. Moderate temperatures are optimal for sealant application. High temperature and windy conditions can cause insufficient penetration and runoff. Also the deck should be allowed to dry for approximately two days if power washing is used or rainfall is experienced. The weather forecast should also be determined for up to 12 hours after application to avoid excessive temperatures or precipitation.

Whiting (2006b) indicated that reapplication of a water based silane did not have a significant impact on the chloride ion content in the bridge deck. However it was later determined that water-based penetrating sealants are not suited for reapplication because existing sealant in the bridge deck repels the water carrier of the product. Due to this fact, solvent based products should be used for all reapplication purposes. Weyers (1995) estimates the service life for silane and siloxane sealants to be limited to eight years due to traffic abrasion.

The second part of Section I considers concrete crack sealers. The most common crack sealers used are epoxy, high molecular weight methacrylate (HMWM), methacrylate, and polyurethane. HMWM sealers have a low viscosity and are typically applied using a flood coat. This makes the HMWM crack sealers advantageous when the bridge deck has very narrow cracks or if the deck has extensive cracking. Epoxy sealers typically have a higher bond strength, higher viscosity, and are typically (but not exclusively) applied to individual cracks. This means epoxy crack sealers are beneficial when sealing larger cracks or decks with sporadic cracks.

The four performance measures used for the crack sealing portion of the literature review are depth of penetration, bond strength, seepage, and chloride ingress and corrosion. Depth of penetration is tested by splitting the specimen perpendicular to the sealed crack and measuring the depth of the crack sealer. Occasionally ultraviolet lighting or microscopes can be used if the sealer cannot easily be identified with the naked eye. Bond strength of the sealers are typically measured using three-point bending or tensile testing. Seepage is normally quantified by counting the amount of leaks below a bridge deck. Chloride ingress is determined by standard chloride testing. HMWM sealers generally perform the best in depth of penetration tests due to their low viscosity. Epoxy sealers normally perform better in bond strength testing. Seepage and chloride ingress tests are generally inconclusive due to the large uncertainty in test results.

General trends such as lifespan of sealed cracks, presence of re-cracking, and track free time for sealers are also discussed. Research indicates that the lifespan of sealed cracks is highly variable. Laboratory results determined that epoxy sealers outperformed HMWM sealers with respect to sealer lifespan (Meggers 2002). The laboratory lifespan of the sealers varied from eight to 15 years. Field tests (depending on location) showed a large variation in the lifespan of HMWM sealers. The lifespan of these products can range from a very short period to as long as 30 years. Little research was found on the presence of re-cracking on sealed bridge decks. The little information reviewed indicated that re-cracking did not present a significant problem. The track free time for most crack sealers normally ranged between three to six hours.

Variables affecting performance such as effect of temperature, moisture, crack cleanliness, and cracks age are considered in the report. Temperature greatly affects the crack sealer's gel time. This means the temperature at time of application directly affects how fast the crack sealer hardens. Moderate days, with temperatures between 45 and 90 degrees Fahrenheit, are recommended (Krauss 1985). Moisture in the cracks and concrete can also reduce the sealer's penetration depth and bond strength. Because of this, a waiting period of approximately two days prior to application should be given after power washing or rainfall. The cleanliness of cracks prior to sealer application has the greatest effect on the penetration depth and bond strength of the sealer. Because of this dependence, some form of crack cleaning process should be used (e.g., power washing, sand/shot blasting, compressed air, brooms, etc.). Moreover, since contaminants play such an important role in the crack sealing process, older bridge decks are typically harder to seal effectively. This is due to more contaminants being present in older cracks than newer cracks.

The second part of the report (Section II) involves a performance survey and a chloride study. 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 survey indicated that silane is the most commonly used deck sealant. Most states used linseed oil in the past, however Missouri is the only state still using linseed oil. Shot blasting and power washing were the most common types of surface preparation used. The type of surface preparation often depended on the age of the bridge deck. Light cleaning or no cleaning was used on 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. When using this process an application rate of 200-300 ft^2/gallon is typically used. Generally, penetrating sealants are applied immediately after construction and curing of the bridge 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. AASHTO T259 (90-day ponding) and ASTM C642 (absorption) are two common acceptance tests used by states. Very few states perform QA/QC testing on sealants after they are applied in the field. If QA/QC testing is used, penetration depth and chloride content are the most common tests.

The crack sealer portion of the survey indicated that most states use epoxy to seal cracks. HWMW sealers are also common but not as common as epoxy. Compressed air and power washing were the most common types of surface preparation used to clean the cracks. HMWM sealers are typically applied using flood coats at a rate of 90-150 ft^2/gallon. Epoxy sealers are typically applied to individual cracks using a push cart apparatus with a tapered nozzle delivery system. Unlike deck sealants, crack sealers are typically applied long after the bridge deck is constructed. This is done because most decks do not develop cracks until later in their lifespan. However most states indicate that if extensive early age cracking occurs, the cracks will be sealed immediately after construction. States typically did not use acceptance testing for crack sealers. Like deck sealing, very few states use QA/QC testing on the sealed cracks after application. Depth of penetration and chloride content are the most common tests used.

The product assessment chapter (Section III) compiles all the information from the first two sections. The deck sealant portion of this section reiterates the superior performance of silane over either siloxane or linseed oil. Solvent based penetrating sealants perform better than their water based counterparts. Also water based sealants are not fit for reapplication. Lastly, a high content of solids is 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 the product assessment indicates that HMWM and epoxy sealers can both be effectively used. HMWM products are more beneficial for decks with extensive cracking due to the flood coat application. They are also beneficial for decks with very fine cracks because they have a very low viscosity. Epoxy sealers are more beneficial for decks with minimal cracking because they are typically applied to individual cracks. Also epoxy is better suited for larger cracks because they have higher bond strengths.

Finally the last chapter of the report (Section IV) discusses conclusions and recommendations for material selection, application, and testing. The following conclusions and recommendations correspond to concrete bridge deck sealants:

- 90-day ponding (AASHTO T259) and absorption (ASTM C642) tests are commonly used acceptance tests.
- NCHRP 244 Series II test is widely used to quantify performance .
- NCHRP 244 Series II requirements: 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 (if any) QA/QC tests conducted on bridge decks (highly variable and scattered field results).
- 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.
- Solvent based silanes with 40 percent solids are the most commonly produced sealant that fits this criterion.
- Sealants should be applied between the temperatures of 40 and 100 degrees Fahrenheit.

- 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 determine acceptable crack sealing products.
- Products are typically chosen based on well-known research (i.e., Pincheira 2005).
- Depth of penetration and chloride content tests are the most common (if any) QA/QC tests conducted on bridge decks (highly variable and scattered field results are prevalent).
- HMWM products typically provide better penetration (beneficial for smaller cracks).
- Epoxy products typically provide higher bond strength.
- Although variable, epoxy sealers tend to possess good resistance to freeze-thaw effects.
- Choose crack sealer with viscosity less than 500 cP (or 25 cP for HMWM sealers).
- Choose crack sealer with tensile strength more than 8 MPa.
- Choose a crack sealer with tensile elongation larger than ten percent.
- Crack sealers should be applied between the temperatures of 45 and 90 degrees Fahrenheit.
- 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.

SECTION I – LITERATURE REVEIW

Part A – Concrete Deck Sealants

1. Background

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 will be used to quantify results.

1.1 Classifications

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.

1.1.1 *Penetrating Sealants*

Products commonly marketed as penetrating sealers include silicates, siliconates, silanes, and siloxanes. The classification breakdown can be seen in Figure 1. 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.

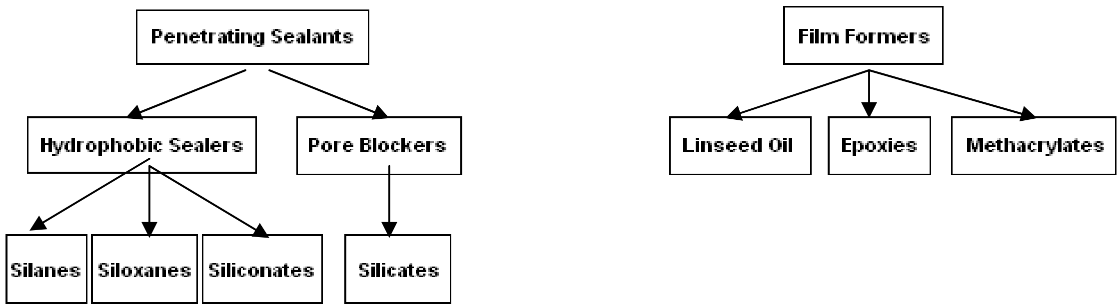


Figure 1: Deck sealant classification breakdown

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. A graphical breakdown of the alkyl and alkoxy groups can be seen in Figure 2.

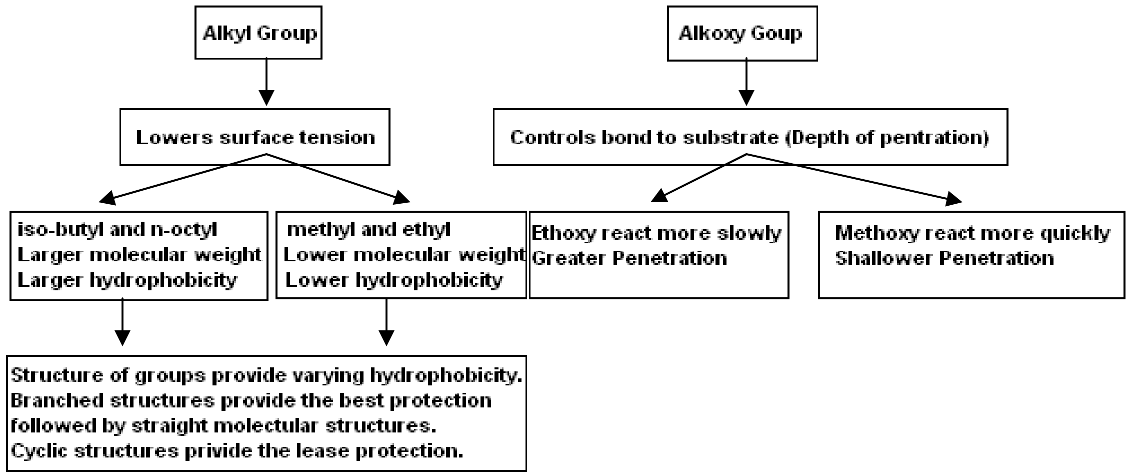


Figure 2: Breakdown of alkyl and alkoxy groups

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.

1.1.2 *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.

1.2 Performance Measures

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.

1.2.1 *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 (picture of setup can be seen in Figure 3). 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.

Figure 3: Example of specimen ready to be ponded (Pincheira 2005)

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 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.

1.2.2 *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.

1.2.3 *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 can be seen in Figure 4.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.

Figure 4: Depth of penetration measurement (Pincheira 2005)

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 6.69×10^{-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 6.69×10^{-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).

1.2.4 *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.

2. Analyzing Performance Measure Data

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.

2.1 Scatter in Data

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.

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).

2.2 Correlation among Performance Measures

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 ingress 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.

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 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.

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. 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).

3. Best Performers

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.

3.1 Chloride Ingress

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 degrees Fahrenheit 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 didn't 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.

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 indicated 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 indicated 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.

Summary

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 performing 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 Figure 5, Tables 1.1, and 1.2 for laboratory and field data pertaining to chloride intrusion.

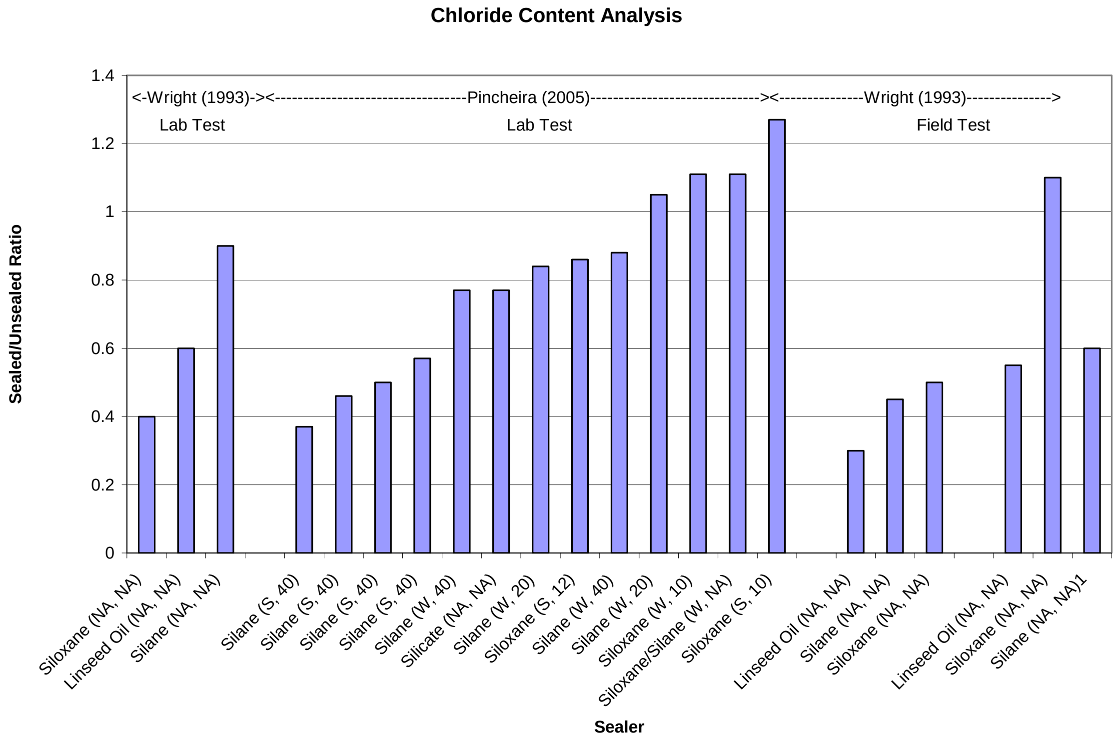


Figure 5: Chloride content analysis different studies

Table 1.1: Laboratory Results for Chloride Ingress

Materials (Water/Solvent Based, Solids %) -list from best to worst performance-	Whiting	Wright	Weyers	Smutzer	Pincheira's
	1992	1993	1995	1993	2005
	Laboratory				
	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

Materials (Water/Solvent Based, Solids %) -list from best to worst performance-	Wright 1993/Street	Wright 1993/Highway	Whiting 2006a	Smutzer 1993	Hagen's 1995
	Field				
	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

3.2 Absorption

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.

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.

Summary

Pfeifer's (1981) results indicated that all surface coatings of a generic composition (i.e., epoxies, methacrylates) do not exhibit similar salt-water absorption 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%).

3.3 Penetration Depth

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.

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.

Summary

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 and Figure 6 for depth of penetration results.

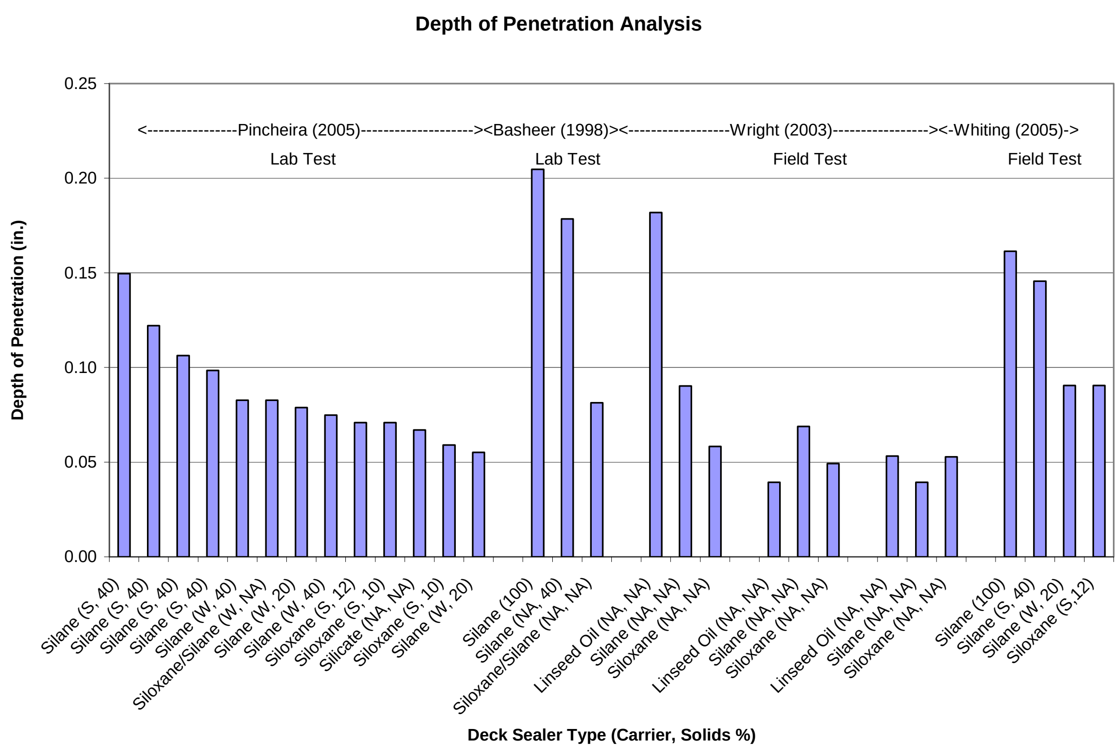


Figure 6: Depth of penetration analysis for different studies

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 (Water/Solvent Based, Solids %) -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

3.4 Vapor Transmission

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.

Field Investigations

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

Summary

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.

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 will be quantified using the four previously mentioned performance measures.

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.

4.1.1 *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.

4.1.2 *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 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.

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.

4.2.1 *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.

4.2.2 *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 at 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.

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). Figure 7 shows an example of a bridge being sandblasted prior to application.

Figure 7: An example of a sandblasting surface preparation (Smutzer 1993)

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.

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.

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 lab

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.

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 (seen in Figure 8). 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.

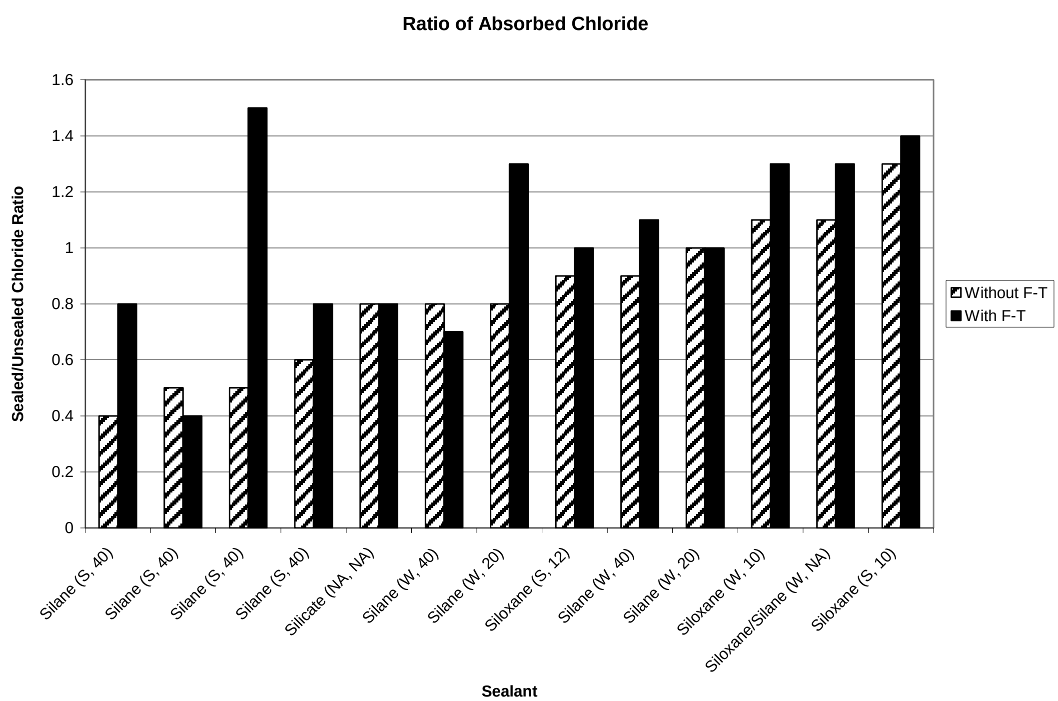


Figure 8: Freeze-thaw effects on sealants (Pincheira 2005)

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.

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.

4.8.1 *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 manufacturer 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 the application day should be taken into consideration.

4.8.2 *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.

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.

Part B – Concrete Crack Sealers

6. Background

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.

6.1 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 respondents (i.e., six of the 25 states and provinces or 24%) indicated the use of either epoxies and methacrylates when repairing bridge decks. Although the survey indicated the use of epoxies and methacrylates as 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 the 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.

6.2 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.

6.2.1 *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 0.1 in. 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.

6.2.2 *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 a 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) which can be seen in Figure 9. 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.

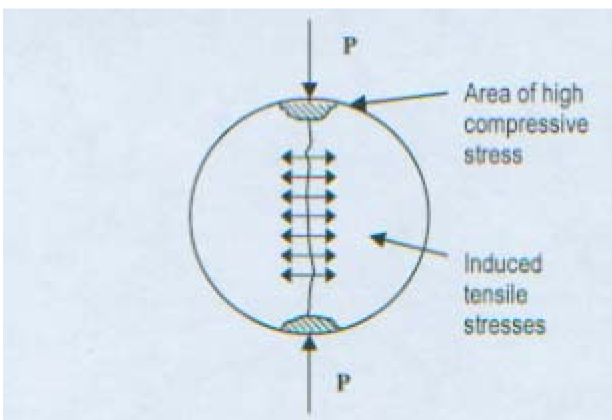


Figure 9: Tensile splitting test (Pincheira 2005)

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.

6.2.3 *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 water seepage would protect the rebar better than a deck with a faster water 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.

6.2.4 *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.

7. Performance

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.

7.1 Depth of Penetration

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 degrees Fahrenheit. 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.

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.

Summary

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.

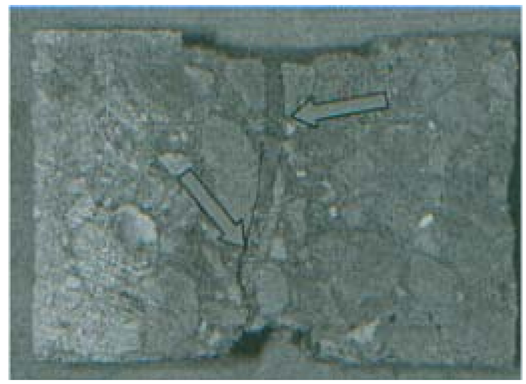
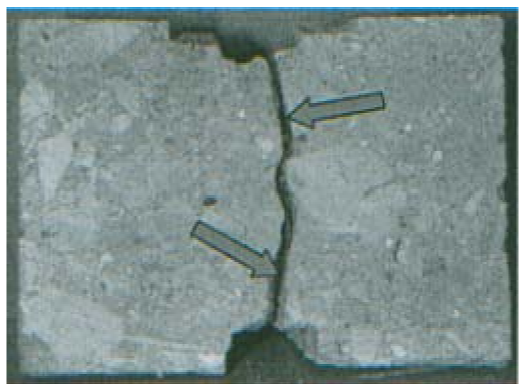
The field tests indicate that HMWM and methyl-methacrylates performed the best in penetration tests. Krauss (1985) documented a case in which an epoxy sealer failed to penetrate the cracks of a bridge deck. After the epoxy's failure, a HMWM was used to successfully seal the same cracks. Meggers (1998) 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.

7.2 Bond Strength

The bond strength section will be 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.

7.2.1 *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. Examples of these three failure types can be seen in Figures 10, 11, and 12. 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.

Figures 10, 11, and 12: The upper left figure shows an example of a concrete failure. The upper right figure shows an example of a bond failure. The final (lower) figure shows an example of a sealant failure (Pincheira 2005).

<u>*Laboratory Investigations*</u>

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.

Field Investigations

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.

Summary

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.

7.2.2 *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.

Laboratory Investigations

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.

Field Investigations

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.

Summary

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.

7.2.3 *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 that will be used in Minnesota. A picture of a freeze-thaw chamber can be seen in Figure 13.

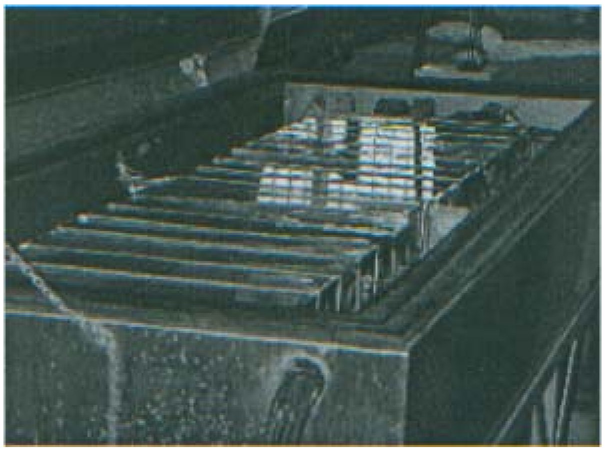


Figure 13: An example of a freeze-thaw chamber (Pincheira 2005)

Laboratory Investigations

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.

Field Investigations

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.

Summary

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.

7.2.4 *General Performance*

<u>*Laboratory Investigations*</u>

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 degrees Fahrenheit. 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.

<u>*Field Investigations*</u>

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.

Summary

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.

7.3 *Seepage*

Laboratory Investigations

No laboratory investigations found.

Field Investigations

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.

Summary

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.

7.4 Chloride Ingress and Corrosion

The chloride ingress and corrosion section will be 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.

7.4.1 *Increased Chlorides Concentration Locations*

This section will discuss where higher levels of chloride ions can be located. Once problem areas 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 the sample was measured from.

Laboratory Investigations

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.

Field Investigations

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 was 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.

Summary

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.

7.4.2 *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 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.

Laboratory Investigations

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.

Field Investigations

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.

Summary

Very little literature covers a cracks sealer's ability to 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 likely contained high levels of chlorides in the deck. This problem may 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.

7.4.3 *General Performance*

Laboratory Investigations

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 $1.0\mu A/cm^2$ was considered the maximum rate. This is due to that fact that when the corrosion rate gets to$1.0\mu A/cm^2$, damage from the corrosion begins to take place. The unsealed cracked beam reached the corrosion rate of $1.0\mu A/cm^2$ in 50 days. After plugging this into an equation, it was determined that the unsealed crack could keep corrosion below $1.0\mu A/cm^2$ 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.

Field Investigations

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.

Summary

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, Meggers 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.

8. 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 will be split into the following topics: lifespan of sealed cracks, the presence of recracking, and track free time for sealers.

8.1 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.

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 1.0μA/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 1.0μA/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.

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-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 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.

Summary

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.

8.2 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.

Laboratory Investigations

No sources included laboratory tests that investigated re-cracking of concrete.

Field Investigations

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.

8.3 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.

Laboratory Investigations

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.

Field investigations

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.

Summary

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.

9. 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 will be addresses are the effect of temperature, moisture, age of crack, cleanliness of crack., thermal effect on crack width, and type of initiator.

9.1 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 epoxies, 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 degrees Fahrenheit (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 by temperature 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 degrees Fahrenheit 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).

9.2 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).

9.3 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.

9.4 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.

9.5 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.

9.6 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 will be 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 ¾^{ths} 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.

10. 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.

SECTION II – PERFORMANCE SURVEY AND CHLORIDE STUDY

Part A – Performance Survey

11. 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.

12. 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.

12.1 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 will be discussed. Deck sealants that have not made it past the testing phase or which are not widely used will be discussed in section 15.3 of this report.

12.1.1 *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).

12.1.2 *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).

12.1.3 *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.

12.2 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 will be summarized. Crack sealers that have not made it past the testing phase or which are not widely used will be discussed in section 15.3.

12.2.1 *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.

12.2.2 *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 high the sealant will gel too fast and not penetrate the crack. If the temperature is too low 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.

13. 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.

13.1 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 (which can be seen in Figure 14). 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.

Figure 14: An example of a deck sealant applied using hand sprayers (Whiting)

13.2 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 were the next most common procedures 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 (which can be seen in Figure 15) 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 (which can be seen in Figure 16 and 17). 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.

Figure 15: An example of a flood coat (Smutzer 1993)

Figure16 and 17: Examples of sealing individual cracks (Soriano 2002)

14. Application Timing

This section discusses the timing states choose to seal the 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.

14.1 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.

14.2 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.

15. 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.

15.1 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.

15.2 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 resistance 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).

15.3 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.

15.4 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.

15.4.1 *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.

15.4.2 *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.

Part B – Chloride Study

16. Introduction

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.

17. 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.

17.1 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).

17.2 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.

18. 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 18) 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.

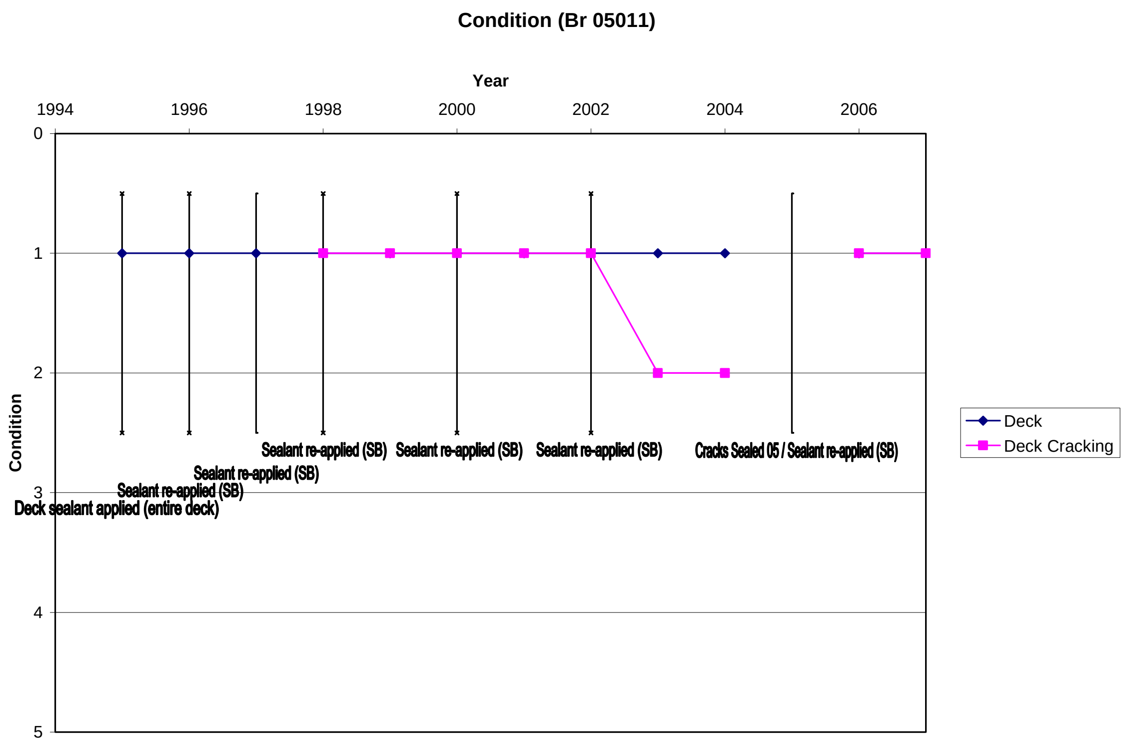


Figure 18. Bridge of Hope deck inspection condition

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 19). 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.).

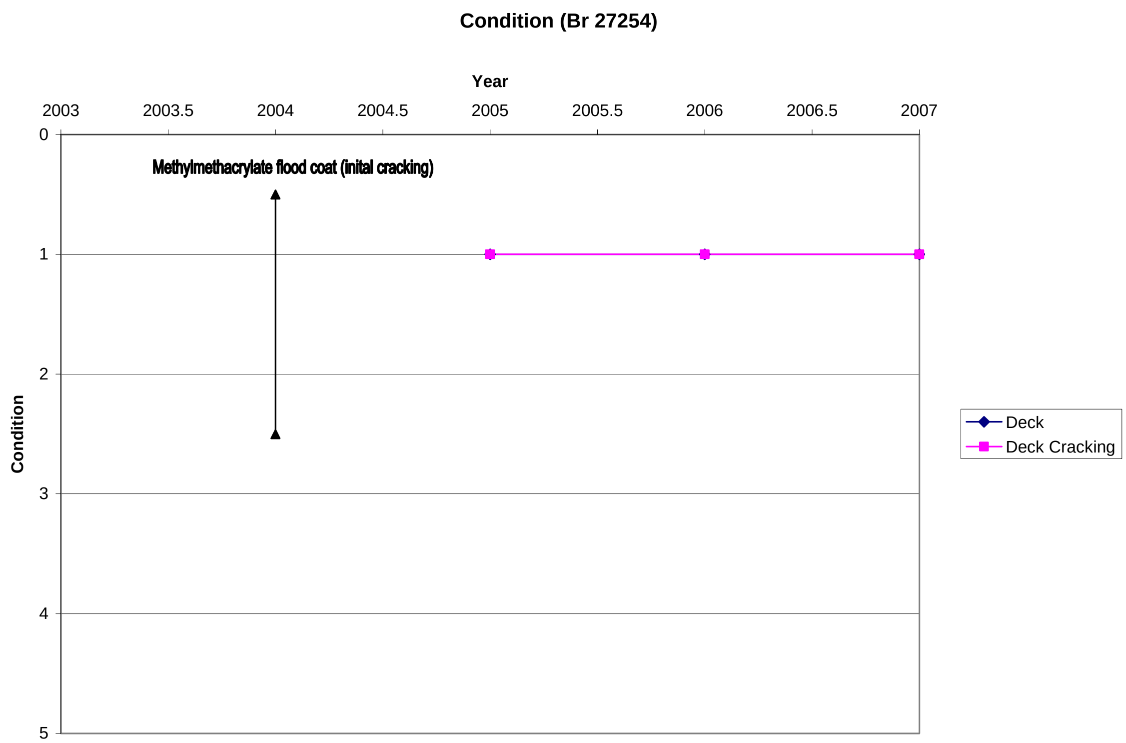


Figure 19. Bridge #27254 deck inspection condition

SECTION III – PRODUCT ASSESSMENT

19. 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 20 and 21). As shown in Figure 22, 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.

20. 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. Because of this, 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, which noted all recipient states used some form of surface preparation prior to application of deck sealants.

20.1 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.

20.1.1 *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.

(a) Solvent Based Silanes with 0-39 Percent Solids Content

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.

(b) Solvent Based Silanes with 40 Percent Solids Content

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.

20.1.2 *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).

(a) Water Based Silanes with 0-39 Percent Solids Content

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).

(b) Water Based Silanes with 40 Percent Solids Content

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.

20.1.3 *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.

20.2 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.

20.2.1 *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 siloxane 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 (20.1.1), 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.

(a) Solvent Based Siloxanes with 0-10 Percent Solids Content

Little information could be gathered from the literature review on solvent based siloxane products with a solids content of ten 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 ten 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.

(b) Solvent Based Siloxanes with 11-20 Percent Solids Content

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 ten 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.

20.2.2 *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 reapplication. 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 windy conditions.

(a) Water Based Siloxanes with 0-10 Percent Solids Content

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.

(b) 11-20 Percent Solids

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

20.3 <u>Testing of Deck Sealants</u>

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 one percent after 48 hours and two 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 resistance 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.

21. 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 of 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 degrees Fahrenheit (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 most common sources are rainfall and surface cleaning methods that 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.

21.1 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 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.

21.2 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).

21.3 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.

21.4 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 the considered. 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.

21.5 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 ten 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					

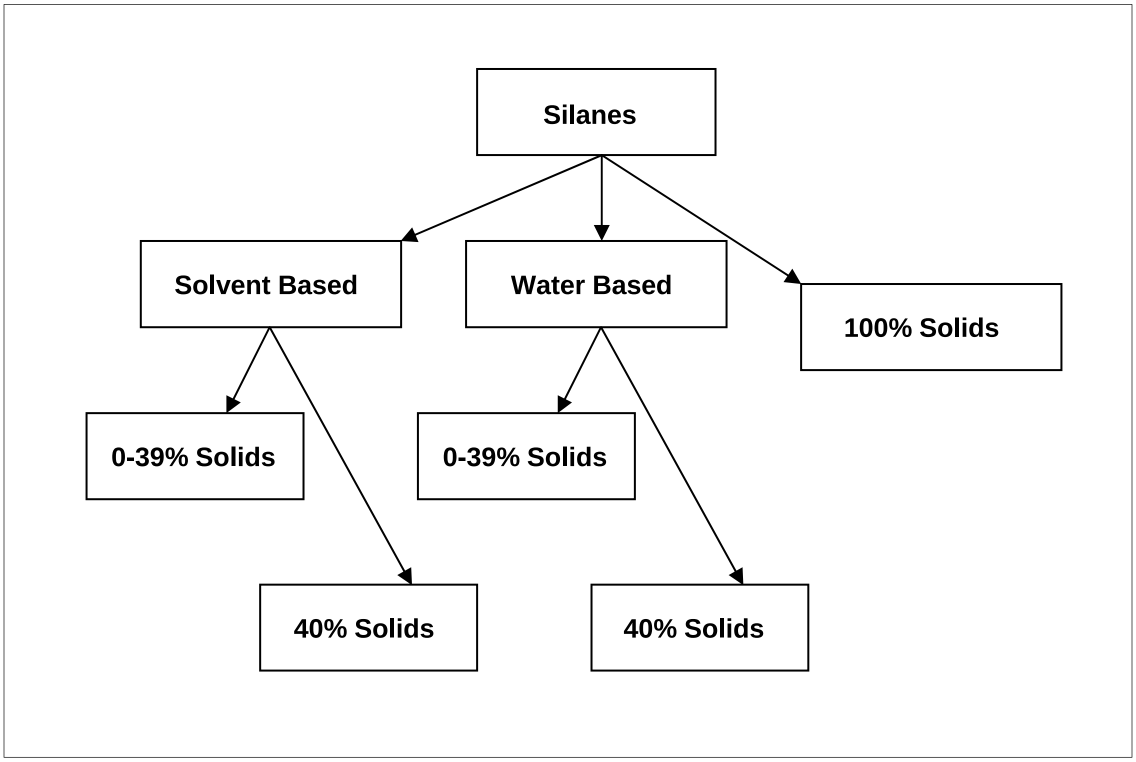


Fig. 20 Classification of Silane Deck Sealants

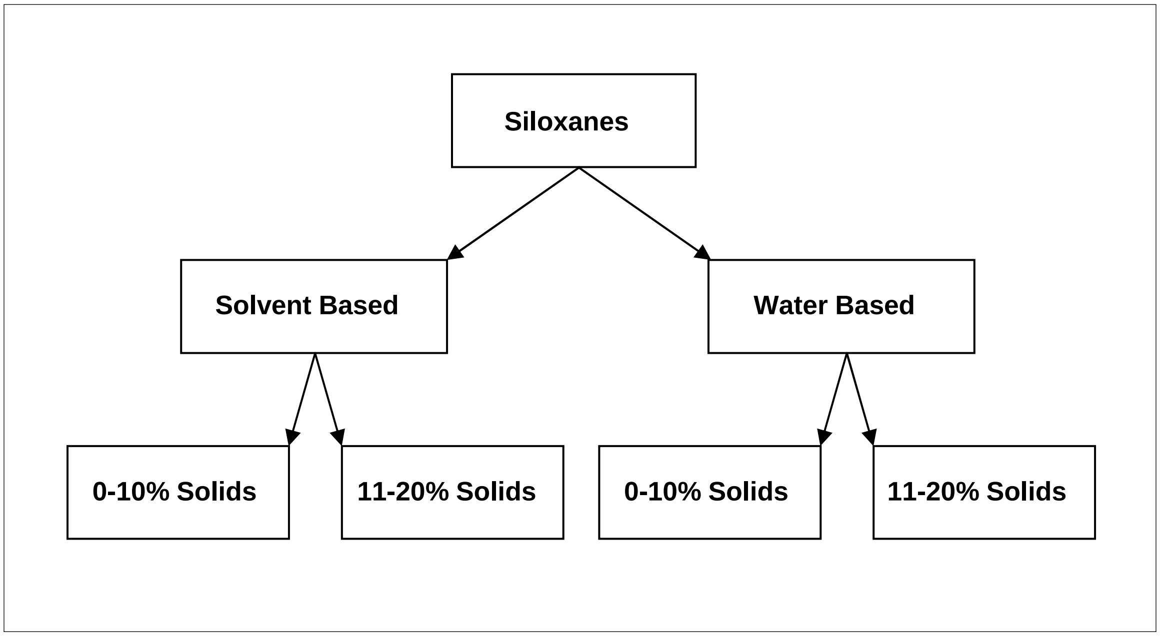


Fig. 21 Classification of Siloxane Deck Sealants

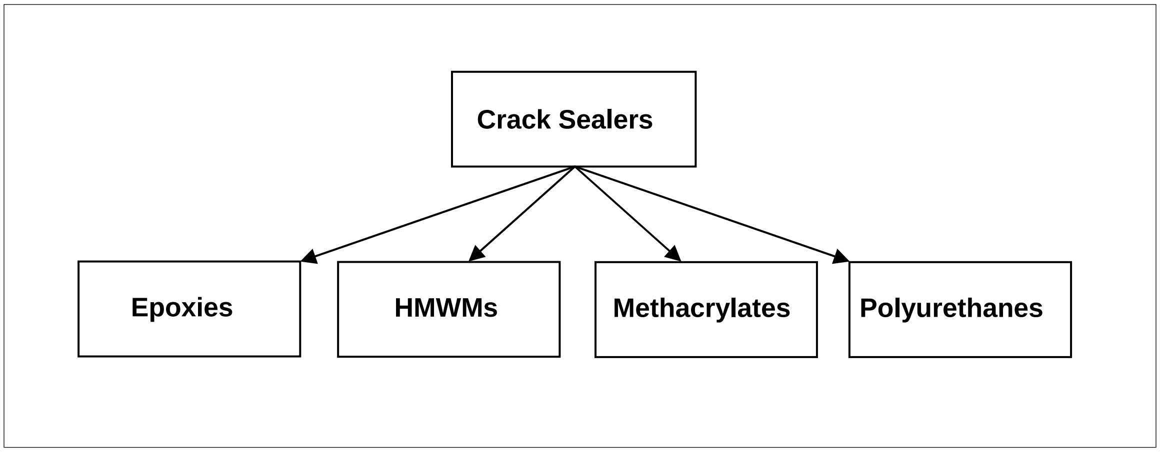


Fig. 22 Crack Sealants Classification

SECTION IV – CONCLUSIONS AND RECOMMENDATIONS

22. Summary, Conclusion and Recommendations

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

22.1 Deck Sealants 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 displayed 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.

22.2 Deck Sealants Conclusions

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 degrees Fahrenheit. 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 test is widely used to quantify performance .
- NCHRP 244 Series II requirements: 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 (if any) QA/QC tests conducted on bridge decks (highly variable and scattered field results).
- 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 most commonly produced sealant that fits this criterion.
- Sealants should be applied between the temperatures of 40 and 100 degrees Fahrenheit.
- A drying period of at least two days should be enforced if the deck is moist.

22.3 Crack Sealers Summary

The survey indicated that very little acceptance testing was done during the selection process of concrete crack sealers. Also, no ASTM tests 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 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).

22.4 Crack Sealers Conclusions

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 ten percent. Crack sealing products should be applied between the temperatures of 45 and 90 degrees Fahrenheit. 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 research is needed because of the lack of information on the topic, with the existing research having 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 determine acceptable crack sealing products.
- Products are typically chosen based on well known research (i.e., Pincheira 2005).
- Depth of penetration and chloride content tests are the most common (if any) QA/QC tests conducted on bridge decks (highly variable and scattered field results).
- HMWM products typically provide better penetration (beneficial for smaller cracks).

- Epoxy products typically provide higher bond strength.
- Although variable, epoxy sealers tend to possess good resistance to freeze-thaw effects.
- Choose crack sealer with viscosity less than 500 cP (or 25 cP for HMWM sealers).
- Choose crack sealer with tensile strength more than 8 MPa.
- Choose a crack sealer with tensile elongation larger than ten percent.
- Crack sealers should be applied between the temperatures of 45 and 90 degrees Fahrenheit.
- 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

Appendix A – Deck Sealant and Crack Sealer Survey

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. Transcripts of the individual surveys follow the sample questions.

A.1 Sample Survey Questions

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 Mike Lee (California, CalTrans)

A.2.1 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.2.2. 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.2.3 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 not correct the sealant may not penetrate the crack or 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.2.4 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.2.5 Contacts

No contacts were provided.

A.3 Ali Harajli (Colorado, CDOT)

A.3.1 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.3.2 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.3.3. 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.3.4 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.3.5 Contacts

No contacts were provided.

A.4 Carl Puzey (Illinois, IDOT)

A.4.1 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.4.2 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.4.3 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.4.5 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.4.5 Contacts

No contacts were provided.

A.5 Jaffar G. Golkhajeh (Indiana, INDOT)

A.5.1 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 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.5.2 Materials Used

Epoxy deck sealants and latex modified overlays are used.

A.5.3 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.5.4 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.5.5 Contacts

No contacts were provided.

A.6 David Meggers (Kansas, KDOT)

A.6.1 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.6.2 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.6.3 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.6.4 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.6.5 Contacts

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

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

A.7.1 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.7.2 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.7.3 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.7.4 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.7.5 Contacts

No contacts were provided.

A.8 Steve Kavanagh (Minnesota, Mn/DOT) Dist. 3

A.8.1 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.8.2 Materials Used

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

A.8.3 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.8.4 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.8.5 Contacts

No contacts were provided.

A.9 John Wenzlick (Missouri, MoDOT)

A.9.1 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.9.2 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.9.3 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.9.4 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.9.5 Contacts

No contacts were provided.

A.10 Nigel Mends (Montana, MDT)

A.10.1 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.10.2 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.10.3 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.10.4 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.10.5 Contacts

The following contact was recommended:
Jim Wong, Alberta, Canada

A.11 Jim Laughlin (Nebraska, NDOR) Dist. 2

A.11.1 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.11.2 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.11.3 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.11.4 Contacts

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

A.12 Dan Holderman (North Carolina, NCDOT)

A.12.1 Experience

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. 13 Larry Schwartz (North Dakota, NDDOT)

A.13.1 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.13.2 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.13.3 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.13.4 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.14 Walter Peters (Oklahoma, ODOT)

A.14.1 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.14.2 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.14.3 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.14.4 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.14.5 Contacts

The following contact was recommended: Dave Darwin

A.15 Tom Gilsrud (South Dakota, SDDOT)

A.15.1 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.15.2 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.15.3 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.15.4 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.15.5 Contacts

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

A.16 Jay Larson (South Dakota, SDDOT) Region Bridge Specialist

A.16.1 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.16.2 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.16.3 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.16.4 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.16.5 Contacts: No contacts were provided.

A.17 Bruce Thill (Washington, WSDOT)

A.17.1 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.17.2 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.17.3 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.17.4 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.17.5 Contacts

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

A.18 Bruce Karow (Wisconsin, WisDOT)

A.18.1 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.18.2 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.18.3 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.18.4 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.18.5 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
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