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15. Abstract

Objective

The objective of this research project is to evaluate concrete sealants to determine which sealant best prevents chlorides from entering micro cracks in concrete.

Scope

This research project has two parts; a literature review and State DOTs Survey for part one, part two involves the evaluation of sealers based on lab tests. Test data for the different sealants were combined to find the most adequate sealer for improving resistance to the deterioration of concrete properties.

Summary

The sealants were tested to determine how susceptible the concrete is to chloride after a sealant is applied. The different tests are as follows; water absorption in hardened concrete, scaling resistance of concrete exposed to deicing chemicals, freeze thaw tests, chloride ion penetration resistance, ability to seal cracks up to 0.2 mm in width, and electrical indication of concrete's ability to resist chloride ion penetration.

The different types of sealant used are Tamms Dural 335 (D335), Degadeck Crack Sealer (DCS), star Sealer (SS), Radcon Formula #7 (R7), and ChemTrete BSM-40 VOC (CT40). It was concluded that the most efficient sealer is Tamms Dural 335 for the cases of normal and fly-ash concrete mixes.

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FINAL REPORT

Application of Sealing Agents in Concrete Durability of Infrastructure Systems

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EXPERIMENTAL PROJECT REPORT

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CHRONOLOGY	Date Work Plan Approved	Date Feature Constructed:	Evaluation Scheduled Until:	Evaluation Extended Until:	Date Evaluation Terminated:
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	277	281	285	289	293

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	297	1 LIN. FT; 2 SY; 3 SY-IN; 4 CY; 5 TON; 6 LBS; 7 EACH; 8 LUMP SUM; 305	306

AVAILABLE EVALUATION REPORTS	CONSTRUCTION	PERFORMANCE	FINAL
315			X

EVALUATION	CONSTRUCTION PROBLEMS	PERFORMANCE
	318: 1 NONE; 2 SLIGHT; 3 MODERATE; 4 SIGNIFICANT; 5 SEVERE	319: 1 EXCELLENT; 2 GOOD; 3 SATISFACTORY; 4 MARGINAL; 5 UNSATISFACTORY

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REMARKS 321

This research project has two parts; a literature review and State DOTs Survey for part one, part two involves the evaluation of sealers based on lab tests. Test data for the different sealants were combined to find the most adequate sealer for improving resistance to the deterioration of concrete properties.

Disclaimer

The contents of this report reflect the views of the author or authors who are responsible for the facts and accuracy of the data presented herein. The contents do not reflect the official views of the North Dakota Department of Transportation or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

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ABSTRACT

This report consists of two parts, Part-I and Part-II. Part-I deals with the literature review and survey of state Department of Transportations (DOTs) on application of sealing agents in concrete durability of infrastructure systems. Part-II deals with evaluation of sealers based on lab tests conducted at the structural laboratory in University of North Dakota. A comprehensive literature review and state DOTs survey are conducted to explore application of various sealing agents in concrete durability of infrastructure systems. The main focus of the literature review is to identify: (1) current research dealing specifically with concrete sealing agents with regards to applications on bridge decks, (2) current sealing agents available in the market for use on bridge decks for sealing cracks and the entire surface. The significant findings on certain products, the type, application rates, cost, benefits, and pitfall of the sealers for this intended use are presented. State DOTs were surveyed for use of various sealers on their bridge decks by using a survey quationary and reviewing literature both immediately after construction and several years later as part of preventative maintenance. The survey includes application of sealers on the new and existing concrete bridge decks. Information on the products used, when and how often they are used, application rates, costs, and type of sealer are gathered and evaluated. Five sealing agents tested in this project were Radcon Formula #7, Tamms Dural 335, Degussa Degadeck Crack Sealer, Chem-Trete BSM-40 VOC Silane and Star Macro-Deck. These sealers were selected for testing in consultation with the North Dakota DOT. These sealers are evaluated for three groups of concrete mixes: normal concrete without adding fly ash, concrete with fly ash (i.e., 70% Portland Cement and 30% Coal Creek Fly Ash by weight) and old concrete cut from existing bridge deck. The effectiveness of these sealers on permeability of concrete is investigated.

PART-I

Literature Review and State DOTs Survey

1. INTRODUCTION

Reinforcement corrosion in concrete is one of the most frequently encountered causes of premature failure of highway bridges and other reinforced concrete structures and has serious economic and safety implications. Carbon dioxide from the atmosphere can gradually migrate into the concrete and react with the alkaline pore solution (a process known as carbonation). Chloride ions from winter maintenance operations, marine environment or other contamination can penetrate through the concrete pores to the passive layer on the reinforcement and depassivate the passive film. Chloride ingress, carbonation, and low quality of the concrete cover can induce steel corrosion in concrete. This causes a build up stress in concrete and leads to concrete deterioration (cracking, delamination, or spalling) and dangerous loss of structural durability.

Many steel-reinforced concrete bridges in the United States are subject to corrosion from chloride ions. This corrosion is a more significant problem in chloride-rich coastal areas and in northern states with heavier snowfall, (e.g., in North Dakota), where roads are kept free of snow and ice with the use of chloride salts. Chloride ions and other aggressive agents from marine environments and de-icing/anti-icing salts have a considerable impact on the structural durability of state DOTs' reinforced concrete bridge decks. Many concrete bridges in these areas become contaminated with chlorides, which in turn begin to corrode the reinforcing steel. The corrosion affects bridge components, including the deck, abutments, and beams. Innovative measures are needed to offer protection for newly constructed and existing concrete bridge decks against carbonation and chloride-induced corrosion, thus improving their structural integrity and service life. The permeability of the concrete is one of the most important factors which will affect the rate of deterioration of rebar corrosion, alkali-aggregate reaction, carbonation, and the effects of freeze-thaw cycles of which all could occur at the same time.

Bridge decks that provide a shelter to the superstructure and substructure are expected to provide a durable and safe riding surface. The superstructure and substructure of the bridge are being protected from direct exposure to water, deicing salt, etc. Therefore, a durable deck is the key for a long-lasting bridge. Durability is a performance parameter in the performance-related concrete specifications for the construction of transportation infrastructure. Most concrete deterioration mechanisms are initiated by the ingress of moisture into concrete interior. For that reason, resistance to penetration of liquids is most commonly used to characterize concrete durability (Yaman 2000).

Under severe and harsh environments, like in North Dakota, bridge decks are subjected to effects of deicing salts, severe thermal gradients, alternate wetting and drying, freeze and thaw cycles, and high live load stresses. While physical actions cause internal stresses, chemical actions of penetrating agents cause deterioration such as steel corrosion. Especially, the use of large amounts of deicing salts introduce chloride ions that reach the reinforcing bars through cracks and water-filled pores. There is an eminent need of a bridge deck protective system, especially, for ingress of chlorides due to deicing salts and moisture.

The purpose of concrete sealing is to slow the rate of water intrusion into the concrete, providing better protection for the steel reinforcement. Applying a sealer to the concrete can be an effective and initially inexpensive method of tackling this corrosion problem, thus increasing the service life of a reinforced concrete structure. There are commercially available penetrating sealers that are reported to penetrate deep into the porous concrete surface and thus provide protection for the concrete. By applying penetrating sealers to existing concrete surfaces, the permeability of the concrete is reduced. The sealing system is expected to provide resistance to water, gasoline, diesel, ultraviolet (UV) light, mild chemical exposures, etc. Penetrating sealers are used on highway Portland Cement Concrete bridge decks to reduce the rate of chloride attack on the reinforcing steel corrosion thereby extending service life and reducing life-cycle structure costs of the bridge deck (preventative maintenance). However, not all sealers have an equal service life; some will require more maintenance costs and more frequent reapplications.

There have been a number of studies exploring the use of penetrating sealers as a means of bridge deck protection, among others, Yaman et al. (2002), Cady (1993,1994), Carter (1994), McGettigan (1990, 1992), Pfeifer and Scali (1981), and Whiting et al. (1992). The use of penetrating sealers provide additional protection for the portions of the deck with increased permeability due to shrinkage cracking or increased water-to-cement-ratio (w/c). Application of penetrating sealers is expected to provide a concrete surface with more uniform durability characteristics.

Concrete sealers fall into two main groups: pore blockers and penetrating water repellent (hydrophobic) sealers. Pore blockers penetrate into concrete and block the pores. Water repellents penetrate into concrete, react with the surface hydroxyl groups in the substrate, coating the pore walls, rendering them hydrophobic. Water repellents prevent moisture ingress, but allow water vapor transmission. Pore blockers hinder both moisture ingress as well as water vapor transmission that will adversely affect concrete durability. Pore blockers do not penetrate as deep as water repellents due to larger molecular size (Cady, 1993). There is a possibility to wear off the sealed surface due to abrasion of vehicular traffic as well as exposure to UV radiation. For this reason, sealers functioning as water repellents will last longer thus are more preferred for sealing concrete bridge decks.

To-date the rate of application of penetrating sealer, number of coatings, and drying period between coatings are estimated from laboratory or field experimental data. Even though the same concrete mix design is used in bridge decks, permeability may vary among and within the bridge decks (Yaman, 2000). For this reason, the use of penetrating sealers for a particular bridge deck should be determined based on the concrete properties of that specific bridge deck and the properties of candidate sealers. In the meantime, there is an eminent need of a testing procedure for measuring sealer effectiveness and for Quality Control/Quality Assurance (QC/QA) that can be implemented in the field.

The study will investigate the use of various penetrating sealers typically applied to steel reinforced concrete bridge decks and evaluate their effectiveness in preventing carbonation and chloride-induced corrosion.

Part I of this report is a synthesis of the scattered information currently available in literature and survey of state DOTs. Authors present the properties of penetrating sealers and concrete compatibility properties that govern sealer penetration. The information on concrete and sealer property, sealer selection and evaluation criteria would be helpful for the NDDOT as well as other State Highway Agencies. Part II of this report deals with evaluation of sealers based on lab tests conducted at the structural laboratory in University of North Dakota.

2. MATERIAL PROPERTIES

Understanding physical and chemical properties of concrete and penetrating sealers leads to a proper usage of these materials. This further helps to determine how sealers react with concrete substrate to work as sealing materials for moisture and chloride ions.

2.1 Properties of Concrete

Concrete is a conglomerate of sand and rock glued together by cement paste (hydrated cement in which cement reacts with water to form calcium silicate chemical bonds). Concrete is a synergistic material; the whole has greater structural properties than the sum of the individual parts. The concrete properties depends on cement raw materials (limestone, iron ore, sand, clay or shale), and composition of concrete which include aggregates (coarse and fine), cement, water, voids (connected and isolated), supplementary cementing materials (fly ash and silica fume), admixtures (air entraining, water reducers, superplasticizers, retarders, etc.). Concrete deteriorates because of its permeability to moisture, chlorides, and gases, lack of properly entrained air, and exposure conditions. The factors causing deterioration of concrete are freeze-thaw damage (internal), alkali aggregate reaction AAR (internal), salt scaling (surface), abrasion damage (surface), spalling (potholes), and rebar corrosion. The durability of concrete is affected by its cement content, quality of aggregates, exposure conditions, surface finish, rebar cover depth, weather conditions at time of placement, mix design, and mixing procedure. Deterioration caused by reinforcing steel corrosion in concrete bridge decks has been recognized as one of the greatest maintenance challenges facing many state DOTs today.

2.1.1 Corrosion of Steel in Reinforced Concrete

Among the many problems facing North America’s infrastructure, one of the most significant is the continued deterioration of reinforced concrete bridges. Sodium chloride is sometimes called the friendly enemy. It protects winter travelers but shortens the life of steel-reinforced concrete bridges. The path of deterioration is simple: water enters the pores in concrete and freezes, breaking off small pieces. This process, called scaling, is repeated leading to cracking and spalling. Eventually, water reaches the steel reinforcement bars. When the water carries chloride, the steel corrodes and expands at a greatly accelerated rate. Chloride also gets into the non-traffic bearing surfaces when contaminated water splashes or runs off the deck onto the superstructure. Barriers,

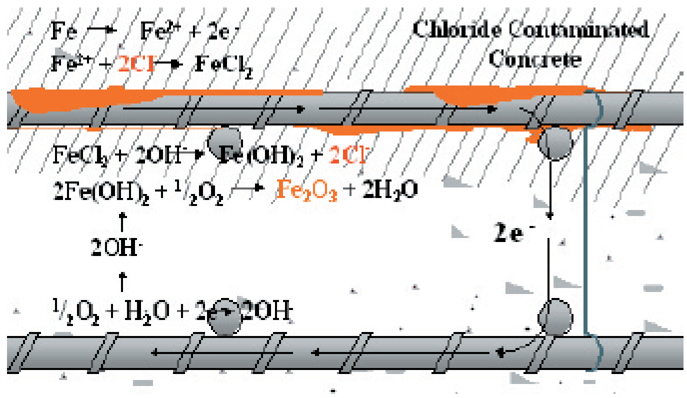

FIGURE 1: Typical Corrosion Cell in a Concrete Deck.

columns, bents, girders, abutments, guardrails and other structural elements can suffer from chloride-induced deterioration.

The extensive use of sodium chloride as a de-icing agent in cooler climates is causing serious corrosion problems. Figure 1 shows a typical corrosion cell in a concrete deck. Chloride ions penetrate through the concrete, break down and destroy the passive oxide layer that protects the reinforcing steel leaving it vulnerable to corrosion. When steel corrodes, the corrosion products (rust) can expand to as much as eight hundred percent of its original volume, thus creating large stresses that crack and delaminate the concrete. Once chloride induced corrosion begins maintenance costs tend to increase exponentially as the structure ages (Fallaha and Whitmore, 2004).

2.1.2 Chloride Intrusion

"It's better to stay out than to get out." That is certainly true of chloride intrusion into concrete. Once in, desalinization treatment or removal of the contaminated concrete, both of which are expensive, are the only ways to get rid of the chlorides. Cathodic protection can halt corrosion, but it is even more costly. However, according to one study that measured percent of chloride intrusion two inches below the surface, proper maintenance can reduce water and chloride intrusion into concrete by 86 percent or better (Attanayaka et al. 2003). While early damage is often not a serious structural concern, corrosion acts like a disease and must therefore be treated before it becomes a significant problem. The rate of deterioration due to corrosion is dependent upon the amount and difference in chloride content, moisture availability, temperature, and permeability of the concrete.

2.1.3 Concrete Pore Properties and Permeability

Flow into uncracked concrete is primarily through the capillary pores. Much smaller cement gel pores contribute to the permeability of concrete, but the cement paste as a whole is 20 to 100 times more permeable than the gel itself. Therefore the permeability of hardened cement paste is primarily controlled by its capillary porosity (ACI 224.1R-93, 2001).

The degree of surface permeability is related in large part to the amount of water that migrates to the exposed surfaces (bleed water). Therefore, any measures such as low water-to-cementitious (w/c) ratios and moist curing, used to reduce water migration to the surface will also reduce the surface permeability. To reduce capillary porosity is one of the reasons why many governing agencies and consultants emphasize low w/c ratios. However, certain modern construction practices, such as curing, can offset the benefit of low w/c ratios. It is well known that wet curing (fogging, ponding, wet burlap, etc.) is one of the most effective construction practices for reducing, or eliminating, surface moisture loss, and drying shrinkage – major causes of early-age cracking and other distress. On the other hand, project labor and time allotments discourage the regular practice of wet curing. Therefore, the industry developed and promoted the use of spray-applied curing compounds/membranes to reduce, not eliminate, the amount of moisture loss at the surface. Consequently, the degree of surface capillary porosity is somewhere between concrete that was moist cured and concrete that was air cured (Yaman et al. 2002).

In bridge deck concrete, the most common w/c ratio is between 0.4-0.5 (Yaman et al. 2002). For 28 days old concrete, with w/c ratio ranges from 0.4-0.5, the diameter of capillary pores varies from 45 to 1000 Angstrom (ACI 224.1R-93, 2001). Permeability is controlled by the pore size distribution in the hardened cement paste. Pore size distribution is controlled by the w/c ratio and the age (degree) of cement hydration (Mehta and Monteiro, 1993). There are well known references that discuss the properties of hydrated cement paste and concrete in detail (ACI 224.1R-93, 2001).

The concrete mix specified for bridge decks by the NDDOT (w/c ratio between 0.35 - 0.40) will produce a concrete with properties that is sufficiently durable for the loads and environmental conditions in North Dakota. However, the states DOTs' experience and the literature indicate that field practices and other construction constraints often result in a variability of concrete durability properties between decks as well as within a deck surface. Exact quantification of permeability of cracked concrete is not viable because of varying crack widths. Through an extensive study on permeability of cracked concrete, Aldea et al. (1999) showed that cracks in concrete having mean crack width of 0.007-inches (0.18 mm) considerably increased permeability compared to uncracked concrete. Furthermore, previous research by Yaman et al. (2002) showed a significant variation in permeability values on three newly constructed concrete bridge decks in Michigan (Table 1). These test results indicate that there are vulnerable portions on the deck surface where distress will first initiate.

TABLE 1: Permeability Properties of Concrete Bridge Decks at 56-Day.

Bridge ID Number	Gas Permeability (10^{-13} in^2)	Gas Permeability (10^{-7} in/s)	Water Permeability (10^{-8} in/s)
S04-82062	16.00	27.00	40.00
S17-82112	26.40	44.00	66.00
S26-82251	2.64	4.40	6.60

The use of penetrating sealers provide additional protection for the portions of the deck with increased permeability due to shrinkage cracking or increased w/c. Application of penetrating sealers is expected to provide a concrete surface with more uniform durability characteristics.

2.1.4 Cracking Severity

American Concrete Institute (ACI) defines cracking severity in ACI 201 as:

- Fine < 0.04 in.
- Medium 0.04 – to– 0.08 in.
- Wide > 0.08 in.

In ACI 224, the tolerable crack width for structures exposed to deicing chemicals is reported to be 0.007 inch, which is six times smaller than the “fine” crack defined in ACI 201. Survey results from literature identify typical acceptable crack widths to range from 0.001 to 0.125 inches (0.025-3.0 mm) (Soriano, 2002). It is obvious that there is a wide range of opinions regarding tolerable crack widths. For the purpose of evaluating crack and surface sealers in this study, the ACI 201 crack severity definitions may be used.

2.2 Properties of Concrete Bridge Deck Sealers

Cracking of concrete decks is described as an inevitable phenomenon that drastically increases concrete permeability (Krauss and Rogalla, 1996). Sealers are applied on concrete bridge decks to reduce the permeability of the concrete, preventing moisture and road salts from being absorbed into the concrete slab, as well as to prevent water leakage into the space below through cracks or joints. The most important property the sealer must have is that it must protect the concrete and at the same time it must be breathable (Krauss and Rogalla, 1996). That is, water vapor is allowed to freely pass in either direction. Concrete sealers prevent the absorption of chloride ions. Depending upon the exposure condition of the unprotected deck, the average internal moisture is about 50 to 80 percent of the saturation level. Concrete sealers allow the progressive internal drying of concrete to a 30 to 40 percent level by reducing the rate of moisture gain from the environment.

Many different crack and deck sealers were found during the literature search. Concrete sealers fall into two main groups: pore blockers and penetrating water repellent (hydrophobic) sealers.

2.2.1 Pore Blockers

Pore blockers, such as a water-based epoxy and a solvent-based epoxy, are products that provide little penetration and form instead a thin film (of up to 2.0 mm) on the concrete's surface (coating) that blocks the pores. Pore blockers do not penetrate as deep as water repellents due to larger molecular size (Cady 1994). Pore blockers are further distinguished by their ability to partially or fully fill the surface pores, a capability not shared by hydrophobic sealers. This distinction means that pore blockers should only be used on substructure components and other areas not subject to traffic wear, because it will wear off quickly if used on traffic surfaces. Pore blockers also hinder both moisture ingress as well as water vapor transmission that will adversely affect concrete durability. Pore blockers generally cost less, last longer for non-traffic bearing surfaces and are more pleasing to the eye.

2.2.2 Penetrating Water Repellent (Hydrophobic) Sealers

Penetrating water repellent sealers, such as silane and siloxane, are products that are absorbed into the surface of the concrete and react with the concrete (hydroxyl group in the substrate) to form a water repellent (hydrophobic) surface. No film is formed; therefore pores in the concrete are not blocked. Water repellents prevent moisture ingress, but allow water vapor transmission. For this reason, sealers functioning as water repellents will last longer, because they become part of the concrete, thus are more preferred for sealing concrete bridge decks. There is a possibility to wear off the sealed surface due to abrasion of vehicular traffic as well as exposure to UV radiation.

For surfaces free from tire abrasion, some state DOTs prefer pigmented epoxy sealers that have low permeability and are extremely durable - a big advantage on bridges. They are available in any color; although most state DOTs prefer whites and grays. One drawback is that epoxies can chalk and discolor with UV exposure. Water-dispersed epoxies can be applied on green concrete just like a cure-and-seal wax product. But unlike wax seals, epoxy will remain in place as an effective screener of water and water-borne chlorides. Solvent-based epoxies can be applied in colder weather but not on green concrete. Like all solvent-based products, they raise volatile organic compounds (VOC) compliance issues. High-build latex modified cements are rubbery liquids applied in a relatively thick coating. Because of the latex additive, they are much more effective at reducing water and chloride intrusion than untreated concrete. These cementitious materials, the most aesthetic products for coating non-traffic surfaces, dry to a uniform textured surface and are available in any color imaginable. While these are the least expensive and easiest to install, they can be worn away relatively easily by the whipping action of water and road debris.

DOTs that prefer to work with a minimum number of products often choose to use penetrating water repellent sealers on traffic and non-traffic surfaces (Attanayaka et al., 2003).

3. PENETRATING WATER REPELLENT TREATMENT

This section discusses the importance of understanding the fundamentals of sealer penetration and function. As mentioned before, understanding physical and chemical properties of penetrating water repellent sealers helps to determine how sealers react with concrete substrate to work as sealing materials for moisture and chloride ions. This further leads to a proper usage of these materials.

3.1 Silane and Siloxane Penetrating Sealers

Silanes, which are monomers, have only one silicon atom. Siloxanes can have longer chains consisting several repetitive units of silane monomers, see Figure 2. Siloxanes that have shorter chains up to five silicon atoms can be used as penetrating sealers. One branch of silane and siloxane molecular structures is comprised of an organofunctional group (R) that is an organic hydrocarbon group having straight or branched-chain structure. The silicon functional groups (OR') are responsible for the reactivity with

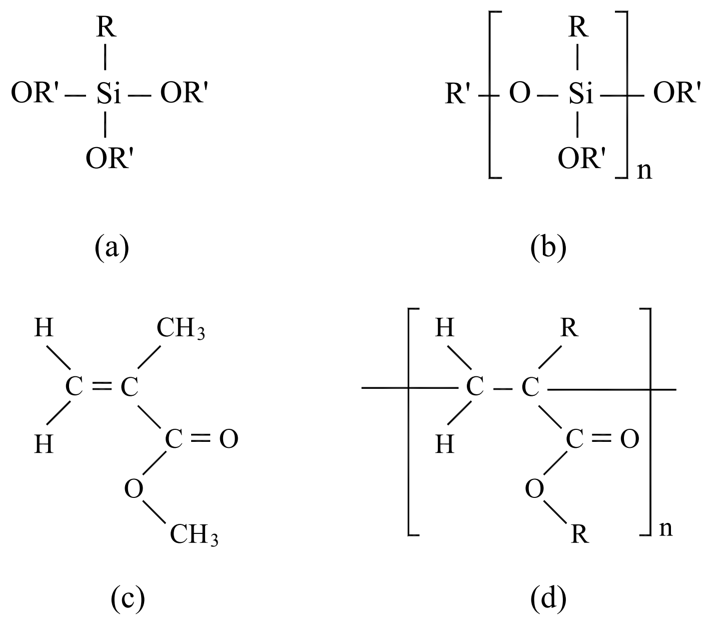

FIGURE 2: Molecular Structure of (a) Silane, (b) Siloxane, (c) Methyl Methacrylate, and (d) High Molecular Weight Methacrylate.

siliceous substrate. The exposed organofunctional groups provide a hydrophobic (water-repellent) layer on pore walls. The organofunctional groups and the silicon functional groups are referred as alkyl and alkoxy groups, respectively. Therefore this class of substance is named as alkyl trialkoxy silane. The nature of the organofunctional group (CH3-, CH3CH2-, (CH3)2CHCH2-) establishes the degree of water repellency while penetrability primarily depends on the size of the silicon functional groups (CH3O-, CH3CH2O-) (Cady, 1994).

Organofunctional groups having several carbon atoms, in general, will furnish higher degree of hydrophobicity to the concrete substrate. A branched structure of alkyl group is the most preferred when compared with straight chain and cyclic structures. From all these structure types, cyclic structure of alkyl group imparts the least hydrophobicity to the substrate. McGettigan (1992) investigated the effectiveness of few organofunctional groups to water absorption in the most commonly used penetrating sealers. Methyl (CH3-), ethyl (CH3CH2-), propyl (CH3CH2CH2-), n-octyl (C8H17-), and iso-butyl ((CH3)2CHCH2-) were the organofunctional groups used in this investigation. His conclusion was that the high molecular weight iso-butyl and n-octyl groups reduce water absorption more than the relatively smaller groups like methyl and ethyl. However, larger organofunctional and/or silicon functional groups increase the molecular size of the penetrating sealer. Molecular size defines the range of pores in concrete that can be treated and the depth of penetration reached. Molecular size of silane (10 to 15 Angstrom) and siloxanes (25 to 75 Angstrom) are small enough to enter the pores in concrete (45 to 1000 Angstrom). But molecules of silane or siloxane become larger (double, triple, or even quadruple) during hydrolysis and condensation thus limiting their penetration depth (McGettigan, 1992). Even though the water repellency is comparatively lower, penetrating sealers having smaller alkyl and alkoxy groups may furnish greater penetration depths.

Most of the water repellents available in the market are dissolved in a carrier such as alcohol. Alcohol solvents have low surface tension and they are miscible with water that reduces the adverse influence of moisture to the penetration of the water repellent in the substrate. Since it is possible to optimize the chemical and physical properties (such as viscosity, contact angle, molecular size, hydrolysis rate, etc) of certain classes of neat (solventfree) silanes or siloxanes, penetration depths can be maximized and solvent-borne silane or siloxanes may not be needed (McGettigan, 1992). Solvent based penetrating sealers also become more viscous as solvent evaporates becoming more difficult to penetrate. But for neat silanes as silane reacts with silicon atoms on the concrete pore surface, pore surface area is reduced allowing the non-reacted silane to penetrate deep in to the substrate. In any case, certain classes of neat silanes appear to be the best penetrating products (McGettigan, 1992).

3.2 High Molecular Weight Methacrylate (HMWM) Sealers

HMWM sealers with the molecular structure shown in Figure 2 are used by several highway agencies for sealing cracks in concrete decks (Attanayaka et al., 2003). HMWM is a broad category used to describe blends of methacrylate monomers with various constituents. HMWM sealers can be used to treat the cracks ranging from 0.001- to 0.08-inches (0.025-2.0 mm) and even finer cracks are possible to treat with low viscosity resins. For new decks, it is better to treat the early age cracks at least after 6 months because most of the initial shrinkage cracks occur during the first 6 months after concrete placement (Krauss and Rogalla, 1996; ACI Committee 224, 2000). Silane and siloxane penetrating sealers will be effective on finer cracks of which the width is less than 0.002-inches (0.05 mm). Since silane sealers are compatible with HMWM, it is possible to treat the cracks with HMWM after applying silane sealers. HMWM application will reduce the skid resistance of the deck surface and broadcast of sand is necessary (ACI Committee 224, 2001).

3.3 Penetration Depth Evaluation

Penetration depth of sealer is an important property to provide long-term durability for bridge decks. Often, the penetration depth stated by manufacturers cannot be practically attainable in bridge deck concrete (Cady 1994, McGettigan 1992). Penetration depth depends on the properties of sealers and concrete and the prevailing environmental conditions. Therefore this is a unique factor for a particular bridge deck and a selected sealer under the environmental conditions at the time of sealer application. But with the proper description of the flow phenomenon and the effective factors, more reasonable estimations of the depth of penetration can be achieved (Aldea et al., 1999).

The depth of penetration formulation is derived for cylindrical specimens to avoid edge/corner effects. The side of cylinder is coated and the liquid allowed flowing only through the top surface. Assuming steady flow within the porous network, and using Darcy's law for a small-impregnated volume, and capillary driving forces for fluid migration, the penetration depth *h* is related to the penetration duration *t,* and is given as:

$$h^2 = \alpha t \quad (1)$$

where,

$$\alpha = 4\frac{\gamma}{\eta}\frac{k}{pa}\cos\delta \quad (2)$$

Here k is the intrinsic permeability coefficient, η is the dynamic viscosity, p is the porosity, γ is the surface tension, a is the pore radius of the cylindrical capillary, and δ is the contact angle (Attanayaka et al., 2003). Eq. 2 represents the slope between square of depth of penetration, h^2, and penetration duration, t. The intrinsic permeability coefficient can also be expressed as:

$$k = \alpha \cdot p \cdot a \frac{\eta}{4\gamma\cos\delta} \quad (3)$$

According to Eq. 3, intrinsic permeability coefficient, which defines the sealer penetration, can be determined from specific concrete properties (porosity and mean pore radius) and sealer properties (viscosity, surface tension, and contact angle). In addition to these properties, tortuosity of the pore structure, the pore surface topology, reactivity of sealers with concrete substrate, and other unaccounted factors will affect the intrinsic permeability coefficient. These factors are tabulated in Table 2. In Eq. 3, α incorporates these effects and can be determined from an impregnation experiment by plotting h^2 versus t.

TABLE 2: Factors Controlling the Depth of Penetration of Sealers.

Concrete	Penetrating Sealers	Environmental and Other
Pore size Pore distribution Moisture Crack width and density Tortuosity of pore structure Pore surface topology	Viscosity Contact angle Surface tension Molecular size Molecular weight	Temperature Relative humidity Application pressure Sealer reactivity with substrate

Using the formulation given above, permeability values measured on Michigan decks (Table 1), and physical properties of a silane sealer [Surface tension (γ = 1.142 x 10^{-4} lbf/in), density (ρ = 0.0325 lb/in^3), contact angle (δ = 0 Deg.), viscosity (η = 7.25 x 10^{-7} lbf.s/in), porosity (p = 10%), and mean pore radius (a = 6 x 10^{-7} inch)] a theoretical depth of penetration of 0.25-inch can be achieved by flooding the concrete surface for about 5 to 25 seconds (Attanayaka et al., 2003).

3.4 Methods for Performance Evaluation of Penetrating Sealers

Most of the State Highway Agencies use National Cooperative Highway Research Program (NCHRP) Report 244 (Series – II) test procedures for sealer selection and evaluation criterion (Pfeifer and Scali, 1981). The test procedures given in NCHRP Report 244 (Series-II) are developed for selection and evaluation of sealers for concrete surfaces that are not subjected to abrasion. Several other Highway Agencies developed specifications, especially, for the application of penetrating type sealers for bridge decks (Attanayaka et al., 2003).

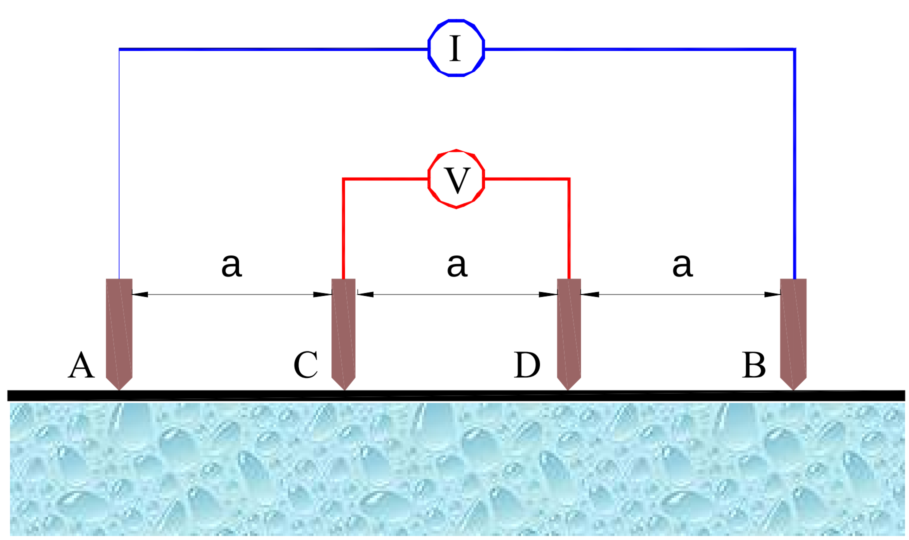

FIGURE 3: Schematic of Wenner Four-probe Resistivity Measurement Method.

Understanding the difference between "visible penetration" and "working penetration" is necessary to evaluate the sealer performance (McGettigan 1992). Visible penetration can be measured by splitting the concrete specimen and measuring the non-wetting band. This method is simple, but it is destructive which requires coring of the deck. Working or effective depth of penetration can be measured using the test procedure recommended by Alberta Transportation & Utilities (AT&U). This test requires sandblasting the specimen surfaces. The limitations for the weight of material removed are established as per face and per cube. Immersing the test cubes in water and measuring the weight gain determine waterproofing performance after surface abrasion. This test procedure is adopted by several highway agencies and many researchers for evaluating sealer performance. McGettigan (1992) has implemented this test procedure for evaluating sealer performance after several abrasion cycles.

Another method of evaluating relative performance of the hydrophobic sealer treatments is the electrical resistivity method. This method is based on measurement of electrical resistivity (ρ) with the four-electrode probe (Figure 3) that is expressed as

$$\rho = 2\pi a \frac{\Delta V}{I} \tag{4}$$

The constant current (I) is applied to two outer electrodes (A&B) and the arising difference of potential (ΔV) is measured between two inner electrodes (C&D) (Attanayaka et al., 2003).

The electrical resistivity method is used to measure surface resistivity that indicates the functioning of sealers as hydrophobic agents. It is possible to implement this method in the laboratory as well as in the field. The most common resistivity measurement technique is the Wenner four-probe method; see Figure 3, (McCarter, 1996). Current is conducted between electrodes through continuous water filled pores. After applying sealers continuous path for electrical conduction, near the surface, may not exist. Treated concrete dries faster than untreated concrete due to lesser amount of absorbed water. For that reason, the surface resistivity of treated concrete is greater than that of untreated concrete. Distance between electrodes is determined based on the size of the treated surface in order to avoid edge effects as well as the desired depth of penetration of electrical currents. Greater spacing between electrodes will reflect the resistance of the body of unsealed concrete because a very small thickness is affected by the penetrating sealer (Whiting et al. 1992). Contact between electrodes and the concrete surface can be made using spots of conductive paints. Surface resistivity values may also vary depending on the ionic concentration of pore water (McCarter, 1996).

Cady (1993) proposed a test procedure for determining the relative effectiveness of penetrating sealers. It is required to use model 400 solid-state 4-pin soil resistance meter from Nilsson Electrical Laboratory, Inc. He proposed to use a 2-pin mode instead of the generally accepted 4-pin mode. Based on test results, he proposed resistance values for evaluating the effectiveness of penetrating sealers (Table 3). These values are based on a current supply with a carrier frequency of 100 Hz. According to the instruction manual of

TABLE 3: Categories of Relative Effectiveness of Sealers.

100 Hz Resistance (kilo ohms)	Relative Effectiveness of Sealer (Category)
0 to 200	Ineffective (or not sealed)
200 to 400	Borderline effective
Over 400	Effective

the proposed soil resistance meter, the reading obtained using the 2-pin mode includes the resistance of the two probes, the concrete resistance between them, and the resistance of any cables from the connections to the probes (Nilsson Electrical Laboratory, 2002).

4. SEALER SELECTION CRITERIA

There is no clear consensus on when and how to seal bridge deck cracks, or what material(s) to use. However, before selecting crack treatments, determining crack criteria must be performed first. For decks subject to deicing agents, typical acceptable crack widths ranged from 0.001 to 0.125 in. After evaluating all the information, it was considered reasonable to use the American Concrete Institute (ACI) recommended tolerable crack width for structures exposed to deicing chemicals of 0.007 in. (ACI 224) as a trigger for planned maintenance activities. This is a realistic tolerance level considering other investigators have found water leakage through cracks as narrow as 0.002 inch (Krauss and Rogalla, 1996). Given this information and the widely recognized increase of early age cracking on bridge decks, it is reasonable to recommend crack sealing activities approximately three to six months after construction completion.

Many different crack and deck sealers were found during the literature search, for examples see Appendix I. There are many factors to be considered when selecting what type of sealer would be right for a bridge deck. New concrete may require a different type of sealer than when re-applying. If the concrete is old, and being re-sealed, it is important to know what type of sealer was used on it before to make sure it is compatible with the new sealer. It is also important to know what kind of weather the sealer is going to have to protect against. For example, sealers used in the northern states where it snows would have to be more durable to snow, ice, and salt. Meaning they would have to withstand freeze-thaw tests with good results. Cost can play a role in determining which kind of sealer to use. Some are more expensive to buy and to apply. Also some sealers require a more frequent re-application rate. The labor cost and maintenance will also vary from sealer to sealer. Application features are important to look at. Some sealers can only be applied between certain temperatures and might not work well for cooler areas. If the site is located in a busy area, a faster drying sealer may be needed.

4.1 Crack Sealers

For crack sealers, high molecular weight methacrylate (HMWM) is cited as demonstrating the best performance with respect to crack penetration, bridging, and sealing (McGettigan 1992; Weyers et al. 1993; Krauss and Rogalla, 1996). HMWM is a three-component system [monomer resin, cumene peroxide (initiator), and cobalt (promoter)] that requires extra precaution during mixing because a violent reaction may occur if the initiator and promoter are mixed first or improperly. To avoid this problem, some product manufacturers started mixing the promoter directly into the resin before shipping so that field personnel only had to add one component – the initiator. The problem with this solution is that it reduces the shelf life of the product because of slow polymerization. For a product that starts out with a viscosity of 5 – 15 cp (centipoise or 0.001 pascal-seconds), it has been reported that after 3 – 4 months the viscosity could be as high as 1,000 – 1,500 cp, resulting in a decrease of the product's crack penetrating capability (Soriano, 2002).

One alternative developed by producers is reactive methyl methacrylate (MMA) catalyzed by a 50% dibenzoyl peroxide powder. This two-component crack sealer, without the volatility potential, possesses similar performance characteristics to HMWM. Other sealing materials that exhibit good performance are epoxy, modified polyurethane (MPU), and urethane crack sealers. These sealers exhibit flow characteristics similar to the methacrylates but are reported to have superior extensibility characteristics. The MMA and epoxy exhibit similar crack penetration depths of 0.10 inch (2.5 mm) while the MPU exhibits a little less penetration depth of 0.06 inch (1.5 mm) (Soriano, 2002).

Most of the products described in this section have a pH above 7 and are considered alkaline in nature. These product hazards include skin irritation, dermatitis, and other allergic responses due to prolonged exposure. This is an irritant to skin, eyes, and respiratory tissues. Safe handing of all these products would minimally require eyeglasses with safety shields or goggles (McGettigan, 1990). An eyewash station should also be provided. Skin protection requires rubber or neoprene gloves, an apron, and full-length shirt and pants. Most of the products need to be protected from freezing because they contain water. Some products do have volatile components and need to be kept away from open flames or other ignition sources. With all material types, make sure the area is adequately ventilated.

4.2 Bridge Deck Surface Sealers

A number of manufacturers claim their products penetrate the surface of cementitious substrates (penetrating sealers) to seal the pore structure. The penetrating sealers are produced in both water-based and VOC releasing formulations. The surface sealers such as silanes and siloxanes react chemically with concrete components and forms precipitates to seal the pores at or below the surface of the concrete. They wet the surface and limit the penetration of chlorides and water into the concrete. They also improve freeze/thaw damage resistance, and reduce efflorescence and dusting. Silanes and siloxanes are the best overall penetrating surface sealer for the following reasons (Soriano, 2002):

- Low Viscosity (10-50 cps)
- Low molecular size (2-4 x 10^{-5} in.) versus concrete pore size (5-50 x 10^{-5} in.)
- Resistance to alkaline environments-depending on chemistry

Silanes and siloxanes have achieved up to 0.24 inch (6.1 mm) of penetration into concrete surfaces – depending on their chemistry, and concrete quality, porosity, and moisture content. Siloxanes have larger molecular sizes that may reduce their concrete penetrating capability in comparison to silanes. However, after penetrating into the concrete and "wetting" the pore structure surfaces, both materials polymerize in the presence of moisture and bond to silica-containing materials to reduce the surface tension of the substrate concrete and reduce the moisture and chloride penetration that accelerates concrete and rebar deterioration. If the substrate surface tension is less than water, it will be water-repellant (McGettigan, 1992). There are indications that silanes and siloxanes may be effective at waterproofing cracks as large as 0.010 inches (0.25 mm) (McGettigan 1992; Weyers et al. 1993; Krauss and Rogalla, 1996).

They can be installed with a common low-pressure garden sprayer, although production field spraying equipment will improve installation time and application uniformity. At a price range of $0.16 to $0.40 per square foot with coverage rates ranging from 150 to 175 square feet per gallon, it is a relatively low cost preventive maintenance material (see Appendix A). The water and chloride repellent performance of these materials are recognized and well documented (McGettigan 1992; Weyers et al. 1993; Krauss and Rogalla, 1996; Kepler et al., 2000).

4.3 Selection Process and Condition Assessment of Penetrating Sealers

The factors pertaining to the sealer as well as the concrete surface to be considered while selecting a suitable penetrating sealer are summarized in Table 4. Considering the factors given in Table 4 and the available test methods a flow chart, as shown in Figure 4, was developed for the selection of penetrating sealers for a particular concrete bridge deck. Based on the considerations given in Table 4, Figure 5 shows a flowchart to assist in the condition assessment of concrete bridge decks and the selection process of penetrating sealers for concrete bridge decks (Basheer et al., 1997).

According to literature, certain sealers can provide the required levels of performance in protecting concrete from chloride intrusion and water permeation, but may not be the suitable when durability is considered. Therefore there is a necessity in understanding the relationship between the performance and durability of penetrating sealears for the effective use of the flowcharts given in Figure 4 and Figure 5 (Basheer et al., 1997). It is also important to note that all silanes and siloxanes are not created equal. As discussed in the previous section, those products that have larger molecular weight alkyl groups (iso-butyl and n-octyl groups versus methyl and ethyl groups) will exhibit better water and chloride repellency, and better stability in an alkaline environment (McGettigan, 1992).

TABLE 4: Factors to Be Considered in Selection of Penetrating Sealers.

Feature	Consideration
Original substrate	New construction or remedial work Condition of the deck Prior surface treatments Surface contamination
Environment	Atmospheric, marine, etc Presence of moisture Presence of pollutants
Sealer durability	Penetration depth Ultraviolet resistance Reactivity with hydrated cement paste Weathering Alkali resistance
Protection of concrete	Chloride absorption Water absorption Water vapor transmission Deicer scaling resistance
Service	Skid resistance
Application features	Surface preparation requirements Brushing or spraying characteristics Tolerance to substrate moisture Temperature dependence Site access and lane closure time
Life cycle cost	Unit material cost Number of applications Labor costs Maintenance

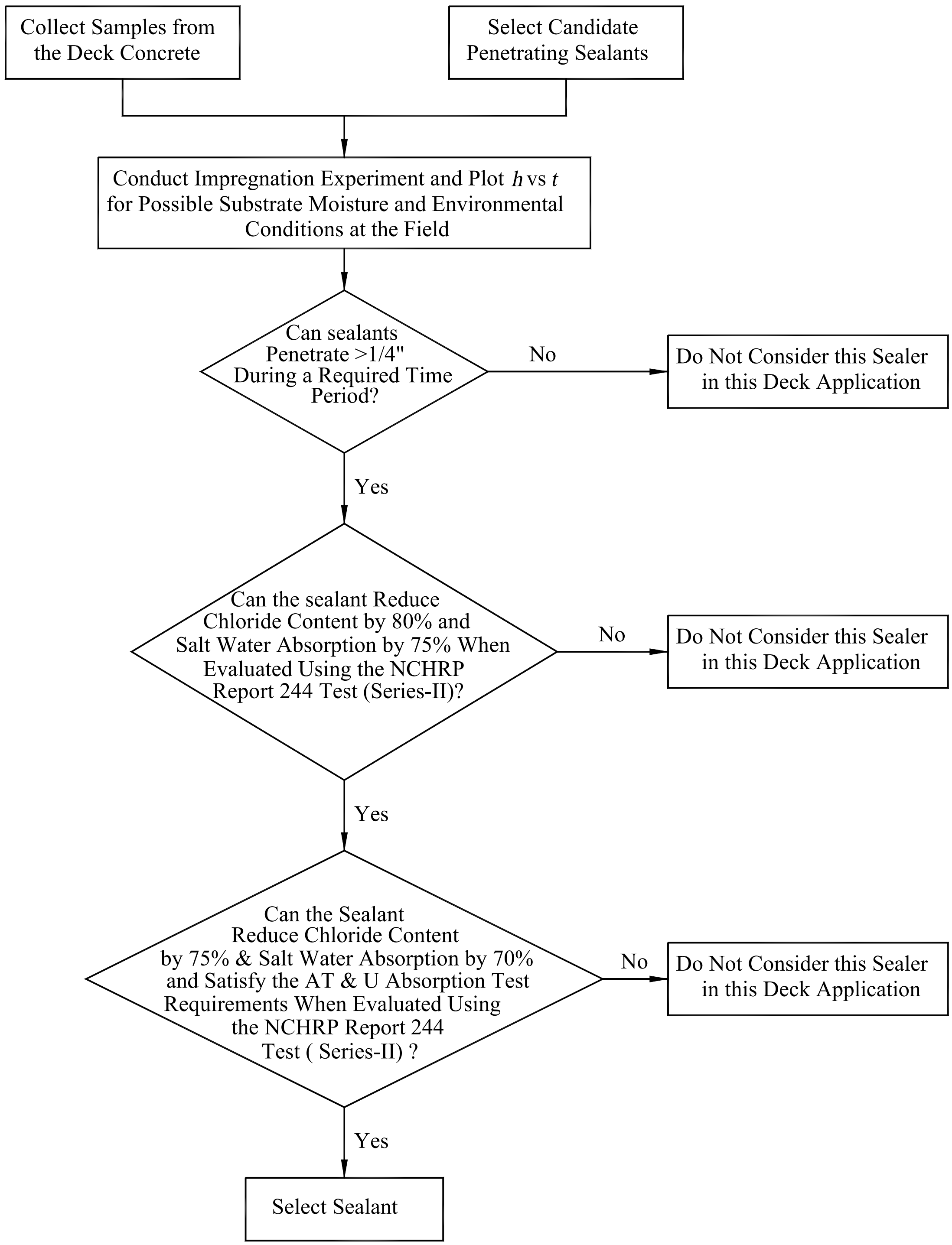

FIGURE 4: Penetrating Sealer Selection Procedure Flowchart.

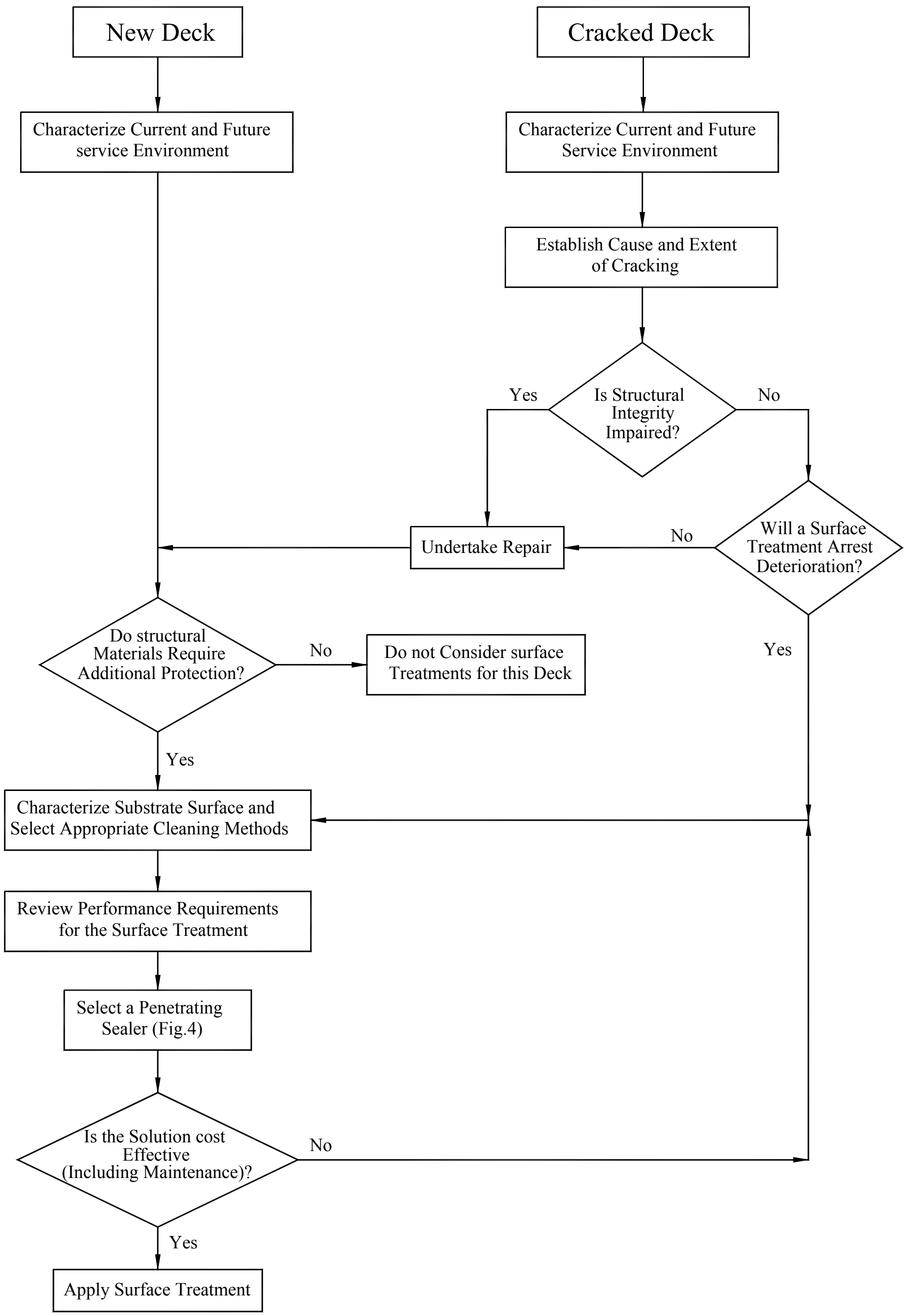

FIGURE 5: Condition Assessment and Surface Treatment Procedure Flowchart.

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5. CURRENT PRACTICE

For sealed new decks after approximately 6 months, in general, cracking of the concrete deck should be appraised. If the crack widths are less than 0.002-inches (0.05 mm), silane sealers can further be used. Generally, if the crack width is less than 0.08-inches (2.0 mm), HMWM in conjunction with silane sealers can be used. Use of HMWM on crack widths greater than 0.08-inches (2.0 mm) is not effective and cracks should be repaired following the other treatments proposed in ACI 224.1R (2001). The sealing of previously untreated bridge decks with cracks, older than one year, can be performed using the same procedure as described above provided that adequate surface cleaning and preparation methods are employed.

5.1 Surface Preparation and Application Procedures

Concrete surface requires specific preparation for the application of penetrating sealers. According to manufacturers' recommendations as well as data published in the literature, concrete must be at least 28 days old. It is also recommended that the surface needs to be clean, dry, open capillary, and free of curing compounds and pore blocking contaminants. If the concrete bridge deck is more than one year old and silane or siloxane sealer is going to be applied for the first time, the carbonated layer formed at the surface of the concrete must be removed (Cady, 1994). For decks in service, surface cleaning methods are needed in order to remove oil, grease, rubber and other organic contaminants present on the deck surface. For example, the Alberta DOT power washes the bridge decks on a yearly basis and the decks that are on the 4-year sealing cycle are sealed 2 days after power washing. Before the application of sealer, two days drying period is recommended by most of the manufacturers and Highway Agencies.

In most of the cases application procedures described by State Highway Agencies are based on manufacturers' recommendations. Before you can apply any sealer, the following steps must be taken:

1. Have the deck cleaned by washing, power sweeping and whatever method the contractor chooses to remove all dirt, sand, clay and other debris from the deck. The DOT's best practice is to clean the deck one week in advance of sealer application, thereby reducing the need for further cleaning as a result of tracked on dirt and contaminants. To meet environmental constraints, schedule the deck-washing program in conjunction with the deck-sealing program.
2. Before the sealer is applied, the deck must be allowed to dry and this may take 1 to 3 days depending upon weather conditions, air temperature, sunshine, last rainfall, type of concrete surface, porosity of the concrete and relative humidity in the air. In order to obtain maximum waterproofing in the concrete, the deck has to be very dry before application of sealer. The drier the surface, the better the penetration depth.
3. The coverage rate of the sealer needs to be calculated depending on the type of sealer used. The approved products list by the state DOTs indicates the minimum application rate for each product under ideal conditions. For best results, the

application rate as indicated on the sealer product should be increased by 30% to allow for variable concrete condition. At least two coats of sealer should be applied on the cleaned surface. The second coating should be applied perpendicular to the first coating.

4. Check for compatibility of the products on previously sealed concrete surfaces.
5. Several methods are available for sealer application. The survey conducted for NCHRP Synthesis 209 (Cady, 1994) indicates that roller, air-less spray, and broom are the preferred methods for silane. For siloxane, air-less spray and roller are preferred. The nozzle of the air-less spray gun atomizes the sealers at low pressures, achieving a controllable spray that results in minimal over spray. Surface flooding is also another preferred method provided that necessary steps have been taken to prevent the runoff of the sealer.
6. Silane sealer should be kept in airtight drums and should be stirred to mix the active ingredient prior to use. The product is to be used within the manufacturer's specified shelf life.

In general, surface sealers were limited to those products that could be relatively easily applied via spray, squeegee, brush, or roller onto the bridge deck. From an economic and performance standpoint, it is desired to use State DOT's maintenance personnel instead of contractors to install the products (Cady, 1994).

5.2 Sealers Application Intervals

It is very important to note that sealing the cracks and deck surface after water and chloride threshold levels are achieved does not immediately, if ever, mitigate the corrosion process. Therefore, delaying the achievement of these water and chloride corrosion thresholds as long as possible is the most cost-effective sealing guideline. In addition, the more aggressive deicing chemicals which are being used such as: sodium chloride, calcium magnesium acetate, magnesium chloride, calcium chloride, and potassium acetate, have a high probability of being detrimental to the concrete matrix. Therefore, early treatment, approximately 3 to 6 months after construction and every 5 years afterward, is recommended to minimize the intrusion of deleterious materials. Five-year application intervals are recommended because Taber abrasion test results (McGettigan, 1992) show that water penetration resistance is good for about 7 years of simulated traffic abrasion. Reducing the interval to 5 years is to take into account application, concrete permeability, and traffic variability.

5.3 Effectiveness of Sealers at Reducing Chloride Penetration into Bridge Decks

MNDOT has done some research on field performance of penetrating sealers for concrete bridge decks (Hagen et al., 1995). The objective of the research was to evaluate the effectiveness of various concrete sealers at reducing chloride penetration into a bridge deck with a low slump concrete overlay.

They tested sixteen different concrete sealers plus their untreated control section for a period of three years. Drill dust samples of concrete were collected annually from each test section for 3 years and then the sealers were rated on the chloride content of the test sections versus the control section. The effectiveness of the sealers compared with the untreated control section was determined by the following formula:

$$\frac{(\text{Control -}B) - (\text{Test Section - }B)}{(\text{Control - }B)} \times 100 = \text{Effectiveness} \tag{5}$$

Where "*B*" is the baseline chloride content of uncontaminated concrete and effectiveness considers the chlorides added to the deck after the sealers were applied. The baseline chloride content value was determined by averaging to be 110 parts per million (PPM). Listed in Table 5 are the different brands of sealers tested along with the chloride content in PPM after three years (Hagen et al., 1995).

TABLE 5: Comparison of Various Sealers on Chloride Content After 3 Years (MnDOT).

	Average Chloride Content (PPM)		
Product	1/16 to 1/2"	1/2 to 1"	1-1 1/2"
Hydrozo Enviroseal	970	240	110
Dekguard P-40	1650	470	160
Hydrozo Silane 40	1680	460	170
Paragon 15	1920	520	140
Horsey Set WDE	2260	330	100
Deck Seal PD 20	2280	370	110
Stifel H	2360	440	120
Deck Seal PD 30	2370	760	140
Sikaguard 70	2550	750	220
Sil Act ATS 42	2560	610	140
Dekguard WB	2610	790	110
Sil Act Multiguard	2630	570	120
Untreated Control	2710	690	120
Denii 315 + 615	2840	450	140
Trojan Masonry Sealer	3010	700	150
Genii 115	3040	810	130
Genii 315	3530	510	150

TABLE 6: Percent Effectiveness of the Sealers Against Chloride Penetration After 3 Years (MnDOT).

Product	Percent Effective 1/16 to 1/2"	1/2 to 1"
Hydrozo Enviroseal	67	76
Dekguard P-40	41	37
Hydrozo Silane 40	39	39
Paragon 15	30	29
Horsey Set WDE	17	61
Deck Seal PD 20	16	54
Stifel H	13	42
Deck Seal PD 30	13	-12
Sikaguard 70	6	14
Sil Act ATS 42	6	-10
Dekguard WB	4	-17
Sil Act Multiguard	3	20
Denii 315 + 615	-5	41
Trojan Masonry Sealer	-11	-2
Genii 115	-13	-20
Genii 315	-31	31

Table 6 shows the percent effectiveness of the sealer against chloride penetration. The Hydrozo Enviroseal and Dekguard P-40 along with Hydrozo Silane 40 rated in the top on chloride penetration prevention. Based on the MNDOT tests (Hagen et al., 1995) the following conclusions were drawn from this study:

1. Concrete sealers provide temporary protection to bridge decks with low slump concrete overlays. The best penetrating sealers appear to provide protection for about 3 years.
2. After 3 years, the best performed sealers were Hydrozo Enviroseal, a water-based silane; Fosroc Dekguard P-40 and Hydrozo Silane 40, both solvent-based silanes; and Paragon 15, a siloxane. There were all penetrating sealers.
3. Fosroc Dedguard P-40 has been one of the best sealers in the last two research studies of this type.
4. Silanes and siloxanes as a group appear to be the best performers, but there was considerable variability among products. Pore blocker sealers were generally not effective after only one year.
5. Runoff of excess material is a problem when attempting to get the recommended coverage in one coat. Multiple wet-on-wet applications at a lighter coverage rate seem to be necessary.

5.4 Performance of Alternative Bridge Deck Sealers

The South Dakota Department of Transportation (SDDOT) carried out research on alternative sealers for bridge decks (Soriano, 2002). To evaluate the sealers performance 30 cores were tested from 3 bridge decks. One deck was sandblasted, one was subjected to a power broom/forced air, and the last was left alone (The do nothing bridge). The samples were put through a 56-day ponding test using fluorescence dye so that water, as well as sealer penetration could be measured. After running laboratory tests on the bridge decks with sealer the following implementation recommendations were given (Soriano, 2002):

1. Bridge deck crack and surface sealing activities should be conducted within 3 to 6 months after construction and repeated every 5 years. Existing bridge decks should be treated to minimize further chloride and water ingress, thus reducing corrosion potential.
2. Linseed oil should be replaced with penetrating sealers (silanes, siloxanes, and siliconates) that incorporate alkyl groups larger than methoxy and ethoxy groups as their concrete bridge deck surface sealing materials.
3. Concrete crack sealing materials [Methyl Metacrylate (MMA), Modified Polyurethane (MPU), Epoxy] with viscosities of 15 cp should be used. If crack widths are 0.040 in (1.0 mm), epoxy should not be used because their extensibility properties are generally less than that of MMA and MPU.

In general, sealer penetration was greatest on the bridge deck that was sandblasted. The bridge that was left alone showed the best results. The MMA product that was applied with a roller had the best crack penetration. One of the crack sealing products, Unitex Pro-Seal, was applied with a garden sprayer. Its penetration depth was similar to the methyl methacrylate and exhibited similar results in the water ponding test. The 100% silane exhibited slightly better penetration than the 40% silanes.

It is found that high molecular weight methacrylate (HMWM) exhibits the best performance with respect to crack penetration, bridging, and sealing. It has also been found that HMWM crack and deck sealing products with viscosities less than 15 cp (centipoise or 0.001 pascal-seconds) appear to achieve good penetration (0.10 inch) into cracks and deck surface, respectively. Table 7 shows the products tested, along with the cost of each material per square foot (Soriano, 2002). From a labor standpoint, all of these products are quick-curing (approximately 1 hour) with the exception of Dow 888. For an average bridge deck (approximately 130ft x 26ft = 3,380ft^2), traffic control, deck preparation, application, and curing will take approximately 4 to 6 hours.

6. STATE DOTs BRIDGE DECK CRACK SEALING PRACTICIES

SDDOT conducted a survey of 25 northern tier states and Canadian provinces with respect to current bridge deck crack sealing strategies. The summary of survey regarding their crack and deck sealing practices is given in Table 8 (Soriano, 2002). The survey did

TABLE 7: Cost Comparison of Sealer.

Product	Cost ($/SF)
100% Silane – Degussa	0.35 – 0.40
40% Silane –Hydrozo	0.16 – 0.20
40% Silane – Masterbuilders	0.16 –0.20
Reactive Methyl Methacrylate – Degussa	0.45
Modified Polyurethane – Roadware	1.40
Two - Component Epoxy-Vnitex ProSeal	0.70
Dow 888 Silicone	1.25 ($/LF)

not reveal any consensus with respect to bridge deck crack sealing strategies, but it did contain general tendencies toward the use of certain crack and deck sealing materials, See Table 8.

With consultation of the NDDOT, a survey questionnaire was prepared and sent to state DOTs. The survey responses for several state DOTs (Ohio, Montana, Michigan, Idaho, California, Mississipi, Maryland, and Texas) are given in Appendix B. By reviewing the literature and State DOTs survey responses the following information was attained regarding State DOTs crack and deck sealing practices.

Alberta DOT

Concrete sealing has a long history in Alberta; in the 1960's boiled linseed oil was used for maintenance of existing bridge curbs. Epoxies and other types of sealers were also tried in the 60's. The first epoxy-wearing surface in Alberta was in 1963 at Morley. Dehydratine, a black tarry substance, was routinely used on abutments, since the late 1960's. Epoxy and acrylic sealers were routinely used on standard precast girders starting in the middle of 1970's. Penetrating silane sealers were first used in Alberta on concrete bridge decks in 1986. The Alberta DOT now uses penetrating sealers and coatings, which offer better protection against the ingress of deicing salts. The Alberta DOT generally seals bridges on a 4-year cycle (this cycle could vary from region to region).

Colorado DOT

The current practice for the Colorado DOT is to apply CDOT-approved silane sealers to bare bridge decks where needed. The CDOT is considering avoiding the use of silane or siloxane type of sealers due to the fact that they need to be replenished on a regular basis. They are also looking into thin bonded polymer overlays for protecting the bridge decks, but have not used any officially yet. After 30 years using the waterproofing membranes, they have had a successful track record.

Michigan DOT

Michigan DOT uses penetrating water repellent treatment for some of their bridge decks. This is a clear sealer with the consistency of water that provides water repellency to horizontal and vertical concrete surfaces. It is typically used for vertical surfaces of substructure units but it can also be applied to deck surfaces that are relatively new and may need the protection of a water sealer. This sealer offers negative aesthetic value, so it should only be used where aesthetics are not important. To use this sealer, all concrete to

TABLE 8: SDDOT Agency Survey Summary.

#1	Which of the following cracking types do your bridge Decks experience?		Response
	Transverse	=	19
	Random	=	20
	Other	=	8
#2	Does your agency consider bridge deck cracking an adverse problem?		
	Yes	=	20
	No	=	3
	Other	=	2
#3	Does your agency have a bridge deck maintenance program?		
	Yes	=	20
	No	=	6
	Other	=	1
#4	What deicing technology do you use?		
	NaCl	=	22
	CaCl	=	11
	MgCl	=	11
	Other	=	3
	N/A	=	0
#5	Do you require epoxy-coated rebar in your bridge deck design specifications?		
	Yes	=	21
	No	=	4
	Other	=	0
#6	What methods of bridge deck failure detection does your agency use?		
	Sounding	=	21
	Coring	=	19
	Non-Destructive	=	9
	Visual	=	22
	Other	=	3
#7	Does your agency have a policy for sealing cracks on bridge deck?		
	Methacrylate	=	6
	Epoxy	=	6
	Polyesters	=	0
	No	=	15
	Yes for AC Sealer	=	1

TABLE 8: SDDOT Agency Survey Summary (Continued).

#8a	What is your criterion to begin surface crack repair?		Response
	1/6" or less	=	5
	1/8" or less	=	4
	Other	=	5
	N/A	=	11
	Do not for PCC	=	1
	No Policy	=	1
	Crack width: 1/16" or less, 1/8" or less, Other		
#8b	Extent over bridge deck surface: Low, Medium, High		
	Low	=	6
	Medium	=	3
	High	=	3
	N/A	=	14
	No Policy	=	1
#9	Which restorative products do you use to seal and/or restore failed bridge decking?		
	Methacrylate	=	7
	Epoxy	=	8
	Other	=	7
	N/A	=	9
#10	What bridge overlay products does your agency use?		
	Low Slump Concrete	=	10
	Polymer Concrete	=	4
	Latex Modified Concrete	=	10
	Asphalt	=	11
	Other	=	12
#11	Does your agency use sealing products on bridge decks?		
	Barrier	=	4
	Penetrating	=	11
	Other	=	1
	No	=	13
#12	Does your agency use membranes?		
	Yes	=	12
	No	=	11
	Other	=	3

be sealed must be at least 28 days old. The surface of the concrete to be sealed should be prepared using high-pressure power washing (for a new deck sandblasting would be good to remove the curing compound). Once the surface is dried the material is applied using rollers.

Minnesota DOT

Generally the MNDOT does not use concrete sealers, but they cited that under certain circumstances the use of a sealer is necessary. These situations may include late season concrete pours and certain problem conditions, such as hardened concrete with low air content or high water/cement ratio (Hagen, 1995). Common types of crack sealers used by MNDOT are Baytec Reactive, Dow Corning 888, Crafco RoadSaver Silicone #34902, Dow Corning 890, Crafco RoadSaver Silicone #34903, and CSL 316 SL.

The Minnesota DOT has done some research in penetrating sealers, such as Hydrozo Enviroseal, Fosroc Dekguard P-40, Hydrozo Silane 40, and Paragon 15, for concrete bridge decks. They concluded that silanes and siloxanes as a group appear to be the best performers, but there was considerable variability among products. The best penetrating sealers appear to provide protection for about 3 years. Also they cited that good laboratory results do not necessarily mean good performance in the field. All the sealers subjected to NCHRP 244 series II chloride reduction, a laboratory test, scored 83% or better, while after one year in the field no sealer was more than 75% effective.

Montana DOT

For deck sealing the Montana DOT uses a HMWM sealer for sealing deck cracks. Their first installation was in 1990 and those applications are still working so they don't have an approximation of how long the sealer will last. The Montana DOT is planning bridge deck highway maintenance by applying HMWM sealers to 13 concrete bridge decks in Missoula and Mineral County. The project will place the HMWM sealers on the bridge decks and then will apply new pavement markings. The purpose of this project is to seal the decks, thus extending their useful life.

Nevada DOT

The Nevada DOT uses linseed oil (more a membrane sealer than a penetrating sealer) for sealing roadways, but they have found that silanes exhibit the greatest degree of concrete permeability reduction of products they have used (Attanayaka et al., 2003).

Ohio DOT

The Ohio DOT did work treating concrete wearing surfaces of bridge decks with a penetrating sealer. The material they used was HMWM sealer.

South Carolina DOT

The South Carolina DOT considers the following three requirements for sealers to be used for sealing bridge decks.

Chemical Requirements: The silane compound shall be Monomeric Alkyltrialkoxy silane. It may be iso-butyltrimethoxy, n-octyl-trimethoxy or iso-octyl-trimethoxy silane. The treatment solution shall be 40% silane compound by weight, mixed with an anhydrous alcohol solvent or mineral spirits. Fugitive Dye, an ultraviolet (UV) sensitive color additive, may be premixed by the manufacturer but is not required.

Performance Requirements (Treated surface at maximum rate of 125 sf/gal ($3m^2/L$): The treatment solution shall be capable of producing a non-wettable concrete surface and provide a minimum penetration depth of 4 mm at any single spot in the deck concrete matrix. The color or friction properties of the deck surface shall not be changed when the treatment solution is applied in accordance with these specifications at the recommended rate not to exceed 125 sf/gal ($3m^2/L$).

Physical Requirements: The treated surface shall be capable of performing in accordance with the physical requirements for product approval. Testing shall be performed as indicated using 40% silane treatment solution at the rate of 125 sf/gal (3 m^2/L).

1. OHD-L-35 and/or ASTM D 1653
   The moisture vapor transmission rate should be minimum 98% in relation to uncoated specimen.
2. NCHRP 244 Series II Cube Test (Accelerated Weathering Test)
   The weight gain should be maximum 20% of the weight gain of uncoated cubes. The absorbed chloride should be maximum 20% of the chloride content of uncoated cubes.
3. NCHRP 244 Series IV Slab Test (Southern Climate)
   The absorbed chloride content at the end of 24 weeks should be maximum 10% of the chloride content of uncoated slabs.

South Dakota DOT

The SDDOT has done research on alternative sealers such as, silanes and siloxanes that incorporate alkyl groups larger than methoxy and ethoxy groups as their concrete bridge deck surface sealing materials. Table 9 shows the recommended sealer products (Soriano, 2002). They agree that HMWM sealers exhibit the best performance with respect to crack penetration, bridging, and sealing. It is also noted that using the sealing agent after a few years, when cracks have already occurred, is not as effective as using it right away after the bridge deck is constructed. They also concluded that the 100% silane exhibited slightly better penetration than the 40% silanes.

TABLE 9: SDDOT Recommended Products.

Product Number	Product	Application
1	100% Silane-Degussa	Surface Sealer
2	40% Silane-Hydrozo	Surface Sealer
3	40% Silane-Masterbuilders	Surface Sealer
4	Reactive Methyl Methacrylate-degussa	Crack Sealer
5	Modified Polyurethane-roadware	Crack Sealer
6	Two-Component Epoxy-Unitex Pro-Seal	Crack/Surface Sealer
7	SDDOT Epoxy Chip Seal	Crack/Surface Sealer

They recommended that bridge deck crack and surface sealing activities should be conducted within 3 to 6 months after construction and repeated every 5 years. Existing bridge decks should be treated at 5-year intervals to minimize further chloride and water ingress, thus reducing corrosion potential. The recommended product and application time guidelines are shown in Tables 10, 11 and 12. In all cases where surface and crack sealers are combined, it is recommended that the crack sealer should be applied first, then the surface sealer.

TABLE 10: Product Guidelines for Crack Frequency Smaller than 5 Feet.

Crack Width, in.	Bridge Deck Age, Years		
	0 to 5	6 to 10	>10
<0.04	(1, 2, or 3) and (4 or 6) or 7	(1, 2, or 3) and (4 or 6) or 7	(1, 2, or 3) and (4 or 6) or 7
0.04 to 0.08	(1, 2, or 3) and (4 or 6) or 7	(1, 2, or 3) and (4 or 6) or 7	(1, 2, or 3) and (4 or 6) or 7
>0.08	(1, 2, or 3) and (4) or 7	(1, 2, or 3) and (4) or 7	(1, 2, or 3) and (4) or 7

TABLE 11: Product Guidelines for Crack Frequency from 5 to 10 Feet.

Crack Width, in.	Bridge Deck Age, Years		
	0 to 5	6 to 10	>10
<0.04	(1, 2, or 3) or (1, 2, or 3) and (4, 5, or 6)	(1, 2, or 3) or (1, 2, or 3) and (4, 5, or 6)	(1, 2, or 3) or (1, 2, or 3) and (4, 5, or 6)
0.04 to 0.08	(1, 2, or 3) and (4, 5, or 6) or 7	(1, 2, or 3) and (4, 5, or 6) or 7	(1, 2, or 3) and (4, 5, or 6) or 7
>0.08	(1, 2, or 3) and (4 or 5) or 7	(1, 2, or 3) and (4 or 5) or 7	(1, 2, or 3) and (4 or 5) or 7

TABLE 12: Product Guidelines for Crack Frequency Larger than 10 Feet.

Crack Width, in.	Bridge Deck Age, Years		
	0 to 5	6 to 10	>10
<0.04	(1, 2, or 3)	(1, 2, or 3)	(1, 2, or 3)
0.04 to 0.08	(1, 2, or 3) or (1, 2, or 3) and (4, 5, or 6)	(1, 2, or 3) or (1, 2, or 3) and (4, 5, or 6)	(1, 2, or 3) or (1, 2, or 3) and (4, 5, or 6)
>0.08	(1, 2, or 3) and (4 or 5)	(1, 2, or 3) and (4 or 5)	(1, 2, or 3) and (4 or 5)

Virginia DOT

The Virginia DOT Test results showed the wear life for the tested sealers (silane, and siloxane) to be slightly less than nine years. Bridges that have a lower traffic volume [less than 24,270 average annual daily traffic (AADT)] may have a longer life. It was also shown that a maximum service life for hydrophobic sealers is about seven years and about ten years for bridge members not exposed to traffic wear.

7. CONCLUSIONS AND RECOMMENDATIONS

This project dealt with the application of sealing agents in concrete durability of bridge decks. When a concrete deck cracks it increases its permeability drastically. By applying penetrating sealers to concrete surfaces the permeability of the concrete is reduced.

A comprehensive state-of-the-art literature review was carried out on the application of sealing agents on concrete. The project investigated the type of sealers state Department of Transportations (DOTs) used in the past few years on their bridge decks, when and how sealers were used, how often the sealers reapplied, and the cost effectiveness of each type of sealer. It is concluded that the service life of a sealer is affected by various factors including: environmental conditions, traffic wear, penetration depth, ultraviolet (sun) light, exposure type, and by the quality of the concrete used. Also good quality concrete significantly enhances the chloride diffusion life extension characteristic of sealed surfaces.

Based on this study the following conclusions and recommendations can be made when applying penetrating sealers on concrete bridge decks:

- The silanes and siloxanes, sealing products with viscosities less than 15 cp, have achieved from 0.10 (2.5mm) to 0.24 inches (6.1 mm) in penetration into the cracks and deck surfaces, depending on the condition of bridge decks.
- Measuring chloride diffusion through the sealer is a rational way to estimate the corrosion protection service life of a sealer.
- The maximum service life for hydrophobic sealers varies from 3 to 7 years. The average service life is about 5 years. This would be extended to about 10 years for bridge members not exposed to traffic wear.
- Using a sealing agent after a few years, when cracks are already happening is not as effective as using it right away after the bridge deck is constructed. Bridge deck crack and surface sealing activities should be conducted within 3 to 6 months after construction and repeated every 5 years.
- Existing bridge decks should also be treated to minimize further chloride and water ingress, thus reducing corrosion potential.
- The average time for traffic control, deck preparation, application, and curing will take approximately 4 to 6 hours (Soriano, 2002).
- Sealer penetration was greatest on the bridge deck that was sandblasted before application of sealer.
- Runoff of excess material is a problem when attempting to get the recommended coverage in one coat. Multiple wet-on-wet applications at a lighter coverage rate seem to be necessary.

In summary, Part-I of this report discusses the fundamentals of using penetrating sealers as a means of concrete bridge deck protection. The factors affecting the depth of penetration are identified through this fundamental approach and the literature on penetrating sealers, concrete deterioration, concrete durability, and concrete permeability. Properties and the use of silane, siloxane, and high molecular weight methacrylate sealers are discussed. The main objective of this research was to identify the properties and use of penetrating sealers for uncracked and cracked concrete. Based on the literature review findings, penetrating sealers are effective if proper surface cleaning and application procedures are employed. Silane and siloxane sealers are effective on concrete decks having crack width less than 0.002-inches (0.05 mm). Decks having crack widths less than 0.08-inches (2.0 mm) can be treated with high molecular weight methacrylate in conjunction with silane sealers.

PART II

Evaluation of Sealers Based on Lab Tests

8. INTRODUCTION

This task deals with the evaluation of the sealers based on the eight sets of laboratory tests listed in Table 13. This Table gives the test methods and a description of each test conducted under this project. These tests were recommended by the North Dakota Department of Transportation (NDDOT) Research Advisory Committee.

TABLE 13. Laboratory Test Methods.

Test Set	Test Method	Description
A	ASTM C 642-97	Water Absorption Test in Hardened Concrete
B	ASTM C 672/C 672M-03	Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals
C	AASHTO T 161-00	Resistance of Concrete to Rapid Freezing & Thawing
D	AASHTO T 259-02	Resistance of Concrete to Chloride Ion Penetration
E	AASHTO T 260-97(01)	Sampling and Testing for Chloride Ion in Concrete and Concrete Raw Materials
F	NDDOT Method	Test for Average Depth of Penetration
G	NDDOT Method	Test for sealants ability seal crack widths up to 2mm wide (test to be devised in-house with NDDOT cooperation)
H	AASHTO T 277-96(00)	Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration

There are a total of 5 concrete sealant treatments (D335, DCS, SS, R7, and CT40):

1. Tamms Dural 335 (D335): is a solvent free, two components, moisture insensitive and ultra low viscosity epoxy sealer.
2. Degadeck Crack Sealer (DCS): is a low viscosity, low surface tension, rapid curing methacrylate reactive resin.
3. Star Sealer (SS): is based on specialty polymers and concrete saturants.
4. Radcon Formula #7 (R7): is a biochemically modified silicate solution.
5. Chem-Trete BSM-40 VOC (CT40): is an isobutyl-trialkoxy silane in an alcohol carrier.

The properties of sealers used in this project are given in Table 14. These sealants are evaluated for three groups of concrete mixes:

1. Group "C" is a regular concrete mix design without the addition of fly ash (i.e., 100% Portland cement). The details of Group "C" mix is given in Table 15.
2. Group "F" is a concrete containing fly ash (i.e., 70% Portland cement and 30% Coal Creek Fly Ash by weight). The details of Group "F" mix is given in Table 16.
3. Group "O" is on samples of old (hardened) concrete, which has been previously placed in the field.

TABLE 14. Properties of Sealers.

Tamms Dural 335 (D335)	is a solvent free, two components, moisture insensitive, and ultra low viscosity epoxy sealer.
Degadeck Crack Sealer (DCS)	is a low viscosity, low surface tension, rapid curing methacrylate reactive resin.
Star Sealer (SS)	is based on specialty polymers and concrete saturants.
Radcon Formula #7 (R7)	is a biochemically modified silicate solution.
Chem-Trete BSM-40 VOC (CT40)	is an isobutyl-trialkoxy silane in an alcohol carrier.

For each grouping, one specimen was left unexposed to any sealant and used as a control sample for comparison purposes. Thus there are a total of 18 separate concrete specimens evaluated for each laboratory procedure. Table 17 gives the total number of test specimens required for each set of tests.

The NDDOT furnished concrete mix designs (see Tables 15 and 16) and exposed concrete from the field (Group O) for laboratory testing. The field samples were from the Peak Interchange 94-296.741 bridge deck in North Dakota that was built in 1959 and was overlaid in 1989. The bridge was demolished and replaced by a new bridge in 2005. The field samples were delivered in large pieces to UND by the NDDOT. They were cut to proper dimensions by UND. All material used in the research met NDDOT specifications, this means that aggregate gradations/tests was completed, cement and fly ash met specifications by certification, and any admixtures that were used. The deicing chemical (potassium acetate) used for test set “B” was provided by the NDDOT. Concrete prepared in the laboratory was cast into compartments of a meshed solid slab of 3 inches thick. The compartments were sized according to the test specimen requirements. This resulted in individual rectangular specimens with proper dimensions. The aggregate characteristics and procedures for testing aggregate are given in Table 18.

For each group, a total of four batches of concrete mixes were used to cast the specimens. The mixes contain 40% of fine aggregate (sand) and 60% of coarse aggregate (Rock-1), see Tables 15, 16, and 18). The measured concrete mix properties: w/c ratio, air content, water reducer, slump and temperature, for Groups “C” and “F” are given in Tables 20 and 21, respectively. For these mixes, the measured slump varied from 2.25 to 3.0 inches and the measured air content varied from 5.0 to 6.0 percent, see Tables 19 and 20. It is worth noting that representatives from the NDDOT Materials and Research Division supervised part of mixing and preparation of the concrete mixes. The measured test data are given in Appendix-C (See Tables C1-C9). In what follows the conducted tests will be presented and discussed.

TABLE 15. Concrete Mix: Group C

NDDOT Specification

North Dakota Department of Transportation

Concrete Proportion Design

Project	NDDOT		Date	12/9/2005	
Contractor	UND Civil Engineering		Mix Design	C - Control	
Class of Concrete	Well Graded		Cement Type & Brand/Source	TypeI/II-Lafarge Dakota	
Sacks/CY	6.5	SP of Cement	3.14	% FA	0
Gals H_2O/Sack	4.2	SP of FA	2.54	% Air	6.0
Water/CM	0.377				

Admixtures	**Air (oz/cwt)**	**Wtr Reducer (oz/cwt)**	**Other (oz/cwt)**	**Other (oz/cwt)**
	1.0	6.0		

Material	**Rock**	**Intermediate**	**Sand**	**Filler**
Specific Gravaties	2.68	1.00	2.67	
Blend #1	60.00	0.00	40.00	
Blend #2	0.00	0.00	0.00	
Blend #3	0.00	0.00	0.00	
% Moisture	0.35	0.00	0.52	
Absorption	1.23	0.00	0.65	

Gradations	**Rock**	**Intermediate**	**Sand**	**Filler**
Sieve	**Percent Passing**			
1-1/2"	100.0	100.0	100.0	
1"	100.0	100.0	100.0	
3/4"	95.0	100.0	100.0	
1/2"	65.0	100.0	100.0	
3/8"	45.0	100.0	100.0	
#4	6.0	96.0	99.0	
#8	1.0	34.0	86.0	
#16	1.0	11.0	65.0	
#30	1.0	1.0	45.0	
#50	1.0	1.0	17.0	
#100	1.0	0.7	2.0	
#200	1.0	0.6	1.0	

North Dakota Department of Transportation

Concrete Proportion Design

Material	**One Cubic Yard**			**Single Batch (0.45 ft^3)**			**Double Batch (0.90 ft^3)**			**1**		
Blend #1	**ft^3**	**Lbs or fl oz**	**ml**	**ft^3**	**Lbs or fl oz**	**ml**	**ft^3**	**Lbs or fl oz**	**ml**	**ft^3**	**Lbs or fl oz**	**ml**
Air	1.62	0	-	0.03	0.00	-	0.05	0.00	-	0.06	0.00	-
Air Entrainment	-	6.11	180.7	-	0.10	3.0	-	0.20	6.02	-	0.23	6.7
Water	3.97	247.44	112,240	0.07	4.46	2022.2	0.14	8.92	4044.36	0.16	9.91	4,493.7
Water Reducer	-	36.66	1084.0	-	0.61	18.1	-	1.22	36.13	-	1.36	40.1
Cement	3.12	611.00	-	0.05	10.18	-	0.10	20.37	-	0.12	22.63	-
Flyash	0.00	0.00	-	0.00	0.00	-	0.00	0.00	-	0.00	0.00	-
Rock	10.96	1833.09	-	0.18	30.66	-	0.37	61.32	-	0.41	68.13	-
Intermediate Agg	0.00	0.00	-	0.00	0.00	-	0.00	0.00	-	0.00	0.00	-
Sand	7.33	1222.06	-	0.12	20.47	-	0.24	40.93	-	0.27	45.48	-
Filler	0.00	0.00	-	0.00	0.00	-	0.00	0.00	-	0.00	0.00	-
Batch Weight		3913.59			65.77			131.53			146.15	
Batch Size	27.00			0.45			0.90			1.00		
Free Water				-0.01	-0.33	-151.5	-0.01	-0.67	-303.03	-0.01	-0.74	-336.7

Combined Properties (One Cubic Yard)

Unit Weight (lbs/ft^3)	Vol of Paste (ft^3)	Vol of Aggregate (ft^3)	Combined Agg SP	Total Agg Weight (lbs)
144.95	8.70	18.30	2.68	3055.14

TABLE 16. Concrete Mix: Group F
NDDOT Specification
North Dakota Department of Transportation
Concrete Proportion Design

Project	NDDOT	Date	12/8/2005
Contractor	UND Civil Engineering	Mix Design	F - 30% Fly Ash
Class of Concrete	Well Graded	Cement Type & Brand/Source	TypeI/II-Lafarge Dakota

Sacks/CY	6.5	SP of Cement	3.14	% FA	30
Gals H_2O/Sack	4.01	SP of FA	2.54	% Air	6.0
Water/CM	0.360				

Admixtures	**Air (oz/cwt)**	**Wtr Reducer (oz/cwt)**	**Other (oz/cwt)**	**Other (oz/cwt)**
	0.80	6.0		

Material	**Rock**	**Intermediate**	**Sand**	**Filler**
Specific Gravaties	2.68	2.65	2.67	
Blend #1	60.00	0.00	40.00	
Blend #2	0.00	0.00	0.00	
Blend #3	0.00	0.00	0.00	
% Moisture	0.09	0.00	1.65	
Absorption	1.05	0.00	1.08	

Gradations	**Rock**	**Intermediate**	**Sand**	**Filler**
Sieve	**Percent Passing**			
1-1/2"	100.0	100.0	100.0	
1"	100.0	100.0	100.0	
3/4"	95.0	100.0	100.0	
1/2"	65.0	100.0	100.0	
3/8"	45.0	100.0	100.0	
#4	6.0	96.0	99.0	
#8	1.0	34.0	86.0	
#16	1.0	11.0	65.0	
#30	1.0	1.0	45.0	
#50	1.0	1.0	17.0	
#100	1.0	0.7	2.0	
#200	1.0	0.6	1.0	

North Dakota Department of Transportation
Concrete Proportion Design

Material	**One Cubic Yard**			**Single Batch (0.45 ft^3)**			**Double Batch (0.90 ft^3)**			**1**		
Blend #1	**ft^3**	**Lbs or fl oz**	**ml**	**ft^3**	**Lbs or fl oz**	**ml**	**ft^3**	**Lbs or fl oz**	**ml**	**ft^3**	**Lbs or fl oz**	**ml**
Air	1.62	0	-	0.03	0.00	-	0.05	0.00	-	0.06	0.00	-
Air Entrainment	-	4.888	144.5	-	0.08	2.4	-	0.16	4.82	-	0.18	5.35
Water	3.48	217.12	98,486.3	0.06	3.80	1723.0	0.12	7.60	3445.96	0.14	8.44	3,828.8
Water Reducer	-	36.66	1084.0	-	0.61	18.1	-	1.22	36.13	-	1.36	40.1
Cement	2.18	427.70	-	0.04	7.13	-	0.07	14.26	-	0.08	15.84	-
Flyash	1.16	183.30	-	0.02	3.06	-	0.04	6.11	-	0.04	6.79	-
Rock	11.12	1859.63	-	0.19	31.02	-	0.37	62.04	-	0.41	68.94	-
Intermediate Agg	0.00	0.00	-	0.00	0.00	-	0.00	0.00	-	0.00	0.00	-
Sand	7.44	1239.75	-	0.12	21.00	-	0.25	42.01	-	0.28	46.67	-
Filler	0.00	0.00	-	0.00	0.00	-	0.00	0.00	-	0.00	0.00	-
Batch Weight		3927.50			66.01			132.01			146.68	
Batch Size	27.00			0.45			0.90			1.00		
Free Water				0.00	-0.18	-81.5	-0.01	-0.36	-163.08	-0.01	-0.40	-181.2

Combined Properties (One Cubic Yard)

Unit Weight (lbs/ft^3)	Vol of Paste (ft^3)	Vol of Aggregate (ft^3)	Combined Agg SP	Total Agg Weight (lbs)
145.46	8.44	18.56	2.68	3099.38

TABLE 17. Description of Sample Specimens.

Test Set	Test Method	Dimensions	No. of Specimens	Total
A	ASTM C 642-97	Any shape, 800 g. minimum	3 per mix	54
B	ASTM C 672/C 672M-98	7" x 13" x 3" (LxWxT)	2 per mix	36
C	AASHTO T 161-00	12" to 16" x 3" x 3"	3 per mix	54
D	AASHTO T 259-02	6" x 5" x 3"	4 per mix	72
E	AASHTO T 260-97(01)	Same specimens in "d" were used for this test.		0
F	NDDOT Method	8" x 8" x 3"	3 per mix	54
G	NDDOT/UND Method	12" x 3" x 3"	2x2 per mix	60
H	AASHTO T 277-96(00)	4" diameter, 2" length	2 per mix	36

TABLE 18. Aggregate Characteristics

<u>Procedures for testing aggregate:</u>
ASTM C702 – Reducing Samples of Aggregate to Testing Size
ASTM C29 – Bulk Density ("Unit Weight") and Voids in Aggregate
ASTM C136 – Sieve Analysis of Fine and Coarse Aggregates
ASTM C566 – Total Evaporable Moisture Content of Aggregate to Drying
ASTM C128 – Density, Relative Density (Specific Gravity), and Absorption of Fine Aggregate
ASTM C127 – Density, Relative Density (Specific Gravity), and Absorption of Coarse

NDDOT Projet: Sealer Date: 11/10/2005
Coarse aggregate for concrete
Seive Analysis (Gradation)

				% of Retained	Cum. %R	% passing	% passing	% passing
Seive #	S (g)	S+A (g)	A (g)	(A/2158)*100			NDDOT (3)	NDDOT (4)
1 inch	7294.7	7294.7	0	0	0	100	95-100	100
3/4 inch	7465.2	7580.7	115.5	5.35	5.35	95	N/A	90-100
1/2 inch	7306.5	7938.6	632.1	29.29	34.64	65	25-65	N/A
3/8 inch	7192.3	7628.8	436.5	20.23	54.87	45	15-55	20-55
4	7247.5	8096.6	849.1	39.35	94.22	6	0-10	0-10
8	6926.1	7024.4	98.3	4.56	98.77	1	0-5	0-5
200	6134.4	6147.0	12.6	0.58	99.36	1	1	1
Pan	5991.5	6005.4	13.9	0.64	100.00	0		
Total			2158	100				

S=Passed Aggregate; A=Retained Aggregate

(a) Coarse aggregate characteristics (Rock-1)
Specific Gravity = 2.68
Absorption = 1.23%
Unit weight = 109.5 pcf
Moisture Content = 1.64%

NDDOT Projet: Sealer Date: 11/10/2005
Fine aggregate for concrete
Seive Analysis (Gradation)

				% of Retained	Cum. %R	% passing	% passing
Seive #	S (g)	S+A (g)	A (g)	(A/496.4)*100			NDDOT
3/8 inch	547.1	547.1	0	0	0	100	100
4	705.1	708.1	3	0.60	0.60	99	95-100
8	675.6	740.9	65.3	13.15	13.76	86	N/A
16	593.2	699.7	106.5	21.45	35.21	65	45-80
50	406.8	643.3	236.5	47.64	82.86	17	10-30
100	421.5	495.1	73.6	14.83	97.68	2	0-10
200	514.7	523.4	8.7	1.75	99.44	1	0-3
Pan	393.1	395.9	2.8	0.56	100.00	0	
Total			496.4	100			

(b) Fine aggregate characteristics (Sand)
Specific Gravity = 2.67
Absorption = 0.65%
Unit weight = 112.0 pcf
Moisture Content = 2.26%
S=Passed Aggregate; A=Retained Aggregate

TABLE 19. Concrete Mix Properties (Group C).
Mix: 100% Cement (without fly-ash)

Mix	W/C Ratio	Air (oz/cwt)	Water Reducer (oz/cwt)	Slump $(inches)$	Air (%)	Temp (^oF)
C-1	0.38	0.5	6.0	2.5	5.3	76
C-2	0.38	0.5	6.0	2.5	5.3	73
C-3	0.38	0.5	6.0	2.5	5.2	74
C-4	0.38	0.5	6.0	2.25	5.0	71

TABLE 20. Concrete Mix Properties (Group F).
Mix: 30% Fly-ash + 70% Cement

Mix	W/C Ratio	Air (oz/cwt)	Water Reducer (oz/cwt)	Slump $(inches)$	Air (%)	Temp (^oF)
F-1	0.35	0.5	6.0	2.5	5.9	75
F-2	0.35	0.5	6.0	2.5	5.4	74
F-3	0.35	0.5	6.0	3.0	6.0	70
F-4	0.35	0.5	6.0	2.5	6.0	70

9. Test A: Water Absorption Test in Hardened Concrete ASTM C 642-97

9.1 Test Procedures

The purpose of this test was to determine the absorption of water using various sealants on concrete specimens. The lab procedures of ASTM C 642-97 were followed in this test. There were five different sealers and three concrete mixes used in this test. Each sealer was applied to nine specimens of similar weight. Of the nine specimens, there were old concrete, normal concrete mix, and fly-ash concrete mix, (three specimens of each concrete mix). There were also nine separate "control specimens" that did not use any type of sealer. After applying sealers and following the ASTM C 642-97 standards, the absorption of water after immersion, absorption after immersion and boiling, bulk specific gravity, and other important characteristics that are important in determining the best performed sealer could be obtained.

To obtain the desired results of this test, all concrete specimens were to dry for 72 hours prior to application of sealers. This ensured that all moisture from the concrete was removed. Once the moisture from the concrete was completely removed, all five sealants were applied to the specimens in accordance with the supplier's instructions. The sealers were allowed to soak into the specimens and the added weight that the sealers added to the dry specimens were recorded. After the sealers were allowed to penetrate and settle into the specimens, the specimens were then immersed in water for a 48-hour soak period. The change in weight of specimens was recorded after the soak period. Continuing to follow the ASTM C 642-97 standards to complete the analysis of the test data, the absorption of water after immersion post sealer application and the volume of permeable pore space in each specimen were calculated.

9.2 Test Results

To analyze what sealer performed best in preventing penetration of water into the concrete, the measured data (see Tables C1-C3 in Appendix-C) are plotted in Figures 6 to 10. Figure 6 and 7 are plots of graphs showing the absorption percentage after immersion versus three trial specimens of identical sealer and concrete mix (repeated tests). Figure 8 shows the averaged absorption after immersion (%). The results are plotted for various sealers and concrete mixes. Figure 9 shows plots of graphs depicting the volume of permeable pore space (void) percentage versus three trial specimens of identical sealer and concrete mix (repeated tests). Figure 10 shows plots of graphs depicting the averaged volume of permeable pore space (void) percentage versus various sealers and concrete mixes. In these figures the average are taken for the results on three repeated trial specimens. With regards to the results in these figures the following observation can be made.

The most efficient sealers appear to be CT40, D335, and R7 Sealers. The results of absorption of water after immersion varying with normal, old, and fly-ash concrete indicate that the CT40, D335, and R7 sealers perform the best. The CT40, D335, and R7 sealers performed the best in terms of reducing the volume of permeable pore (void) space. The DCS and SS sealers show no effects on the volume of permeable pore (void) space, as the results for these sealers are almost the same as the specimen with no sealer (control specimen), see Figure 10. It also can be noted that the use of fly ash in concrete mix decreases the volume of permeable pore (void) space, because it is reduced significantly as compared to that of the normal and old concrete mixes. In addition, the old concrete showed relatively larger volume of permeable pore (void) space as compared to that of the other two specimens with normal and fly ash concrete mixes.

According to test data and analysis of the five sealers on the three different types of concrete specimens, it is concluded that the most efficient sealers are the CT40, D335, and R7 sealers. The fly-ash concrete mix performed best among the concrete mixes. It is also concluded that the best concrete for preventing absorption is the fly-ash concrete mix.

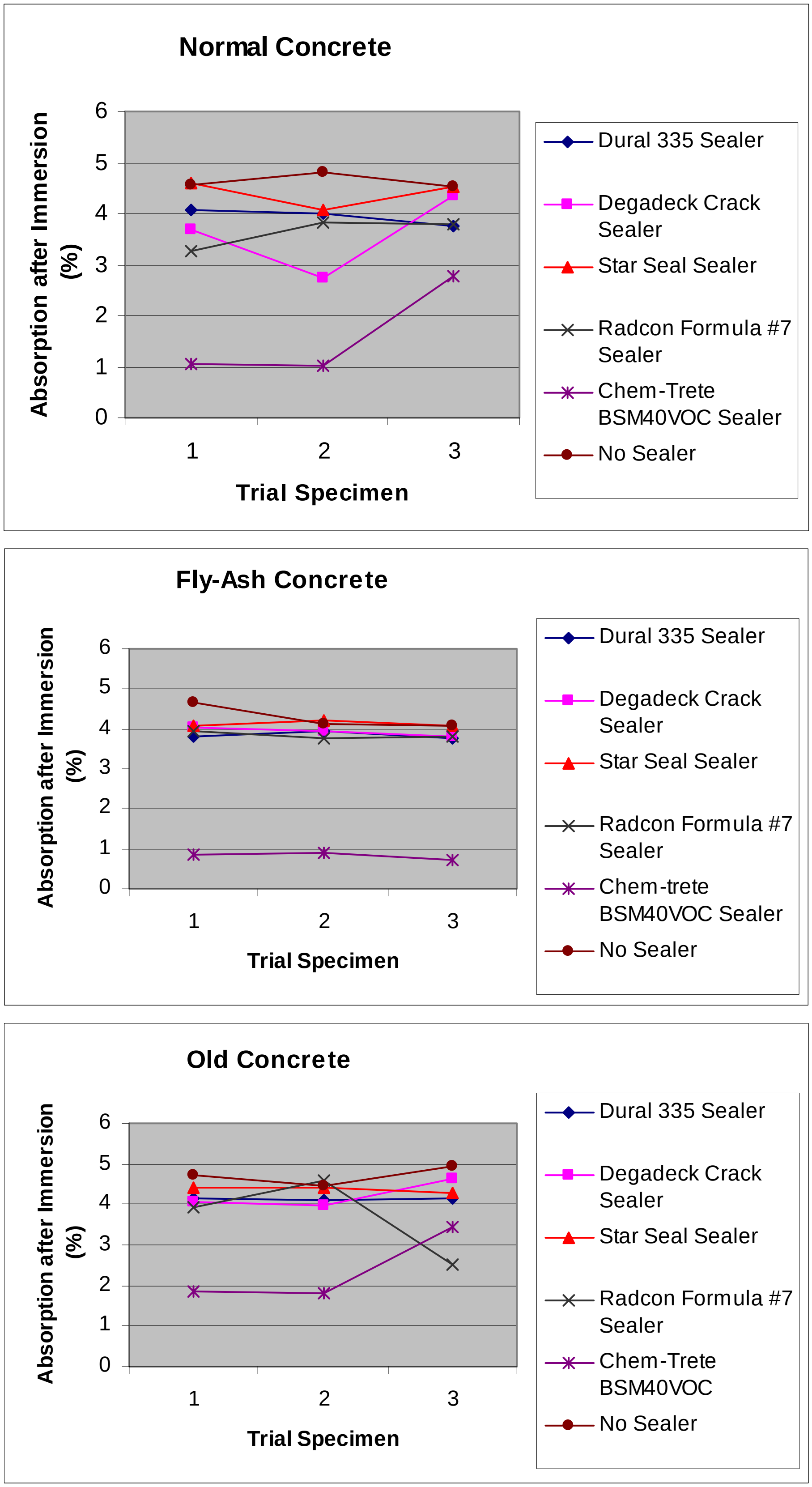
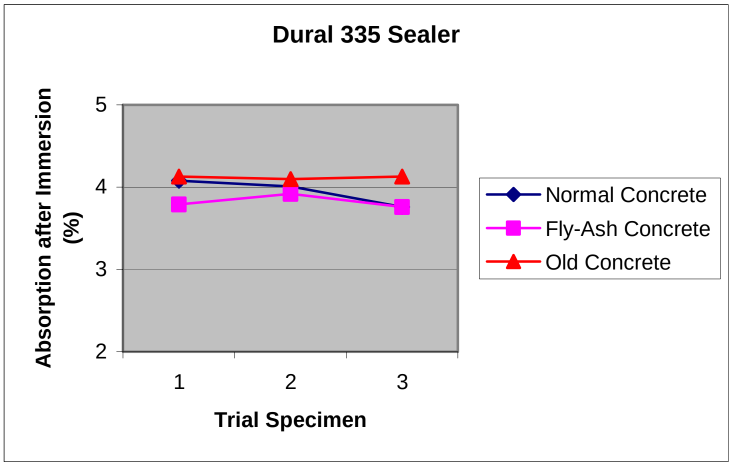
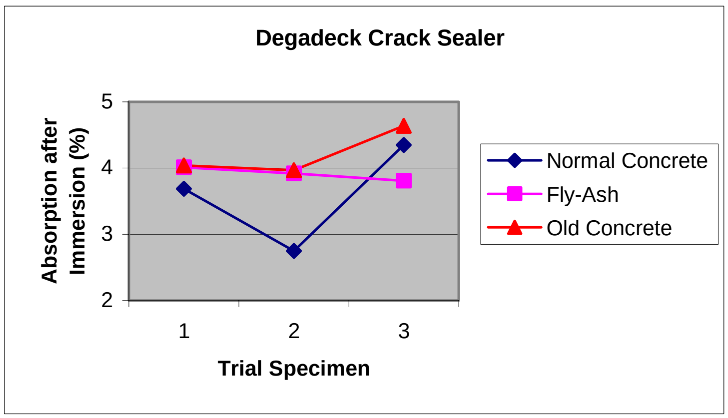


FIGURE 6. Absorption After Immersion (%).





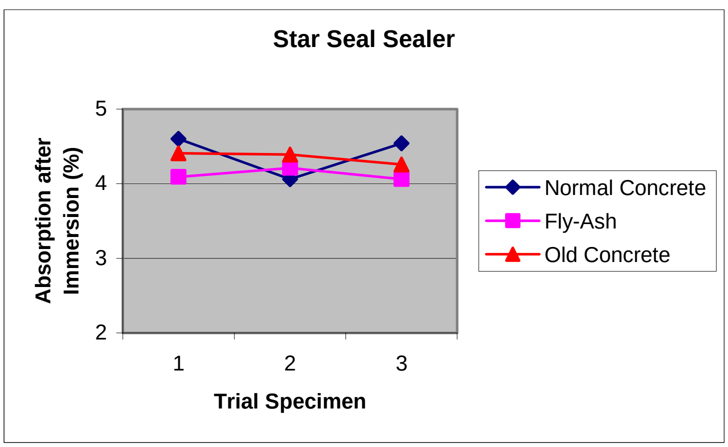
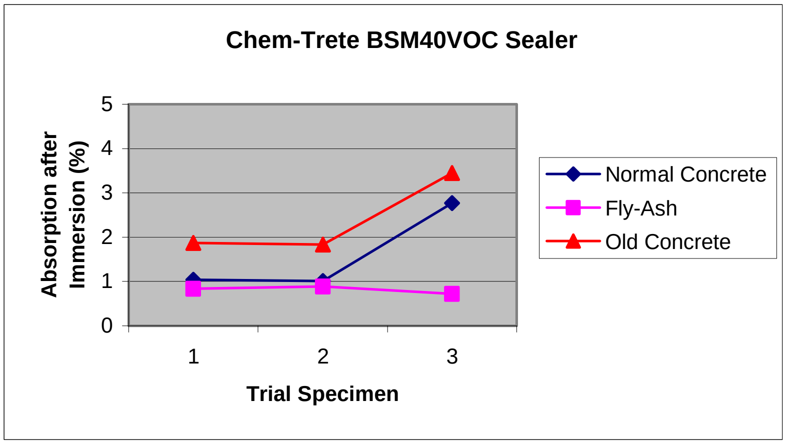


FIGURE 7. Absorption After Immersion (%).



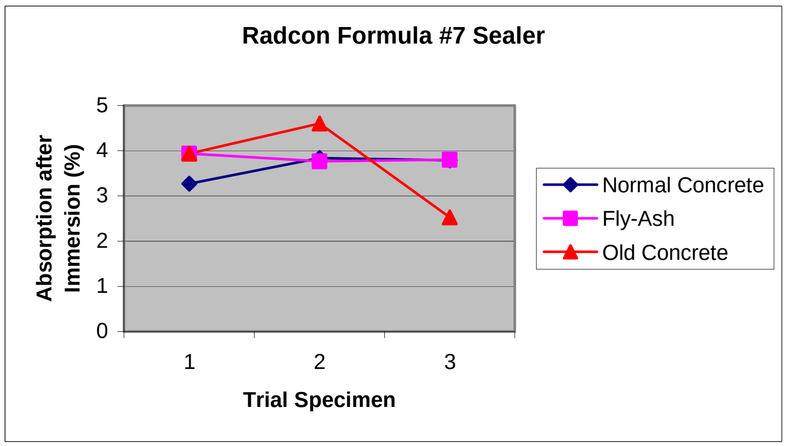
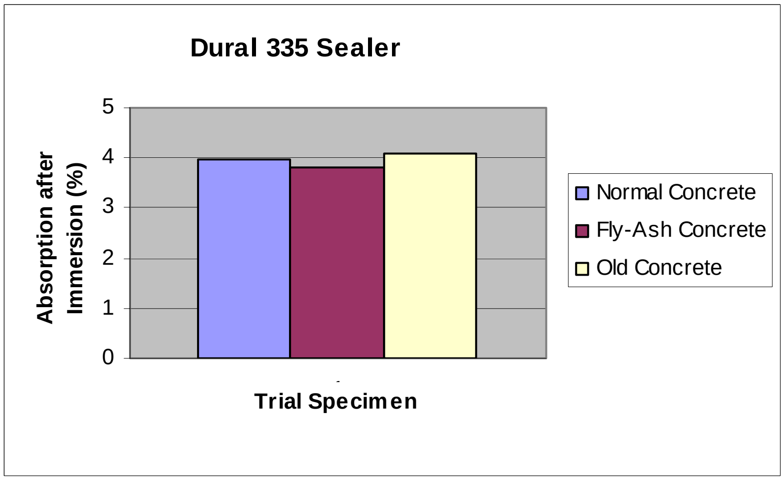
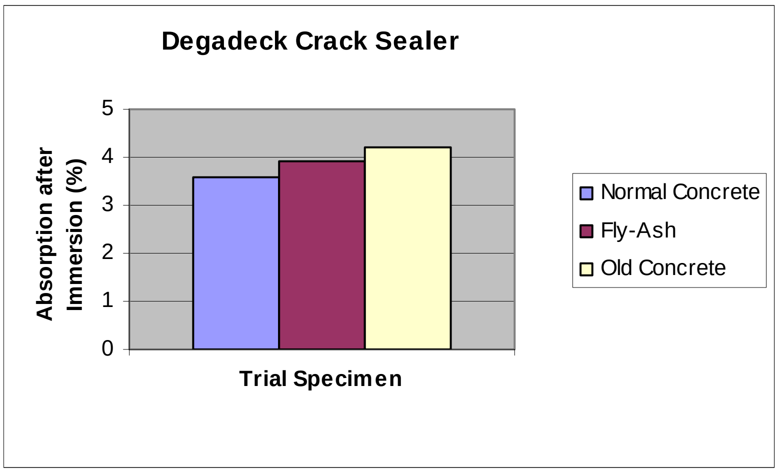


FIGURE 7. Absorption After Immersion (%) (continued).





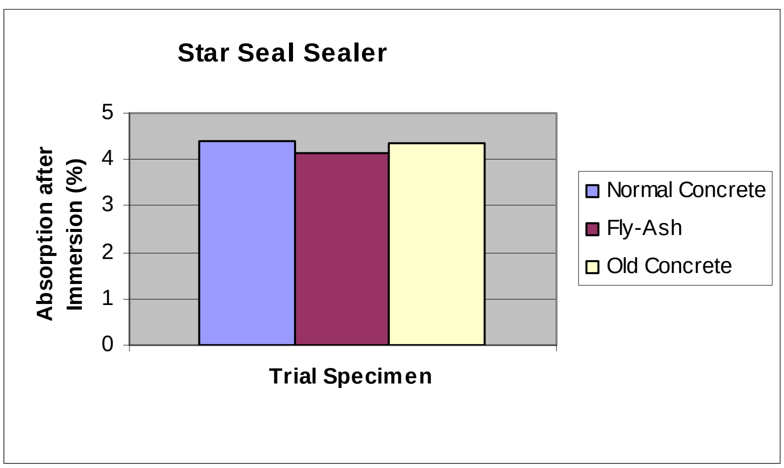
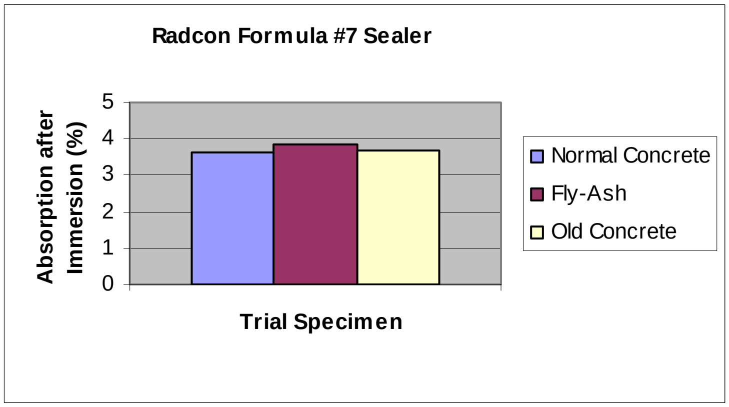


FIGURE 8a. Averaged Absorption After Immersion (%).



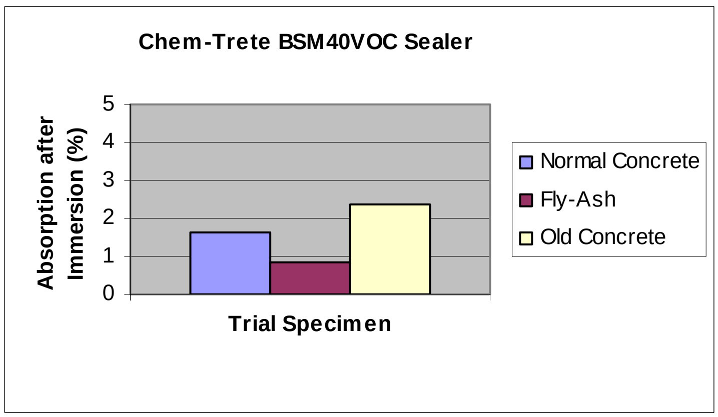
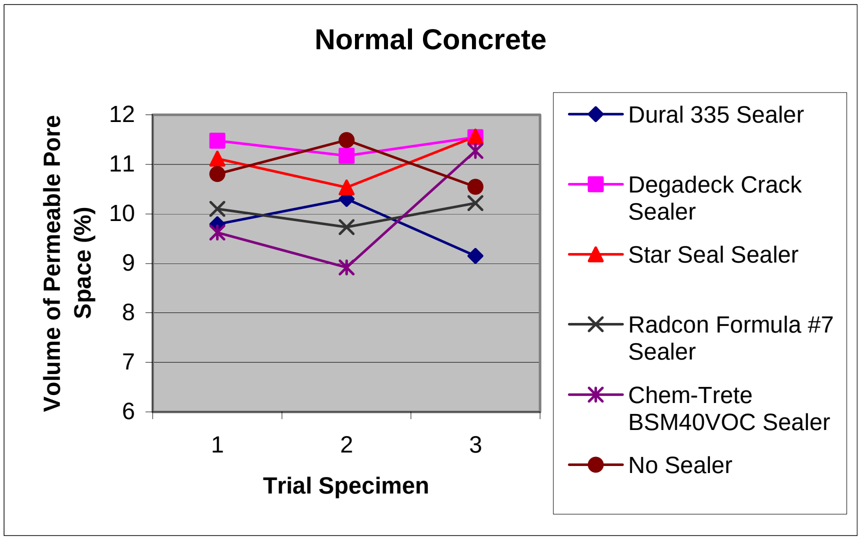
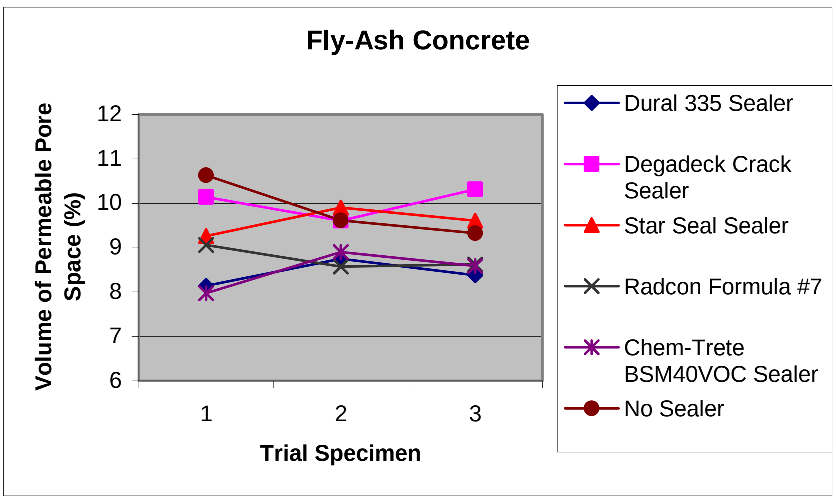


FIGURE 8b. Averaged Absorption After Immersion (%).

According to data and analysis of the five sealers on the three different types of concrete specimens, it is concluded that the most efficient sealer is the Chem-Trete-BSM40VOC sealer.





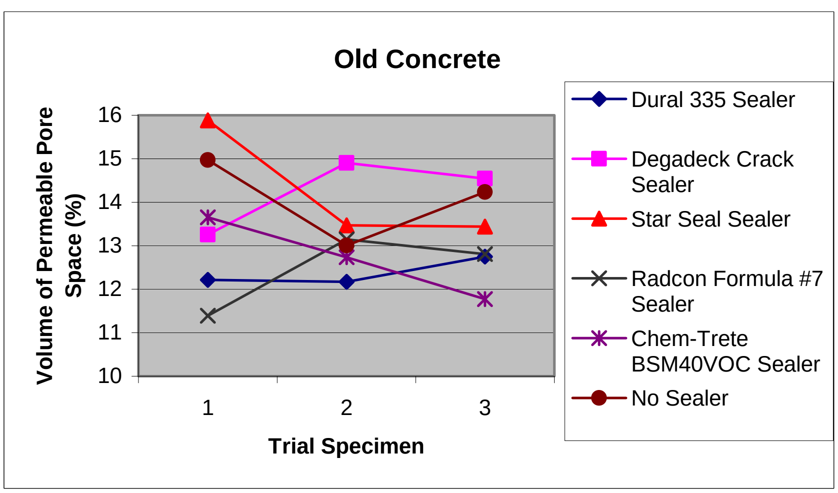
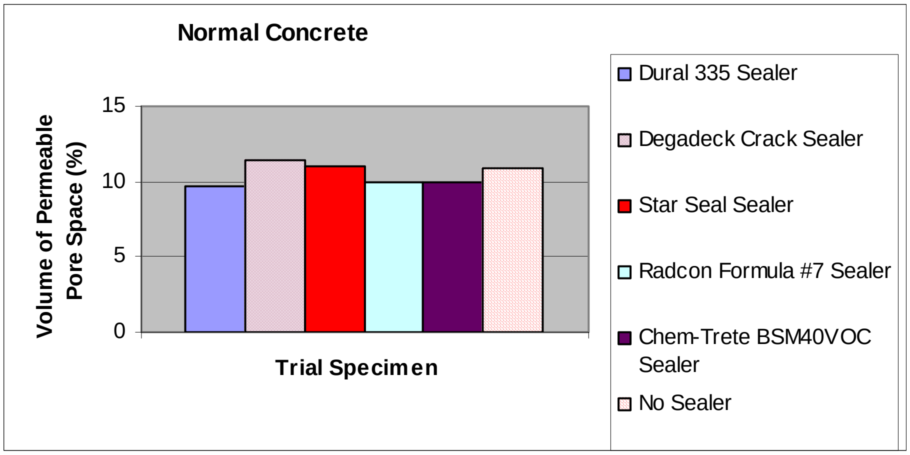
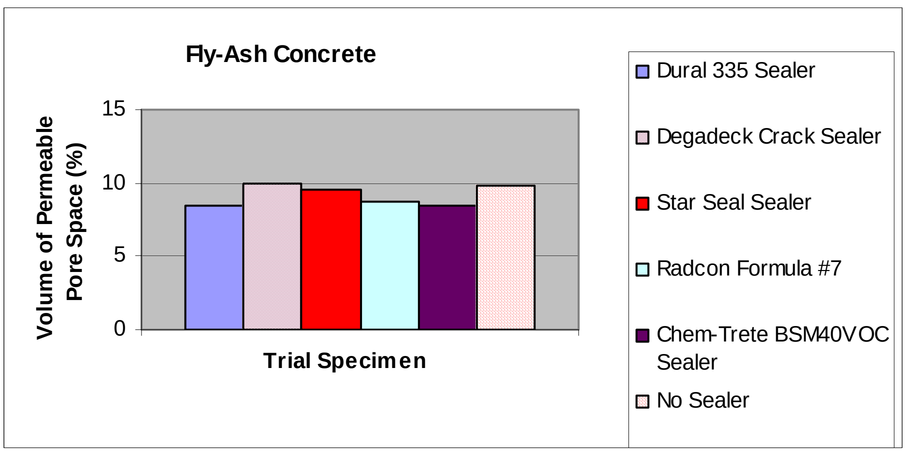


FIGURE 9. Volume of Permeable Pore (Void) Space (%).





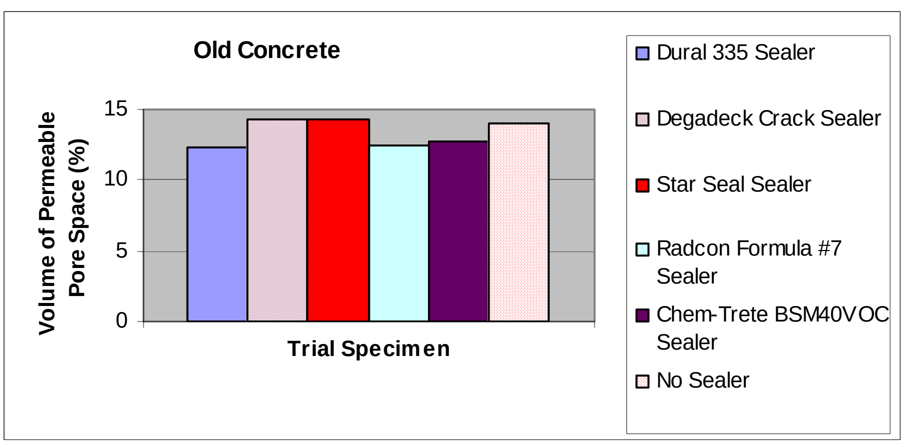


FIGURE 10. Averaged Volume of Permeable Pore (Void) Space (%).

It is concluded that the best concrete for preventing absorption is the Fly-Ash concrete mix.

10. Test B: Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals ASTM C 672/C 672M-03

10. 1 Test procedures

The purpose of this test is to determine the scaling resistance of sealant aided concrete surfaces exposed to deicing chemicals (Potassium Acetate). There were a total of five different sealers applied to the concrete specimens. Three different types of concrete mixes: normal concrete, fly-ash concrete, and old concrete mixes were used. Five sealers were applied to the specimens made with three different types of concrete mixes. The tests were performed using the ASTM C 672/C 672 M-03 standards. The concrete specimens were subjected to freeze-thaw cycles and the exposed surfaces were monitored at each cycle. The extent of concrete surface scaling on each specimen (with the pairing sealers and concrete mix) was recorded.

Following the ASTM C 672/C 672 M-03 standard procedures, this experiment is intended for use in evaluating the surface scaling resistance qualitatively by visual examination. Each of the three concrete types was paired with the five different types of sealers along with one specimen that had no applied sealer, used as the control specimen. In this experiment, each pairing of sealer and concrete mix had two concrete specimens used of that specific combination, giving us a total of 36 specimens used.

The sealers were applied to the concrete specimens at the age of 28 days. The protective coatings were applied at the proper time of application for curing compounds, as described in test Method C 156. Once the specimens had the sealers applied and completion of moist and air curing took place, the flat surface of the specimen was covered with approximately 0.25 in of a solution of potassium acetate provided by the NDDOT. Once the specimens have their deicing solution applied, they are put into a freezing environment for 16 to 18 hours (freezing period), see Figure 11. At the end of this time period the specimens were removed from the freezer and were placed into laboratory air with a relative humidity of 45%-55% for 6 to 8 hours (thawing period), see Figure 12. Water was added between each cycle to maintain the proper depth of the solution. The freeze-thaw cycle was repeated daily, flushing off the surface thoroughly at the end of each 5 cycles. Visual examination was done after the fifth cycle with observation and pictures, for examples see Figures 13 and 14. The freeze-thaw cycles of the specimens were repeated up to 100 cycles.

FIGURE 11. Freezing of the Specimens in the Freeze Room.

FIGURE 12. Thawing of the Specimens in the Laboratory.

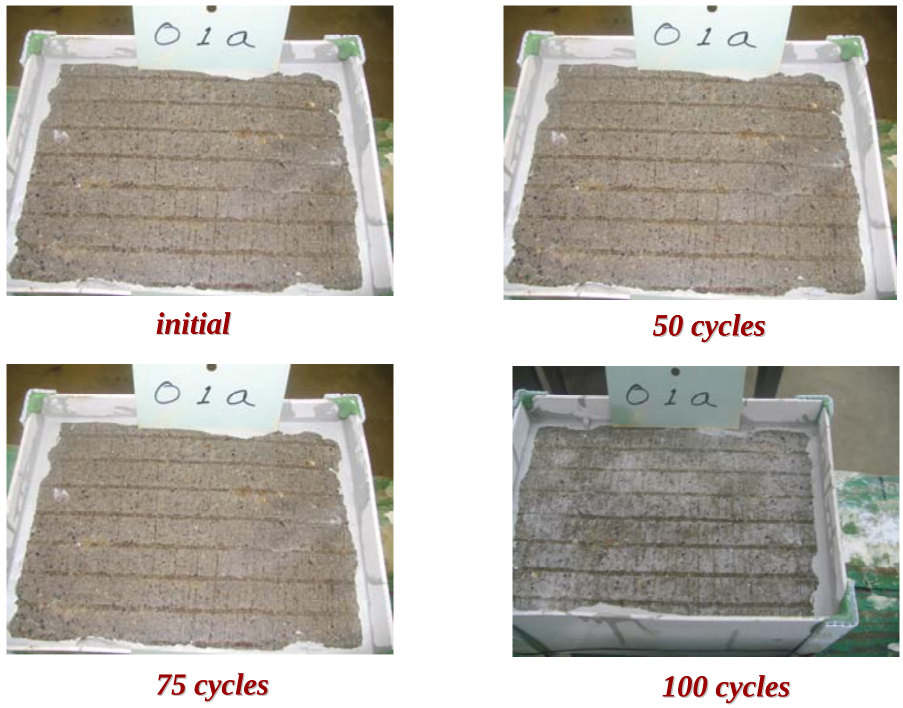


FIGURE 13. Visual Examination of Concrete Surface Scaling for Control Specimen with no Sealer (Scaling index = 0 up to the 100th Cycle).

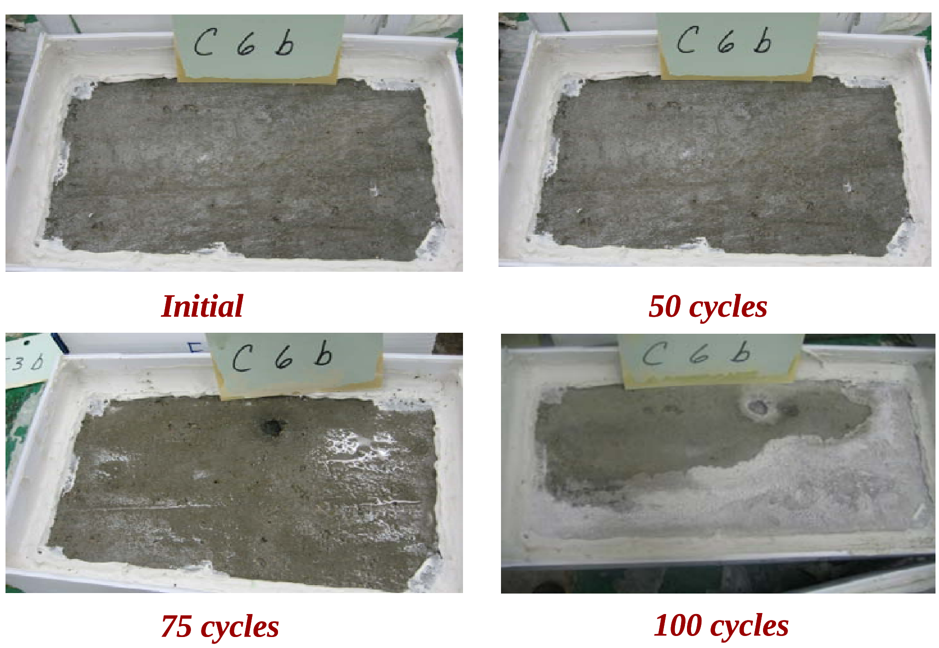


FIGURE 14. Photos of Concrete/Sealers: Visual Examination of Concrete Surface Scaling for Specimen with CT40 Sealer and Normal Concrete Mix (Scaling Index =0 up to the 50th Cycle, Scaling Index =1 up to the 75th Cycle, and Scaling Index = 2 up to the 100th Cycle).

10.2 Test Results

To analyze what sealant performed the best in preventing scaling of the concrete specimens with the application of the deicing chemical, a 0-5 rating index was used. The description of rating index for concrete surface scaling is given in Table 21.

TABLE 21. Description of Rating Index for Concrete Surface Scaling.

0	No scaling
1	Very slight scaling (1/8 in. depth max, no coarse aggregate visible)
2	Slight to moderate scaling
3	Moderate scaling (some coarse aggregate visible)
4	Moderate to severe scaling
5	Severe scaling (course aggregate visible over the entire surface)

The monitored scaling resistance indices for the normal concrete mix, fly-ash concrete mix and old concrete are summarized in Tables 22, 23 and 24, respectively (see also Table C4 in Appendix-C). From these results it is evident that scaling first began to appear in the 75th cycle, at a degree of classification index 1.

As an example, Figure 13 compares scaling resistance of specimen with no sealer (control specimen) and old concrete subjected to initial, 50, 75 and 100 cycles. This specimen is rated for surface scaling with index 0 (no scaling) up to 100th freeze-thaw cycle. As another example, Figure 14 compares scaling resistance of specimen with CT40 sealer and normal concrete mix subjected to the initial, 50, 75, and 100 cycles. This specimen is rated for surface scaling with the index = 0 (no scaling) up to 50th cycle, index = 1 (very slight scaling) for the 75th cycle and index = 2 (slight to moderate scaling) for the 100th cycle.

From the results in Tables 22-24, it is apparent that the D335 sealer performs the best in the resistance to concrete scaling due to deicing chemicals in freeze thaw cycles. In all three different types of concrete, the D335 sealer exhibits no sign of scaling (with scaling index of zero) until 100 cycles of freeze-thaw. In Table 24 for the Fly ash concrete mix, the CT40 sealer also showed no sign of scaling up to the 100th cycle.

In Table 24 for the old concrete, the D335 sealer also exhibits no sign of scaling up to the 100th cycle. The maximum scaling index for old concrete is 1 (very slight scaling) and for normal concrete and fly-ash concrete is 2 (slight to moderate scaling). The control specimen for old concrete almost show no sign of scaling (with scaling index of zero for one specimen and 1 for the other, see Table 24 and Figure 13) and the maximum scaling index for the control (without sealer) specimens with normal and fly ash concrete mixes is 2 (see Tables 22 and 23). This indicates that the concrete mixes are very sound and they performed very well in resisting scaling of the concrete surface due to the deicing chemical (Potassium Acetate) under freeze-thaw cycles.

TABLE 22. Scaling Resistance of Normal Concrete Surface.

Specimen	Sealer	C#:75	C#:85	C#:90	C#:100
C1A	Control	0	0	0	1
C1B	Control	1	1	1	2
C2A	D335	0	0	0	0
C2B	D335	0	0	0	0
C3A	DCS	0	0	1	2
C3B	DCS	1	1	1	2
C4A	SS	0	0	0	1
C4B	SS	1	1	1	2
C5A	R7	1	1	1	2
C5B	R7	0	0	1	1
C6A	CT40	1	1	1	1
C6B	CT40	1	1	2	2

TABLE 23. Scaling Resistance of Fly-ash Concrete Surface.

Specimen	Sealer	C#:75	C#:85	C#:90	C#:100
F1A	Control	1	1	1	2
F1B	Control	1	1	2	2
F2A	D335	0	0	0	0
F2B	D335	0	0	0	0
F3A	DCS	0	0	1	2
F3B	DCS	1	1	1	2
F4A	SS	1	1	2	2
F4B	SS	0	0	1	2
F5A	R7	1	1	1	2
F5B	R7	1	1	2	2
F6A	CT40	1	1	1	1
F6B	CT40	0	0	0	0

TABLE 24. Scaling Resistance of Old Concrete Surface.

Specimen	Sealer	C#:75	C#:85	C#:90	C#:100
O1A	Control	0	0	0	0
O1B	Control	0	0	0	1
O2A	D335	0	0	0	0
O2B	D335	0	0	0	0
O3A	DCS	0	0	0	1
O3B	DCS	0	0	0	1
O4A	SS	0	0	1	1
O4B	SS	0	0	1	1
O5A	R7	1	1	1	1

11. Test C: Resistance of Concrete to Rapid Freezing & Thawing AASHTO T 161-00

11.1 Test Procedures

The purpose of the test is to determine the resistance effectiveness of sealers used on varying types of concrete subject to rapid freezing and thawing cycles. The lab procedure followed the standard method test of AASHTO T 161-00 and test procedure A was used. Test procedure A consisted of rapid freezing and thawing in water. This procedure is intended to determine the effects of variations in the properties of concrete on resistance of the concrete due to the freeze and thaw cycles with the aid of five different sealers.

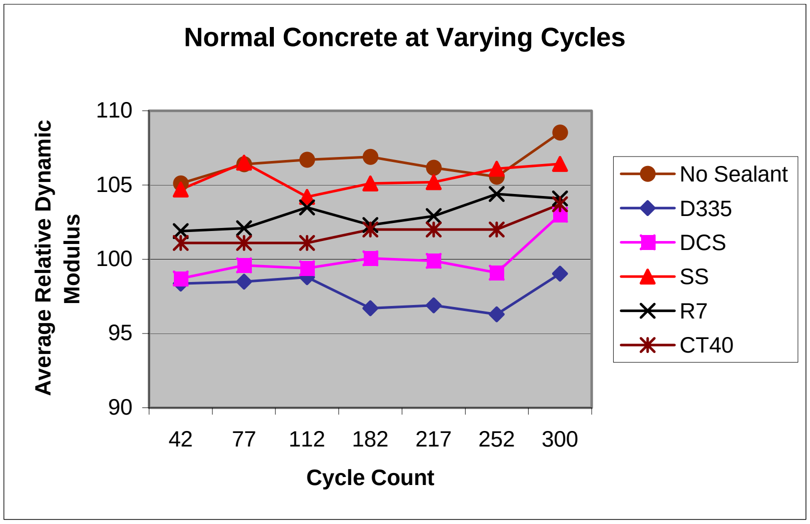
The specimens for this test were cast into standard steel mold with the inserted pins. Each sealer was applied to nine separate specimens of three concrete mixes: old concrete, normal concrete, and fly-ash concrete, (three specimens of each). There were also nine separate "control specimens" with no sealer. The combinations of the sealers and concrete mixes are tested to determine which sealer provides for the best resistance to the freeze thaw cycles. As noted above, the test intends to determine the effects of variations in both properties and condition of the concrete specimens subjected to the freeze and thaw cycles. The sealers were to be applied to the concrete to determine which was most effective in limiting the deterioration of concrete properties.

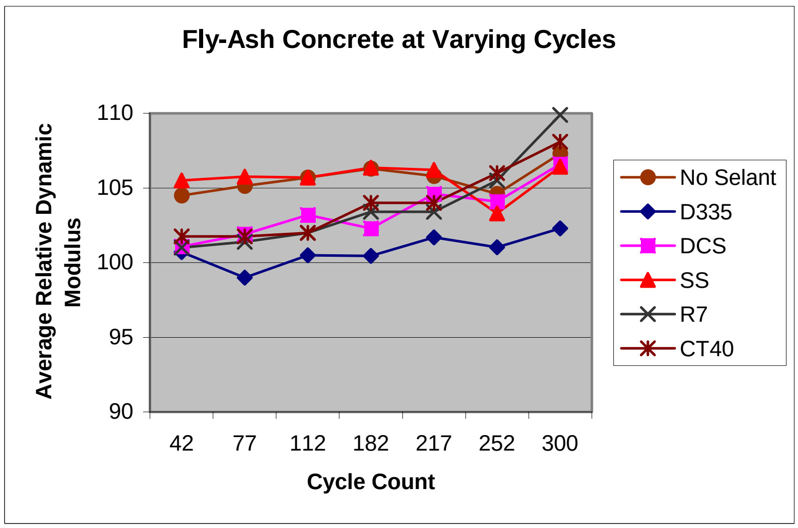
In following the AASHTO T 161-00 standards, the sealers were applied to concrete specimens that were molded and cured for 28 days prior to testing. After the 28-day period the concrete was brought to a temperature within –2 and +4 degrees Fahrenheit of the target thaw temperature that was used in the freeze-thaw cycle. At this point, the concrete specimens were tested for the fundamental transverse frequency, mass, average length and cross-section dimensions within the tolerance required in the ASTM C 215. The initial length of the specimens was also measured. The specimens were protected from loss of moisture between the time of removal from curing and the start of freezing and thawing cycles. The specimens were then induced to a freeze and thaw cycle not to exceed 36 cycles of exposure before testing again for frequency, mass, length/cross section. Continually following the AASHTO T 161-00 Procedure A of the freeze and thaw cycles, the percent change in length, the percent change in weight, and the relative dynamic modulus of the specimens were measured and calculate. This data used to determine which sealer/concrete combination was the most adequate in improving resistance to the deterioration of concrete properties.

11.2 Test Results

To analyze what sealer performed the best in improving resistance to the deterioration of concrete properties, the relative dynamic modulus up to the 300th cycle was plotted for the specimens with combination of five different sealers and three types of concrete mixes using the measured test data given in Table C5 (Appendix-C). Figures 15 and 16 compare the average relative dynamic modulus up to 300 cycles, and at the 300th freeze-thaw cycle, for all sealers and concrete mixes used in this project, respectively. The smaller the decrease of the relative dynamic modulus the better the specimen performance against deteriorating the concrete properties due to freeze-thaw cycles. With regards to these figures and the data in Table C5 (see Appendix-C) the following observations can be made.

It is evident that the various sealers had a relatively small effect on the concrete specimen's performance due to freeze thaw cycles, in terms of altering the relative dynamic modulus as compared to the control specimens with no sealer (see Figure 15 and 16). The same pattern of performance was observed from early freeze-thaw cycles up to the 300th cycle at which the tests were terminated (see Figure 15). That is there is not a big difference between using the control specimens (concrete without sealer) and sealed specimens. The concrete that did not have sealer applied performed as well as any of the other sealed specimens. This may be due to the high quality of the concrete mixes used in this study for normal concrete and fly ash concrete mixes. That is the concrete was made with sound aggregate, proper air void system, and allowed to mature properly. The old concrete performed the worst of all the materials tested because the old concrete specimens were cut to sizes and thus were not prepared in the normal manner (i.e., cast in molds). It is believed that the micro (hairline) cracks in old concrete specimens that were cut from demolished bridge deck probably affected the test results. The samples appeared to have two layers of concrete. The top layer was 2-3 inches thick (from bridge deck overlay). The bottom layer had a different color, and in most cases the bottom layer began to disintegrate (break apart) as the freeze-thaw testing progressed. This deterioration affected the performance of the applied sealers. The old concrete, which used DCS sealer and CT40 sealer, had the highest weight loss (see Table C5 in Appendix-C).





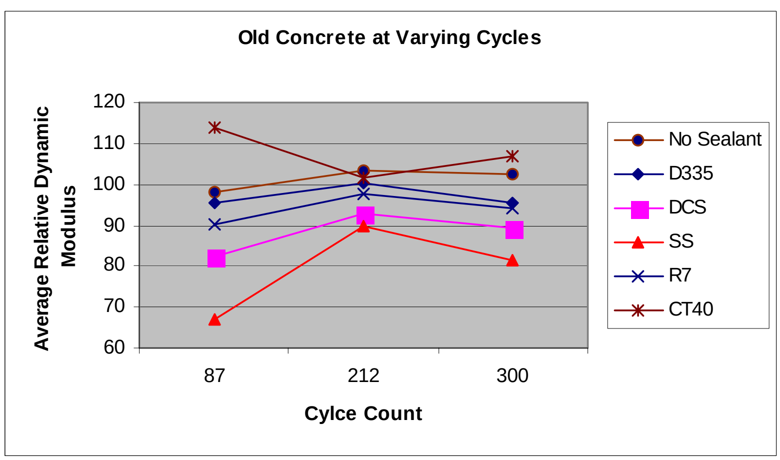


FIGURE 15. Variation of the Average Relative Dynamic Modulus up to 300 Freeze-thaw Cycle.

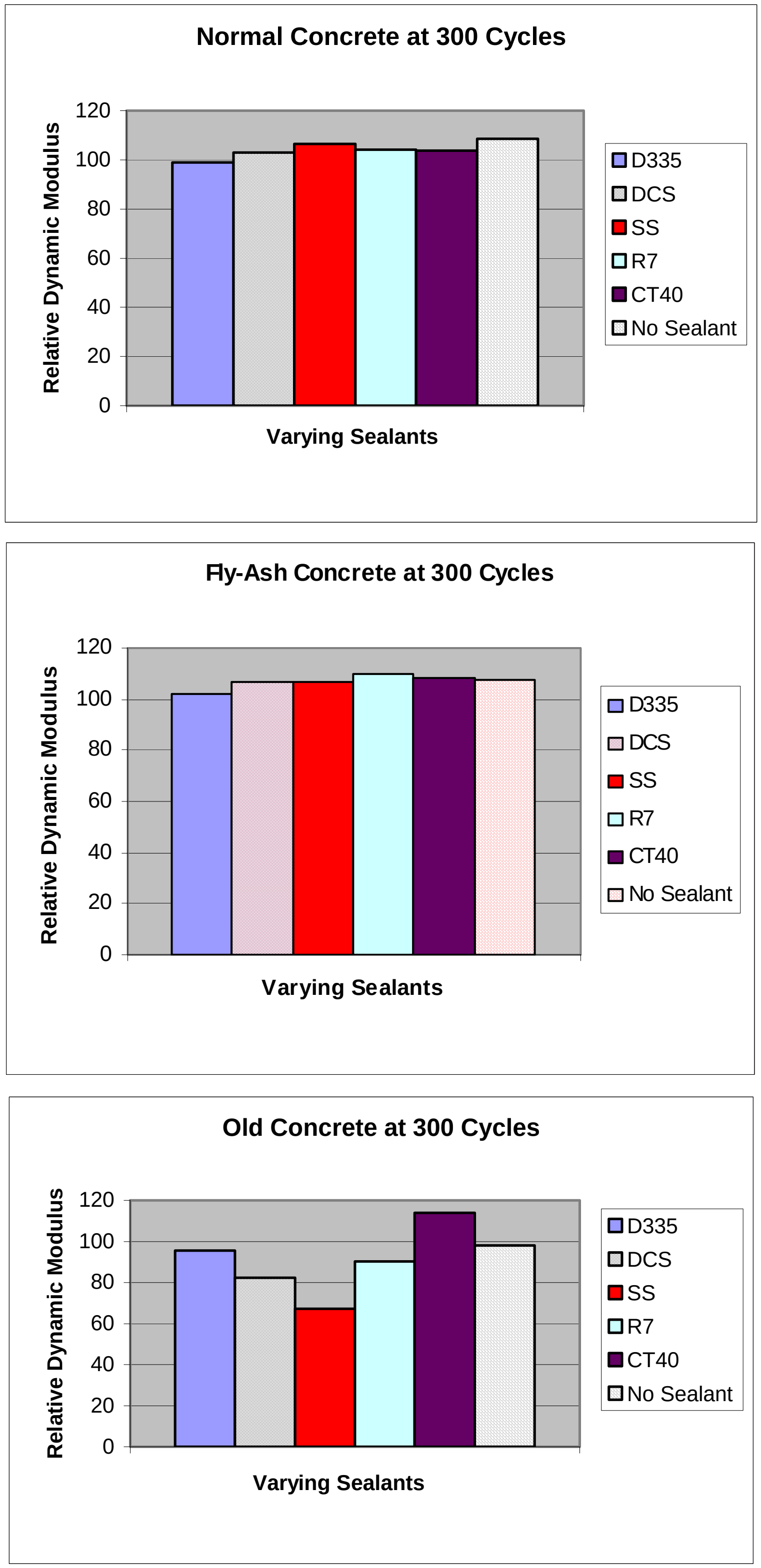


FIGURE 16. Average Relative Dynamic Modulus at the 300th Freeze-thaw Cycle.

12. Test D: Resistance of Concrete to Chloride Ion Penetration AASHTO T 259-02

12.1 Test Procedures

The purpose of this test is to determine the resistance of sealer-aided concrete to chloride ion penetration. The procedures of AASHTO T 259-02 standard were followed in this test. Five different sealers were applied to the specimens of three different types of concrete mixes: normal concrete, fly-ash concrete, and old concrete. After application of the sealers and following the AASHTO standard of T 259-02 the resistance of each concrete to the chloride ion penetration is determined. With each pairing of sealers and concrete mix, there were four specimens (repeated tests) used in the tests giving each sealer an application on 12 individual specimens corresponding to the above mentioned three types of concrete mixes. There were also 12 specimens that did not have any sealer applied; these specimens were used as the "control specimens" that allowed to investigate the resistance of concrete with no sealer to the chloride ion penetration.

The specimens were removed from moist curing at 14 days of age. The specimens were then stored under drying conditions until 28 days of age was reached. The concrete sealer treatment was applied at the 28 days age. Immediately after the drying period, the specimen surfaces were abraded using grinding techniques to simulate the wearing effect of vehicular traffic. All the specimens were then surrounded with 0.75 inch wide dams around the top edge of the specimens. This allows the chloride ion rich solution to settle on top of the specimen and penetrate into the concrete. The specimens were then subjected to continuous ponding with three-percent sodium chloride solution to a depth of approximately 0.5 inch for 90 days following the AASHTO T 259-02 procedures.

12.2 Test Results

After the concrete specimens were subjected to the chloride ion ingress following the AASHTO T 259-02 standards, the Test-D procedure was completed and sampling of the specimens was done under the Test-E procedures that are presented in the next section.

13. Test E: Sampling and Testing for Chloride Ion in Concrete and Concrete Raw Materials- AASHTO T 260-97(01)

13.1 Test Procedures

The purpose of this test is to determine the resistance of sealant-aided concrete to chloride ion penetration. The test procedures of AASHTO T 259-02 and T 260-97 were followed in these tests. This test is a continuation of Test D and therefore, the same specimens used in Test D were used in this test. To perform the sampling and testing for chloride ion penetration in the concrete specimens the AASHTO T 260-97 standards procedure was adopted.

To investigate the penetration of the chloride ions into concrete, sampling and testing of the concrete raw materials was done at 0.5 inch and 1.0 inch depths from the concrete surface exposed to chloride ion, see Figure 17. The samples were analyzed to determine the most efficient sealer in resisting to chloride penetration.

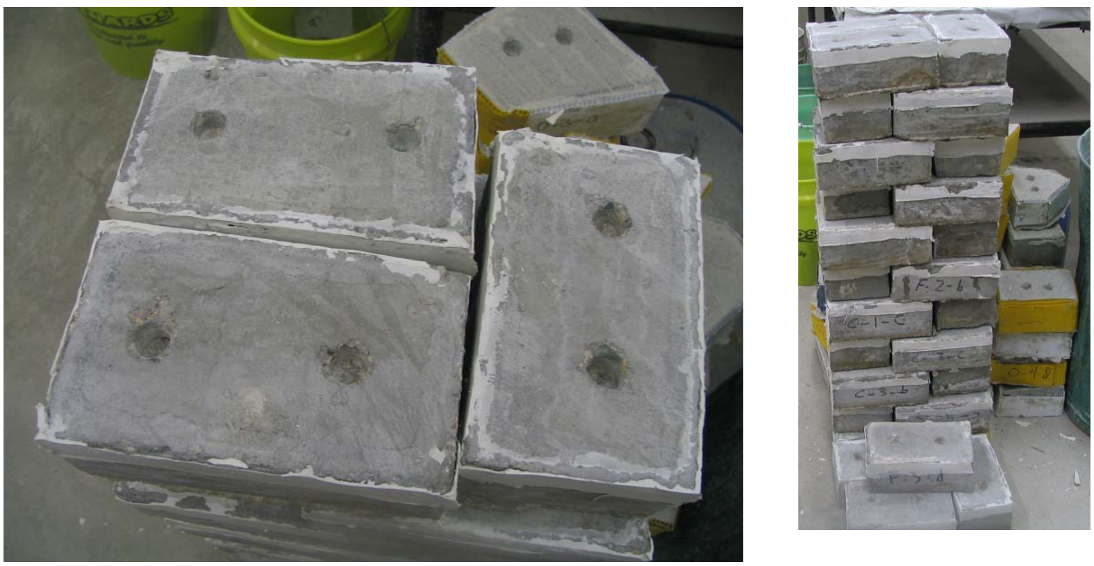
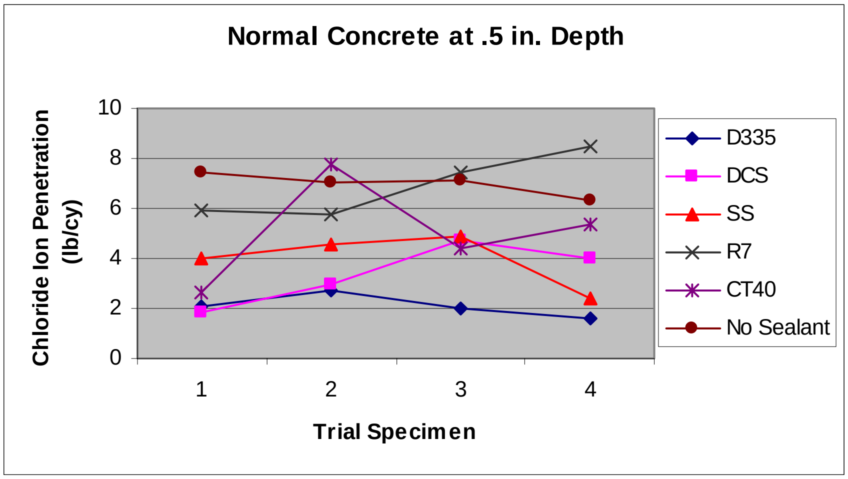
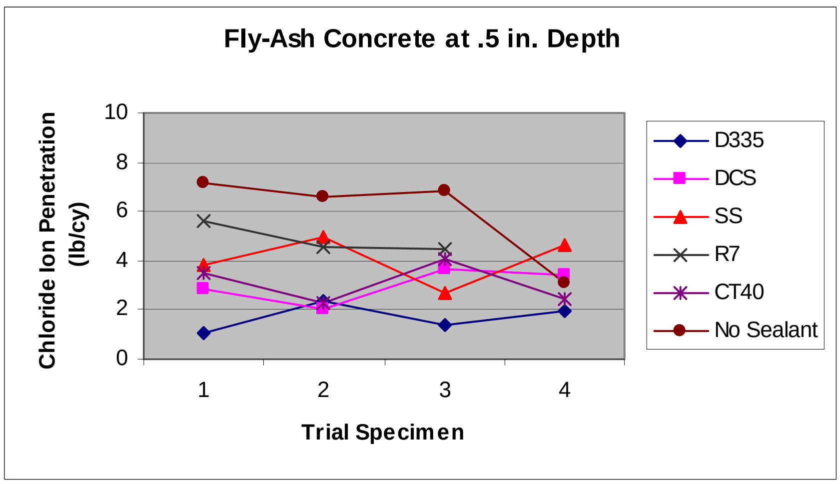


FIGURE 17. Sampling and Testing for Chloride Ion Penetration in Concrete and Concrete Raw Materials: AASHTO T 260-97 Standards.

14.2 Test Results

To analyze what sealer performed the best in terms of improving resistance of concrete to the chloride ions penetration, the measured data was plotted in Figures 18, 19 and 20 (see Tables C6a and C6b in Appendix-C). These figures show the penetration of the chloride ion into the concrete specimens. During sampling procedure, two sample depths were used. The first depth was at 0.5 inch and the second at 1.0 inch depth. The test results in terms of chloride ion penetration (lb/cy) versus the four repeated trial specimens corresponding to the 0.5 inch and 1.0 inch depths and five sealers along with control specimen are plotted in Figures 18a and 18b. The averaged values of the chloride ion penetration (lb/cy) for the repeated four trial specimens for 0.5 inch and 1.0 inch depth of sampling are plotted in Figures 19 and 20, respectively. These two different depths are included in the testing process to analyze the change in penetrated chloride ion measured





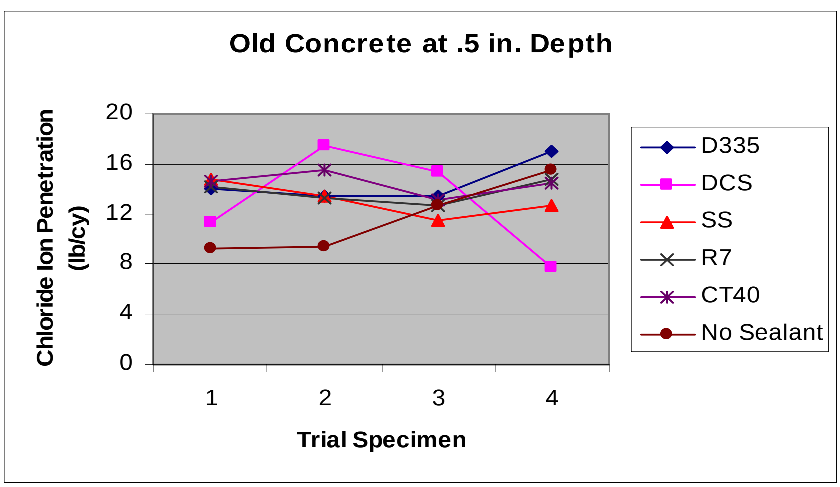
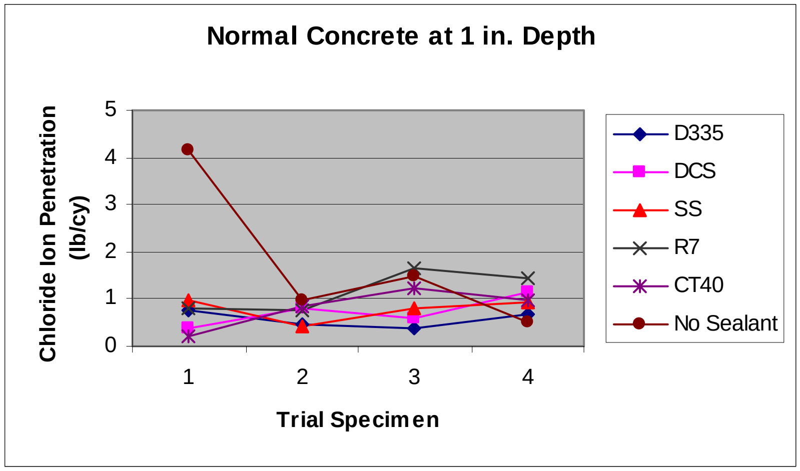
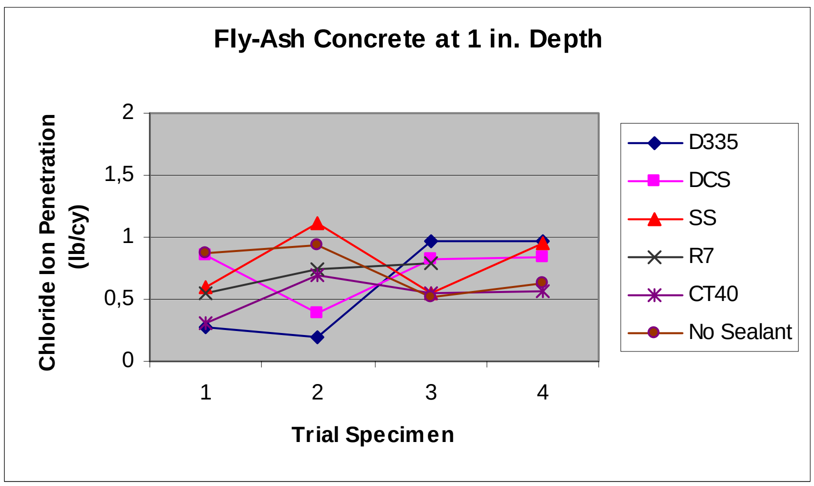


FIGURE 18a. Sealer Aided Resistance of Concrete to Chloride Ion - Penetration at 0.5 Inch Depth.





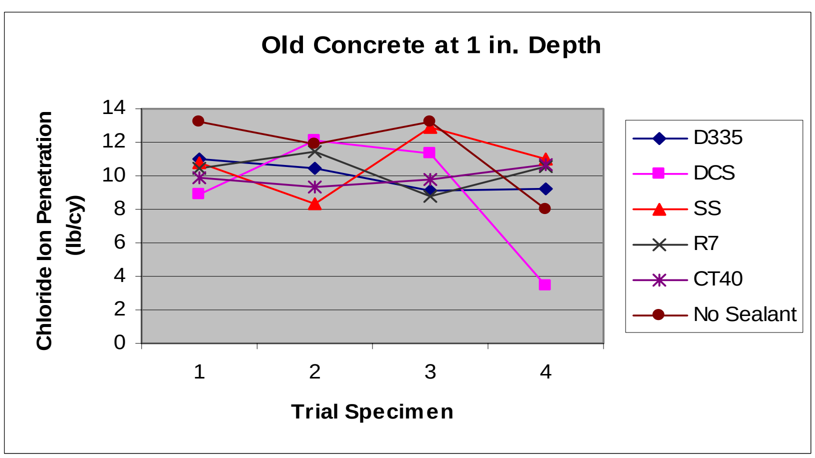


FIGURE 18b. Sealer Aided Resistance of Concrete to Chloride Ion Penetration at 1.0 Inch Depth.

in lb/cubic yard with depth from the exposed concrete surface to chloride ion solutions. With reference to these figures the following observation can be made.

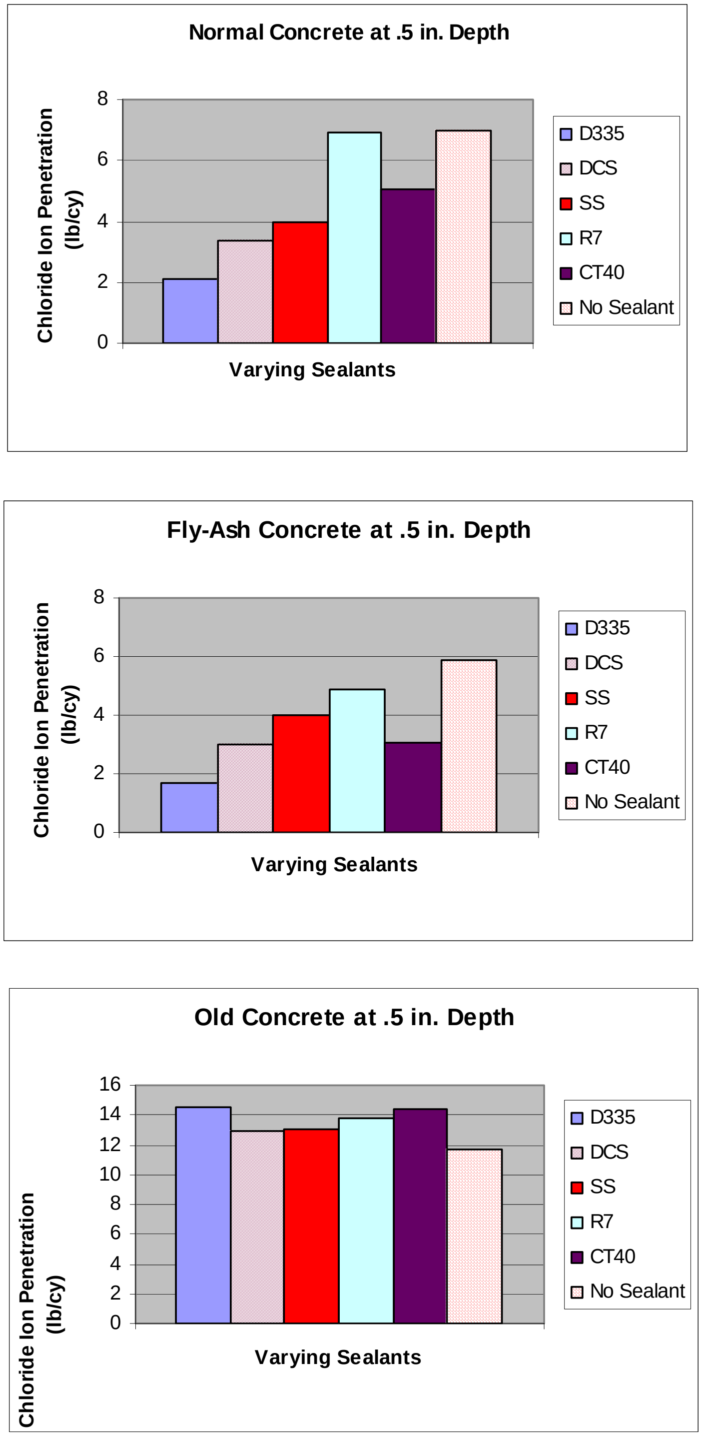
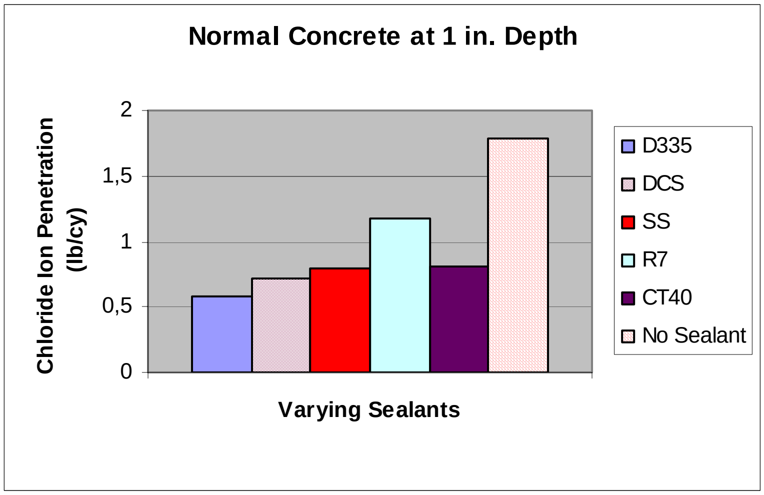
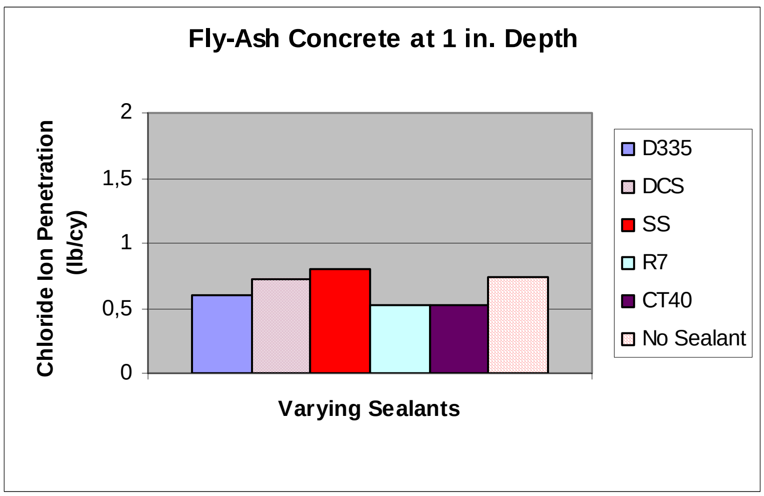


FIGURE 19. Averaged Chloride Ion Concentration at 0.5 Inch Depth Sampling.





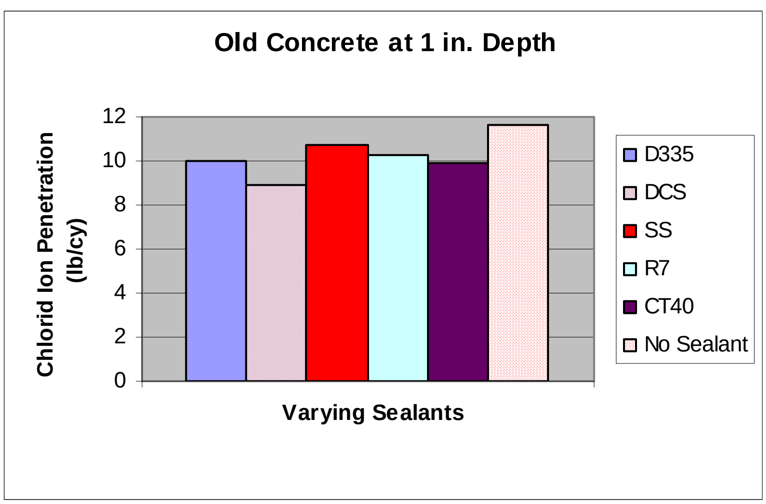


FIGURE 20. Averaged Chloride Ion Concentration at 1.0 Inch Depth Sampling.

From the results in Figures 18-20, it is evident that the most efficient sealer appears to be the D335 sealer for the cases of normal and fly ash concrete mixes. Under all concrete conditions at the 0.5-inch and 1.0 inch depths, the D335 sealer had the least amount of chloride ion penetration into concrete specimens. Also it can be concluded that the fly-ash concrete mix improved the resistance to the chloride ion penetration as compared to the normal concrete mix and old concrete. The largest amount of chloride ion penetration was observed for the case of normal concrete mix without sealer (control Specimen): 7.0 lb/cy for the 0.5 inch depth and 1.75 lb/cy for 1.0 inch depth, see Figures 19 and 20. The performance of old concrete was significantly worse at both depths of 0.5 inch and 1.0 inch, see Figures 19 and 20, because the untreated old concrete specimens contained large amount of chloride ion, see Table 25.

The concentration of chloride ion in untreated old concrete obtained from tests on three control specimens at the depths of 0.5 inch and 1.0 inch are summarized in Table 25. The averaged concentration of Chloride ion is 12.66 lb/cy at the depth of 0.5 inch and 7.31

TABLE 25. Concentration of Chloride Ion in Untreated Old Concrete.

Specimen	Depth 0.5 inch		Depth 1.0 inch	
	% Cl	Cl (lb/cy)	% Cl	Cl (lb/cy)
1	0.32	12.53	0.15	5.87
2	0.37	14.49	0.19	7.44
3	0.28	10.96	0.22	8.61
Average	0.32	12.66	0.19	7.31

lb/cy at the depth of 1.0 inch. That is old concrete cut from the existing bridge deck exhibits considerable amount of chloride ion concentration before it is treated with potassium acetate in the laboratory. The charts in Figures 18, 19 and 20 for old concrete at depths of 0.5 inch and 1.0 inch include the already existing chloride ion concentrations values of untreated concrete.

In conclusion, it can be noted that the D335 Sealer was the most effective in reducing the penetration of the chloride ion solution into the concrete specimens in the case of normal and fly-ash concrete mixes. The best concrete type to use to prevent the chloride ion penetration is the fly-ash concrete mix. The combination of D335 sealer and the fly-ash concrete mix was the best combination and was significantly better than the concrete used with no sealer (control Specimen), see Figures 19 and 20. In the case of old concrete the use of sealers appears to have no significant effect on the chloride ion penetration into concrete at the 0.5 inch depth (see Figure 19 for old concrete) whereas the presence of concrete sealers improve the resistance to chloride ion penetration at 1.0 inch depth (see Figure 20 for old concrete). The chloride ion penetration substantially decreased with depth in the cases of normal and fly ash concrete mixes (see Figures 19 and 20). However, it is not the case for old concrete mix in which the chloride ion penetration is high for both 0.5 inch depth (above 12 lb/cy) and 1.0 inch depth (above 10 lb/cy). As discussed above these values include the chloride ion concentration of untreated old concrete cut from an existing bridge deck, which was under service for many years. From these observations it can be concluded that application of sealers at early age of concrete will be helpful in improving resistance to chloride ion penetration whereas the sealers effectiveness diminishes in the case of old concrete. As shown in Figure20 for the case of old concrete, application of sealers on old concrete decreases the rate of chloride ion penetration at 1.0 inch depth. Therefore, application of sealers is effective as a maintenance activity on existing bridge decks.

14. Test F: Test for Average Depth of Penetration -- NDDOT Method

14.1 Test Procedures

The purpose of this test is to determine the penetration of sealers in concrete. There were five different types of sealers used in the experiment and three different types of concrete mixes: normal concrete mix, fly-ash concrete mix, and old concrete. The test procedure for determining treatment penetration of sealers into concrete is the NDDOT-developed and recommended test method. Following this procedure, the concrete blocks of 8x8x3 inches for each combination of concrete mix and sealer along with control specimen without sealer (three blocks for each sealer and concrete mix combination) were cast, broom finished on one side, and cured for seven days. After curing, the blocks were oven-dried to constant weight and then sealed with paraffin wax on five sides, leaving the broom-finished side exposed. The exposed sides of the test specimens were treated with sealers. After proper curing each treated block was fractured into four sections and then placed in water, see Figures 21 and 22. The sealants are hydrophobic; thus the depth of effective penetration is indicated by a lighter color than the untreated concrete. The pairing of the sealers and the concrete mixes are analyzed to determine how much each particular sealer penetrates into the concrete mix.

This allowed us to readily check the specimens to see how much each sealant was penetrating into the specimens. In measuring the penetration of the specimen, the specimen was removed from the water and it was measured in 10 spots around the outside of the specimen where the lighter color differed from the non-treated concrete (see Table C7 in Appendix-C). These measurements were collected on each specimen and the average was used to analyze the test results.

14.2 Test Results

To analyze what sealer performed the best in penetrating into the concrete specimens, the measured data (see Table C7 in Appendix-C) was analyzed and was plotted as a graph shown in Figure 23. This figure only shows the results for CT40 Sealer's Penetration into three Concrete mixes because only this sealer exhibits penetration into the concrete specimens. The other sealers have shown no sign of penetration into the concrete. This may be because of the high quality of concrete mixes. It seems the concrete quality was so good that four out of the five sealers were not able to penetrate into the specimens.

In conclusion, it is evident that that due to the high quality of concrete mixes, the majority of the sealers, except the CT40 sealer, could not penetrate into any of the three types of concrete mixes. In the case of CT40 sealer, the depth of penetration into the fly ash concrete mix is the largest followed by the normal concrete mix and old concrete (see Figure 23).

FIGURE 21. Test for Average Depth of Penetration: NDDOT Specifications, Cutting of Each Specimens into Four Pieces.

FIGURE 22. Test for Average Depth of Penetration; Specimens in Water.

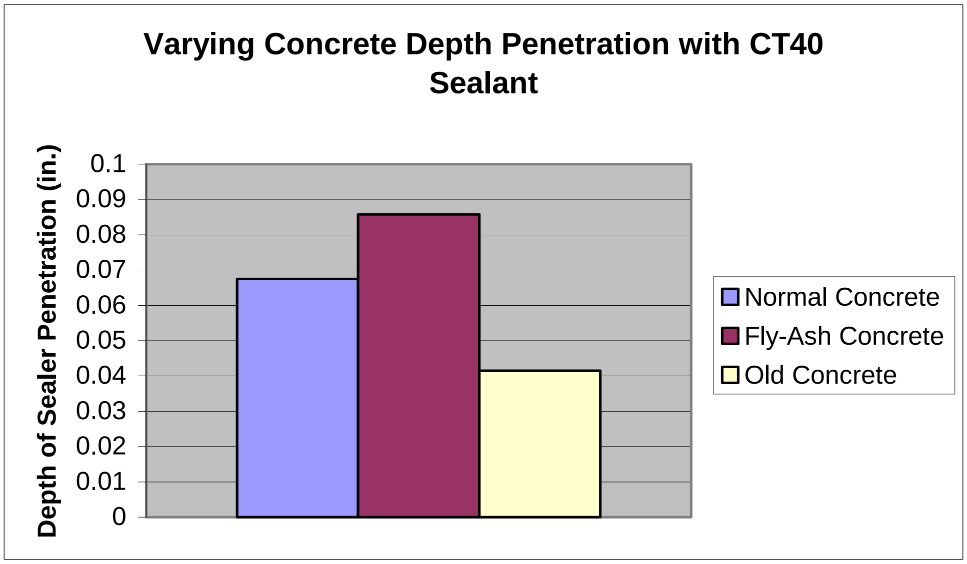


FIGURE 23. CT40 Sealer's Penetration into Three Concrete Mixes.

15. Test G: Test for sealants ability seal crack widths up to 2mm wide (test devised in-house with NDDOT cooperation) – NDDOT/UND Method

15.1 Test Procedures

The purpose of this test is to determine the ability of various sealers to seal cracks of widths between 0.2mm and 2.0 mm wide. The methodology for determining sealers ability to seal cracks between 0.2 and 2.0 mm wide is obtained from a report produced by the University of South Wales with some modifications based on the NDDOT recommendations. In this modified procedure rectangular specimens of 3”x3”x12” were split into four parts and then were mated and clamped back together. The specimens were cemented with epoxy on the sides. The clamps were released once the epoxy sets up. The parts of the specimens were held 0.2, 0.4, 0.7, 1.0, 1.5, and 2.0 mm apart (representing 3 cracks per specimen, as shown in Figure 24) using shims. Figure 24 shows the example of prepared pairs of specimens for testing sealers ability to seal crack widths of 0.2 mm up to 2.0 mm wide using the NDDOT Procedure. After sealing the cracks the samples were fitted into test cells and tested for leaks. This testing procedure was used after consultation on methodology between UND and the NDDOT.

0.2, 0.4, 0.7 mm

1.0, 1.5, 2.0 mm

FIGURE 24. Example of Prepared Specimens for Testing Sealers Ability to Seal Crack Widths up to 2.0 mm Wide, NDDOT/UND Procedure.

For the test there were five sealers tested to see if they could seal cracks in concrete. The five different sealers were each applied to three different types of concrete mixes: normal concrete mix, fly-ash concrete mix, and old concrete. For each combination of concrete mix and sealer, there were two specimens used. For each pairs of the specimens there were six separate cracks of varying widths that were sealed by each sealer, see Figure 24. The five sealers and three concrete mixes were paired for numerous tests to determine which sealer was the most efficient in sealing the cracks.

FIGURE 25. Additional tests on 0.2 mm cracks.

To test the ability of five sealers to fill cracks began with fully laterally restraining specimen to ensure that there was no possibility of movement across the crack The sealer was allowed to flood the crack. All specimens were then sealed on the side faces using a non-shrink epoxy. All the specimens were then vacuum saturated in dematerialized, deaerated water for 96 hours before testing. Finally, the finished saturated specimens were then fitted into pressure cells in high-pressure water permeability rigs and tested for leaks.

The test results of this test will help to investigate how the sealers and concrete mix may enhance the durability of concrete in industrial use, specifically in highway infrastructures.

TABLE 26. Sealers Sealing Cracks of 0.2 mm Width.

Specimen	Sealer	Crack width	Status of sealing
C2a1	D335	0.2 mm	sealed
F2a1	D335	0.2 mm	sealed
F2b1	D335	0.2 mm	sealed

15.2 Test Results

In analyzing the test results, it can be seen from the data in Tables C8a and C8b (see Appendix-C) that no sealer was able to provide any ability to seal the cracks between 0.2 and 2.0 mm of width on any types of the concrete mixes, except for sealers given in Table 27 for Cracks of width 0.2 mm even before attaining the required pressure by the test specification. In all tests, all of the sealers failed to seal and prevent the leakage of water under pressure, except for the D335 sealer that only sealed the cracks of 0.2 mm wide as given in Table 26. To further check the ability of this sealer to seal cracks of 0.2 mm wide subjected to the required maximum pressure under this test specification (2±0.2 bar as recommended in the report by the NDDOT, see report by Dockter (1998). The specimens were cut off into segments with the cracks of 0.2 mm width and coated on the side and top faces using a non-shrink epoxy as shown in Figure 25 for example. These specimens were then vacuum saturated in dematerialized, deaerated water for 96 hours before testing. Finally, the finished saturated specimens were then fitted into pressure cells in high-pressure water permeability rigs and tested for leaks. No leak was observed for the specimens given in Table 26 for D335 sealer and crack width of 0.2 mm for normal concrete mix and fly ash concrete mix.

In summary, it can be concluded that only the D335 sealer could seal cracks of 0.2 mm width for normal concrete mix and fly ash concrete mix. Therefore, none of the sealers; D335, DCS, SS, R7, or CT40 would be recommended as an efficient sealer to seal concrete cracks larger that 0.2 mm. The D335 sealer could be used for sealing cracks of the normal concrete mix and fly ash concrete mix with crack widths not exceeding 0.2 mm.

16. Test H: Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration - AASHTO T 277-96(00)

16.1 Test Procedures

The purpose of this test is to determine the electrical conductance of concrete to provide rapid indication of its resistance to the penetration of chloride ions. The procedure followed for this report is the AASHTO T 277-96(00) standards. This test is applicable to types of concrete where the correlations have been established between the test procedure and the long-term types such as the ponding used in the test procedures described in AASHTO T 259 standards which we applied in an earlier laboratory test (Test D). The experiment consisted of using specimens of three concrete mixes: normal concrete mix, fly-ash concrete mix, and old concrete to check for the chloride ion penetration via electrical induction. Each of the three concrete mixes was also paired with five different sealers used in this test. This gave us a total of 15 different combinations of concrete mixes and sealers. Along with the 15 concrete mixes /sealer parings, there are three specimens of each concrete mix that had no sealer applied. These are used as the control specimens for comparison. The tests were performed on the test specimens to determine which sealer is the most efficient in resisting chloride ion penetration.

This test consisted of monitoring the amount of electrical current passing through 2 inches thick slices of 4 inches nominal diameter cores during a six-hour period. A potential difference of 60 V DC is maintained across the ends of the specimen, one that was immersed in a sodium chloride solution and the other in a sodium hydroxide solution. The total charge passed can then be measured in coulombs, which is related to the resistance of the specimen to chloride ion penetration. This test is used primarily to do a further investigation of the testing that was done following the AASHTO T 259 standards (Test D). The AASHTO T 259 standards can be related to this test to get more data to analyze the chloride ion penetration and how the sealers were able to improve resistance of concrete to chloride ion penetration.

The tests were started by removing the specimen from water, and blotting off the excess drops, while transferring the specimen to a sealed container, which maintained the moisture in 95 percent or higher humidity. Next the test procedures 10.2.1 to 10.9 of the ASTM 1202-94 testing standards were followed to appropriately set up this test procedure and apply the correct amount of voltage into the specimen. Once careful completion of these testing procedures was done, the measured data are analyzed.

16.2 Test Results

The measured electrical indication of concrete's ability to resist chloride ion penetration with the aide of applied sealers is given in Tables C9a and C9b (see Appendix-C). To analyze what sealer performed the best in terms of chloride ion resistance, a graph was constructed showing the average level of Coulombs that passed through the three specimens during each test of the different sealers on the concrete mixes. Figure 26 show the chloride ion penetration rate (in Coulombs) versus the concrete mixes and sealer used in this test. In this test, the higher the coulomb values, the lower the resistance of the concrete is to the chloride ion penetration. Thus, the larger values of coulombs, the worse

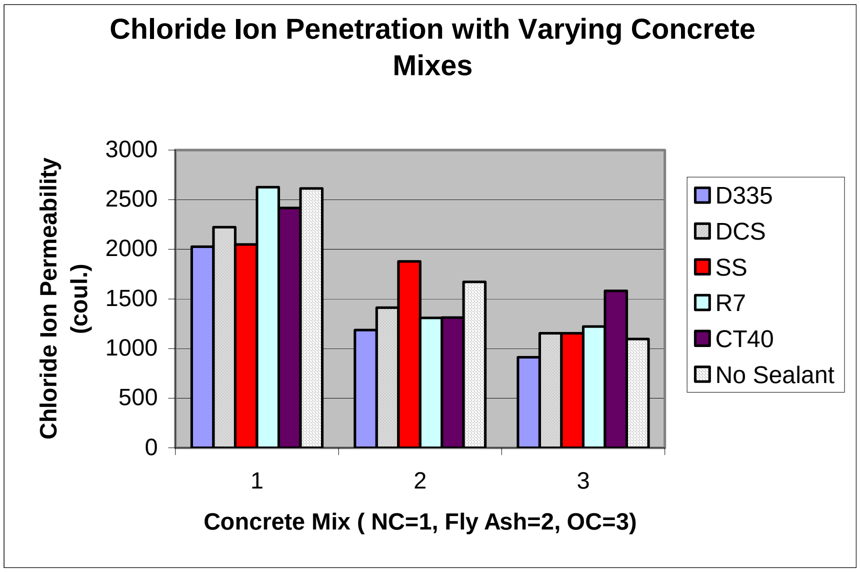


FIGURE 26. Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration, ASTM C 1202-94 standards.

the sealer is in improving the resistance of chloride ion penetration into concrete. This is why the control (the concrete with no sealer) specimens had the relatively high readings of coulombs for all of the three concrete mixes.

In conclusion, it is apparent that the application of the sealers makes a difference in the amount of chloride ion penetration according to electrical indication. It can also be noted that the values of coulombs decrease from normal concrete mix to fly-ash concrete mix, and then to old concrete, see Figure 26. This indicates that the fly-ash concrete mix is superior in resisting to the chloride ion penetration as compared with the normal concrete mix. According to the results in Figure 26, the D335 sealer was the best in limiting the amount of coulombs, or having a greater resistance to chloride ion penetration. The D335 Dural sealer was also the most efficient when analyzed under AASHTO T 259 standards (Test D). It is worth noting that the results in previous chloride ion penetration test (Test E) agree well with the results for this test (compare the results in Figures 19 and 20 with those in Figure 26).

17. CONCLUSIONS AND RECOMMENDATIONS

This task dealt with the evaluation of the sealers based on the eight sets of laboratory tests. There were a total of five concrete sealer treatments: Tamms Dural 335 (D335), Degadeck Crack Sealer (DCS), Star Sealer (SS), Radcon Formula #7 (R7), and Chem-Trete BSM-40 VOC (CT40). These sealers were evaluated for three groups of concrete mixes: normal concrete mix, fly ash concrete mix, and old concrete. There were also “control specimens” that did not use any type of sealer for comparison purposes. The test results are summarized in Table 27. The test data used to determine which sealer/concrete mix combination was the most adequate in improving resistance to the deterioration of concrete properties. With regards to the conducted test results, the following conclusion can be made:

- From the water absorption test in hardened concrete, it is concluded that the most efficient sealers are the Chem-Trete-BSM40VOC sealer, Dural 335 sealer, and Radcon Formula #7 sealer. The fly-ash concrete mix performed best among the concrete mixes.
- From the scaling resistance of concrete surfaces exposed to deicing chemicals (potassium acetate), it is concluded that the sealer to have the greatest effect in resisting deterioration of concrete properties due to freeze thaw cycles is the D335 sealer for the normal and fly ash concrete mixes and the old concrete. The scaling first began to appear in the 75^{th} cycle, at a degree of classification index 1 (very slight scaling). The maximum scaling index for the control (without sealer) specimens with normal and fly ash concrete mixes is 2 (slight to moderate scaling). This indicates that the concrete mixes are very sound and they performed very well in resisting scaling of the concrete surface due to the deicing chemical (potassium acetate) under freeze-thaw cycles.
- From the resistance of concrete to rapid freezing and thawing tests, it is concluded that the various sealers had a small effect on the concrete specimen’s performance due to freeze thaw cycles, in terms of altering the relative dynamic modulus as compared to the control specimens with no sealer. This may be due to the high quality of the concrete mixes.
- From the test results on resistance of concrete to chloride ion penetration, and sampling and testing for chloride ion in concrete and concrete raw materials, it is concluded that the most efficient sealer is the D335 sealer for the cases of normal and fly-ash concrete mixes. The best concrete type to use to prevent the chloride ion penetration is the fly-ash concrete mix. The combination of D335 sealer and the fly-ash concrete mix was the best combination and was significantly better than the concrete used with no sealer (control specimen). In the case of old concrete the use of sealers appears to have no significant effect in preventing the chloride ion penetration into concrete. The chloride ion penetration substantially decreased with depth in the cases of normal and fly ash concrete mixes. From these observations it can be concluded that application of sealer at early age of concrete will be helpful in improving resistance to chloride ion penetration whereas the sealers effectiveness diminishes in the case of old concrete.

Table 27. Summary of test results.

Test/Sealer			D335	DCS	SS	R7	CT40	Control
A		Averaged Volume of Permeable Pore (Void) Space (%)						
	C		9.8%	11.4%	11.1%	10.0%	10.1%	11.0%
	F		8.4%	10.0%	9.6%	8.8%	8.5%	9.9%
	O		12.4%	14.2%	14.3%	12.4%	12.7%	14.1%
B		Scaling resistance index of concrete surface after 100 freez-thaw cycles						
	C		0.0	2.0	1.5	1.5	1.5	1.5
	F		0.0	2.0	2.0	2.0	0.5	2.0
	O		0.0	1.0	1.0	0.5	1.0	0.5
C		Average relative dynamic modulus at the 300th freez-thaw cycle						
	C		99.0	103.0	106.5	104.1	103.7	108.5
	F		102.3	106.6	106.4	109.9	108.1	107.3
	O		95.6	82.4	67.2	90.3	113.9	98.0
D & E		Averaged Chloride ion concentration at 0.5 inch and 1.0 inch depth sampling (lb/cy).						
	C	0.5 inch Depth	2.12	3.38	4.72	6.91	5.05	6.99
	F		1.69	3.01	4.01	4.78	3.15	5.79
	O		14.51	12.96	13.08	13.74	14.45	12.95
	C	1.0 inch Depth	0.57	0.73	1.07	1.17	0.81	1.78
	F		0.60	0.73	0.80	0.72	0.53	0.74
	O		9.98	8.96	10.76	10.32	9.89	11.60
F		Depth of sealer penetration (inch)						
	C		0.00	0.00	0.00	0.00	0.07	N/A
	F		0.00	0.00	0.00	0.00	0.09	N/A
	O		0.00	0.00	0.00	0.04	0.04	N/A
G		Sealers sealing cracks between 0.2 mm to 2.0 mm widths.						
	C	0.2 mm crack width	sealed	not sealed	not sealed	not sealed	not sealed	not sealed
	F		sealed	not sealed	not sealed	not sealed	not sealed	not sealed
	O		not sealed	not sealed	not sealed	not sealed	not sealed	not sealed
	C	0.4 mm and larger crack widths	not sealed	not sealed	not sealed	not sealed	not sealed	not sealed
	F		not sealed	not sealed	not sealed	not sealed	not sealed	not sealed
	O		not sealed	not sealed	not sealed	not sealed	not sealed	not sealed
H		Chloride ion permeability (Coulombs)						
	C		2027	2223	2049	2627	2418	2614
	F		1185	1411	1880	1307	1312	1674
	O		913	1154	1155	1222	1581	1096

C: Concrete without fly ash mix
F: Concrete with fly ash mix
O: Old concrete cut from bridge deck

Test Description:

A	ASTM C 642-97	Water Absorption Test in Hardened Concrete
B	ASTM C 672/C 672M-03	Scaling Resistance of Concrete Surfaces Exposed to Deicing
C	AASHTO T 161-00	Resistance of Concrete to Rapid Freezing & Thawing
D	AASHTO T 259-02	Resistance of Concrete to Chloride Ion Penetration
E	AASHTO T 260-97(01)	Sampling and Testing for Chloride Ion in Concrete and
F	NDDOT Method	Test for Average Depth of Penetration
G	NDDOT Method	Test for sealants ability seal crack widths up to 2mm wide (test
H	AASHTO T 277-96(00)	Electrical Indication of Concrete's Ability to Resist Chloride

From the test for average depth of penetration, it is concluded that due to the high quality of concrete mixes, the majority of the sealers, except the CT40 sealer, could not penetrate into any of the three types of concrete mixes. In the case of CT40 sealer, the depth of penetration into the fly ash concrete mix is the largest followed by the normal concrete mix and old concrete.

- From the test for sealants ability to seal crack widths up to 2mm wide, it is concluded that only the D335 sealer could seal cracks of 0.2 mm width for normal concrete mix and fly ash concrete mix. Therefore, none of the sealers; D335, DCS, SS, R7, or CT40 would be recommended as an efficient sealer to seal concrete cracks larger that 0.2 mm. The D335 sealer could be used for sealing cracks of the normal concrete mix and fly ash concrete mix with crack widths not exceeding 0.2 mm.
- From the test on electrical indication of concrete's ability to resist chloride ion penetration, it is concluded that the application of the sealers makes a difference in the amount of chloride ion penetration according to electrical indication. The fly-ash concrete mix is superior in resisting to the chloride ion penetration as the values of coulombs decrease from normal concrete mix to fly-ash concrete mix. It is concluded that the D335 sealer was the best in limiting the amount of coulombs, and therefore having a greater resistance to chloride ion penetration.

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APPENDIX-A: SEALING PRODUCTS

In this appendix, examples of concrete sealing products are given along with their rate of applications, and characteristics provided by the product suppliers. The information was gathered from the product suppliers' websites.

Approximately 16 generic types and more than 450 concrete sealers are used as corrosion protection agents in the United States. Some examples are listed as follows:

1. Tamms Dural 335 (D335)*

Description of Product
Dural 335 is a solvent free, two components, moisture insensitive, and ultra low viscosity epoxy sealer. It is often used on bridge decks, parking garage decks, ramps, airport runways, and roadways.

Important Features:

- Application rate: 100 to 200 ft^2/gal.
- Penetrating epoxy crack healer-sealer
- Alternative to hazardous methylmethacrylates
- Solvent free
- Odorless
- Ultra low viscosity
- High strength
- Moisture intensive
- Protects treated surface from salts, chemicals, and water absorption

Considerations:

- Must be stored between 50˚ and 90˚ F
- Must be applied when the temperatures are between 50˚ and 90˚ F
- The shelf life is only guaranteed for 1 year

2. Degussa DegaDeck Crack Sealer (DCS)*

Description of Product
Degadeck Crack Sealer is a low viscosity, low surface tension, rapid curing methacrylate reactive resin used to penetrate and seal cracks in concrete structures. It is mainly used in bridge decks, parking decks, and related civil engineering applications to repair, penetrate and seal cracks in concrete. It seals cracks from 0.125 inches (3 mm) to hairline wide.

Important Features:

- Solvent free
- Fast curing (1 hour) enabling rapid turnaround

* = products used in the experiment.

- Weather and aging resistant

- Compatible with methacrylate coatings and wearing course materials
- Low viscosity
- Reduces surface tension ensures deep crack penetration

3. Star Sealer Macro-Deck (SS)*

Description of Product
Star Sealer Macro-Deck is based on specialty polymers and concrete saturants. It quickly penetrates into concrete surfaces and forms a rubber matrix network inside the physical concrete structure. This rubber matrix network stops water, deicing salts, and other damaging elements. STAR Macro-Deck is suitable on all types of concrete surfaces including concrete bridge decks.

Important Features:

- Application rate: 200-300 ft^2/gallon
- Cost: $18.0/gal
- Shields and protects against the irreversible effects of salt and chemical damage to concrete.
- Improves flexural and tensile strength of the concrete.
- 100% Acrylic Polymer Concrete Saturant
- Easy to apply, fluid -water like consistency.
- Water based product is safe to handle and easy to store
- Non-flammable

4. Radcon Formula #7 (R7)*

Description of Product
Radcon Formula #7 is a biochemically modified silicate solution that provides long-term waterproofing and durability benefits to concrete. It will penetrate into the concrete to react with free calcium and water to form a calcium silicate gel complex in cracks, pores, and capillaries. In forming this gel complex, it creates a barrier against chloride ions and water. Radcon Formula #7 is typically used for sealing road bridge decks.

Important Features:

- Application rate: 200 ft^2/gal (5.0m^2/liter).
- 15 year guarantee when approved application methods are used
- USDA and FAA P606 specification approved
- Meets various applicable ASTM standards
- Permanently waterproofs concrete
- Has a breathable subsurface membrane
- Seals cracks up to 0.08 inches (2 mm) wide
- Seals hairline cracks that open in the future
- Preserves old or new concrete
- Hardens concrete surface

- Simple fast installation
- Wisconsin and California DOT's have approved
- West Virginia DOT bridge Authority has approved

5. Chem-Trete BSM-40 VOC (CT40)*

Description of Product
Chem-Trete BSM-40 VOC is an isobutyltrialkoxy silane in an alcohol carrier. The silane is designed to penetrate deep into the substrate and impart a high level of water and chloride ion screening. This provides the substrate with long lasting protection.

Important Features:

- Application rate: 100 to 250 ft^2/gal
- Excellent resistance to water intrusion
- Excellent resistance to chloride ion ingress
- High resistance to wind driven rain
- Breathable system
- Deep penetration into the substrate
- No masking of windows necessary
- No blushing, peeling or yellowing
- High resistance to alkali attack
- Reduced efflorescence
- No change in surface appearance

Considerations:
Sealers must not be applied if the surface temperature falls below 20^{o}F (-7^{o}C) or above 100^{o}F (38^{o}C) or if raining.

6. Hydrozo Enviroseal 40

Description of Product
Hydrozo Enviroseal 40 is a clear, water based 40% alkylalkoxysilane penetrating sealer. It protects against moisture and chloride intrusion.

Important Features:

- Application rate: 125 ft^2/gal (3.1 m^2/liter)
- Cost: $17.80/gal ($4.70/liter)
- Water based, VOC compliant
- USDA compliant
- Transparent, non-staining
- Breathable
- One component
- Water repellent

Benefits of using this product:

- Environmentally friendly
- Doesn't alter the surface appearance
- Allows interior moisture to escape without damaging the sealer
- Easy to apply (saves labor)
- Protects against damage from moisture intrusion and chloride ion penetration.

Considerations:

Color: The sealer is a milky white liquid; clear when dry
Shelf Life: 18 months when stored properly (in unopened containers at 35˚ to 110˚ F)

7. Fosroc Dekguard P-40

Description of Product

Fosroc Dekgurad P-40 is another silane material. It is a high performance crack accommodating elastomeric acrylic protective and decorative coating. One comment to mention is the Fosroc Dekguard p-40 took on a dark appearance after traffic and also exhibited some tracking.

Important Features:

Application rate: 110 ft^2/gal (2.7 m^2/liter)
Cost: $38.00/gal ($10.04/liter)

8. Hydrozo Silane 40

Description of Product

Hydrozo Silane 40 VOC is a clear, breathable, solvent-based VOC-compliant, greater than 40% alkylakoxysilane penetrating sealer. It penetrates deeply and chemically reacts with concrete to form long lasting water-repellent surfaces.

Important Features:

- Greater than 40% silane
- Water repellent
- Solvent based
- Breathable
- Transparent, non-staining
- Surface sealing
- VOC compliant

Benefits of using this product:

- Penetrates deeply into the substrate
- Helps to protect from damage caused by chloride intrusion, extends life of structures
- Excellent for cold-weather applications
- Allows interior moisture to escape without damaging sealer

- Does not alter the natural surface appearance
- Helps reduce efflorescence, atmospheric staining, and mildew
- Environmentally friendly

Considerations:

Color: The color is clear

Shelf Life: 18 months when stored properly (in unopened containers at 35˚ to 110˚ F)

9. Pavix CCC100

Description of Product

The material is a hygroscopic solution that applies hydrophilic and hydrophobic actions. It seeks water and combines with it to grow crystals that resist water. The crystals, which adhere tightly to the concrete pores, grow and shrink according to the amount of available moisture. Consequently, the impregnate provides water-resistance and reduced vapor permeability according to the prevailing conditions. A major innovation is that the material is formulated as a stable liquid. Unlike silane, it is not necessary to use special equipment to detect fraudulent dilution.

Important Features:

- Application rate: 150-200 ft^2/gal (5.0m^2/liter)
- Water-based crystal forming moisture-repelling material
- Environmentally friendly
- Fast curing (1 hour)
- Pavix CCC100 crystals can fill cracks with significant widths (up to 1.4mm).
- Prevents penetration of chlorides ions from de-icing salts.
- Protects against damage caused by repeated freezing/thawing cycles

10. Tamms Baracade Silane 40 IPA

Description of Product

Baracade silane 40 IPA is a breathable, ready to use, colorless, non-staining, non-yellowing, deep penetrating concrete and masonry water repellent.

Important Features:

- Application rate: 100 to 125 ft^2/gal
- Alkylalkoxysilane concentration of greater than 40%
- Penetrates deep into capillaries of treated surface
- Reduces intrusion of water, deicing chemicals, and airborne contaminants
- Improves freeze-thaw resistance
- Will now alter texture or appearance of treated surface
- Colorless, non-staining, non-yellowing
- Breathable
- VOC compliant

Considerations:
Color-- Colorless when dry
Shelf Life-- One year in proper storage (in unopened containers at 40˚ to 90˚)

11. Bridge Seal

Unitex Bridge Seal is a two-component, fluorescent polyoxarine sealer designed both for the protection of new concrete and for the preservation of older concrete. It penetrates into the pores structure to form a sub-surface sealing layer that will impede moisture intrusion and chloride ion penetration. Coverage rate depends on the porosity of the concrete.

Important Features:

- Application rate: 65-200 ft^2/gal
- Good bond strength, tensile strength, waterproofing surfaces, and crack filler
- Not volatile when improperly mixed, and not moisture sensitive

12. Sinak Sealers S-101 and S-102

Sinak Sealers are water-based liquids, with a proprietary formula in solution that doesn't require mixing, diluting, or agitating. These sealers are non-toxic and contain no volatile organic compounds. They were made to protect concrete even in the most adverse environments. There capabilities have been determined by extensive testing and field results. The concrete treated with SINAK S-101 or S-102 is protected against chloride penetration on traffic bearing surfaces, surface scaling, salt penetration and freeze-thaw damage. There is a minimum of two coats needed for sealing bridge decks, so it may take more time to apply. Sealers are applied using a low-pressure tank-type or airless sprayer. All threat areas must then be sprayed with a water-coat.

Important Feature:
Application rate: 150 to 250 ft^2/gal

APPENDIX-B: STATE DOTs SURVEY

B1. Ohio State DOT

This survey is intended to collect data for the purpose of literature review for a research project at the University of North Dakota funded by the North Dakota Department of Transportation. The project is titled "**Application of Sealing Agents in Concrete Durability of Infrastructure Systems**." I would like to gather information from state DOTs in order to identify common trends in application of sealing agents on concrete bridge decks. Please take a moment to fill out the survey and return it as soon as possible. For your convenience, please copy this word file on your hard disk and fill it up electronically and save it. Please email the completed survey to me as an attached file. Also, upon your request, a hard copy of survey along with a stamped return envelope will be sent to you if it is more convenient for you. I greatly appreciate your time and willingness to participate in this survey and I hope that you will forward this survey to people having expertise in this area if needed.

Participant's Information

State: Ohio Department of Transportation
Name: John Randall
Title: Bridge operations and Maintenance_
Address: 1980 West Broad Street Columbus Ohio
Phone: 614-387-6210
E-mail: John.Randall@dot.state.oh.us

May I contact you for further discussion of the subject matter? **Yes** No

Survey

1. Does your DOT have a concrete bridge deck maintenance program?

   a. **Yes** b. No

2. Does your DOT (agency) consider concrete bridge deck cracking an adverse problem?

   a. **Yes** b. No

3. Which of the following cracking do your concrete bridge decks experience?

   a. **Transverse** b. Random c. Other

4. What deicing technology does your DOT use?

a. **NaCl** b. MgCL c. Potassium Acetate d. Other

5. What type of sealer does your DOT use for sealing cracks on concrete bridge decks?

   a. **Methacrylate** b. Epoxy c. Polyesters d. Other **See C &MS 512 HMWM, Gravity Fed Resin, SRS Sealers**

6. What crack width does your DOT use for criterion to begin sealing surface cracks?

   a. Cracks of size 1/6" or less b. Cracks of size 1/8" or less
   c. Other **Size not specified see C &MS 511.22 use on various locations other than cracks**

7. Please list the sealers that are approved (or frequently applied) by your DOT.

   1. http://www.odotonline.org/materialsmanagement/qpl.asp?specref=705.15
   2. http://www.odotonline.org/materialsmanagement/qpl.asp?specref=705.24
   3. http://www.odotonline.org/materialsmanagement/qpl.asp?specref=705.25
   4. http://www.dot.state.oh.us/testlab/applists/QPLWEB/Epoxy_705.23.htm

8. How influential are the following factors in selecting sealer type to be applied on bridge decks {Please rank from 1 (not at all) to 5(Extreme)}(RANK & LIST SPEC)

   a. Type of sealer (methocrylate, epoxy, etc.) **For existing decks District Engineers selection. Designer guidance not available. Designer guidance or matrix needs to be developed. A preventative maintenance manual is available for information but not typically part of a consultant's scope of services.**

   b. Temperature **Application limits are specified per C &MS 512**
   c. Sealer cost **Based upon bid history**

   d. Traffic Volume **Designer guidance not available A preventative maintenance manual is available for information but not typically part of a consultant's scope of services**
   e. Temperature Effects (freeze/thaw) **Designer guidance not available A preventative maintenance manual is available for information but not typically part of a consultant's scope of services**

9. What determines which products are specified? **Qualified product list based upon material test requirements specified in the 705 series of the C & MS**

10. What products or types of concrete sealing products does your DOT specify to be applied on a new concrete bridge deck? **HMWM at cracks and construction joints**

11. What products or types of concrete sealing products does your DOT specify to be applied on an old (existing) concrete bridge deck? **Typically HMWM per 511 C & MS for new bridges decks just at cracks and C & MS 512 epoxy urethane for other new exposed surfaces: railings, concrete superstructure and exposed substructures. Existing bridges non deck are the C & MS 512 epoxy urethane and the existing deck is C & MS 512 – Non epoxy, HMWM, SRS or the Gravity Fed Resins based upon district preference or experience.**

12. Is application of sealer done under the construction contract or do state maintenance forces do this? **Mostly by construction contract, only one district has developed in house capability for applying sealers.**

13. What are the unit costs associated with the application of sealer - material costs, and labor costs, whether it is with State forces or under a contract? **See the unit cost data base from our Office of Contracts**

    http://www.odotonline.org/contracts/estimating/itemsearch.asp?p=2&item=512E&specYr=05&desc=&cpage=2

14. What is your state's estimated annual maintenance (repair and sealing) cost for concrete-bridge decks?

    We currently do not have a sealer program budget. Each of the twelve districts develops an annual work plan based upon need and budget constrains. The contract work for sealing must be balanced against all preservation/ repair needs. District allocations are based upon dividing State Funds available for system preservation by the cost $/square foot of bridge deck area with a deficient inspection rating (department definitions and program definitions can be seen http://www.dot.state.oh.us/BusinessPlan0607/Default.htm)

15. On what frequency does your DOT repeat reapplication of sealers on concrete bridge decks?
    Depends upon district's program; No designer guidance is available. A preventative maintenance manual is available for information but not typically part of a consultant's scope of services. One district is using Ground penetrating radar to prioritize the application of sealers, deck overlays and deck replacements.

16. What determines if a bridge deck is going to be sealed or perhaps overlaid?

    Visual + minimum sounding with NBIS inspection ratings for wearing surface and floor condition are the first level of sorting. The districts then prioritize the

list based upon experience as a minimum. Several districts use Ground penetrating radar (% delaminated, % spalled) as a stand alone or in conduction with concrete cores for chloride content, aggregate condition etc. We typically overlay a deck with concrete overlays once sometimes twice before replacing a bridge deck. Due to maintenance of traffic this 20 year old pattern is starting to change with various applications of faster set concrete overlays (weekends), epoxy overlays + patching, asphalt overlays and other experiments. The use of sealers is typically not considered on a systematic basis except in a few districts.

17. The compatibility of sealers for reapplication should also be addressed further beyond their chemical makeup. Please list existing applied sealer and their compatible sealer for reapplication, the frequency and cost (material and labor) of reapplication by your DOT. **No data on this concern. Typically the existing sealer would be worn off or could be easily removed during the surface preparation process.**

18. Has your state previously conducted research on application of sealers on concrete bridge decks?

a. Yes b. **No**

Only know of some partial in house investigations

B2. Montana State DOT

Participant's Information

State: Montana
Name: Kent Barnes
Title: Bridge Engineer
Address: 2701 Prospect, Helena, MT 59620-1001
Phone: 406-444-6260
E-mail: kbarnes@mt.gov

May I contact you for further discussion of the subject matter? **Yes**

Survey

1. Does your DOT have a concrete bridge deck maintenance program?

a**. Yes** **We just started one.**

2. Does your DOT (agency) consider concrete bridge deck cracking an adverse problem?

a. **Yes**

3. Which of the following cracking do your concrete bridge decks experience?

a. **Transverse** b. **Random** c. Other _**We consider cracks as Material related or Detail related**

4. What deicing technology does your DOT use?

a. NaCl b. MgCL d. Other _We are looking for alternates.

5. What type of sealer does your DOT use for sealing cracks on concrete bridge decks?

Methacrylate

6. What crack width does your DOT use for criterion to begin sealing surface cracks?

a. Cracks of size 1/6" or less b. Cracks of size 1/8" or less
c. Other
Based on Deck Condition State and Exposure State in BMS

7. Please list the sealers that are approved (or frequently applied) by your DOT.
HMWM and Silane

8. How influential are the following factors in selecting sealer type to be applied on bridge decks {Please rank from 1 (not at all) to 5(Extreme)}(RANK & LIST SPEC)

a. Type of sealer (**methocrylate, epoxy, etc**.)
b. Temperature
c. Sealer cost
d. Traffic Volume
e. Temperature Effects (freeze/thaw)

9. What determines which products are specified? We have tried many materials with varying success.
The HMWM seem to be a good product at the right condition state.

10. What products or types of concrete sealing products does your DOT specify to be applied on a new concrete bridge deck?
Silane

11. What products or types of concrete sealing products does your DOT specify to be applied on an old (existing) concrete bridge deck?
HMWM (If condition states warrant)

12. Is application of sealer done under the construction contract or do state maintenance forces do this? **Contract**

13. What are the unit costs associated with the application of sealer - material costs, and labor costs, whether it is with State forces or under a contract?
Silane is included in the deck price. Separate cost unknown. HMWM program is new and no data.

14. What is your state's estimated annual maintenance (repair and sealing) cost for concrete-bridge decks?
Unknown.

15. On what frequency does your DOT repeat reapplication of sealers on concrete bridge decks?
Based on BMS

16. What determines if a bridge deck is going to be sealed or perhaps overlaid?
Condition states in BMS

17. The compatibility of sealers for reapplication should also be addressed further beyond their chemical makeup. Please list existing applied sealer and their compatible sealer

for reapplication, the frequency and cost (material and labor) of reapplication by your DOT.

18. Has your state previously conducted research on application of sealers on concrete bridge decks?
    No
19. Please send to me the copies of the specifications for sealers that are **listed under question 7 using the above email or mail address**.

HMWM

1. HIGH MOLECULAR WEIGHT METHACRYLATE DECK SEAL (Revised 6-12-06)

A. Description

1) General. Prepare concrete deck surfaces and furnish and apply High Molecular Weight Methacrylate (HMWM) treatment materials to seal deck cracks. Use the methods described in this special provision, and with the Engineer's approval, follow the manufacturer's recommendations to accomplish the work.
2) Submittals. Submit the following items to the Engineer with one copy of each item to the MDT Bridge Bureau in Helena. The Engineer will not allow work to begin until one week after he receives and approves all the items listed below.

a) A manufacturer's safety data sheet (MSDS) for each of the HMWM components.
b) MDT will accept for use on this project only approved products that have certification from an independent testing laboratory that the materials meet the requirements of these special provisions on file with the Department. In particular, this certification from an independent testing laboratory must demonstrate that these materials meet all the physical property requirements listed in Section B.
c) The dates of manufacture of the polymer materials, along with their lot numbers and date of shelf-life expiration for each lot number.
d) A table showing the likely cure time in minutes for the allowable ambient temperature range, in increments of ten degrees Fahrenheit (6^oC).
e) Documentation of the relevant experience level of the site supervisor. The Department will not allow substitution of the site supervisor once it has accepted this information.
f) A work plan for each structure. This plan must include estimated times for surface preparation and HMWM application.
g) A Fourier Transform Infra-Red (FTIR) spectrum analysis of each bulk component in a format compatible with Excel 2003 or a Perkin-Elmer Paragon 1000 FTIR machine. Note: MDT will maintain confidentiality with respect to this submittal. Its purpose is to allow the Department to characterize a formulation for future reference. A letter from the resin manufacturer, confirming that the manufacturer's representative on the site

speaks for the manufacturer and that the manufacturer commits to assume liability for the representative's actions and statements.

h) In addition, supply material samples in compliance with section C.1), below

B. Materials

1) Specifications. Seal concrete deck surfaces with a low viscosity, non-fuming, HMWM resin conforming to the following:

Resin Specifications:

Physical Properties of Resin	
Viscosity:	1.4 x 10^{-3} lb/in-s (25 centipoise) maximum (Brookfield Model RVT Viscometer, No. 1 Spindle at 60 RPM) (ASTM D2393)
Specific Gravity:	0.90 minimum at 77°F (25°C)
Tensile Elongation:	30% minimum (ASTM D638)
Odor:	Low
Vapor Pressure:	0.02 psi at 77°F (140 Pa at 25°C) maximum
Flash Point:	175°F (80°C) minimum (ASTM D3278)
Solids Content:	100%
Performance Properties of Resin	
Cure Speed	
Bulk Cure:	less than 3 hours at 73°F (25°C)
Surface Cure:	less than 8 hours at 73°F (25°C) less than 24 hours at application temperature
Gel Time:	25-75 min. at application temperature, 1.7 fl. oz. (50 ml) sample

The three following products meet the requirements of this specification.

Transpo Sealate T 70 – MX 30 [phone: (800) 321-7870]
Hallemite 230 HMWM Lo-Mod [phone: (800) 272-7752]
Watson Bowman Acme Crack Sealer ULV-HE [phone: (716) 691-7566].

Provide an experienced, qualified, manufacturer's technical representative on-site to provide expert advice on storage, mixing, application, clean up, and disposal of materials. The representative must speak for the manufacturer and the manufacturer must commit to assuming liability for the representative's actions and statements.Use only silica sand containing less than 0.5% moisture and meeting the following gradation:

Sieve Size	% Passing
#8 (2.4 mm)	100%
#16 (1.2 mm)	80-100%
#50 (300 µm)	0-72%

2) Substitution of Two-Component HMWM Material. The Department will consider a two-component HMWM, provided that:
a) The Department receives a request for the use of such material no later than one month before delivery of the materials to the job site.
b) The two-component system meets or exceeds the requirements of this specification, as demonstrated by testing results from an independent laboratory.

C. Construction Requirements

1) Material Delivery and Storage. Store sufficient quantities of all HMWM materials at the site to perform the entire application before starting deck surface preparation. Store containers of promoters and initiators in a manner that prevents leakage or spillage from one to contact the containers or material of the other. Note that direct contact between the promoter and initiator can result in a spontaneous explosion! Store these materials in their original containers. These containers must bear the manufacturer's label. The label must show the manufacture date, the batch number, the trade name brand, the quantity, and the mixing ratio. Include a Materials Safety Data Sheet (MSDS) with each shipment of resin. Take two, one-half pint (0.25 liter) samples of each lot number of base resin, under the Engineer's direct supervision. Store one sample at the site. Provide the other sample from each lot to the Engineer. The Department will use these samples to verify the infrared signature of the resins against the earlier submittal from the manufacturer. Submit these samples at least three calendar weeks before starting the resin application. Do not send samples of the initiator or promoter to Helena for testing. The Engineer will not allow resin application until the Department's FTIR results match the manufacturer's FTIR submittal and the FTIR spectrum filed with the Department as part of the previous approval for use process.
Provide a clean, dry storage facility for the materials that will shelter them from the elements and preserve their fitness for use. The storage facility must have a thermometer that records extreme temperatures. Replace the materials at no expense to the Department if the temperature exceeds the range the manufacturer recommends or if the materials' shelf life has expired. Repeat the FTIR sampling and testing in this case.

Require all workers to handle the resins in compliance with the Manufacturer's Safety Data Sheets, especially with respect to the proper protective clothing. The Engineer will shut down the job in the event of failure to meet this criterion.

2) Deck Preparation
a) Surface Condition. The deck surface must appear dry to a visual inspection at the time of HMWM treatment.
b) Surface Preparation Equipment. Use shot blast equipment such as Blastrac, Wheelabrator Frye, or Turbo Blast, Turbo Blast Company to clean the deck surface. Determine the size and type of equipment based on specific job conditions. Select the size of shot or sand and travel speed of the equipment

to provide a uniformly clean surface with a uniform profile. Sand blast areas that are not cleaned with the shot blast equipment.

c) Surface Preparation. Clean all concrete surfaces for HMWM treatment by blasting prior to the HMWM application. Remove all traces of curing compound, laitance, grease, dirt, dust, salt, oil, asphalt, paint, striping, coating, or other foreign materials.
Protect the concrete surface from undue damage during the cleaning process. Provide a reasonably uniform surface color.

Generally expose coarse aggregate with slight reveal (maximum reveal: 1/8 inch - or 3 mm). The Engineer will review concrete surfaces for compliance with this specification prior to allowing HMWM treatment application.

3) HMWM Application. Apply resin to the entire deck at a rate of 100 to 150 ft^2/gal (3 to 4 m^2/l). The application rates may vary depending on field conditions, temperature of deck and slight variations in specific gravity. Apply the resin to the deck within 5 minutes of complete mixing. Do not use material showing any visible increase in viscosity prior to application. Porous or tined concrete requires application rates at the lower end of this range. After application of the resin, continuously sweep excess resin to untreated areas of the deck. Stop this sweeping between 5 and 10 minutes before the HMWM gels. Re-fill all cracks visible to the eye constantly after application until 5 minutes before gel formation by using brooms, brushes, or squeegees. The Engineer has the discretion of requiring that decks with tined surfaces receive a separate pre-treatment for visible cracks. In this case, fill the cracks and keep them full until 5 minutes before gel formation. This pre-treatment requires approximately one gallon per 100 lineal feet (1 liter per 8 meters) of crack.

4) Application of Sand. Broadcast silica sand mechanically over the entire treated area of the bridge deck to obtain a visually uniform coverage of 1 lb. per square yard (0.5 kg/m^2). Apply the sand before the resin gels. Remove excess sand if the technical representative requires it.

5) Limitation of Operations. Protect people and vehicles from injury or damage. Cover membrane and elastomeric material in deck joints, plug deck drain scuppers, seal cracks on underside of deck, and institute other protective measures to protect traffic, waterways, and bridge components. If materials or solvents harm the appearance or the function of bridge components, replace or repair the component to the Engineer's satisfaction at no cost to the Department.
Perform no work without the consent of the Engineer. The following conditions govern work on each individual portion of a structure unless otherwise approved.

a) Initiate work on any portion of a structure only if the local weather forecast predicts daytime temperatures favorable for HMWM application and no rain is forecast for a period of 48 hours prior to the scheduled HMWM application time.

b) Conduct the work in a continuous operation with the HMWM application immediately following surface preparation.
c) Do not apply HMWM treatment if rain is likely within 4 hours following the application.
d) Apply HMWM treatment only if the deck surface temperature and the air temperature are 50º F (10º C) or above and 90º F (32º C) or below and the weather forecast shows they will remain within that temperature range for at least twelve hours after the end of the work day.
e) Apply HMWM treatment only between 1 May and 1 September.
The Engineer will not permit traffic on the treated surface until the sand cover adheres sufficiently so that no tracking will occur.

D. Method of Measurement

1) Bridge Deck Treatment. Measure by the square yard (square meter) of deck surface area treated.
2) Furnish HMWM. Measure by the gallon (liter) of methacrylate actually used.

E. Basis of Payment

1) Bridge Deck Treatment. The unit price bid per square yard (meter) provides full compensation for surface preparation, resin application, sand application, provision of a manufacturer's technical representative, protection of waterways and traffic, cleanup, and all labor, tools, equipment, and incidentals necessary to complete the work.
2) Furnish HMWM. The unit price bid per gallon (liter) of HMWM is full compensation for furnishing all resin treatment material to the site of work ready for application. The Department will make no payment for material wasted or not used.
3) Silane. After the deck is grooved, cleaned and at least 28 calendar days after the deck is cast, apply Tamms Baracade 40 IPA, Sivento BSM 40 VOC, ChemRex Penetrating Seal 40 VOC, or ChemRex Silane 40 VOC sealer before the bridge is open for traffic. Apply sealer by spray until refusal. Refusal means that additional spray applications remain on the surface of the concrete and do not soak in.

B3. Michigan State DOT

Participant's Information

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May I contact you for further discussion of the subject matter? Yes No

Survey

1. Does your DOT have a concrete bridge deck maintenance program?

   a. **Yes** b. No

2. Does your DOT (agency) consider concrete bridge deck cracking an adverse problem?

   a. **Yes** b. No

3. Which of the following cracking do your concrete bridge decks experience?

   a. **Transverse** b**. Random** c. **Other**

4. What deicing technology does your DOT use?

   a. **NaCl** b**. MgCL** c. **Other**

5. What is your DOT policy for sealing cracks on concrete bridge decks?

   a. Methacrylate b. **Epoxy** c. Polyesters d. **Other**

6. What is your DOT criterion to begin surface crack repair?

   a. Cracks of size 1/6" or less b. Cracks of size 1/8" or less c. **Other**

7. Please list the approved (or frequently applied) sealers by your DOT.
   1. Unitex Bridge Seal
   2. Tamms Dural 335
   3. E-Bond 120
   4. Sika Sikadur 55 SLV
   5. Masterseal GP

8. How influential are the following factors in selecting sealer type to be applied on bridge decks {Please rank from 1 (not at all) to 5(Extreme)}

   a. Type of sealer - **5**

   b. Temperature **- 3**

   c. Sealer cost - **1**

   d. Traffic Volume - **1**

   e. Temperature Effects (freeze/thaw) **- 1**

9. What determines which products are specified?
   Approved products on Special Provision

10. What products or types of concrete sealing products does your DOT specify to be applied on a new concrete bridge deck?
    Epoxy healer/sealers for crack chasing

11. What products or types of concrete sealing products does your DOT specify to be applied on an old (existing) concrete bridge deck?
    a) epoxy healer/sealer crack chasing
    b) two layer epoxy/aggregate deck overlay
    c) epoxy healer/sealer floodcoat over entire deck surface in select applications

12. Is application of sealer done under the construction contract or do state maintenance forces do this?
    Both

13. The costs of applying sealers, whether it is with State forces or under a contract need to be obtained?
    These costs are obtained by each individual region within MDOT and the costs may vary by region

14. What is the cost associated with the application of sealer, material wise and labor cost?
    Application costs vary by region

15. What is your state's estimated annual maintenance (repair and sealing) cost for concrete-bridge decks?
    Cost figures for only bridge deck maintenance are not available

16. On what frequency does your DOT repeat reapplication of sealers on concrete bridge decks? **Varies by region**

17. What determines if a bridge deck is going to be sealed or perhaps overlaid?
    Deck condition survey/bridge deck preservation matrix

18. The compatibility of sealers for reapplication should also be addressed further beyond their chemical makeup. Please list existing applied sealer and their compatible sealer for reapplication, the frequency and cost (material and labor) of reapplication by your DOT.
    n/a

19. Has your state previously conducted research on application of sealers on concrete bridge decks?
    a. **Yes** b. No

    Report No. RC-1422
    Title: Field Performance of Polymer Bridge Deck Overlays In Michigan

    Report No. RC-1424: Title: Criteria and Benefits Of Penetrating Sealants For Concrete Bridge Decks

B4. Idaho State DOT

Participant's Information

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May I contact you for further discussion of the subject matter? **Yes** No

Survey

1. Does your DOT have a concrete bridge deck maintenance program?

a. **Yes** b. No

2. Does your DOT (agency) consider concrete bridge deck cracking an adverse problem?

a. **Yes** b. No

3. Which of the following cracking do your concrete bridge decks experience?

a. **Transverse** b. Random c. Other

4. What deicing technology does your DOT use?

a. **NaCl** b. **MgCL** c. Other

5. What is your DOT policy for sealing cracks on concrete bridge decks?

a. Methacrylate b. Epoxy c. Polyesters d. Other HMWM and low **modulus epoxy on a few projects, just getting started**.

6. What is your DOT criterion to begin surface crack repair?

a. Cracks of size 1/6" or less b. Cracks of size 1/8" or less c. Other **0.02" or 0.50mm**

7. Please list the approved (or frequently applied) sealers by your DOT.
1.Unitex

2.Transpo
3. Sika

8. How influential are the following factors in selecting sealer type to be applied on bridge decks {Please rank from 1 (not at all) to 5(Extreme)}

   a. Type of sealer

   b. Temperature

   c. Sealer cost

   d. Traffic Volume

   e. Temperature Effects (freeze/thaw)

9. What determines which products are specified? **Good question, we are trying HMWM and epoxy, have not developed a good criteria.**

10. What products or types of concrete sealing products does your DOT specify to be applied on a new concrete bridge deck? **This is a source of internal debate in our office, our deterioration models show that 8" thick concrete, epoxy coated rebar decks with 2.5" of cover, perform quite well even with some degree of cracking. So what is the cost/benefit of sealing cracks and how much additional life is added to the bridge deck?**

11. What products or types of concrete sealing products does your DOT specify to be applied on an old (existing) concrete bridge deck?
    We have used HMWM and epoxy, our current tried and true bridge deck rehabilitation is rigid latex or silica fume overlay.

12. Is application of sealer done under the construction contract or do state maintenance forces do this? **Both**
13. The costs of applying sealers, whether it is with State forces or under a contract need to be obtained?
14. What is the cost associated with the application of sealer, material wise and labor cost?
15. What is your state's estimated annual maintenance (repair and sealing) cost for concrete-bridge decks? **No set state wide amount**
16. On what frequency does your DOT repeat reapplication of sealers on concrete bridge decks? **No policy**
17. What determines if a bridge deck is going to be sealed or perhaps overlaid? **Deck condition, we have been sealer more newer structures than older ones.**
18. The compatibility of sealers for reapplication should also be addressed further beyond their chemical makeup. Please list existing applied sealer and their compatible

sealer for reapplication, the frequency and cost (material and labor) of reapplication by your DOT.

19. Has your state previously conducted research on application of sealers on concrete bridge decks?
    a. Yes b. **No**

B5. California State DOT

Participant's Information

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May I contact you for further discussion of the subject matter? **Yes**

Survey

1. Does your DOT have a concrete bridge deck maintenance program?

a. **Yes** b. No

2. Does your DOT (agency) consider concrete bridge deck cracking an adverse problem?

a. **Yes** b. No

3. Which of the following cracking do your concrete bridge decks experience?

a. Transverse b. **Random** c. Other

4. What deicing technology does your DOT use?

a. **NaCl** with $CaCl_2$ b. MgCL c. Other

5. What is your DOT policy for sealing cracks on concrete bridge decks?

a. **Methacrylate** b. Epoxy c. Polyesters d. Other

6. What is your DOT criterion to begin surface crack repair?

a. Cracks of size 1/6" or less b. Cracks of size 1/8" or less c. **Other**

7. Please list the approved (or frequently applied) sealers by your DOT.
   1. Kwikbond Polymers
   2. Sika Pronto 19

8. How influential are the following factors in selecting sealer type to be applied on bridge decks {Please rank from 1 (not at all) to 5(Extreme)}

- **a.** Type of sealer **5**
- b. Temperature **3**
- c. Sealer cost **1**
- d. Traffic Volume **1**
- e. Temperature Effects (freeze/thaw) **1**

9. What determines which products are specified? **We currently specify HMWM, the contractor selects the material based on cost of materials and cost of application to make the lowest bid.**

10. What products or types of concrete sealing products does your DOT specify to be applied on a new concrete bridge deck? **HMWM to repair unacceptable cracking.**

11. What products or types of concrete sealing products does your DOT specify to be applied on an old (existing) concrete bridge deck? **HMWM to repair cracking.**

12. Is application of sealer done under the construction contract or do state maintenance forces do this? **It is generally installed under a construction contract. State forces have done it in the past.**

13. The costs of applying sealers, whether it is with State forces or under a contract need to be obtained? **The question is not clear. If you want installed costs, please refer to the contract cost data. See the following web page: http://www.dot.ca.gov/hq/esc/oe/awards/**

14. What is the cost associated with the application of sealer, material wise and labor cost? **See contract cost data.**
15. What is your state's estimated annual maintenance (repair and sealing) cost for concrete-bridge decks? **$63,000,000 for treating and joint seals.**

16. On what frequency does your DOT repeat reapplication of sealers on concrete bridge decks? **A repeat treatment has not been done yet (20+ years)**

17. What determines if a bridge deck is going to be sealed or perhaps overlaid? **Element level inspection guidelines condition state level. -- See attached powerpoint document for more information.**

18. The compatibility of sealers for reapplication should also be addressed further beyond their chemical makeup. Please list existing applied sealer and their compatible sealer for reapplication, the frequency and cost (material and labor) of reapplication by your DOT.
19. Has your state previously conducted research on application of sealers on concrete bridge decks?

    a. **Yes** b. No

    Report No. **FHWA/CA/TL-85/16**
    Title: New Materials and Techniques for the Rehabilitation of Portland Cement Concrete
    Location Online:
    http://www.dot.ca.gov/research/researchreports/1981-1988/85-16.pdf

B6. Mississipi State DOT

Participant's Information

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May I contact you for further discussion of the subject matter? **Yes**

Survey

1. Does your DOT have a concrete bridge deck maintenance program?

a. Yes b. No

2. Does your DOT (agency) consider concrete bridge deck cracking an adverse problem?

a. Yes, but due to our mild climate and lack of historically using deicing chemicals, bridge deck cracks have not been the known source of premature degredation b. No

3. Which of the following cracking do your concrete bridge decks experience?

a. Transverse b. Random c. Other

4. What deicing technology does your DOT use?

a. NaCl b. MgCl c. Other

5. What is your DOT policy for sealing cracks on concrete bridge decks?

a. Methacrylate **b. Epoxy** c. Polyesters d. Other

6. What is your DOT criterion to begin surface crack repair?
   a. Cracks of size 1/6" or less b. Cracks of size 1/8" or less c. Other
   No specific criteria

7. Please list the approved (or frequently applied) sealers by your DOT.
   Approved sealers used to seal a bridge deck after grinding as follows:

- **Advanced Chemical Technologies, Inc.**
- **Pecora Corporation – KlereSeal**
- **Rainstopper Sealer**
- **Tamms Industries**
- **Enviroseal**

8. How influential are the following factors in selecting sealer type to be applied on bridge decks {Please rank from 1 (not at all) to 5(Extreme)}

   Type of sealer - **5**

   Temperature - **1**

   Sealer cost - **4**

   Traffic Volume - **3**

   Temperature Effects (freeze/thaw) - **1**

9. What determines which products are specified?
A review of products by our Bridge Division (and/or perhaps Materials Division).

10. What products or types of concrete sealing products does your DOT specify to be applied on a new concrete bridge deck?
Seal after any grinding on the deck. Seal with Alkyltrialkoxysilane.

11. What products or types of concrete sealing products does your DOT specify to be applied on an old (existing) concrete bridge deck?
Depends on the reason for the need for sealing.

12. Is application of sealer done under the construction contract or do state maintenance forces do this?
Both

13. The costs of applying sealers, whether it is with State forces or under a contract need to be obtained?

14. What is the cost associated with the application of sealer, material wise and labor cost?

15. What is your state's estimated annual maintenance (repair and sealing) cost for concrete-bridge decks?

16. On what frequency does your DOT repeat reapplication of sealers on concrete bridge decks?

17. What determines if a bridge deck is going to be sealed or perhaps overlaid?
An individual engineering evaluation as to the extent of the needs based on bridge inspection.

18. The compatibility of sealers for reapplication should also be addressed further beyond their chemical makeup. Please list existing applied sealer and their compatible sealer for reapplication, the frequency and cost (material and labor) of reapplication by your DOT.

19. Has your state previously conducted research on application of sealers on concrete bridge decks?
a. Yes **b. No**

B7. Maryland State DOT

Participant's Information

State:**Maryland**
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May I contact you for further discussion of the subject matter? **Yes**

Survey

1. Does your DOT have a concrete bridge deck maintenance program?

a. **Yes** b. No

2. Does your DOT (agency) consider concrete bridge deck cracking an adverse problem?

a. Yes b. **No**

3. Which of the following cracking do your concrete bridge decks experience?

a. **Transverse mostly** b. Random c. Other

4. What deicing technology does your DOT use?

a. **NaCl** **b. MgCL** c. Other

5. What is your DOT policy for sealing cracks on concrete bridge decks?

a. **Methacrylate** **b. Epoxy** c. Polyesters d. Other

6. What is your DOT criterion to begin surface crack repair?

a. Cracks of size 1/6" or less b. Cracks of size 1/8" or less c. **Other**

7. Please list the approved (or frequently applied) sealers by your DOT.

    1. **Silanes**
    2. **Asphalt Crack Sealers**
    3. **Epoxies**

8. How influential are the following factors in selecting sealer type to be applied on bridge decks {Please rank from 1 (not at all) to 5(Extreme)}

a. Type of sealer - **3**

b. Temperature - **3**

c. Sealer cost - **3**

d. Traffic Volume - **4**

e. Temperature Effects (freeze/thaw) - **4**

9. What determines which products are specified?

Usage history, Durability and Specification Compliance

10. What products or types of concrete sealing products does your DOT specify to be applied on a new concrete bridge deck?

Linseed Oil/Kerosene, Liquid Membrane Curing, Silanes

11. What products or types of concrete sealing products does your DOT specify to be applied on an old (existing) concrete bridge deck?

Silanes, Siloxanes, Asphaltic crack sealers, Epoxy Crack Sealers

12. Is application of sealer done under the construction contract or do state maintenance forces do this?

Both

13. The costs of applying sealers, whether it is with State forces or under a contract need to be obtained?

Not Sure

14. What is the cost associated with the application of sealer, material wise and labor cost?

Varies

15. What is your state's estimated annual maintenance (repair and sealing) cost for concrete-bridge decks?

Varies

16. On what frequency does your DOT repeat reapplication of sealers on concrete bridge decks?

Usually once.

17. What determines if a bridge deck is going to be sealed or perhaps overlaid?

Deck Condition/Distress Level

18. The compatibility of sealers for reapplication should also be addressed further beyond their chemical makeup. Please list existing applied sealer and their compatible sealer for reapplication, the frequency and cost (material and labor) of reapplication by your DOT.

    Information not Available

19. Has your state previously conducted research on application of sealers on concrete bridge decks?

    a**. Yes** b. No

    If yes, please provide:

    Report No. **No Longer Available**

B8. Texas State DOT

Participant's Information

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May I contact you for further discussion of the subject matter? **Yes**

Survey

1. Does your DOT have a concrete bridge deck maintenance program?

   b**. Not specifically – Repair as needed.**

2. Does your DOT (agency) consider concrete bridge deck cracking an adverse problem?

a. **Yes – In some circumstances. If the cracking is widespread and de-icing chemical are used – if cracking is noticed during construction, we have them sealed with gravity feed epoxy.**

3. Which of the following cracking do your concrete bridge decks experience?

   All types.

4. What deicing technology does your DOT use?

   Many types (NaCl, MgCl, others)

5. What is your DOT policy for sealing cracks on concrete bridge decks?

   b**. Epoxy**

6. What is your DOT criterion to begin surface crack repair?

Varies–Please reference http://www.cement.org/bridges/br_newsletter.aspT - PCA Bridge Views–Issue 38 for TxDOT Bridge Divisions recommendations. This is not a policy, just recommendations.

7. Please list the approved (or frequently applied) sealers by your DOT.
Sikadur 55 SLV

8. How influential are the following factors in selecting sealer type to be applied on bridge decks {Please rank from 1 (not at all) to 5(Extreme)}

   a. Type of sealer- **5 – Must be on the approved List.**

   b. Temperature - **1 – Contractor issue**

   c. Sealer cost -**1 – Contractor Issue**

   d. Traffic Volume -**1 – Contractor issue**

   e. Temperature Effects (freeze/thaw) – **1**

9. What determines which products are specified?
They must meet our specification for gravity feed epoxy.

10. What products or types of concrete sealing products does your DOT specify to be applied on a new concrete bridge deck?
Varies – Like to use similar concrete to parent concrete.

11. What products or types of concrete sealing products does your DOT specify to be applied on an old (existing) concrete bridge deck?
We use linseed oil and penetrating materials (Silane)

12. Is application of sealer done under the construction contract or do state maintenance forces do this?
Construction

13. The costs of applying sealers, whether it is with State forces or under a contract need to be obtained?
Not tracked.

14. What is the cost associated with the application of sealer, material wise and labor cost?
Not tracked.

15. What is your state's estimated annual maintenance (repair and sealing) cost for concrete-bridge decks?
Not tracked. (minimal)

16. On what frequency does your DOT repeat reapplication of sealers on concrete bridge decks?
    Seldom done

17. What determines if a bridge deck is going to be sealed or perhaps overlaid?
    Not often done.

18. The compatibility of sealers for reapplication should also be addressed further beyond their chemical makeup. Please list existing applied sealer and their compatible sealer for reapplication, the frequency and cost (material and labor) of reapplication by your DOT.
    Not done.

19. Has your state previously conducted research on application of sealers on concrete bridge decks?
    a. **Yes - Not published**

APPENDIX-C: TEST DATA

Test A: Water Absorption Test in Hardened Concrete
ASTM C 642-97

TABLE C1. Water Absorption Test in Hardened Concrete: Normal Concrete Mix.

Key For Sealer Indication:		IWNoS = Initial Weight with no sealer
D335 = Dural 335 Sealer	DCS = Degadeck Crack Sealer	WAA72HDT = Weight After Additional 72 Hour Drying Time
SS = Star Seal Sealer	CT40 = Chem-Trete BSM40VOC Sealer	WAA24HDT = Weight After Additional 24 Hour Drying Time
Control = No Sealer	R7 = Radcon Formula #7 Sealer	DW = Difference in Weight
		WAAS = Weight After Applying Sealer
		WA48HS = Weight After 48 Hour Soak
		WAA24HS = Weight After Additional 24 Hour Soak
		WA5HB = Weight After 5 Hour Boil
		WSW=Weight Suspended in Water

All Weight In Grams
Normal Concrete

Sample	IWNoS	WA72HDT	DW	WAA24HDT	DW	WAAS A	WA48HS	WAA24HS B	DW	WAA24HS B	DW	WA5HB C	WSW D
D335 1	929.3	898.8	3.39%	898.4	0.04%	902.3	938.5	939.1	0.06%			940.4	551.3
D335 2	894	865.7	3.27%	865.4	0.03%	869.6	904.1	904.5	0.04%			908.6	530
D335 3	939.6	911.7	3.06%	911.3	0.04%	915.5	949.7	949.9	0.02%			951.4	559
DCS 1	903.2	874.4	3.29%	874.2	0.02%	877.4	903.3	909.8	0.71%			921.1	540.4
DCS 2	921.8	893.9	3.12%	893.7	0.02%	895.8	913.9	919.7	0.63%	920.4	0.11%	938.7	554.7
DCS 3	933.6	901.5	3.56%	901.1	0.04%	903.8	935.8	942.9	0.75%	943.1	0.11%	949.2	556
SS 1	879.4	846.9	3.84%	846.5	0.05%	849.4	888.1	888.5	0.05%			890.8	518.4
SS 2	964.5	933.4	3.33%	933	0.04%	936.2	973.8	974.2	0.04%			978.3	578.6
SS 3	947.5	913.6	3.71%	913.3	0.03%	916.3	956.9	957.9	0.10%			962.3	564.5
R7 1	919.9	888	3.59%	887.7	0.03%	892.1	915.4	922	0.72%	921.3	0.11%	930.9	546.9
R7 2	906.5	876.9	3.38%	876.6	0.03%	881.9	913.1	915.8	0.29%			919	537.7
R7 3	1029.3	994.2	3.53%	993.8	0.04%	999.9	1032.9	1037.8	0.47%			1044.3	609.8
CT40 1	936	903.2	3.63%	902.9	0.03%	905.5	913.3	914.9	0.17%			943.6	547.6
CT40 2	943	914.5	3.12%	914.1	0.04%	916.9	924.4	926.2	0.19%			952	558.6
CT40 3	887.8	855.9	3.73%	855.4	0.06%	858.2	876.0	881.2	0.59%	882	0.11%	902	528.5
Control 1	944.2	911.4	3.60%	911.2	0.02%	911.2	952.5	952.7	0.02%			954.5	553.8
Control 2	978.1	943.1	3.71%	942.8	0.03%	942.8	988.1	988.2	0.01%			990	579.1
Control 3	1006.1	970.5	3.67%	970.1	0.04%	970.1	1013.9	1014	0.01%			1014.7	591.9

Equation: [(B-A)/A]*100	Equation: [(C-A)/A]*100	Equation: A/(C-D)=g1	Equation: B/(C-D)	Equation: C/(C-D)	Equation: A/(A-D)=g2	Equation: (g2-g1)/g2*100	Average
Absorption after immersion, %	Absorption after immersion and boiling, %	Bulk sp gr, dry (g1)	Bulk sp gr after immersion	Bulk sp gr after immersion and boiling	Apparent sp gr (g2)	Volume of permeable pore space (voids), %	Average volume of permeable pore space (voids), %
4.08%	4.22%	2.32	2.41	2.42	2.57	9.79%	
4.01%	4.48%	2.30	2.39	2.40	2.56	10.30%	9.75%
3.76%	3.92%	2.33	2.42	2.42	2.57	9.15%	
3.69%	4.98%	2.30	2.39	2.42	2.60	11.48%	
2.75%	4.79%	2.33	2.40	2.44	2.63	11.17%	11.40%
4.35%	5.02%	2.30	2.40	2.41	2.60	11.55%	
4.60%	4.87%	2.28	2.39	2.39	2.57	11.12%	
4.06%	4.50%	2.34	2.44	2.45	2.62	10.53%	11.07%
4.54%	5.02%	2.30	2.41	2.42	2.60	11.56%	
3.27%	4.35%	2.32	2.40	2.42	2.58	10.10%	
3.84%	4.21%	2.31	2.40	2.41	2.56	9.73%	10.02%
3.79%	4.44%	2.30	2.39	2.40	2.56	10.22%	
1.04%	4.21%	2.29	2.31	2.38	2.53	9.62%	
1.01%	3.83%	2.33	2.35	2.42	2.56	8.92%	10.09%
2.77%	5.10%	2.30	2.36	2.41	2.60	11.73%	
4.55%	4.75%	2.27	2.38	2.38	2.55	10.81%	
4.82%	5.01%	2.29	2.40	2.41	2.59	11.49%	10.95%
4.53%	4.60%	2.29	2.40	2.40	2.57	10.55%	

TABLE C2. Water Absorption Test in Hardened Concrete: Fly Ash Concrete Mix.

Key For Sealer Indication:		IWNoS = Initial Weight with no sealer
D335 = Dural 335 Sealer	DCS = Degadeck Crack Sealer	WAA72HDT = Weight After Additional 72 Hour Drying Time
SS = Star Seal Sealer	CT40 = Chem-Trete BSM40VOC Sealer	WAA24HDT = Weight After Additional 24 Hour Drying Time
Control = No Sealer	R7 = Radcon Formula #7 Sealer	DW = Difference in Weight
		WAAS = Weight After Applying Sealer
		WA48HS = Weight After 48 Hour Soak
		WAA24HS = Weight After Additional 24 Hour Soak
		WA5HB = Weight After 5 Hour Boil
		WSW=Weight Suspended in Water

All Weight In Grams

Fly-Ash Concrete

Specimen	IWNoS	WAA72HDT	DW	WAA24HDT	DW	WAAS A	WA48HS	WAA24HS B	DW	WAA24HS B	DW	WA5HB C	WSW D
D335 1	948	922.6	2.75%	922.2	0.04%	926.5	961.0	961.6	0.06%			959.6	552.9
D335 2	918.7	891.8	3.02%	891.8	0.00%	895.8	930.5	930.9	0.04%			930	539.3
D335 3	944.7	918.3	2.87%	917.8	0.05%	923.3	957.6	958	0.04%			956.9	555.8
DCS 1	966.4	936.1	3.24%	935.6	0.05%	937.9	967.0	976.7	0.99%	975.5	-0.12%	979.3	571
DCS 2	938.3	911.9	2.90%	911.6	0.03%	913.7	946.0	949.5	0.37%			951.9	554.3
DCS 3	881.2	854.8	3.09%	854.4	0.05%	858.8	886.3	891.7	0.61%	891.5	-0.02%	898.2	516.1
SS 1	884.7	857.7	3.15%	853.3	0.52%	860.2	894.7	895.4	0.08%			895.1	518.2
SS 2	941	913.6	3.00%	913.2	0.04%	917	954.0	955.6	0.17%			957.2	551.3
SS 3	947.5	919.7	3.02%	919.1	0.07%	922.3	959.4	959.7	0.03%			960.6	562.1
R7 1	942.2	914.4	3.04%	914	0.04%	919.9	955.5	956.1	0.06%			956.2	555.5
R7 2	942	913.1	3.17%	912.6	0.05%	917	950.1	951.6	0.16%			951	554.3
R7 3	942.6	913	3.24%	912.7	0.03%	917.4	950.2	952.3	0.22%			951.6	554.9
CT40 1	898.8	875.3	2.68%	875	0.03%	877.5	883.3	884.9	0.18%			908.1	524.2
CT40 2	923.7	895	3.21%	894.7	0.03%	897.3	903.8	905.3	0.17%			932.1	541.1
CT40 3	968.7	939	3.16%	938.8	0.02%	941.5	947.2	948.3	0.12%			976.9	564.7
Control 1	948.5	918.2	3.30%	917.7	0.05%	917.7	960.5	960.4	-0.01%			960.8	555.4
Control 2	925.4	900.5	2.77%	900.2	0.03%	900.2	937.1	937.4	0.03%			937.7	547.6
Control 3	931.6	905.6	2.87%	905.2	0.04%	905.2	942.2	942.2	0.00%			942.1	546.6

	Equation: [(B-A)/A]*100	Equation: [(C-A)/A]*100	Equation: A/(C-D)=g1	Equation: B/(C-D)	Equation: C/(C-D)	Equation: A/(A-D)=g2	Equation: (g2-g1)/g2*100	Average
Specimen	Absorption after immersion, %	Absorption after immersion and boiling, %	Bulk sp gr, dry (g1)	Bulk sp gr after immersion	Bulk sp gr after immersion and boiling	Apparent sp gr (g2)	Volume of permeable pore space (voids), %	Volume of permeable pore space (voids), %
D335 1	3.79%	3.57%	2.28	2.36	2.36	2.48	8.14%	
D335 2	3.92%	3.82%	2.29	2.38	2.38	2.51	8.75%	8.42%
D335 3	3.76%	3.64%	2.30	2.39	2.39	2.51	8.38%	
DCS 1	4.01%	4.41%	2.30	2.39	2.40	2.56	10.14%	
DCS 2	3.92%	4.18%	2.30	2.39	2.39	2.54	9.61%	10.02%
DCS 3	3.81%	4.59%	2.25	2.33	2.35	2.51	10.31%	
SS 1	4.09%	4.06%	2.28	2.38	2.37	2.52	9.26%	
SS 2	4.21%	4.38%	2.26	2.35	2.36	2.51	9.90%	9.59%
SS 3	4.06%	4.15%	2.31	2.41	2.41	2.56	9.61%	
R7 1	3.94%	3.95%	2.30	2.39	2.39	2.52	9.06%	
R7 2	3.77%	3.71%	2.31	2.40	2.40	2.53	8.57%	8.75%
R7 3	3.80%	3.73%	2.31	2.40	2.40	2.53	8.62%	
CT40 1	0.84%	3.49%	2.29	2.31	2.37	2.48	7.97%	
CT40 2	0.89%	3.88%	2.29	2.32	2.38	2.52	8.90%	8.49%
CT40 3	0.72%	3.76%	2.28	2.30	2.37	2.50	8.59%	
Control 1	4.65%	4.70%	2.26	2.37	2.37	2.53	10.63%	
Control 2	4.13%	4.17%	2.31	2.40	2.40	2.55	9.61%	9.86%
Control 3	4.09%	4.08%	2.29	2.38	2.38	2.52	9.33%	

TABLE C3. Water Absorption Test in Hardened Concrete: Old Concrete.

Key For Sealer Indication:		
D335 = Dural 335 Sealer	DCS = Degadeck Crack Sealer	IWNoS = Initial Weight with no sealer
SS = Star Seal Sealer	CT40 = Chem-Trete BSM40VOC Sealer	WAA72HDT = Weight After Additional 72 Hour Drying Time
Control = No Sealer	R7 = Radcon Formula #7 Sealer	WAA24HDT = Weight After Additional 24 Hour Drying Time
		DW = Difference in Weight
		WAAS = Weight After Applying Sealer
		WA48HS = Weight After 48 Hour Soak
		WAA24HS = Weight After Additional 24 Hour Soak
		WA5HB = Weight After 5 Hour Boil
		WSW=Weight Suspended in Water

All Weight In Grams
Old Concrete

Sealer	IWNoS	WAA72HDT	DW	WAA24HDT	DW	WAAS	WA48HS	WAA24HS	DW	WAA24HS	DW	WA5HB	WSW
						A		B		B		C	D
D335 1	1313.2	1279.4	2.64%	1278.9	0.04%	1288.3	1337.4	1341.5	0.31%			1357.7	789.6
D335 2	1515.2	1474.7	2.75%	1473.6	0.07%	1479.8	1535.6	1540.5	0.32%			1559.3	905.9
D335 3	1387.4	1351.6	2.65%	1350.9	0.05%	1356.2	1408.5	1412.2	0.26%			1432.1	836.7
DCS 1	1588.1	1544.9	2.80%	1544	0.06%	1547.3	1603.5	1609.8	0.39%			1636.5	963.8
DCS 2	1802.6	1753.9	2.78%	1753.1	0.05%	1757.5	1818.9	1827.2	0.45%			1873.2	1097.1
DCS 3	1779	1734.2	2.58%	1733.3	0.05%	1738.8	1810.9	1819.5	0.47%			1851.1	1079
SS 1	1806	1748.7	3.28%	1746.8	0.11%	1752.1	1827.5	1829.3	0.10%			1876.8	1091.6
SS 2	1259.5	1227.3	2.62%	1226.7	0.05%	1231.2	1279.9	1285.2	0.41%			1303.3	768.2
SS 3	1618.3	1573.3	2.86%	1572.4	0.06%	1577.9	1640.5	1645.1	0.28%			1670.5	981.4
R7 1	1400.3	1364.2	2.65%	1363.3	0.07%	1378.9	1431.2	1433.2	0.14%			1446.6	852.1
R7 2	1369.2	1327.4	3.15%	1326.8	0.05%	1335.1	1389.2	1398.1	0.64%	1396.5	0.11%	1414.2	812.7
R7 3	1668.6	1616	3.25%	1615	0.06%	1623.7	1649.8	1659.5	0.58%	1664.7	0.31%	1718.3	979.6
CT40 1	1759.7	1718.5	2.40%	1717.7	0.05%	1721.2	1749.1	1753.4	0.25%			1824.9	1065.6
CT40 2	1448.3	1409.8	2.73%	1407.7	0.15%	1411	1431.1	1436.8	0.40%			1490.6	865.5
CT40 3	1296.4	1262.5	2.69%	1261.9	0.05%	1266.9	1307.0	1310.6	0.27%			1331.2	785
Control 1	1447	1400.6	3.31%	1399.8	0.06%	1399.8	1465.4	1465.8	0.03%			1495.5	856.1
Control 2	2141.6	2088.8	2.53%	2087.7	0.05%	2087.7	2179.9	2180.5	0.03%			2207.5	1286.5
Control 3	2178.9	2123.4	2.61%	2122.3	0.05%	2122.3	2226.2	2227.3	0.05%			2253.7	1330.8

	Equation: [(B-A)/A]*100	Equation: [(C-A)/A]*100	Equation: A/(C-D)=g1	Equation: B/(C-D)	Equation: C/(C-D)	Equation: A/(A-D)=g2	Equation: (g2-g1)/g2*100	Average
Sealer	Absorption after immersion, %	Absorption after immersion and boiling, %	Bulk sp gr, dry (g1)	Bulk sp gr after immersion	Bulk sp gr after immersion and boiling	Apparent sp gr (g2)	Volume of permeable pore space (voids), %	Volume of permeable pore space (voids), %
D335 1	4.13%	5.39%	2.27	2.36	2.39	2.58	12.22%	
D335 2	4.10%	5.37%	2.26	2.36	2.39	2.58	12.17%	12.38%
D335 3	4.13%	5.60%	2.28	2.37	2.41	2.61	12.75%	
DCS 1	4.04%	5.76%	2.30	2.39	2.43	2.65	13.26%	
DCS 2	3.97%	6.58%	2.26	2.35	2.41	2.66	14.91%	14.24%
DCS 3	4.64%	6.46%	2.25	2.36	2.40	2.64	14.54%	
SS 1	4.41%	7.12%	2.23	2.33	2.39	2.65	15.88%	
SS 2	4.39%	5.86%	2.30	2.40	2.44	2.66	13.47%	14.26%
SS 3	4.26%	5.87%	2.29	2.39	2.42	2.65	13.44%	
R7 1	3.94%	4.91%	2.32	2.41	2.43	2.62	11.39%	
R7 2	4.60%	5.92%	2.22	2.32	2.35	2.56	13.15%	12.45%
R7 3	2.53%	5.83%	2.20	2.25	2.33	2.52	12.81%	
CT40 1	1.87%	6.02%	2.27	2.31	2.40	2.63	13.66%	
CT40 2	1.83%	5.64%	2.26	2.30	2.38	2.59	12.73%	12.72%
CT40 3	3.45%	5.08%	2.32	2.40	2.44	2.63	11.77%	
Control 1	4.71%	6.84%	2.19	2.29	2.34	2.57	14.97%	
Control 2	4.45%	5.74%	2.27	2.37	2.40	2.61	13.01%	14.07%
Control 3	4.95%	6.19%	2.30	2.41	2.44	2.68	14.24%	

Test B: Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals ASTM C 672/C 672M-98

TABLE C4. Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals up to 100 Cyles of Freezing and Thawing.
C: Normal Concrete Mix, F: Fly Ash Concrete Mix, O: Old concrete.

Rating	
0	No scaling
1	very slight scaling (3mm[1/8 in.]depth, max, no coarse aggregare visible
2	slight to moderate scaling
3	moderate scaling (some coarse aggregate visible)
4	moderate to severe scaling
5	Severe Scaling (Course aggregare visible over the entire surface)

Specimen	Sealer	C#05	C#10	C#15	C#25	C#50	C#75	C#85	C#90	C#100
C1A	Control	0	0	0	0	0	0	0	0	1
C1B	Control	0	0	0	0	0	1	1	1	2
C2A	D335	0	0	0	0	0	0	0	0	0
C2B	D335	0	0	0	0	0	0	0	0	0
C3A	DCS	0	0	0	0	0	0	0	1	2
C3B	DCS	0	0	0	0	0	1	1	1	2
C4A	SS	0	0	0	0	0	0	0	0	1
C4B	SS	0	0	0	0	0	1	1	1	2
C5A	R7	0	0	0	0	0	1	1	1	2
C5B	R7	0	0	0	0	0	0	0	1	1
C6A	CT40	0	0	0	0	0	1	1	1	1
C6B	CT40	0	0	0	0	0	1	1	2	2
F1A	Control	0	0	0	0	0	1	1	1	2
F1B	Control	0	0	0	0	0	1	1	2	2
F2A	D335	0	0	0	0	0	0	0	0	0
F2B	D335	0	0	0	0	0	0	0	0	0
F3A	DCS	0	0	0	0	0	0	0	1	2
F3B	DCS	0	0	0	0	0	1	1	1	2
F4A	SS	0	0	0	0	0	1	1	2	2
F4B	SS	0	0	0	0	0	0	0	1	2
F5A	R7	0	0	0	0	0	1	1	1	2
F5B	R7	0	0	0	0	0	1	1	2	2
F6A	CT40	0	0	0	0	0	1	1	1	1
F6B	CT40	0	0	0	0	0	0	0	0	0
O1A	Control	0	0	0	0	0	0	0	0	0
O1B	Control	0	0	0	0	0	0	0	0	1
O2A	D335	0	0	0	0	0	0	0	0	0
O2B	D335	0	0	0	0	0	0	0	0	0
O3A	DCS	0	0	0	0	0	0	0	0	1
O3B	DCS	0	0	0	0	0	0	0	0	1
O4A	SS	0	0	0	0	0	0	0	1	1
O4B	SS	0	0	0	0	0	0	0	1	1
O5A	R7	0	0	0	0	0	1	1	1	1
O5B	R7	0	0	0	0	0	0	0	0	0
O6A	CT40	0	0	0	0	0	0	0	0	1
O6B	CT40	0	0	0	0	0	0	0	1	1

Test C: Resistance of Concrete to Rapid Freezing & Thawing AASHTO T 161-00

TABLE C5. Freeze-Thaw Test Results Measured at the 300th Cycle.
C: Normal Concrete Mix, F: Fly Ash Concrete Mix, O: Old concrete.

Cycles: 300							
Specimen	Sealer	Percent Change in Length	Percent Change in Weight	Percent Change in Modulus	Average Change in Length	Average Change in Weight	Average Dynamic Modulus
C-1-A	Control	0.014	0.648	107.5	0.010	0.700	108.5
C-1-B		0.010	0.700	107.5			
C-1-C		0.007	0.745	110.6			
F-1-A	Control	0.014	0.700	106.2	0.007	0.730	107.3
F-1-B		-0.007	0.789	108.1			
F-1-C		0.014	0.688	107.7			
C-2-A	D335	-0.203	0.836	100.2	-0.058	0.720	99.0
C-2-B		0.003	0.728	99.4			
C-2-C		0.027	0.602	97.5			
F-2-A	D335	0.000	0.469	101.9	-0.005	0.490	102.3
F-2-B		-0.037	0.516	103.7			
F-2-C		0.023	0.473	101.3			
C-3-A	DCS	0.017	1.104	104.3	0.016	1.160	103.0
C-3-B		0.027	1.235	103.2			
C-3-C		0.003	1.132	101.5			
F-3-A	DCS	0.047	1.267	106.3	0.044	1.150	106.6
F-3-B		0.057	1.211	107.6			
F-3-C		0.027	0.975	105.9			
C-4-A	SS	0.069	1.059	107.2	0.038	1.040	106.5
C-4-B		0.020	1.075	105.9			
C-4-C		0.024	0.995	106.5			
F-4-A	SS	0.003	0.604	107.2	0.005	0.570	106.4
F-4-B		0.010	0.761	106.0			
F-4-C		0.003	0.352	106.1			
C-5-A	R7	0.014	0.923	102.9	0.019	0.750	104.1
C-5-B		0.024	0.403	103.2			
C-5-C		0.020	0.913	106.3			
F-5-A	R7	0.020	0.159	110.5	0.04	0.16	109.9
F-5-B		0.044	0.153	108.0			
F-5-C		0.043	0.166	111.2			
C-6-A	CT40	0.068	-0.178	108.4	0.06	-0.45	103.7
C-6-B		0.051	-0.166	103.4			
C-6-C		0.055	-1.017	99.3			
F-6-A	CT40	0.106	1.369	112.6	0.07	-0.44	108.1
F-6-B		0.054	-1.309	105.6			
F-6-C		0.057	-1.370	106.1			
O-1-A	Control	-0.040	-0.349	88.3	-0.11	-1.04	98.0
O-1-B		0.334	-1.531	74.7			
O-1-C		-0.624	-1.237	131.1			
O-2-A	D335	-0.562	0.826	91.4	0.03	-3.40	95.6
O-2-B		0.628	0.620	74.6			
O-2-C		0.019	-11.646	120.9			
O-3-A	DCS	-0.823	-10.395	59.4	-7.95	-13.76	82.4
O-3-B		0.061	-1.214	95.6			
O-3-C		-23.101	-29.680	92.2			
O-4-A	SS	-0.306	-1.321	70.7	-0.20	-1.60	67.2
O-4-B		-0.229	-2.323	79.2			
O-4-C		-0.075	-1.148	51.7			
O-5-A	R7	1.350	-0.100	76.5	0.38	-1.58	90.3
O-5-B		-0.182	-4.811	94.6			
O-5-C		-0.032	0.161	99.7			
O-6-A	CT40	-0.128	-13.086	118.9	0.01	-5.90	113.9
O-6-B		0.435	0.433	107.2			
O-6-C		-0.287	-5.035	115.6			

Test D: Resistance of Concrete to Chloride Ion Penetration AASHTO T 259-02

Test E: Sampling and Testing for Chloride Ion in Concrete and Concrete Raw Materials-- AASHTO T 260-97(01)

TABLE C6a. Resistance of Concrete to Chloride Ion Penetration.
C: Normal Concrete Mix, F: Fly Ash Concrete Mix.

Normality of AgSO4 titrant = 0.0108
Normality of NaCl = 0.01
(Note - The specimens with red color (bold) were analyzed by NDDOT.)

Depth	Specimen	Sealer	Mass	ml NaCl	ml Titrant	% Cl	Cl (lb/cy)	Depth	Specimen	Sealer	Mass	NaCl (ml)	Titrant (ml)	% Cl	CL (lb/cy)
0.5	C2A	D335	3.0633	4.3	0	0.054	2.10	1	C2A	D335	3.06	7.1	6	0.019	0.76
0.5	C2B	D335					**2.70**	1	C2B	D335					**0.47**
0.5	C2C	D335					**2.04**	1	C2C	D335					**0.39**
0.5	C2D	D335	3.0362	3.3	0	0.042	1.63	1	C2D	D335	3.07	5.1	4	0.017	0.68
						Ave.	**2.12**							Ave.	**0.57**
0.5	C3A	DCS					**1.84**	1	C3A	DCS					**0.39**
0.5	C3B	DCS	3.0561	6	0	0.075	2.94	1	C3B	DCS 2	3.01	5.3	4	0.020	0.79
0.5	C3C	DCS					**4.74**	1	C3C	DCS					**0.59**
0.5	C3D	DCS	3.0493	8.1	0	0.102	3.98	1	C3D	DCS 4	3.05	6	4	0.029	1.13
						Ave.	**3.38**							Ave.	**0.73**
0.5	C4A	SS	3.0502	8.6	0	0.102	3.99	1	C4A	SS	3.04	6	4	0.025	0.97
0.5	C4B	SS					**4.58**	1	C4B	SS					**0.43**
0.5	C4C						**7.91**								**2.07**
0.5	C4D	SS	3.0459	5.2	0	0.062	2.42	1	C4D	SS	3.09	5.7	4	0.021	0.82
						Ave.	**4.72**							Ave.	**1.07**
0.5	C5A	R7					**5.95**	1	C5A	R7					**0.82**
0.5	C5B	R7	3.0495	12.5	0	0.148	5.80	1	C5B	R7	3.07	5.6	4	0.020	0.77
0.5	C5C	R7					**7.44**	1	C5C	R7					**1.64**
0.5	C5D	R7	3.0147	18	0	0.216	8.45	1	C5D	R7	3.08	7.1	4	0.037	1.46
						Ave.	**6.91**							Ave.	**1.17**
0.5	C6A	CT40					**2.66**	1	C6A	CT40					**0.20**
0.5	C6B	CT40	3.0693	16.8	0	0.198	7.75	1	C6B	CT40	3.04	5.7	4	0.021	0.83
0.5	C6C	CT40					**4.42**	1	C6C	CT40					**1.25**
0.5	C6D	CT40	3.0948	11.7	0	0.137	5.35	1	C6D	CT40	3.02	6	4	0.025	0.97
						Ave.	**5.05**							Ave.	**0.81**
0.5	C1A	Control 1					**7.48**	1	C1A	Control 1					**4.15**
0.5	C1B	Control 2	3.0647	14.4	0	0.180	7.04	1	C1B	Control 2	3.08	2	0	0.025	0.97
0.5	C1C	Control 3	3.0466	14.4	0	0.181	7.09	1	C1C	Control 3	3.03	3	0	0.038	1.49
0.5	C1D	Control 4					**6.34**	1	C1D	Control 4					**0.51**
						Ave.	**6.99**							Ave.	**1.78**
Depth	Specimen	Sealer	Mass	ml NaCl	ml Titrant	% Cl	Cl (lb/cy)	Depth	Specimen	Sealer	Mass	NaCl (ml)	Titrant (ml)	% Cl	CL (lb/cy)
0.5	F2A	D335					**1.06**	1	F2A	D335					**0.27**
0.5	F2B	D335					**2.35**	1	F2B	D335					**0.20**
0.5	F2C	D335	3.01	6.5	4	0.036	1.39	1	F2C	D335	3.04	7.5	6	0.024	0.96
0.5	F2D	D335	3.07	4	0	0.050	1.95	1	F2D	D335	3.08	5.7	4	0.025	0.97
						Ave.	**1.69**							Ave.	**0.60**
0.5	F3A	DCS					**2.86**	1	F3A	DCS					**0.86**
0.5	F3B	DCS					**2.07**	1	F3B	DCS					**0.39**
0.5	F3C	DCS	3.06	7.5	0	0.094	3.68	1	F3C	DCS 3	3.05	5.4	4	0.021	0.83
0.5	F3D	DCS	3.05	7	0	0.088	3.44	1	F3D	DCS 4	3.04	5.4	4	0.021	0.84
						Ave.	**3.01**							Ave.	**0.73**
0.5	F4A	SS					**3.80**	1	F4A	SS					**0.59**
0.5	F4B	SS	3.02	10.6	0	0.127	4.97	1	F4B	SS	3.04	7.8	6	0.028	1.11
0.5	F4C	SS					**2.66**	1	F4C	SS					**0.55**
0.5	F4D	SS	3.05	11.9	2	0.118	4.61	1	F4D	SS	3.02	5.94	4	0.024	0.95
						Ave.	**4.01**							Ave.	**0.80**
0.5	F5A	R7					**5.64**	1	F5A	R7					**0.55**
0.5	F5B	R7					**4.54**	1	F5B	R7					**0.74**
0.5	F5C	R7	3.01	9.5	0	0.114	4.47	1	F5C	R7	3.00	5.6	4	0.020	0.79
0.5	F5D	R7	3.01	9.5	0	0.114	4.47	1	F5D	R7	3.00	5.6	4	0.020	0.79
						Ave.	**4.78**							Ave.	**0.72**
0.5	F6A	CT40					**3.48**	1	F6A	CT40					**0.31**
0.5	F6B	CT40	3.09	5.5	0	0.064	2.52	1	F6B	CT40	3.04	5.4	4	0.018	0.69
0.5	F6C	CT40					**4.07**	1	F6C	CT40					**0.55**
0.5	F6D	CT40	3.07	5.5	0	0.065	2.53	1	F6D	CT40	3.07	7.1	6	0.014	0.56
						Ave.	**3.15**							Ave.	**0.53**
0.5	F1A	Control 1	3.03	14.5	0	0.183	7.17	1	F1A	Control 1	3.08	5.5	4	0.022	0.87
0.5	F1B	Control 2	3.04	12.4	0	0.156	6.11	1	F1B	Control 2	3.02	5.6	4	0.024	0.94
0.5	F1C	Control 3					**6.81**	1	F1C	Control 3					**0.51**
0.5	F1D	Control 4					**3.09**	1	F1D	Control 4					**0.63**
						Ave.	**5.79**							Ave.	**0.74**

TABLE C6b. Resistance of Concrete to Chloride Ion Penetration.
O: Old concrete.

Normality of AgSO4 titrant = 0.0108
Normality of NaCl = 0.01
(Note - The specimens with red colour (bold) were analyzed by NDDOT.)

Depth	Specimen	Sealer	Mass	ml NaCl	ml Titrant	% Cl	Cl (lb/cy)	Depth	Specimen	Sealer	Mass	NaCl (ml)	Titrant (ml)	% Cl	CL (lb/cy)
0.5	O2A	D335	3.03	28.4	0	0.359	14.06	1	O2A	D335	3.06	22.5	0	0.282	11.02
0.5	O2B	D335					**13.47**	1	O2B	D335					**10.45**
0.5	O2C	D335					**13.47**	1	O2C	D335					**9.16**
0.5	O2D	D335	3.06	34.8	0	0.435	17.04	1	O2D	D335	3.01	18.6	0	0.237	9.27
						Ave.	**14.51**							Ave.	**9.98**
0.5	O3A	DCS	3.02	24	0	0.288	11.27	1	O3A	DCS	3.04	21.1	2	0.227	8.91
0.5	O3B	DCS					**17.42**	1	O3B	DCS					**12.14**
0.5	O3C	DCS					**15.35**	1	O3C	DCS					**11.31**
0.5	O3D	DCS	3.04	19.5	4	0.199	7.80	1	O3D	DCS	3.07	7.1	0	0.089	3.47
						Ave.	**12.96**							Ave.	**8.96**
0.5	O4A	SS					**14.84**	1	O4A	SS					**10.77**
0.5	O4B	SS	3.01	26.9	0	0.342	13.40	1	O4B	SS	3.01	16.8	0	0.214	8.37
0.5	O4C	SS					**11.43**	1	O4C	SS					**12.88**
0.5	O4D	SS	3.01	25.4	0	0.323	12.64	1	O4D	SS	3.09	26.4	4	0.281	11.01
						Ave.	**13.08**							Ave.	**10.76**
0.5	O5A	R7					**14.15**	1	O5A	R7					**10.40**
0.5	O5B	R7					**13.31**	1	O5B	R7					**11.47**
0.5	O5C	R7	3.04	33.2	6	0.325	12.73	1	O5C	R7	3.05	20.9	2	0.224	8.79
0.5	O5D	R7	3.04	30	0	0.378	14.78	1	O5D	R7	3.03	22.7	0	0.271	10.61
						Ave.	**13.74**							Ave.	**10.32**
0.5	O6A	CT40	3.08	33.6	4	0.372	14.56	1	O6A	CT40	3.08	20.3	0	0.253	9.89
0.5	O6B	CT40					**15.58**	1	O6B	CT40					**9.28**
0.5	O6C	CT40	3.01	27.9	0	0.336	13.14	1	O6C	CT40	3.01	19.6	0	0.249	9.75
0.5	O6D	CT40					**14.52**	1	O6D	CT40					**10.65**
						Ave.	**14.45**							Ave.	**9.89**
0.5	O1A	Control 1					**14.25**	1	O1A	Control 1					**13.19**
0.5	O1B	Control 2	3.03	19	0	0.240	9.39	1	O1B	Control 2	3.09	26	0	0.305	11.93
0.5	O1C	Control 3	3.08	29.8	4	0.325	12.71	1	O1C	Control 3	3.09	27.3	0	0.339	13.27
0.5	O1D	Control 4	3.09	31.8	0	0.395	15.45	1	O1D	Control 4					**7.99**
						Ave.	**12.95**							Ave.	**11.59**

Test F: Test for Average Depth of Penetration -- NDDOT Method

TABLE C7. Test Results for Average Depth of Penetration.
C: Normal Concrete Mix, F: Fly Ash Concrete Mix, O: Old concrete.

Specimen	Sealer	Depth of Sealer Penetration measured to nearest 0.1 inch (Specimem #1)	Depth of Sealer Penetration measured to nearest 0.1 inch (Specimem #2)	Depth of Sealer Penetration measured to nearest 0.1 inch (Specimem #3)	Depth of Sealer Penetration measured to nearest 0.1 inch (Specimem #4)
C2A	D335	No penetration observed	No penetration observed	No penetration observed	No penetration observed
C2B	D335	No penetration observed	No penetration observed	No penetration observed	No penetration observed
C2C	D335	No penetration observed	No penetration observed	No penetration observed	No penetration observed
C3A	DCS	No penetration observed	No penetration observed	No penetration observed	No penetration observed
C3B	DCS	No penetration observed	No penetration observed	No penetration observed	No penetration observed
C3C	DCS	No penetration observed	No penetration observed	No penetration observed	No penetration observed
C4A	SS	No penetration observed	No penetration observed	No penetration observed	No penetration observed
C4B	SS	No penetration observed	No penetration observed	No penetration observed	No penetration observed
C4C	SS	No penetration observed	No penetration observed	No penetration observed	No penetration observed
C5A	R7	No penetration observed	No penetration observed	No penetration observed	No penetration observed
C5B	R7	No penetration observed	No penetration observed	No penetration observed	No penetration observed
C5C	R7	No penetration observed	No penetration observed	No penetration observed	No penetration observed
C6A	CT40	0.1, 0.1, 0.2, 0.0, 0.1, 0.1, 0.2, 0.0, 0.0, 0.1	0.2, 0.1, 0.0, 0.0, 0.0, 0.1, 0.1, 0.0, 0.1, 0.1	0.1, 0.1, 0.0, 0.1, 0.0, 0.2, 0.1, 0.1, 0.0, 0.0	0.1, 0.0, 0.0, 0.1, 0.1, 0.0, 0.0, 0.0, 0.
C6B	CT40	0.1, 0.1, 0.0, 0.1, 0.1, 0.0, 0.1, 0.1, 0.1, 0.1	0.1, 0.1, 0.1, 0.2, 0.1, 0.0, 0.0, 0.1, 0.1, 0.0	0.2, 0.1, 0.1, 0.1, 0.0, 0.0, 0.0, 0.1, 0.1, 0.1	0.1, 0.0, 0.0, 0.1, 0.1, 0.0, 0.0, 0.0, 0.
C6C	CT40	0.1, 0.1, 0.2, 0.0, 0.1, 0.1, 0.2, 0.1, 0.0, 0.0	0.1, 0.1, 0.0, 0.0, 0.0, 0.1, 0.1, 0.0, 0.1, 0.0	0.1, 0.2, 0.2, 0.0, 0.0, 0.1, 0.1, 0.0, 0.0, 0.0	0.1, 0.0, 0.0, 0.1, 0.1, 0.0, 0.1, 0.1, 0.
C6A	**CT40**	0.09	0.07	0.07	0.04
C6B	**CT40**	0.08	0.08	0.08	0.04
C6C	**CT40**	0.09	0.05	0.07	0.05
F2A	D335	No penetration observed	No penetration observed	No penetration observed	No penetration observed
F2B	D335	No penetration observed	No penetration observed	No penetration observed	No penetration observed
F2C	D335	No penetration observed	No penetration observed	No penetration observed	No penetration observed
F3A	DCS	No penetration observed	No penetration observed	No penetration observed	No penetration observed
F3B	DCS	No penetration observed	No penetration observed	No penetration observed	No penetration observed
F3C	DCS	No penetration observed	No penetration observed	No penetration observed	No penetration observed
F4A	SS	No penetration observed	No penetration observed	No penetration observed	No penetration observed
F4B	SS	No penetration observed	No penetration observed	No penetration observed	No penetration observed
F4C	SS	No penetration observed	No penetration observed	No penetration observed	No penetration observed
F5A	R7	No penetration observed	No penetration observed	No penetration observed	No penetration observed
F5B	R7	No penetration observed	No penetration observed	No penetration observed	No penetration observed
F5C	R7	No penetration observed	No penetration observed	No penetration observed	No penetration observed
F6A	CT40	0.2, 0.2, 0.1, 0.1, 0.0, 0.2, 0.0, 0.1, 0.2, 0.1	0.2, 0.1, 0.0, 0.1, 0.2, 0.0, 0.0, 0.1, 0.1, 0.2	0.1, 0.0, 0.1, 0.2, 0.0, 0.1, 0.1, 0.0, 0.1, 0.2	0.1, 0.0, 0.1, 0.1, 0.1, 0.0, 0.1, 0.1, 0.
F6B	CT40	0.1, 0.2, 0.0, 0.1, 0.1, 0.2, 0.0, 0.1, 0.2, 0.1	0.2, 0.1, 0.1, 0.2, 0.0, 0.1, 0.1, 0.0, 0.1, 0.2	0.1, 0.1, 0.2, 0.1, 0.1, 0.2, 0.1, 0.0, 0.1, 0.1	0.1, 0.0, 0.0, 0.1, 0.1, 0.0, 0.1, 0.2, 0.
F6C	CT40	0.1, 0.2, 0.1, 0.0, 0.1, 0.1, 0.2, 0.1, 0.1, 0.0	0.2, 0.1, 0.0, 0.0, 0.1, 0.1, 0.1, 0.1, 0.0, 0.0	0.1, 0.1, 0.2, 0.0, 0.1, 0.0, 0.0, 0.1, 0.1, 0.0	0.1, 0.1, 0.1, 0.0, 0.2, 0.0, 0.1, 0.1, 0.
F6A	**CT40**	0.12	0.1	0.09	0.06
F6B	**CT40**	0.11	0.11	0.11	0.07
F6C	**CT40**	0.10	0.07	0.07	0.09
O2A	D335	No penetration observed	No penetration observed	No penetration observed	No penetration observed
O2A	D335	No penetration observed	No penetration observed	No penetration observed	No penetration observed
O2C	D335	No penetration observed	No penetration observed	No penetration observed	No penetration observed
O3A	DCS	No penetration observed	No penetration observed	No penetration observed	No penetration observed
O3B	DCS	No penetration observed	No penetration observed	No penetration observed	No penetration observed
O3C	DCS	No penetration observed	No penetration observed	No penetration observed	No penetration observed
O4A	SS	No penetration observed	No penetration observed	No penetration observed	No penetration observed
O4B	SS	No penetration observed	No penetration observed	No penetration observed	No penetration observed
O4C	SS	No penetration observed	No penetration observed	No penetration observed	No penetration observed
O5A	R7	No penetration observed	No penetration observed	No penetration observed	No penetration observed
O5B	R7	No penetration observed	No penetration observed	No penetration observed	No penetration observed
O5C	R7	No penetration observed	No penetration observed	No penetration observed	0.0, 0.1, 0.1, 0.1, 0.1, 0.0, 0.0, 0.0, 0.
					0.04
O6A	CT40	0.0, 0.0, 0.1, 0.0, 0.0, 0.1, 0.0, 0.0, 0.0, 0.0	0.1, 0.0, 0.0, 0.2, 0.0, 0.1, 0.0, 0.0, 0.1, 0.1	0.0, 0.0, 0.0, 0.0, 0.1, 0.0, 0.1, 0.0, 0.1, 0.0	0.0, 0.0, 0.0, 0.1, 0.0, 0.1, 0.1, 0.0, 0.
O6B	CT40	0.0, 0.1, 0.2, 0.0, 0.0, 0.1, 0.0, 0.1, 0.0, 0.0	0.0, 0.0, 0.0, 0.1, 0.0, 0.1, 0.0, 0.0, 0.1, 0.0	0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0	0.0, 0.0, 0.0, 0.1, 0.0, 0.0, 0.0, 0.0, 0.
O6C	CT40	0.1, 0.2, 0.2, 0.1, 0.0, 0.2, 0.2, 0.1, 0.0, 0.1	0.0, 0.0, 0.1, 0.0, 0.2, 0.2, 0.2, 0.2, 0.2, 0.2	0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0	0.0, 0.1, 0.1, 0.0, 0.0, 0.0, 0.1, 0.0, 0.
O6A	**CT40**	0.02	0.06	0.03	0.04
O6B	**CT40**	0.05	0.03	0.00	0.01
O6C	**CT40**	0.013	0.13	0.00	0.03

8. Test G: Test for sealants ability seal crack widths up to 2mm wide (test devised in-house with NDDOT cooperation) – NDDOT/UND Method

TABLE C8a. Sealers ability to seal crack widths up to 2.0 mm wide.
C: Normal Concrete Mix, F: Fly Ash Concrete Mix.

Specimen	Sealer	crack size (mm)	status of sealing	Specimen	Sealer	ack siz (mm)	status of sealing
C2a1	D335	0.2	**sealed**	C2b1	D335	0.2	No Seal
C2a1	D335	0.4	No Seal	C2b1	D335	0.4	No Seal
C2a1	D335	0.7	No Seal	C2b1	D335	0.7	No Seal
C2a2	D335	1.0	No Seal	C2b2	D335	1.0	No Seal
C2a2	D335	1.5	No Seal	C2b2	D335	1.5	No Seal
C2a2	D335	2.0	No Seal	C2b2	D335	2.0	No Seal
C3a1	DCS	0.2	No Seal	C3b1	DCS	0.2	No Seal
C3a1	DCS	0.4	No Seal	C3b1	DCS	0.4	No Seal
C3a1	DCS	0.7	No Seal	C3b1	DCS	0.7	No Seal
C3a2	DCS	1.0	No Seal	C3b2	DCS	1.0	No Seal
C3a2	DCS	1.5	No Seal	C3b2	DCS	1.5	No Seal
C3a2	DCS	2.0	No Seal	C3b2	DCS	2.0	No Seal
C4a1	SS	0.2	No Seal	C4b1	SS	0.2	No Seal
C4a1	SS	0.4	No Seal	C4b1	SS	0.4	No Seal
C4a1	SS	0.7	No Seal	C4b1	SS	0.7	No Seal
C4a2	SS	1.0	No Seal	C4b2	SS	1.0	No Seal
C4a2	SS	1.5	No Seal	C4b2	SS	1.5	No Seal
C4a2	SS	2.0	No Seal	C4b2	SS	2.0	No Seal
C5a1	R7	0.2	No Seal	C5b1	R7	0.2	No Seal
C5a1	R7	0.4	No Seal	C5b1	R7	0.4	No Seal
C5a1	R7	0.7	No Seal	C5b1	R7	0.7	No Seal
C5a2	R7	1.0	No Seal	C5b2	R7	1.0	No Seal
C5a2	R7	1.5	No Seal	C5b2	R7	1.5	No Seal
C5a2	R7	2.0	No Seal	C5b2	R7	2.0	No Seal
C6a1	CT40	0.2	No Seal	C65b1	CT40	0.2	No Seal
C6a1	CT40	0.4	No Seal	C6b1	CT40	0.4	No Seal
C6a1	CT40	0.7	No Seal	C6b1	CT40	0.7	No Seal
C6a2	CT40	1.0	No Seal	C6b2	CT40	1.0	No Seal
C6a2	CT40	1.5	No Seal	C6b2	CT40	1.5	No Seal
C6a2	CT40	2.0	No Seal	C6b2	CT40	2.0	No Seal
F2a1	D335	0.2	**sealed**	F2b1	D335	0.2	**sealed**
F2a1	D335	0.4	No Seal	F2b1	D335	0.4	No Seal
F2a1	D335	0.7	No Seal	F2b1	D335	0.7	No Seal
F2a2	D335	1.0	No Seal	F2b2	D335	1.0	No Seal
F2a2	D335	1.5	No Seal	F2b2	D335	1.5	No Seal
F2a2	D335	2.0	No Seal	F2b2	D335	2.0	No Seal
F3a1	DCS	0.2	No Seal	F3b1	DCS	0.2	No Seal
F3a1	DCS	0.4	No Seal	F3b1	DCS	0.4	No Seal
F3a1	DCS	0.7	No Seal	F3b1	DCS	0.7	No Seal
F3a2	DCS	1.0	No Seal	F3b2	DCS	1.0	No Seal
F3a2	DCS	1.5	No Seal	F3b2	DCS	1.5	No Seal
F3a2	DCS	2.0	No Seal	F3b2	DCS	2.0	No Seal
F4a1	SS	0.2	No Seal	F4b1	SS	0.2	No Seal
F4a1	SS	0.4	No Seal	F4b1	SS	0.4	No Seal
F4a1	SS	0.7	No Seal	F4b1	SS	0.7	No Seal
F4a2	SS	1.0	No Seal	F4b2	SS	1.0	No Seal
F4a2	SS	1.5	No Seal	F4b2	SS	1.5	No Seal
F4a2	SS	2.0	No Seal	F4b2	SS	2.0	No Seal
F5a1	R7	0.2	No Seal	F5b1	R7	0.2	No Seal
F5a1	R7	0.4	No Seal	F5b1	R7	0.4	No Seal
F5a1	R7	0.7	No Seal	F5b1	R7	0.7	No Seal
F5a2	R7	1.0	No Seal	F5b2	R7	1.0	No Seal
F5a2	R7	1.5	No Seal	F5b2	R7	1.5	No Seal
F5a2	R7	2.0	No Seal	F5b2	R7	2.0	No Seal
F6a1	CT40	0.2	No Seal	F65b1	CT40	0.2	No Seal
F6a1	CT40	0.4	No Seal	F6b1	CT40	0.4	No Seal
F6a1	CT40	0.7	No Seal	F6b1	CT40	0.7	No Seal
F6a2	CT40	1.0	No Seal	F6b2	CT40	1.0	No Seal
F6a2	CT40	1.5	No Seal	F6b2	CT40	1.5	No Seal
F6a2	CT40	2.0	No Seal	F6b2	CT40	2.0	No Seal

TABLE C8b. Sealers ability to seal crack widths up to 2.0 mm wide.
O: Old concrete.

Specimen	Sealer	crack size (mm)	status of sealing		Specimen	Sealer	ack siz (mm)	status of sealing
O2a1	D335	0.2	No Seal		O2b1	D335	0.2	No Seal
O2a1	D335	0.4	No Seal		O2b1	D335	0.4	No Seal
O2a1	D335	0.7	No Seal		O2b1	D335	0.7	No Seal
O2a2	D335	1.0	No Seal		O2b2	D335	1.0	No Seal
O2a2	D335	1.5	No Seal		O2b2	D335	1.5	No Seal
O2a2	D335	2.0	No Seal		O2b2	D335	2.0	No Seal
O3a1	DCS	0.2	No Seal		O3b1	DCS	0.2	No Seal
O3a1	DCS	0.4	No Seal		O3b1	DCS	0.4	No Seal
O3a1	DCS	0.7	No Seal		O3b1	DCS	0.7	No Seal
O3a2	DCS	1.0	No Seal		O3b2	DCS	1.0	No Seal
O3a2	DCS	1.5	No Seal		O3b2	DCS	1.5	No Seal
O3a2	DCS	2.0	No Seal		O3b2	DCS	2.0	No Seal
O4a1	SS	0.2	No Seal		O4b1	SS	0.2	No Seal
O4a1	SS	0.4	No Seal		O4b1	SS	0.4	No Seal
O4a1	SS	0.7	No Seal		O4b1	SS	0.7	No Seal
O4a2	SS	1.0	No Seal		O4b2	SS	1.0	No Seal
O4a2	SS	1.5	No Seal		O4b2	SS	1.5	No Seal
O4a2	SS	2.0	No Seal		O4b2	SS	2.0	No Seal
O5a1	R7	0.2	No Seal		O5b1	R7	0.2	No Seal
O5a1	R7	0.4	No Seal		O5b1	R7	0.4	No Seal
O5a1	R7	0.7	No Seal		OF5b1	R7	0.7	No Seal
O5a2	R7	1.0	No Seal		OF5b2	R7	1.0	No Seal
O5a2	R7	1.5	No Seal		O5b2	R7	1.5	No Seal
O5a2	R7	2.0	No Seal		OF5b2	R7	2.0	No Seal
O6a1	CT40	0.2	No Seal		O6b1	CT40	0.2	No Seal
O6a1	CT40	0.4	No Seal		O6b1	CT40	0.4	No Seal
O6a1	CT40	0.7	No Seal		O6b1	CT40	0.7	No Seal
O6a2	CT40	1.0	No Seal		O6b2	CT40	1.0	No Seal
O6a2	CT40	1.5	No Seal		OF6b2	CT40	1.5	No Seal
O6a2	CT40	2.0	No Seal		O6b2	CT40	2.0	No Seal

Test H: Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration -- AASHTO T 277-96(00)

TABLE C9a. Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration.
C: Normal Concrete Mix, F: Fly Ash Concrete Mix.

Concrete	Sample	Measured Cl ion Permeability (Coul.)	Specimem Diameter (in)	Average Cl ion Permeability (Coul.)	Standard dev. Cl ion Permeability (Coul.)
C	D335 1	1982	4	2027	44
C	D335 2	2070	4		
C	D335 3	2030	4		
C	DCS 1	1911	4	2223	636
C	DCS 2	1804	4		
C	DCS 3	2955	4		
C	SS 1	2377	4	2049	527
C	SS 2	1441	4		
C	SS 3	2328	4		
C	R7 1	3141	4	2627	568
C	R7 2	2723	4		
C	R7 3	2017	4		
C	CT40 1	2511	4	2418	331
C	CT40 2	2050	4		
C	CT40 3	2692	4		
C	Control 1	3282	4	2614	867
C	Control 2	2926	4		
C	Control 3	1635	4		
F	D335 1	1074	4	1185	156
F	D335 2	1119	4		
F	D335 3	1363	4		
F	DCS 1	1453	4	1411	139
F	DCS 2	1256	4		
F	DCS 3	1524	4		
F	SS 1	1684	4	1880	307
F	SS 2	2233	4		
F	SS 3	1722	4		
F	R7 1	1557	4	1307	281
F	R7 2	1003	4		
F	R7 3	1361	4		
F	CT40 1	1360	4	1312	352
F	CT40 2	938	4		
F	CT40 3	1637	4		
F	Control 1	982	4	1674	599
F	Control 2	2019	4		
F	Control 3	1061	4		
F	Control 4	2193	4		
F	Control 5	2115	4		

TABLE C9b. Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration.
O: Old concrete.

Concrete	Sample	Measured Cl ion Permeability (Coul.)	Specimem Diameter (in)	Calculated Cl ion Permeability (Coul.)	Average Cl ion Permeability (Coul.)	Standard dev. Cl ion Permeability (Coul.)
O	D335 1	773	3.75	880	913	104
O	D335 2	728	3.75	829		
O	D335 3	903	3.75	1028		
O	DCS 1	1209	3.75	1377	1154	218
O	DCS 2	826	3.75	941		
O	DCS 3	1004	3.75	1144		
O	SS 1	1131	3.75	1288	1155	269
O	SS 2	743	3.75	846		
O	SS 3	1169	3.75	1331		
O	R7 1	1181	3.75	1345	1222	238
O	R7 2	1205	3.75	1372		
O	R7 3	832	3.75	948		
O	CT40 1	1419	3.75	1616	1581	110
O	CT40 2	1280	3.75	1458		
O	CT40 3	1465	3.75	1669		
O	Control 1	848	3.75	966	1096	268
O	Control 2	805	3.75	917		
O	Control 3	1233	3.75	1404		