Evaluation of Penetrating Sealers Applied to Saw Cut Faces in Concrete Pavement Joints

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16. Abstract

The objectives of this study were to assess the use of penetrating sealers to protect concrete pavement joints and to evaluate its cost-effectiveness. Evaluations were first conducted on in-service pavements on I-94, I-41, and I-39 where penetrating sealer was applied. Controlled laboratory tests were completed to investigate the impact of sealer type, application time, application rate, and application method. The best practice was implemented in a field study on I-39. Although there was no visual detection of the presence of sealers in in-service pavements previously treated with sealers, laboratory tests proved the presence and functionality through contact angle, absorption, and penetration depth. The depth of penetration ranged from 1.46 mm (0.06 inch) to 11.75 mm (0.46 inch), with an average of 5.14 mm (0.20 inch). A general trend of decreasing effectiveness along years of service was observed. However, when compared with the samples without sealer, more than half of the joints with sealer were still performing better in terms of contact angle and absorption after 8.2 years of service. The laboratory study found that all penetrating sealers applied to concrete samples resulted in decreased absorption and extension of time to critical (85%) saturation. For the "A-FA" concrete, the silane applied in dry condition extended the time to critical saturation 8 times longer than the control sample without silane, indicating silane's capability of extending the service life of concrete. Core samples from the field study section were hydrophobic with contact angle exceeding 90°. There was no difference in time to critical saturation and no sign of sealer presence in the penetration depth test. The absence of sealer in the field study section was attributed to three possible reasons: (a) high-performance concrete has very low permeability, (b) the polished concrete after saw-cutting is hydrophobic, and (c) vertical surface is challenging for effective coverage. Penetrating sealer may not provide its intended function for low permeability concrete or when it cannot be practically applied to a vertical surface with sufficient penetration. However, the findings of this study are limited to the collected project data.

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Executive Summary

In the last ten years, Wisconsin Department of Transportation (WisDOT) has applied penetrating sealers to the saw cut faces of concrete pavement joints with the goal of improving the joint performance. However, no investigation has been conducted to ascertain that the intended objective is achieved. In addition, there has not been any assessment by WisDOT on the cost-effectiveness of this practice, given that there is variation of products, application methods, and application rate.

The overall objectives of this study were to evaluate the uniformity of current application method, determine the effectiveness of penetrating sealers in protecting concrete joints, and develop standard specification language for applying penetrating sealers to concrete pavement saw cuts. To achieve these objectives, the following four tasks were performed:

i. Literature review: Summarize current practices in protecting concrete joints, the mechanism of penetrating sealers, and lessons learned from bridge deck protection using penetrating sealers.

ii. Evaluation of past Wisconsin projects: Site visit, core samples from the site, and laboratory tests on field cores were completed to evaluate the presence and effectiveness of sealers on three projects I-94, I-41, and I-39/90.

iii. Laboratory study: Assess the performance of various penetrating sealers on common Wisconsin concrete, as well as different application methods and application rates.

iv. Field study: The recommended best practice from laboratory study was implemented in a section on I-39. One year of performance was observed along with laboratory tests of field cores.

A summary of key findings is as follows:

1) Although there was no visual detection of the presence of sealers in in-service pavements (at 2, 6, and 8 years of service) previously treated with sealers, laboratory tests proved the presence and functionality through contact angle, absorption, and penetration depth.

2) The depth of penetration ranged from 1.46 mm (0.06 inch) to 11.75 mm (0.46 inch), with an average of 5.14 mm (0.20 inch). Penetration depth seems to depend on concrete strength; less penetration was associated with high-performance concrete.

3) A general trend of decreasing effectiveness with year of service is observed. However, when compared with the samples without sealer, more than half of the joints with sealer are still performing better in terms of contact angle and absorption after 8.2 years of service.

4) The laboratory study found that all penetrating sealers applied to concrete samples resulted in decreased absorption and extension of time to critical (85%) saturation. For the “A-FA” concrete, the silane applied in dry condition extends the time to critical saturation 8 times

longer than the control sample without silane, indicating silane's capability of extending the service life of concrete.

5) Core samples from the field study section were hydrophobic with contact angle exceeding 90°. There was no difference in time to critical saturation and no sign of sealer in the penetration depth test.

6) The absence of sealer in the field study section was attributed to three possible reasons: (a) high-performance concrete has very low permeability, (b) the polished concrete after saw-cutting is hydrophobic, and (c) vertical surface is challenging for effective coverage.

7) Penetrating sealer may not provide its intended function for low permeability concrete or when it cannot be practically applied to a vertical surface with sufficient penetration.

Recommendations

The following recommendations are provided based on the analysis of this study:

1) The effectiveness of penetrating sealer on horizontal surfaces is well established in the laboratory tests and in the literature. Therefore, this study agrees with previous studies that bridge decks can be protected by the application of penetrating sealers.

2) Whenever possible, multiple applications of sealer should be encouraged since it provided more reduction in absorption over a single application.

3) Penetrating sealer should be applied on dry concrete after at least 7 days of curing.

4) Among the four products tested in this study, silane and SME-PS are more effective than siloxane and lithium silicate.

5) Before further confirmation of field study, it does not seem effective to apply penetrating sealer on saw cut joint faces of high-performance concrete due to the difficulty of sufficient coverage and penetration.

6) Application of penetrating sealer on joints of regular concrete is effective. The following language is recommended to be added into WisDOT Standard Specification.

415.3.7.1 General

(7) Treat sawed surfaces of transverse and longitudinal joints with a penetrating sealer found on the department approved products list for Concrete Protective Surface Treatments. Prepare surface by pressure washing all saw slurry from sawed joints and allow to dry thoroughly prior to application of sealer. Apply the product directly to the interior of the sawed joint. Apply additional passes in 10 to 15 minutes to achieve the required coverage rate. Do not use the broadcast spray method of application.

7) Contractors are suggested to use the masonry block setup to test their sprayer system and application method. This method can visually verify the uniformity of coverage.

8) Conduct a long-term performance study of the field test sections to measure the effectiveness of the sealer treatments.

Acknowledgments

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Chapter 1 – Introduction

1.1 Background

Concrete joints deserve special attention to achieve their intended function without premature failure. The *Guide for Optimum Joint Performance of Concrete Pavements* (Taylor et al., 2012) lists five major mechanisms of joint deterioration: saturated frost damage, incremental cracking, mechanical damage, durability cracking, and early-age drying damage. Methods to reduce the risk of joint deterioration include providing an adequate air-void system within the concrete paste and reducing the permeability of concrete. Only recently has the discussion also come to include the potential application of penetrating sealers after saw cutting (Taylor et al., 2012).

In the last ten years, the Wisconsin Department of Transportation (WisDOT) as part of the high-performance concrete (HPC) pavement standard special provision, has specified the application of penetrating sealer to the saw cut faces in the joints. The HPC pavements on three projects (I-94 North-South Corridor, I-41 Corridor from Oshkosh to Green Bay, and I-39/90 Illinois state line to Madison) have received this joint treatment. The specification requires a silane or siloxane-based concrete penetrating sealer be applied as soon as possible after the sawing operation is complete.

To date, a variety of different products have been used, a number of different application methods have been employed, and the rates of application have been variable. In addition, the construction process and the construction inspection have not been uniform or consistent statewide. Therefore, there is no assurance that WisDOT is accomplishing the goal of distress-free joints and longer life of pavements. Finally, there has been no assessment by WisDOT on the cost-effectiveness of doing this work.

1.2 Objectives

The goals of this project were to (1) evaluate the concrete sealers used to date and the construction methods employed to determine if the achievement of sealing concrete pavement saw cut faces is accomplished with effectiveness and uniformity; (2) assess the work done to date to determine if WisDOT is achieving the goal of longer lasting concrete pavement joints; and (3) develop standard specification language for applying penetrating sealers to concrete pavement saw cuts along with construction inspection guidelines.

The specific objectives to attain the goals listed above were to:

1) Evaluate the penetrating sealers being used and make an assessment on their impacts to the durability of the concrete.
2) Assess the methods of construction and application in regard to the effectiveness of the seal and uniformity of application.
3) Perform field studies to compare pavements with sealed saw cut faces to pavements that were not sealed.
4) Recommend improvements in products and construction methods to assure the extension in the life of concrete pavement joints that is expected.
5) Revise current specifications for construction.

6) Recommend specifications for the future use of sealing sawed joints on WisDOT projects, so benefits and cost-effectiveness are improved.

1.3 Organization of Report

The report is written in six chapters. Chapter 1 is this introduction. Chapter 2 contains literature review about the mechanism and practice in using penetrating sealers to protect concrete infrastructure. Chapter 3 explains the coring, lab testing and lessons learned from past projects on I-94, I-41, and I-39. Chapter 4 describes the laboratory study on the impact from sealer types, application timing, and application rate on sealer performance. Chapter 5 describes the field study on I-39. Performance after one winter and one summer, as well as laboratory test of field cores are discussed. Finally, Chapter 6 summarizes this project and provides recommendations for WisDOT. Supplementary data are included in Appendices.

Chapter 2 – Literature Review

2.1 Optimum Joint Performance

The first section of literature review investigated methods and means to achieve optimum joint performance. Joints are a primary area of failure in concrete pavements with increased exposure to moisture and deicer salts. The *Guide for Optimum Joint Performance of Concrete Pavements* (Taylor et al., 2012) lists five major mechanisms of joint deterioration:

- Saturated frost damage: expansion of water in the saturated capillaries of the concrete as it freezes causes cracking. Cycles of freezing and thawing open these cracks allowing more water to penetrate, and as a result the concrete deteriorates incrementally. Concretes that are highly saturated are prone to accelerated damage.
- Incremental cracking: parallel cracks that form at approximately one-inch increments starting from the joint face. The concrete between the crack and the free face is normally sound. It is hypothesized that this distress is a result of the interfacial zone around coarse aggregate particles being exposed by the saw cut. Water preferentially penetrates the zone when the joint is flooded, and jacks the aggregate away from the paste when frozen.
- Mechanical damage: joint damage can occur from stresses caused by incompressible materials (sand, rocks, other debris) trapped in the joint. Raveling of a saw cut may also be caused by aggregate particles being dislodged during sawing, typically because the concrete strength is too low when sawing is conducted.
- Durability cracking: expansive freezing of water trapped inside some types of aggregate particles leads to damage that normally starts near joints and forms a characteristic D-shape crack pattern.
- Early-age drying damage: high evaporation rates during placement results in large differences in moisture content through the depth of the concrete slab. These differences may lead to stresses high enough to cause fine horizontal cracks and delamination. In areas where these horizontal cracks intersect vertical cracks or joints, concrete material can break free, and “flat bottom” or delamination spalling can occur.

2.2 Practice to Protect Concrete Joints

Recommendations to reduce the risk of joint deterioration include (Taylor et al., 2012):

- Provide an adequate air-void system within the concrete paste.
- Prevent moisture from remaining in contact with the joint face.
- Reduce permeability of the concrete as a preventive measure against the ingress of moisture.

It is generally accepted that 4-6% of small and well-distributed air voids provides sufficient durability. In addition, WisDOT’s position regarding not filling joints as a standard practice has avoided many of the problems, which have plagued other states where poor performing joint fillers actually prevent moisture loss and increase durability distresses. Historically permeability reduction relies on concrete mix design to slow the rate at which concrete becomes saturated. Typical approaches to achieve a lower permeability include low water-to-cementitious materials (w/cm) ratio, appropriate use of supplementary cementitious materials (SCM), well-graded aggregates, and adequate curing. Only recently has the discussion also come to include the potential application of penetrating sealers after saw cutting (Taylor et al., 2012).

In a pool-fund study led by South Dakota Department of Transportation (Sutter et al., 2008), two types of sealers were evaluated in terms of the effectiveness for preventing damage to concrete pavement due to deicing chemicals. The two sealers were a siloxane-based product (12% oligomeric organosiloxane solids in water) and a silane-based product (40% alkylalkoxysilane solids in 2-propanol). Laboratory tests showed that sealers were very effective at reducing the impact of deicing chemicals. In particular, concrete samples coated with the siloxane sealer did not allow the penetration of chloride ions. Therefore, the study recommended applying surface sealers (particularly the use of siloxanes or possibly silanes) at areas of heavy deicing applications to reduce ingress of chemicals.

Another study at Purdue University (Golias et al., 2012) compared the performance of soy methyl ester–polystyrene (SME-PS) with water-based silane and solvent-based silane. Previous research showed that SME-PS has the potential to be an effective and environmentally friendly topical treatment for concrete. The experiments showed that SME-PS reduced fluid ingress, salt ingress, and the potential for freeze–thaw damage. As a result of the positive experimental results, field trials were conducted by the Indiana Department of Transportation. The results (Wiese et al., 2015) from the field application showed that SME-PS worked well in reducing chloride ingress. The sections where the concrete joints were left exposed without any treatment showed substantially more chloride ingress than the section with sealers.

However, the effectiveness of penetrating sealers on improving the durability of joints has not been fully proved. A recent field study at the Minnesota Department of Transportation MnROAD facility on I-94 compared joints condition before and after the application of various silane- and siloxane-based sealers (Sutter & Anzalone, 2016). Based on both visual observation and scanning electron microscopy analysis of field cores, all chloride diffusivities were of the same order of magnitude, indicating no measurable difference. But the researchers pointed out that this was not a conclusive finding due to the short timeframe (only two years) and other reasons such as the high initial chlorine concentration of the 23-year-old pavements.

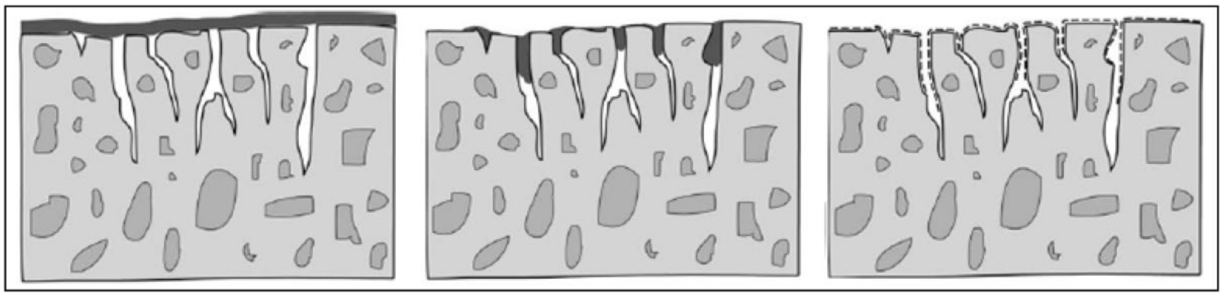
In the latest *Guide to the Prevention and Restoration of Early Joint Deterioration in Concrete Pavements* (Weiss et al., 2016) published by the National Concrete Pavement Technology Center, several challenges are noted:

- First, surface sealers are easy to apply on the horizontal pavement surface near the joint. However, getting the sealer to penetrate and adequately coat the vertical surfaces of a joint is more difficult. In most cases, it is necessary to saturate the concrete with the surface sealer to allow for penetration.
- Second, surface sealers have varying levels of success in reducing joint damage in concrete pavements. Some surface sealers (film-forming treatments) have been shown to be permeable to fluids during temperature changes, which would not have a very beneficial impact on calcium oxychloride formation.
- Thirdly, there are many types of surface sealers and many variables that affect performance. Further research is needed to provide guidance on application rates and timing.
- Fourth, surface sealers must be re-applied periodically. The reapplication cycle depends on the sealer, the exposure, and the wear; research is ongoing. For example, Moradllo et al.

(2016) found that, based on the performance of 60 bridge decks, no silane-based surface sealer failed before 12 years. By 18 years, however, close to 50 percent of the sealers had failed.

2.3 Mechanism of Penetrating Sealers

NCHRP Synthesis 209 (Cady, 1994) classifies concrete sealers to three types: water repellent, pore blocker, and barrier coat.



(a) Barrier Coating **(b) Pore Blocker** **(c) Water Repellent**

Figure 2.1 Sealer Types (Medeiros & Helene, 2008)

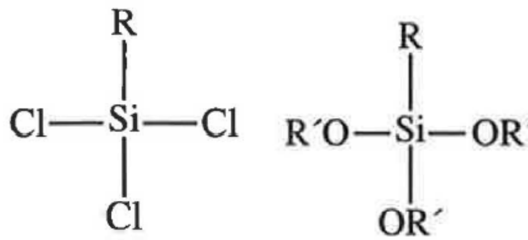
“Water repellent” refers to those materials that penetrate concrete pores to some degree and coat pore walls rendering them hydrophobic. The condition of hydrophobicity is defined by a contact angle between water and the concrete surface that is between 90 and 180 (i.e., water beads up). Under this condition, liquid water and any ions that it contains (e.g., chloride and sulfate) cannot penetrate concrete pores, but gases and vapors can. This mechanism promotes drying of the concrete over time. It can do this by first preventing the entrance of liquid water into treated pores because of the large contact angles for water menisci on the treated surfaced. Second, any water in the pores beyond the treated zone will evaporate as the vapor pressure of the moisture in the atmosphere (relative humidity) falls below the relative vapor pressures needed to maintain the liquid menisci in the pores. This mechanism has been proved by experimental evidence (Cady, 1994).

“Pore blockers” are sealers of sufficiently low viscosity to allow them to penetrate the pores in concrete, sealing them while leaving little or no measurable coating on the exterior surface of the concrete.

“Barrier coatings”, on the other hand, are too viscous to penetrate pores to measurable depths, but form surface coatings of significant thickness and block the pores.

Silane and siloxane are by far the most used “water repellent” sealer (penetrating sealer). They consist of molecules that bond to hydrated cement paste substrate and to each other by means of the silicon functional groups, and provide a hydrophobic (water-repellent) layer on pore walls from the exposed organofunctional groups. Silane and siloxane fall under the general chemical classification of organosilicon compounds. Both are produced from the same raw material – chlorosilane. Some differences between the two are

- Silane has smaller molecule size hence can penetrate deeper than siloxane does.
- Siloxane is practically non-volatile and therefore requires much lower concentrations to achieve complete pore coating. Therefore, silane products usually have a higher concentration (typically 40 percent) than siloxane products (typically 10 or 15 percent).



R is the organofunctional group; OR' is the silicon functional group

Figure 2.2 (a) chlorosilane (b) silane and siloxane

2.4 Lessons Learned from Bridge Deck Sealers

Considering the importance of concrete bridge deck and the damage due to moisture and chloride salts ingress to concrete, sealing bridge decks through various approaches has been a common practice for years. These approaches include the use of waterproofing membranes, rigid cementitious overlays, polymer overlays, and various coatings and sealants (Whiting, 1990). For example, Alberta, Canada generally seals bridges on a 4-year cycle (Filice & Wong, 2008). In the 1960's boiled linseed oils mixed with 50% kerosene were used to seal decks and curbs which offered minimal protection to the concrete. 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.

Penetrating sealers are products that are absorbed into the surface of concrete and react with concrete to form a hydrophobic (or water repelling) surface (Filice & Wong, 2008). Different from surface coating, no film is formed with the use of penetrating sealers; therefore, pores in the concrete are not blocked. The most important property the sealer must have is that it must protect the concrete and at the same time it must be breathable. Products commonly marketed as penetrating sealers include silicates, siliconates, silanes, and siloxanes (Johnson et al., 2009). Silanes and siloxanes can be either solvent or water-based, and the concentration (i.e., percent solids) of silane and siloxane by weight can vary. Solvent-based implies the silane or siloxane is carried in either alcohol, mineral spirits, or petroleum-based solvents. Water-based implies the silane or siloxane is carried in water. A 100% silane formulation exists and contains neither solvent nor water as the carrier because silane is liquid at ambient temperatures.

According to a recent survey (Johnson et al., 2009), silane is the most common deck sealant because silane is made up of smaller particles which tend to penetrate deeper into the concrete deck than does siloxane. In addition, solvent-based silanes are more common than water-based silanes. This is due to the notion that a solvent-based silane achieves a greater depth of penetration than the water-based counterpart does. Of the states that use deck sealants, the majority seal decks immediately after construction. This is typically done because the chloride content in a new deck is very low. By immediately sealing the deck the states hope to repel additional chlorides and keep the chloride content low. Sealants should be applied between the temperatures of 40 and 100 °F. Also, a drying period of at least two days should be allowed if there has been recent rainfall or if water was used to clean the deck. Approximately half of the states surveyed that apply deck sealants (not including states that have no deck sealing program) also reapply the sealant. A three to five year schedule for reapplication of penetrating sealants is ideal, but the reapplication schedule is estimated realistically to occur every five to six years due to shortages in funding and maintenance staff.

The primary performance measures of concrete sealers are chloride ingress, absorption, depth of penetration, and vapor transmission (Johnson, Schultz, French, & Reneson, 2009). The most widely used laboratory test procedures are AASHTO T259/T260 which measures chloride ingress and the NCHRP 244 Series II test procedure which measures salt-water absorption, vapor transmission, and chloride ingress through sealed concrete. Other possible tests include ASTM C672 (scaling resistance to deicing chemicals), AASHTO T277 (electrical induction of concrete's ability to resist chloride ion penetration), ASTM C642 (density, absorption, and voids), and AASHTO T259 modified (crack sealer test). For field QC/QA purpose, depth of penetration and chloride content tests are the only tests conducted (if any).

WisDOT sponsored a research project in 2003 (Pincheira & Dorhorst, 2005) to assess the effectiveness and relative performance of commercially available concrete bridge deck and crack sealants. A total of thirteen deck sealants were selected for study under laboratory conditions that simulated the exposure to deicing salts and freeze-thaw cycles encountered in practice. The first test was to measure the resistance to chloride ion intrusion in concrete specimens ponded with a sodium chloride solution, in accordance with the provisions of AASHTO T 259. In the second test, separate specimens were cast to measure the depth of penetration profile of the sealants using a dye method. Based on test results, two products (Sonneborn Penetrating Sealer 40 VOC and Hydrozo Silane 40 VOC) surpassed the rest and thus they were assigned to Performance Category I. They exhibited the best performance, had the largest depths of penetration and met the current WisDOT acceptance criteria. Six other sealants offered moderate protection and were assigned to Performance Category II. These sealants had shallower penetration depths, their performance severely declined when exposed to freeze-thaw cycles, and they did not meet the current WisDOT acceptance criteria. The remaining five sealants offered the least protection and were assigned to Performance Category III.

The current (2019) *WisDOT Standard Specification* describes about penetrating sealers for concrete bridge in Section 502.2.11 and 502.3.13.2, as shown in Figure 2.3. However, it is worth pointing out the difference between applying penetrating sealers to bridges and to saw cut faces: bridge surface is a horizontal open space while saw cut faces are vertical narrow openings. This difference creates unique challenge during quality control and quality assurance process.

502.2.11 Crack and Surface Sealers

(1) Furnish crack and surface sealers from the department's approved products list as follows:

- Crack sealer: Low Viscosity Crack Sealers for Bridge Decks list.
- Protective surface treatment: Concrete Protective Surface Treatment list.
- Pigmented surface sealer: Cure and Seal Compound for Non-trafficked Surfaces for Structural Masonry list.

502.3.13.2 Protective Surface Treatment

(1) Apply protective surface treatment conforming to 502.2.11 to concrete decks, deck overlays, medians, and sidewalks After deck crack sealing is completed, apply surface treatment to the top of new bridge decks. Do not apply to surfaces where the contract requires staining or other treatment.

(2) Clean and dry surfaces before applying surface treatment. Immediately before application, direct an air blast over the surface to remove dust and any loose particles. Ensure that application equipment is clean inside before filling and that the equipment is functioning properly.

(3) Apply surface treatment no less than 7 days, but preferably a minimum of 21 days, after the curing period has expired. Apply according to manufacturer recommendations, except ensure the concrete is surface dry for a minimum of 2 consecutive days before applying. Ensure that the crack sealer is dry to the touch before applying surface treatment. Apply at the manufacturer's recommended rate. If application in a single coat causes ponding, use two lighter coats allowed to dry between coats.

(4) Complete surface treatment before opening to traffic and before suspending work for the winter. Do not open the bridge deck to traffic until the surface treatment is dry enough to sustain traffic without causing damage to the surface treatment or creating a hazard to traffic.

Figure 2.3 WisDOT Specifications Related to Penetrating Sealers for Concrete Bridges (WisDOT, 2017)

2.5 Summary

The current practice in protecting concrete joints is mainly by providing adequate air-void system and reducing the permeability of concrete. Only recently has the discussion come to apply penetrating sealers after saw cutting.

A few studies have tried silane, siloxane, and SME-PS and found that concrete coated with sealers reduced chloride ingress. However, there is no conclusive study on the service life and cost-effectiveness.

The unique property of penetrating sealer is that it coats concrete pore walls rendering them hydrophobic, hence liquid water and any ions that it contains (e.g., chloride and sulfate) cannot penetrate concrete pores, but gases and vapors can.

Penetrating sealer, as a type of sealers, has been successfully used in protecting bridge decks for decades. Many states also reapply sealers every five to six years. The primary performance measures are chloride ingress, absorption, depth of penetration, and vapor transmission.

Chapter 3 – Lessons Learned from I-94, I-41, and I-39

3.1 Introduction

In the last couple of years, the Wisconsin Department of Transportation as part of the high-performance concrete (HPC) pavement standard special provision has specified the use of a penetrating sealer be applied to the saw cut faces in the joints. The HPC pavements on three projects (I-94 North-South Corridor, I-41 Corridor from Oshkosh to Green Bay, and I-39 Illinois state line to Madison) have received this joint treatment. The specification requires a silane or siloxane-based concrete penetrating sealer be applied as soon as possible after the sawing operation is complete.

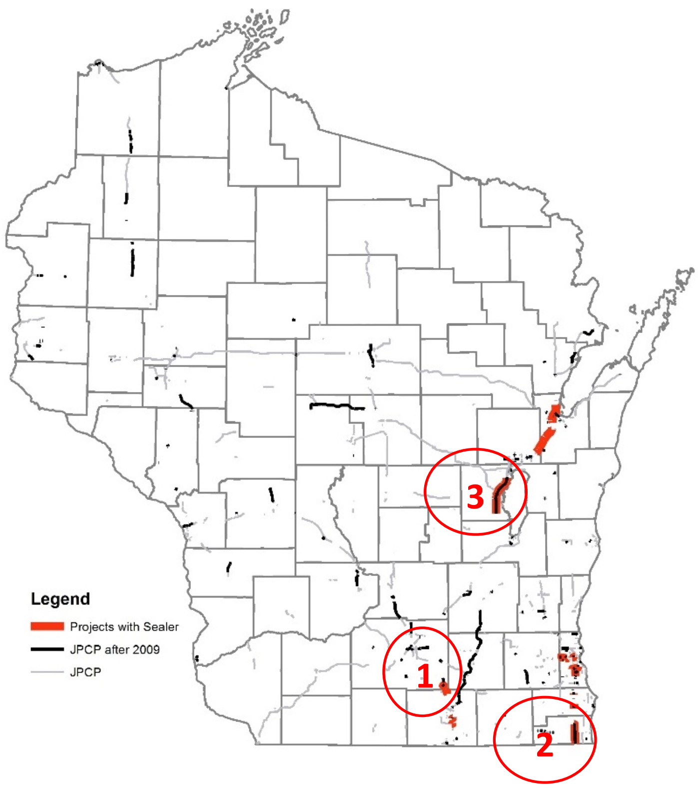


Figure 3.1 Location of Projects where Penetrating Sealers were Applied

The effectiveness of this practice in the field has not been investigated. Therefore, the objective of this chapter is to evaluate the three projects and determine whether penetrating sealer is functioning after several years of service.

3.2 Methodology

The research team first reviewed design file, construction records, and historical pavement performance data of candidate projects. The purpose was to verify that penetrating sealer was indeed applied. Then the latest pavement images in the Pavement Management System (PMS) were reviewed to identify sections with joints in both good and poor condition. The purpose was to take core samples to understand why some joints are performing good and some are not. With all information considered as well as the safety of coring crew, three locations were identified (Figure 3.1). Details of the three projects are listed in Table 3.1.

Table 3.1 Detailed of the Three Projects

Project Attribute	Project Denotation in Figure 3-1		
	1	2	3
Highway	I-39	I-94	I-41
Direction	Southbound	Northbound	Northbound
Station	STA 18+10 ~ 18+30	STA 50+00 ~ 70+00	STA 750+00 ~770+00
Location	Stoughton, before Exit 156	Kenosha, between ML and 104th St	Oshkosh, between CTH Y and STH 76
Project ID	1007-10-79	1031-07-79	1120-09-71
Construction Date	08/24/2016	07/16/2010	06/07/2012
Coring Date	8/13/2018	8/20/2018	8/22/2018
Concrete Type	A-FA	A-FA	A-FA
Cement Content (pcy)	416	394	395
Fly Ash Content (pcy)	179	169	170
Total Aggregate (pcy)	311	3298	3234
Slump (inch)	0	0	0
Air Content	5.4%	6.3%	6.0%
28-day Compressive Strength (psi)	7425.4 7795.6	6650.4 7108.8 7510.4	5558.0 5524.3
Penetrating Sealer	TK-590-1-MS	TK-590-1-MS	N/A

Core samples were then taken at three locations from each project: 2 cores from good performing joints, 2 cores from spalled joints, and 1 core from mid-slab as the control since penetrating sealer was only applied to joints. Figure 3.2 shows the field operation and example of core samples. All cores were taken from the main traffic lane where most trucks use except core #4,5,6 from the ramp of Exit 156 on I-39. A total of 17 cores were collected (Table 3.2).

Figure 3.2 (a) Taking field cores (b) A core sample of good joint (c) A core sample of spalled joint

Table 3.2 Detail of Field Cores

Core No.	Highway	Construction Year	Joint No.	Diameter (in)	Silane Treatment (Y/N)
01	I-39	2016	42	6	Y
02	I-39	2016	Mid-slab	6	N
03	I-39	2016	38	6	Y
04	I-39	2016	74	6	N*
05	I-39	2016	Mid-slab	6	N*
06	I-39	2016	71	6	N*
07	I-94	2010	24	4	Y
08	I-94	2010	25	4	Y
09	I-94	2010	Mid-slab	4	N
10	I-94	2010	41	4	Y
11	I-94	2010	42	4	Y
12	I-94	2010	52	4	Y
13	I-41	2012	3	4	Y
14	I-41	2012	4	4	Y
15	I-41	2012	Mid-slab	4	N
16	I-41	2012	34	4	Y
17	I-41	2012	35	4	Y

Note: *These three cores were taken from the ramp of Exit 156.

Core samples were then subjected to a series of laboratory tests. Contact angle was measured on the joint surface of each sample. Two measurements were made for each sample, one on each side of the water droplet, and then averaged. Contact angle is a quantitative measure of the wetting of a solid by a liquid. It is defined as the angle formed between the liquid/solid and liquid/vapor interfaces. Therefore, a small contact angle means the surface is hydrophilic (water loving), and a large contact angle indicates the surface is hydrophobic (resistant to water). Figure 3.3 shows examples of different contact angle measured in this project. Since penetrating sealer is designed to help with moisture resistance, a larger contact angle is expected for core samples with sealers applied.

Figure 3.3 (a) Definition of contact angle (b) Contact angle=32.5° for core #135 (c) Contact angle =112.5° for core #15

Absorption testing was performed according to ASTM C1585-13 (ASTM, 2013). After cutting the cores, the perimeter perpendicular to the treated surface was wrapped in aluminum tape. The aluminum tape serves as a barrier to ensure absorption is occurring in one dimension only. Before beginning absorption, the untreated side of the sample was covered in plastic secured with rubber bands. Initial dry weight was measured for each sample, then submerged in approximately 2 mm of water. At specified intervals, each sample was removed, wiped off with a towel, and measured for weight (Figure 3.4). Measurements were taken after 1, 5, 10, 20, 30, and 60 minutes. Subsequent measurements were taken every hour until six hours, and then once every day for 14 days.

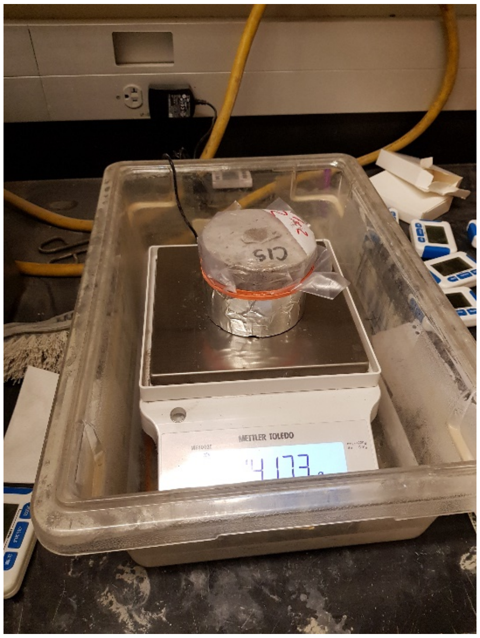
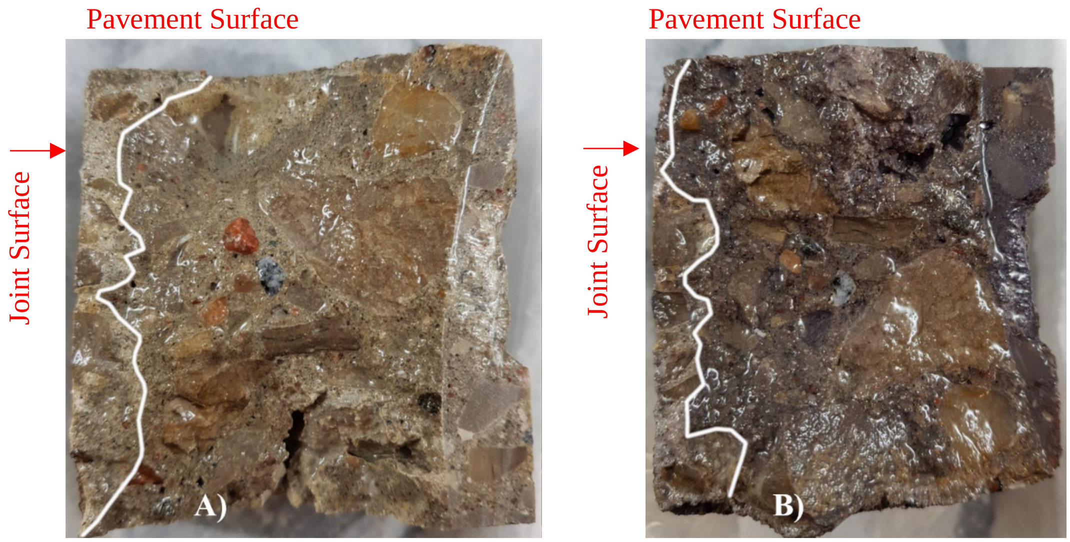


Figure 3.4 Lab setup for absorption test of core samples

After absorption testing was completed on all field samples, one half of each treated core was split using a chisel and tested for depth of penetration. Note the silane was applied to the joint surface and would have penetrated perpendicular to the joint surface.



(a) dipped in water (b) dipped in powder rit dye

Figure 3.5 Lab setup for depth of penetration test

3.3 Results Analysis

Detailed lab test results are listed in Appendix A. The following section discusses the three practical questions: (1) is sealer detected in the field? (2) is the sealer functioning (reducing the ingress of water and chemicals)? and (3) what is the impact of age on sealer effectiveness?

<u>3.3.1 With Sealer vs. No Sealer</u>

During the field visit and coring process, the presence of sealer was visually judged with no success; penetrating sealer does not change the color of concrete, neither does it form any visible surface coating. But lab tests definitely proved the presence and its functionality. As shown in Figure 3.6(a), although with variation, overall, most joints with sealer applied showed a larger contact angle than joints without sealer, with an average of 51.5° and 37.5°, respectively. A larger contact angle means the concrete surface with sealer is more water repellent. Analysis of Variance (ANOVA) proves that sealer is a statistically significant factor at 90% confidence level (*p*-value = 0.09). Details of statistical analysis are presented in Appendix A.

Figure 3.6(b) shows a clearer difference between samples with sealer and without sealer. At the end of 14-day test, the average absorption for samples with sealer is 1.35 mm and the average for samples with no sealer is 1.80, 34% more. This is confirmed with ANOVA analysis (*p*-value = 0.03). Penetrating sealer is designed to slow down the absorption of water and chemicals to concrete. Therefore, the absorption data proved that the sealer in the field is still functioning as intended.

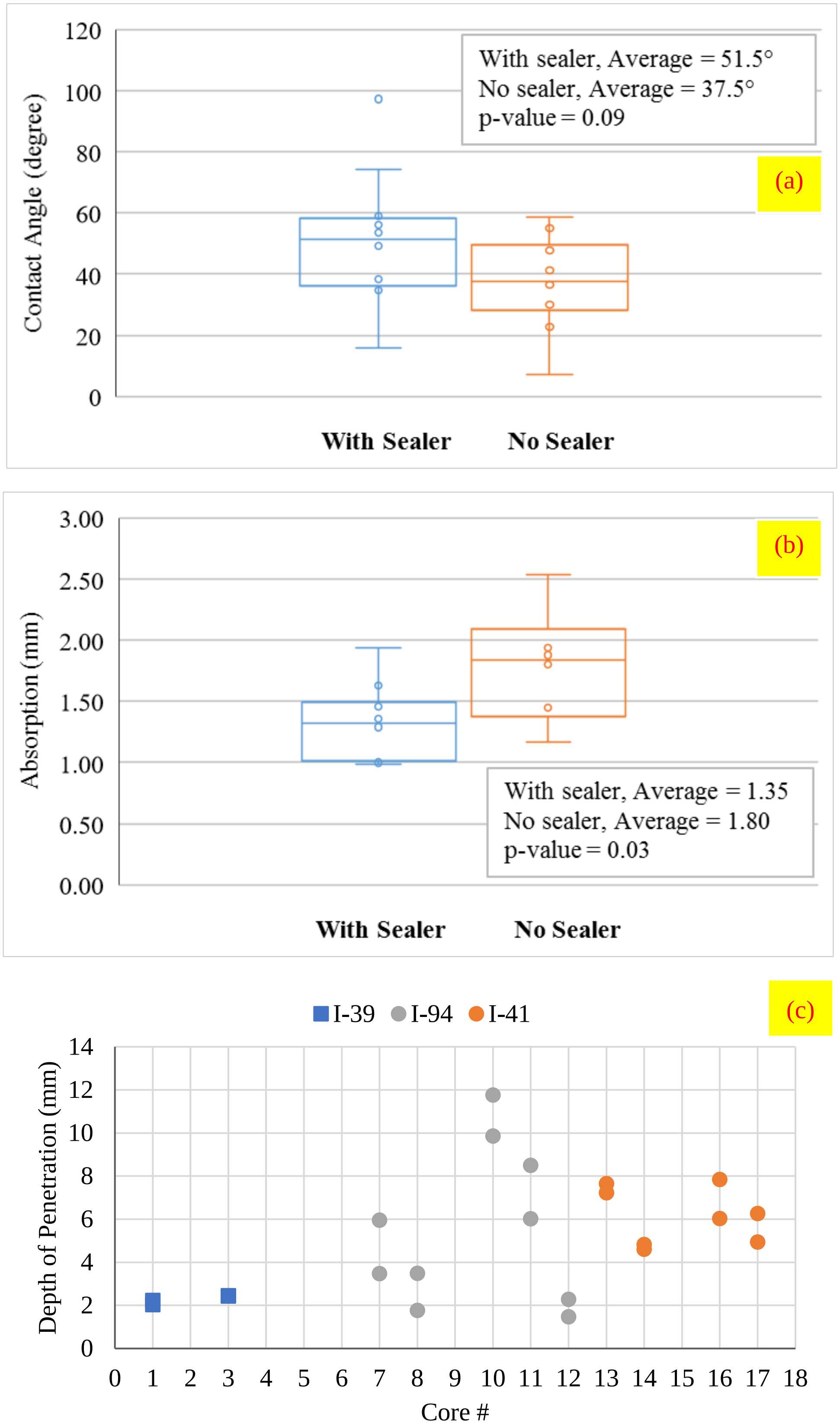


Figure 3.6 Presence of Sealer (a) Contact Angle, (b) Absorption, (c) Depth of Penetration

Figure 3.6(c) shows the depth of penetration. Only core samples from joint were tested. The penetration depth ranges from 1.46 mm (0.06 inch) to 11.75 mm (0.46 inch), with an average of 5.14 mm (0.20 inch). I-39 has the lowest penetration depth; I-94 has a large variation; and I-41 presents a consistent depth around 6 mm. This range agrees with the literature, 2.5 to 6.4 mm (0.10 to 0.25 inch) for silanes (Cady, 1994). The low penetration on I-39 is worth some discussion. First, a certain penetration depth is necessary for the service life to withstand traffic abrasion, weathering and ultra-violet degradation. Cady (1994) recommends a desirable depth of 6 mm (0.25 inch) with a minimum of about 3 mm (0.125 inch). If this is the case, I-39 would have concern of longevity. However, one should not pursue depth of penetration blindly. How deep a sealer can penetrate greatly depends on not only the molecular size, type and quantity of solvent, but also the permeability and moisture content of concrete, and surface preparation (Cady, 1994). Therefore, penetration depth may be greater with poor quality concrete, while a 6 mm (0.25 inch) depth may not be possible with high-quality concrete. Referring to the 28-day compressive strength in Table 3.1, I-41 has the lowest strength (~5500 psi) so it is easier to reach a consistent 6 mm penetration depth, while I-39 has the highest strength (~7600 psi) so it has the thinnest penetration.

Overall, it is proved by lab tests that sealers are found in field cores and are performing their intended function in reducing water absorption.

3.3.2 Service Life

Past studies have showed that the effectiveness of penetrating sealer decreases due to abrasion, weathering, and UV degradation. The service life of silane and siloxane is 5~7 years in general and 4~8 years for bridge decks (Cady, 1994). A study in Oklahoma reported that 100% of the silane applications were still effective after 12 years of service (Ley & Moradllo, 2015). Different from bridge decks, sealers applied to pavement joints are not impacted by tire abrasion and less UV degradation, but have to withstand significant amount of chemicals retained in the joint. There is only one study about the service life of penetrating sealer for concrete joints at the MnROAD facility (Sutter & Anzalone, 2016). In that study, field cores were retrieved after two years of service. The chloride profiles before and after application of sealer were then compared. No appreciable differences were noted. It was believed that two-year was a short time span allowed for ingress and a longer study time is needed to show any difference.

Test results in this study along service life are presented in Figure 3.7. A general trend is observed that, as service life increases, contact angle reduces and absorption increases. In other words, as time passes by, penetrating sealer slowly loses its effectiveness in resisting water ingress. However, when compared with the samples without sealer, more than half of the joints with sealer are still performing better in terms of contact angle and absorption after 8.2 years of service.

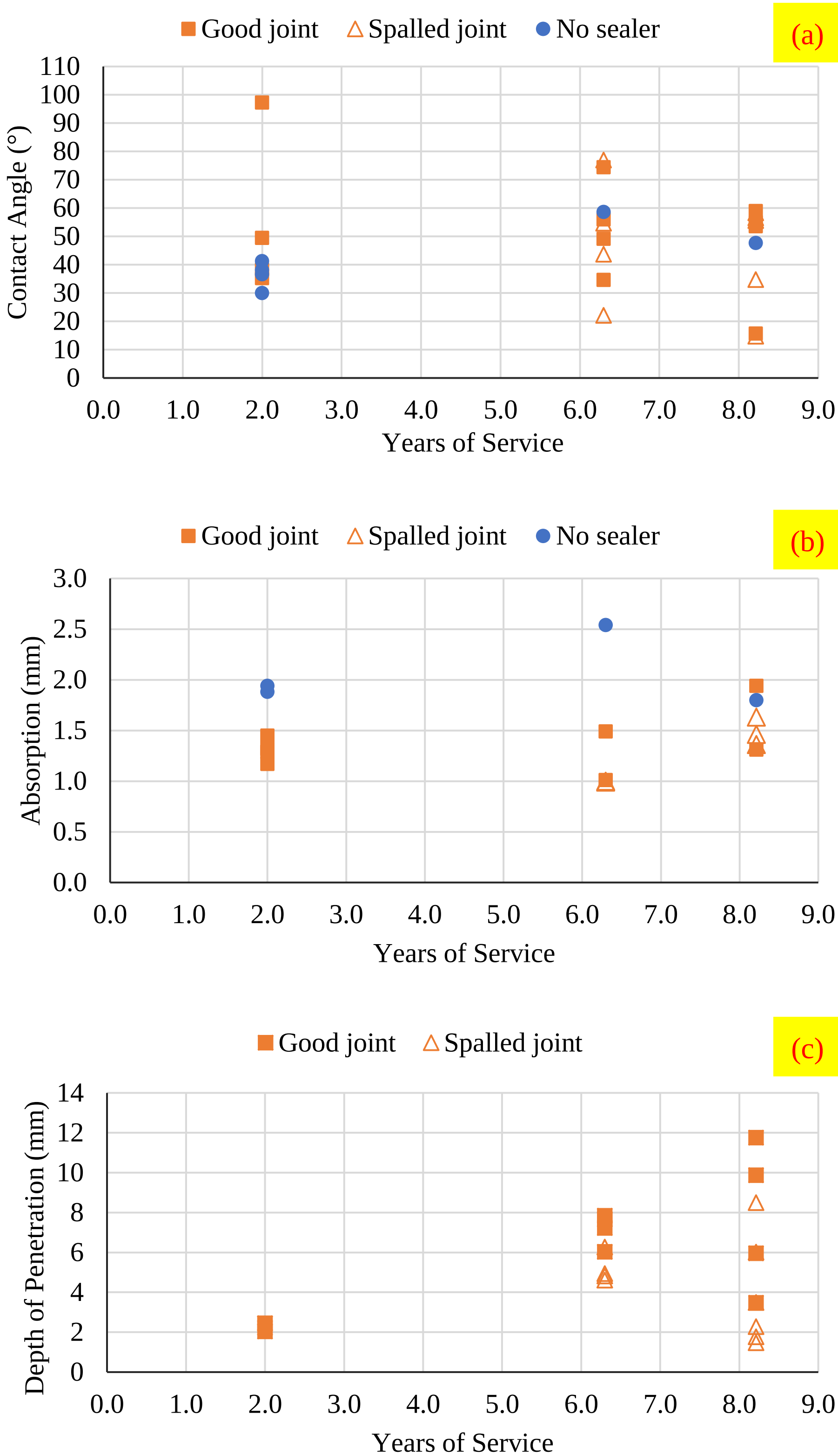


Figure 3.7 Service Life (a) Contact Angle, (b) Absorption, (c) Depth of Penetration

3.3.3 Good Joints vs. Spalled Joints

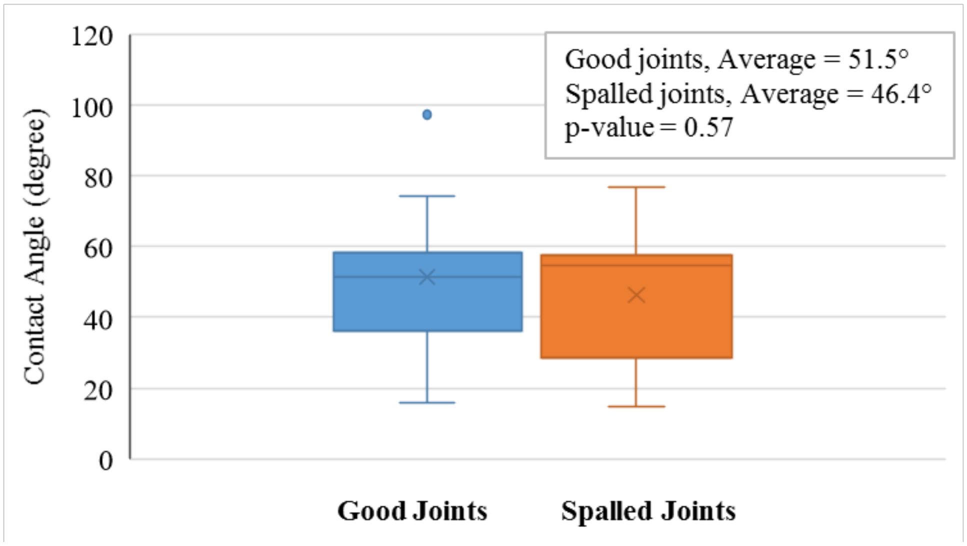
Penetrating sealer is designed to protect concrete from the impact of water and chemicals. But can sealer guarantee the good performance of joints in the field? In other words, it was curious to know why some joints spalled and some joints performed well on the same project where penetrating sealer was applied to all transverse joints. Figure 3.8 shows the contact angle, absorption, and penetration depth between good joints and spalled joints.

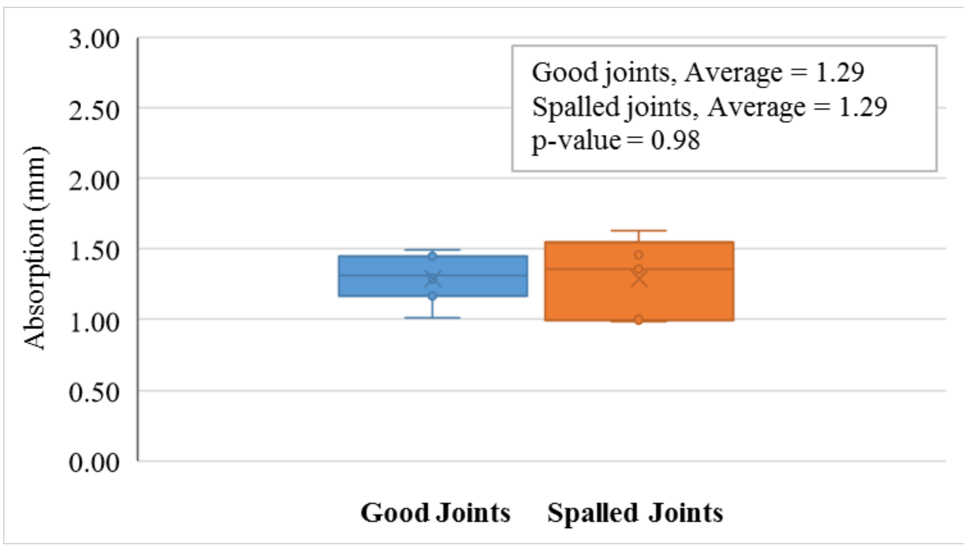
In terms of contact angle, there is no clear cut indicating a larger contact angle for good joints or a smaller contact angle for spalled joints. Statistical analysis resulted in a p-value of 0.57, confirming there is no statistical difference in contact angle between good joints and spalled joints. It should be pointed out the average contact angle of spalled joints with sealers 46.4° is still larger than the average of joints without sealer 37.5°. Penetrating sealer is helping the joint surface repel water even when spalling occurred.

Regarding absorption, there is barely any difference between good joints and spalled joints (the same average). There is no distinctive difference between good joints and spalled joints in terms of penetration depth neither.

Therefore, it can be concluded that penetrating sealer was not a factor distinguishing good joints from spalled joints. In other words, there are other factors that led to the spalling of these joints such as improper saw cut (Crovetti & Kevern, 2018).

One such joint was identified and historical pavement images were retrieved from pavement management system. Core #14 is from a spalled joint on I-41. The nearby joint is in good condition. Several other similar joint spalling led to the suspicion that saw cutting could be the cause. As shown in Figure 3.9, the right side spalling started to occur in 2016 (the 4th year), and the left side spalling did not occur until 2018 (the 6th year). The spall is about one inch from the joint, which agrees with the phenomenon of incremental cracking (Taylor et al., 2012). The concrete between the crack and the free face is normally sound, as is the remaining concrete next to the crack. It is hypothesized that this distress is a result of the interfacial zone around coarse aggregate particles being exposed by the saw cut.





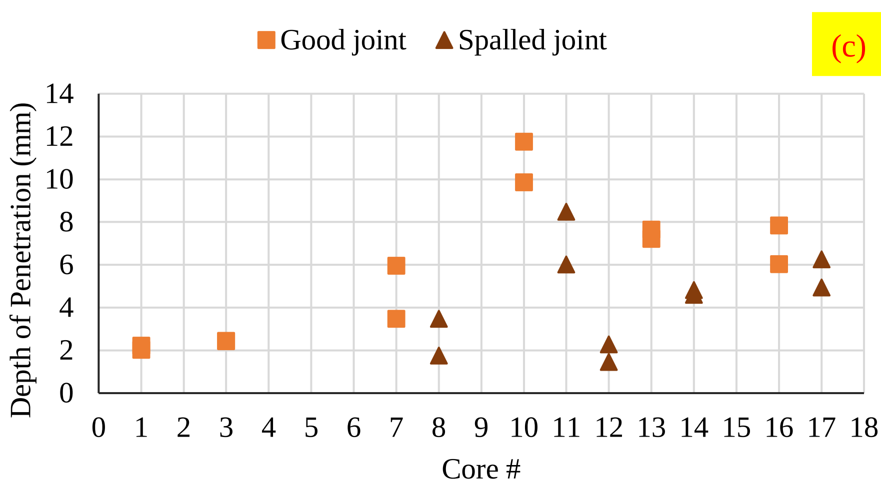
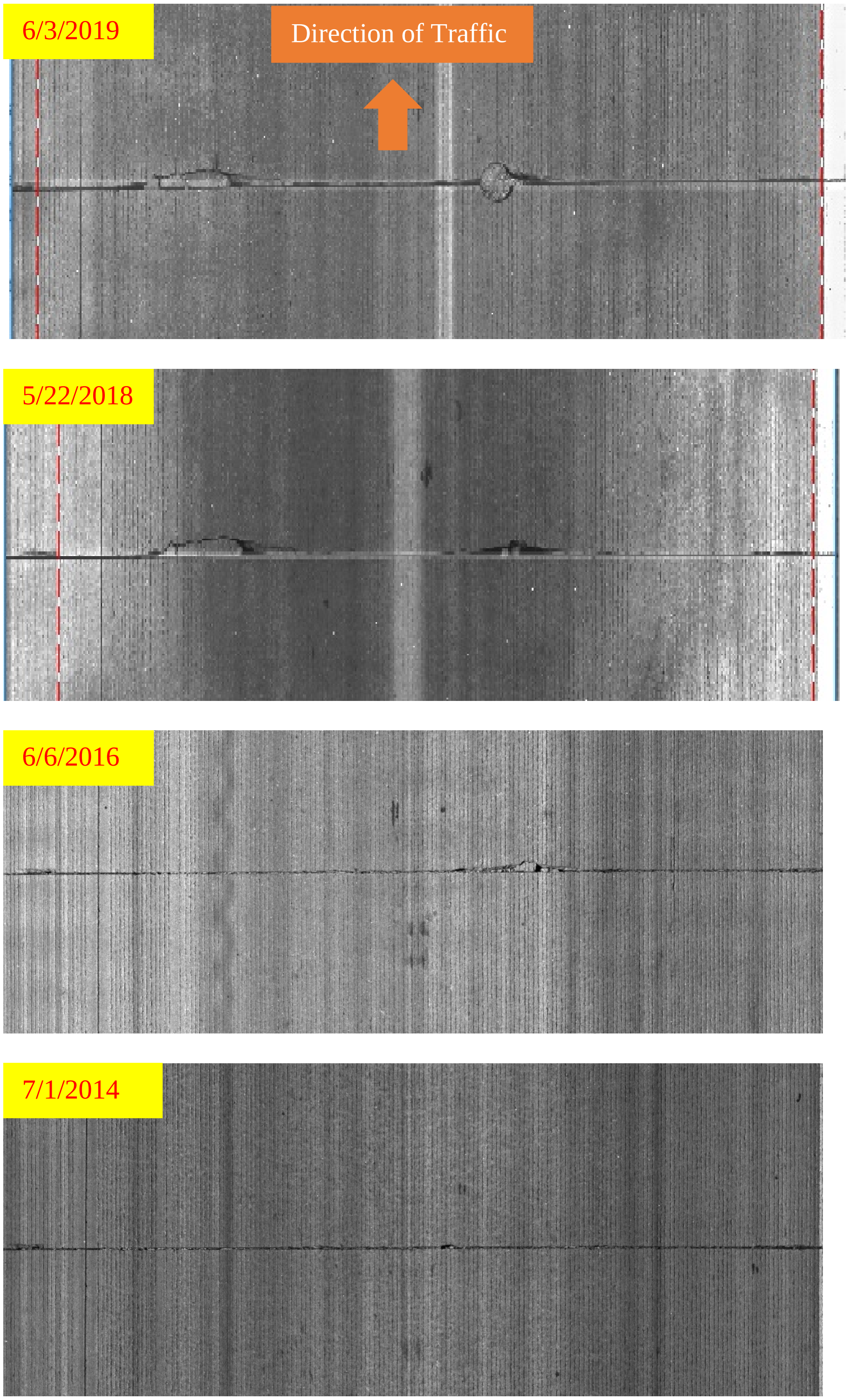


Figure 3.8 Good vs. Spalled Joints (a) Contact Angle, (b) Absorption, (c) Depth of Penetration



6/7/2012 Construction Date (pavement picture not available)

Figure 3.9 An Example of the Progression of Joint Spalling on I-41 (core #14 was taken here)

Figure 3.10 Picture Taken from Shoulder of Core #14 Joint on I-41

3.4 Summary

Site visit and core samples were taken from three projects where penetrating sealer was applied. Contact angle, absorption, and penetration depth were measured in the lab. Results show the following:

1) The presence of sealer in in-service pavements was proved. Joints with sealer applied are more hydrophobic and absorb less water.
2) The depth of penetration ranges from 1.46 mm (0.06 inch) to 11.75 mm (0.46 inch), with an average of 5.14 mm (0.20 inch). Penetration depth seems to depend on the concrete strength; less penetration on high-performance concrete.
3) A general trend of decreasing effectiveness is observed. However, when compared with the samples without sealer, more than half of the joints with sealer are still performing better in terms of contact angle and absorption after 8.2 years of service.
4) No difference was found between good joints and spalled joints in terms of contact angle, absorption, and penetration depth. This means the observed spalling is due to other factors other than penetrating sealer. In addition, historical pictures indicate that saw cut could be the reason of observed spalling on I-41.

Chapter 4 – Laboratory Study

4.1 Introduction

The laboratory study assessed the performance of various penetrating sealers on common Wisconsin concrete, as well as different application methods and application rates. Although the current (6/10/14) approved products list for concrete protective surface treatments only includes silane sealers at 40% solids content, other WHRP research (Pincheira & Dorhorst, 2005) suggests that siloxanes may have adequate performance for the intended application. Additionally, three other classes of topical products were initially investigated to capture new technologies which may also provide benefit and function as a penetrating sealer. The additional classes included in the initial testing were a Soy Methyl Ester Polystyrene (SME-PS), a crystalline waterproofing agent, and a lithium silicate densifier. While penetrating topical materials with the potential to reduce water and ion movement through concrete, no products other than silane are currently approved for WisDOT applications. Although the RFP and proposed research program was not intended as product evaluation, an evaluation protocol (Phase I) was included to allow preliminary evaluation of future products. For this research, the gold standard was a 40% solvent-based silane applied at 7 days to a clean and dry, sawn face at 200 sf/gallon.

4.2 Experimental Design

A partial factorial design was used to address all factors within a practical number of tests. Phase I compared one-dimensional absorption and sealer penetration on mortar samples. The purpose of Phase I was to provide a preliminary evaluation tool for comparing potential future products against the current best practices. For Phase I a generic mortar was used with a sand to cement ratio of 2.5:1 and water-to-cement ratio of 0.40, both by mass. The river sand used met ASTM C33 concrete gradation and had a specific gravity of 2.62 and absorption of 0.4%, determined according to ASTM C128. All mortar samples were mixed according to ASTM C305 and placed in 4 in. by 8 in. plastic cylinder molds. Specimens were stripped after 24 hours and sawn into 4 in. by 2 in. specimens using a water-cooled concrete sawn. Samples were then allowed to dry until day 7 in an environmental chamber at 73°F and 50% relative humidity. At 7 days, sealers were applied to the horizontal surface at an application rate of 200 sf/gallon. Samples were then placed back into the environmental chamber for an additional 7 days for the sealers to dry, cure, or react. ASTM C1585 absorption testing was then started on day 14. A minimum reduction of 50% of the total water absorbed in the ASTM C1585 test on the untreated control samples was a prerequisite for any product or combination to move into the complete concrete testing protocol. The following five products were investigated with both silane products on the current approved products list.

- Silane-40%, solvent-based (SB) (VEXCON-PowerSeal 40)
- Silane-40%, water-based (WB) (ChemMasters-Aquanil Plus 40)
- Soy-Methyl-Ester-Polystyrene (SME-PS) (Environmental Concrete Products-Fluid iSoylator)
- Lithium silicate-3.2 molar (Prosoco-raw lithium silicate ingredient)
- Crystalline water proofer (International Chem-Crete-Pavix CCC100)

The baseline treatment for the Phase I comparison was full coverage using single application timing. Additionally, a sensitivity analysis was performed with respected to application rate and application timing for a total of the following nine (9) different combinations for each product as shown below.

- Full Coverage – 200 sf/gal
- Half Coverage – 400 sf/gal
- Double Coverage – 100 sf/gal
- Single Application Timing – Saw at 24 hrs, dry at 50% RH and 73°F until 7 days, apply sealer, dry until 14 days, begin testing
- Double Application Timing - Saw at 24 hrs, dry at 50% RH and 73°F until 7 days, apply sealer, dry until 14 days, apply sealer, dry 24 hrs, begin testing
- Rapid Application Timing – Saw at 24 hrs, allow to drain 30 minutes, apply sealer, dry until day 2, begin testing

Phase II evaluated concrete mixture performance using the breadth of tests presented in Table 4.1. The concrete mixtures included WisDOT "A" and "A-FA" designs with optimized aggregate gradation (tarantula curve) using WisDOT approved limestone coarse aggregate. Lab mixtures were produced following AASHTO (R60, T23, M201) and ASTM procedures. A Class C fly ash from Portage generating stations was utilized. The standard compliment of conventional fresh and hardened tests were performed to characterize the quality of the concrete mixture as shown in Table 4.1. All concrete mixtures were placed and cured with an approved poly-alpha-methylstyrene (PAMs) curing compound. Joints were sawn using optimal timing for conventional sawing equipment and limestone coarse aggregate.

All Phase II sealer combinations were applied to the sawn joint face at 7 days and in the dry condition. Two additional combinations were included with sealer applied in the damp condition, 30 minutes after sawing. One included a damp application of silane and a second where the PAM curing compound was reapplied to the joint after sawing. The following were the products and treatments used in both Phase II concrete mixtures.

1) Untreated control
2) Silane-40%, water-based (ChemMasters-Aquanil Plus 40) applied after 7 days
3) Silane-40%, water-based (ChemMasters-Aquanil Plus 40) applied 30 minutes after sawing
4) Siloxane/Silane mixture-1%-5% each, water based (Prosoco-Saltguard WB) applied after 7 days
5) Siloxane/Silane mixture-3%-7% each, water based (Prosoco-Siloxane PD) applied after 7 days
6) Lithium silicate/potassium methyl siliconate mixture- (Prosoco-Consolideck LS) applied 30 minutes after sawing
7) Poly-Alpha-Methylstyrene (PAMs) – (Spec Chem-Pave Cure AMS) applied 30 minutes after sawing

8) Soy-Methyl-Ester-Polystyrene (SME-PS) – (Environmental Concrete Products-Fluid iSoylator) applied after 7 days

Table 4.1 List of Conducted Laboratory Tests

Tests	Specification	Notes/Purpose of Test
Air Content of Freshly Mixed Concrete by the Pressure Method	AASHTO T152	Fresh concrete
Slump of Hydraulic Cement Concrete	AASHTO T119	Fresh concrete
Concrete Compressive Strength	AASHTO T22	Cast 6 - 4"x8" cylinders per mix design. Test two specimens each at ages 3, 7 and 28 days
Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration	AASHTO T277	Non-destructive indication of ion mobility
Determining Air Content in Hardened Concrete	ASTM C457	Air voids distribution
Practice for Petrographic Examination of Hardened Concrete	ASTM C856	Competency of baseline concrete
Resistance of Concrete to Chloride Ion Penetration	AASHTO T259/260	Chloride ingress
Determining Chloride Ions in Concrete and Concrete Materials by Specific Ion Probe	AASHTO T332	Chloride ingress
Depth of Sealer Penetration	OHD L-40	Split cylinder staining using Sulfonazo III
Rate of Absorption of Water	ASTM C1585	Absorption
Deicer Scaling	ASTM C672	Deicer scaling performed in a surrounded solution to allow penetration through the saw-cut face

4.3 Results Analysis

4.3.1 Phase I – Initial Evaluation (Mortar)

One-dimensional capillary absorption according to ASTM C1585 reports absorption in terms of "I" in mm of water which is determined using the mass of water absorbed at any given time normalized by the sample geometry and density of water. The reported "I" assumes absorption is uniform throughout the paste, but since aggregate absorption is much less than paste, in reality the true depth of water penetration is much greater than reported by "I." For the initial product evaluation a reduction in absorption of 50% was used as selection criteria for advancement to the full concrete portion.

Figure 4.1 shows the initial absorption results for the five products initially evaluated. The silane products produced the greatest reduction in absorption (~77%) with no difference between the solvent or water-based carrying solutions. The SME-PS and raw lithium silicate both produced similar reductions in absorption (~56%). The crystalline waterproofing product resulted in a 36% reduction in absorption.

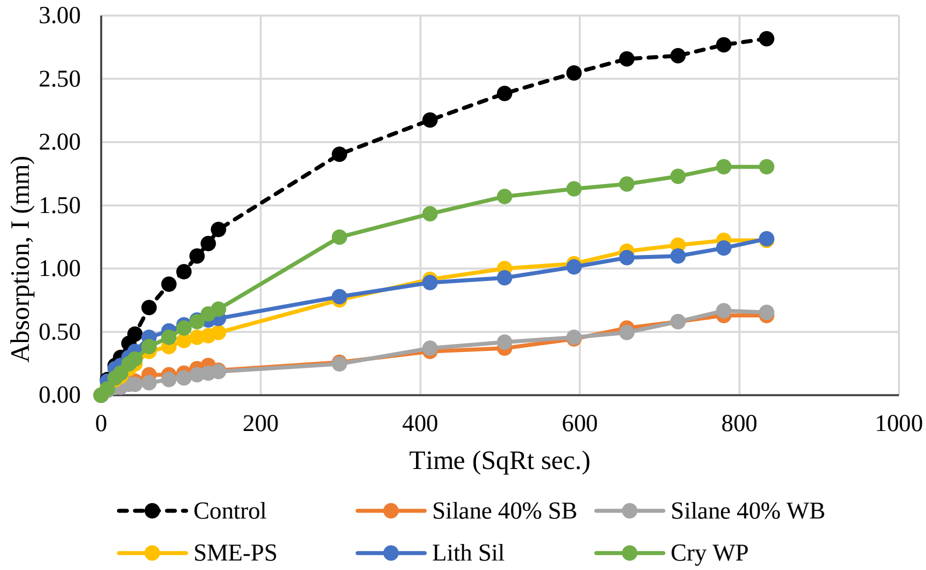


Figure 4.1 Absorption Results for Initial Penetrating Sealer Products

Table 4.2 through Table 4.6 show the reduction in water absorbed for full range of treatment conditions and treatment rates for Phase I testing as compared to the untreated control. As expected the amount of water absorbed generally decreased with increased application rate for the sealers. For the sealers (silanes and SME-PS), application in the moist condition resulted in less penetration as the water-filled pores prevented infiltration of the sealer. Of the two chemical reaction, densification-based sealers (lithium silicate and cystalline water proofer), both were less sensitive to application rate and condition. Increasing the application rate did not provide substantial improvement to absorption.

Table 4.2 Reduction in Absorption for 40% Solvent-Based Silane Treatments

	Silane-40% SB		
sf/gal	**Moist**	**Standard**	**Double**
100	85.1%	79.4%	93.4%
200	82.9%	**77.6%**	89.0%
400	77.2%	53.1%	87.3%

Table 4.3 Reduction in Absorption for 40% Water-Based Silane Treatments

	Silane-40% WB		
sf/gal	**Moist**	**Standard**	**Double**
100	85.5%	89.5%	95.6%
200	82.0%	**76.8%**	93.4%
400	82.5%	85.5%	89.9%

Table 4.4 Reduction in Absorption for Lithium Silicate Treatments

	Lithium Silicate		
sf/gal	**Moist**	**Standard**	**Double**
100	44.3%	50.0%	58.3%
200	51.8%	**56.1%**	56.1%
400	45.6%	53.1%	67.5%

Table 4.5 Reduction in Absorption for the Crystalline Water Proofer Treatments

	Crystaline Water Proofer		
sf/gal	**Moist**	**Standard**	**Double**
100	49.6%	42.1%	46.5%
200	56.1%	**37.3%**	40.8%
400	48.7%	36.8%	32.0%

Table 4.6 Reduction in Absorption for the SME-PS Treatments

	SME-PS		
sf/gal	**Moist**	**Standard**	**Double**
100	68.4%	65.4%	81.1%
200	68.4%	**56.6%**	83.3%
400	54.8%	59.2%	73.7%

Based on the initial evaluation, silane, lithium silicate, and SME-PS produced greater than 50% reduction in absorption from the untreated control when applied to clean and dry concrete at 200 sf/gal. While application rate did influence absorption, 200 sf/gal was determined as most practical for field application as discussed further in section 4.3.3.

4.3.2 Phase II – Concrete Evaluation

The Phase II laboratory investigation broadened testing to two WisDOT concrete mixtures and the more complete suite of tests shown in Table 4.1. Two additional sealer treatments were included in Phase II and included a combination silane/siloxane typically utilized in residential and commercial flatwork to prevent salt scaling and PAM curing compound applied to the joint 30 minutes after sawing.

Concrete used in the Phase II investigation represented two conventional mixtures with optimized gradation and a w/cm of 0.42. Mixtures were identical except for the “FA” mixture containing a 30% replacement for Portland Cement with Class C fly ash from the Portage generating station (Table 4.7). Individual and combined aggregate gradations are shown in Table 4.8.

Table 4.7 Concrete Mixture Proportions (unit: pcy)

Component	Wis "A"	Wis "FA"
Portland Cement	565	395
Fly Ash	0	170
Coarse Agg.	427	422
Intermediat Agg.	1116	1103
Fine Agg.	1525	1507
Water	237	237

Table 4.8 Aggregate Gradations for Concrete Mixtures

	Coarse 1.5" Stone	Intermediate 3/4" Limestone	Fine Sand	Combined
Sieve:	% Pass	% Pass	% Pass	% Pass
2"	100	100	100	100.0
1 1/2"	91.7	100	100	98.8
1"	17.7	100	100	88.5
3/4"	0.9	92	100	83.3
1/2"	0.5	44.4	100	65.9
3/8"	0.5	23.7	100	58.4
# 4	0.5	2.8	96.9	49.3
# 8	0.5	1.5	77	38.9
# 16	0.5	1.1	59.5	30.0
# 30	0.5	0.8	44.8	22.6
# 50	0.5	0.6	24.2	12.3
# 100	0.5	0.4	8.1	4.2
# 200	0.5	0.2	0.9	0.6

Conventional concrete quality control and assurance testing is shown in Tables 4.9 through 4.11. Fresh properties, strength gain, and surface resistivity were acceptable for paving concrete. Hardened air analysis suggested both mixtures possessed a good air system with total air, specific surface, and spacing factors all exceeding ACI recommendations.

Table 4.9 Fresh Concrete Properties

Component	Wis "A"	Wis "FA"
Slump	3.25 in.	4.25 in.
Uni Weight	146.0	146.0
Air	6.0%	6.5%

Table 4.10 Hardened Concrete Properties

	Wis "A"	Wis "FA"
3 day Comp. Str. (psi)	3,284	2,489
7 day Comp. Str. (psi)	3,739	3,551
28 day Comp. Str. (psi)	4,896	5,076
7 day Sur. Res. (kohm*cm)	6.2	4.8
28 day Sur. Res. (kohm*cm)	10.7	16.4

Table 4.11 Results of Hardened Air Analysis

Mixture	Unit Weight (pcf) ASTM C1084	w/cm ASTM C856	Total Air (%)	Specific Surface (in^2/in^3)	Spacing Factor (in)
Wis "A"	148.9	0.42±0.05	4.6	823	0.006
Wis "FA"	149.2	0.45±0.05	5.2	754	0.006
ACI Recommendation	NA	≤0.45	6.0%±1.5%	>600	<0.008

In general, all penetrating sealer samples had a similar appearance after sealer application. Figure 4.2 shows an untreated control sample (left), PAM-coated sample (middle), and SME-PS sample (right) which represent the two greatest visual differences from the control. The PAM samples were obviously white, while the SME-PS samples had a slightly darker color. At least when dry, none of the other samples were visually different than their respective controls. Table 4.12 shows the results of the chloride diffusion testing for both the “A” and “FA” concrete samples. The top results represent average chloride content between 0.0625 in. and 0.5 in. from the surface and the bottom results represent the average chloride content between 0.5 in. and 1.0 in. from the surface per AASHTO T259.

The silane treatments along with the SME-PS produced significant reductions in chloride diffusion. PAM treatment also resulted in a reduction in chloride diffusion. Chloride diffusion was not influenced by the siloxane mixtures and the lithium silicate mixture.

(a) Control (b) PAM-coated Sample (c) SME-PS Sample

Figure 4.2 Samples for Chloride Diffusion Testing

Table 4.12 Chloride Diffusion Results

	A Concrete		FA Concrete	
Treatment	**Top**	**Bottom**	**Top**	**Bottom**
Untreated Control	0.528%	0.185%	0.558%	0.147%
40% silane applied after 7 days	0.384%	0.158%	0.301%	0.103%
40% silane applied 30 min. after sawing	0.376%	0.157%	0.404%	0.148%
7% Siloxane mixture applied after 7 days	0.512%	0.140%	0.386%	0.119%
10% Siloxane mixture applied after 7 days	0.587%	0.266%	0.487%	0.143%
Lithium Silicate mixture applied 30 min. after sawing	0.497%	0.181%	0.580%	0.162%
PAM applied 30 min. after sawing	0.409%	0.177%	0.293%	0.119%
SME-PS applied after 7 days	0.332%	0.072%	0.365%	0.118%

Depth of penetration was utilized as a method of indicating potential life span of a sealer. A deeper penetration would be assumed to provide protection for a greater length of time. ImageJ® analysis was used to determine an average depth of penetration for samples. As observed in Figure 4.3 and Figure 4.4, penetration depth was highly variable. Both water and powdered navy blue fabric dye were similarly effective in delineating water repellency.

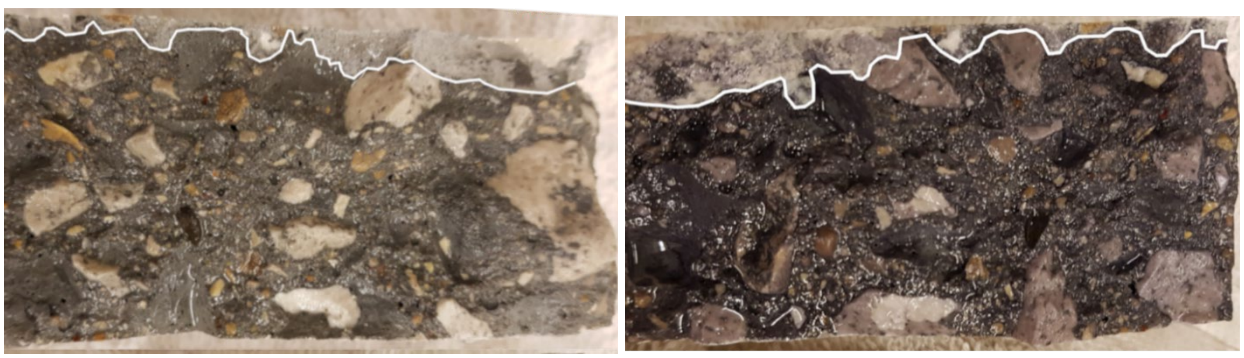


Figure 4.3 Example Depth of Penetration for Silane Treated Specimens (Left: water, Right: blue fabric dye)

Figure 4.4 Example Depth of Penetration for SME-PS Specimen (Left: water, Right: blue fabric dye)

The average depth of penetration for the two concrete mixtures are shown in Table 4.13. The depth of penetration observed from the lab samples is less than reported in field studies in the literature (Ley & Moradllo, 2015) or the field observation reported earlier in Chapter 3 likely due to less controlled, drier conditions during field application. The gold standard silane applied in the dry condition produced the greatest depth of penetration followed by the silane applied in the moist condition and the SME-PS.

Table 4.13 Depth of Penetration Results

Treatment	A Concrete (mm)	FA Concrete (mm)
Untreated Control	NA	NA
40% silane applied after 7 days	4.99	3.01
40% silane applied 30 min. after sawing	0.91	0.79
7% Siloxane mixture applied after 7 days	0.39	0.51
10% Siloxane mixture applied after 7 days	0.27	0.45
Lithium Silicate mixture applied 30 min. after sawing	0.23	0.27
PAM applied 30 min. after sawing	0.25	0.16
SME-PS applied after 7 days	0.97	0.77

The absorption results for the concrete mixtures tested to 90 days are shown in Figure 4.5 for the "A" concrete and Figure 4.6 for the "FA" concrete. Trends were similar between the two mixtures with the "FA" concrete having lower absorption due to the denser pore structure. Although reported in mm, the infiltration "I" is an average absorption of all the concrete components and not an actual distance of water penetration. At the end of 90 days, the 2 in. thick control specimens were fully wetted. The penetrating sealers all produced a reduction in absorption, except for the lithium silicate densifier. Greater differences in performance were observed for the more porous "A" concrete with similar, yet compressed results for the "FA" concrete. The samples treated with PAM as a sealer had initially lower absorption, however ultimately had equal or greater absorption than the control.

For the "A" concrete both silane conditions and the SME-PS produced similar results with a 32-37% reduction. The mixed siloxane/silane products had similar performance with around a 14% reduction in absorption. For the "FA" concrete the gold standard silane applied in the dry condition produced the best performance with a 36% reduction in absorption. The other treatments (silane moist, siloxane mixtures, and SME-PS) all produced similar reductions from 15-20%.

The lithium silicate/potassium methyl siliconate surface densifier produced contrary results to expected. The densified was applied 30 minutes after sawing to the 1 day old concrete to maximize the amount of free calcium hydroxide present for the reaction. The other component, potassium mehyl siliconate, is a concrete waterproofing agent with similar functionality to silane. The additional observed mass increase shows the densification reaction continued after additional water exposure during testing. In the "A" concrete the rate of absorption between the densified samples and the control became similar after 12 days. In the "FA" concrete the reaction completed after 3 days with an ultimate rate much less than the untreated control. If absorption is utilized in future testing, samples containing densifier should be moist-cured for an additional period along with a surrogate control to ensure mass change is a result of water absorption and not addition hydration product formation.

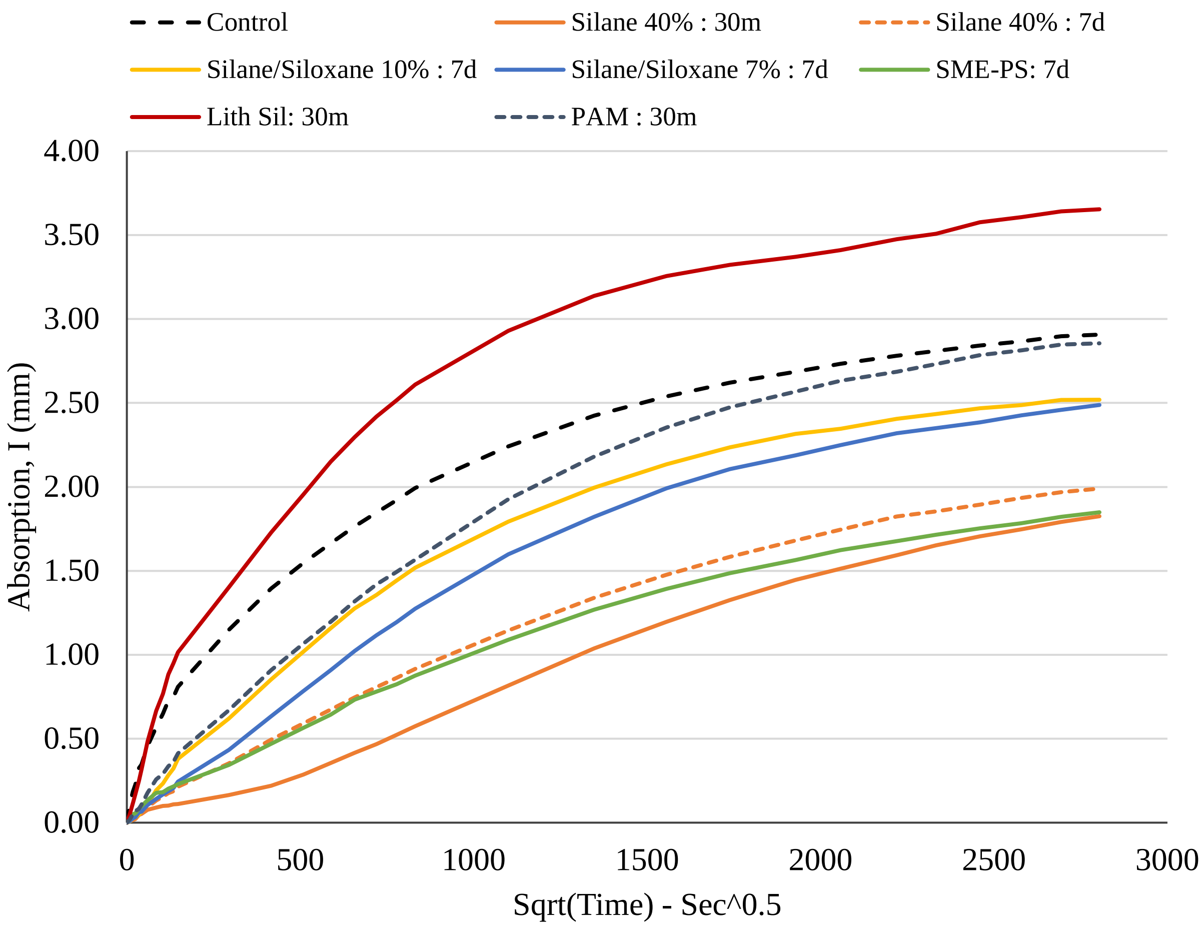


Figure 4.5 Wis “A” Absorption Results

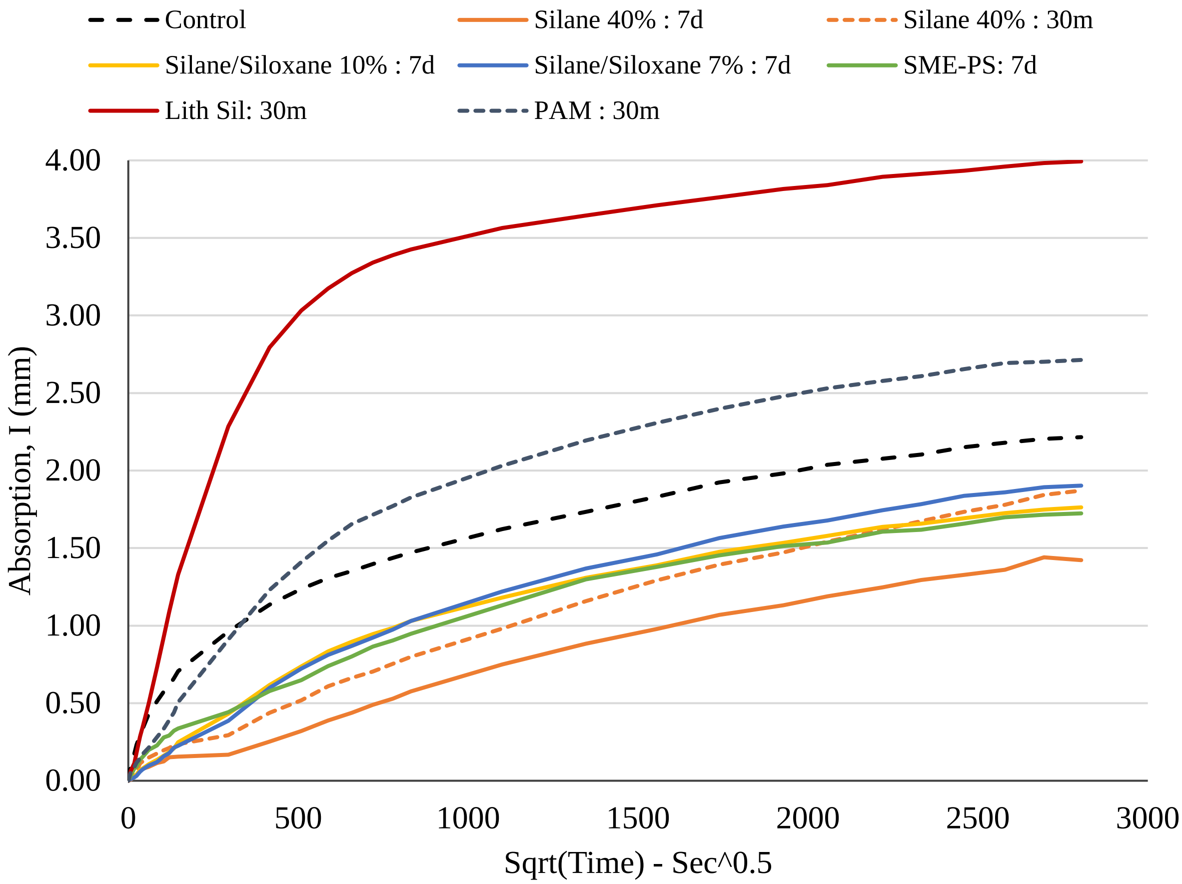


Figure 4.6 Wis "FA" Absorption Results

After absorption testing at 90 days, samples were vacuumed-saturated according to the RILEM critical degree of saturation method for assessing freeze-thaw resistance of concrete to assessment the degree of saturation (Fagerlund, 1977). Table 4.14 and Table 4.15 show the final degree of saturation at the end of testing. If the final degree of saturation exceeded 85% the time to critical saturation was calculated from test data. If the samples had not reached critical saturation at the end of testing, the rate of absorption in the final 30 days of testing was used to extrapolate additional time needed to achieve 85% saturation. For the "A" concrete the SME-PS produced the greatest time extension to critical saturation of 9x with the silane applied in the dry condition at 6.9 and in the moist condition at 6.5. For the "FA" concrete, the silane applied in the dry condition produced the greatest time extension to critical saturation followed by the higher concentration siloxane/silane mixture and SME-PS. Disregarding the lithium silicate mixture and PAM, all of the penetrating sealers produced at least a doubling of time to critical saturation.

Table 4.14 Time to Critical Saturation for Wis "A"

Treatment	Final Degree of Saturation	Days to 85% Saturation	Lifespan Increase (x)
Untreated Control	100%	28	NA
40% silane applied after 7 days	62%	221	6.9
40% silane applied 30 min. after sawing	69%	210	6.5
10% Siloxane mixture applied after 7 days	89%	62	1.2
7% Siloxane mixture applied after 7 days	86%	84	2.0
SME-PS applied after 7 days	63%	279	9.0
Lithium Silicate mixture applied 30 min. after sawing	100%	10	-0.6
PAM applied 30 min. after sawing	100%	19	-0.3

Table 4.15 Time to Critical Saturation for Wis "FA"

Treatment	Final Degree of Saturation	Days to 85% Saturation	Lifespan Increase (x)
Untreated Control	100%	23	NA
40% silane applied after 7 days	64%	218	8.5
40% silane applied 30 min. after sawing	82%	102	3.4
10% Siloxane mixture applied after 7 days	77%	150	5.5
7% Siloxane mixture applied after 7 days	84%	97	3.2
SME-PS applied after 7 days	76%	148	5.4
Lithium Silicate mixture applied 30 min. after sawing	100%	1	-1.0
PAM applied 30 min. after sawing	100%	8	-0.7

Deicer salt scaling was evaluated for samples where penetrating sealers were applied over the PAM curing compound. The intention of this setup was not to evaluate replacing PAM as a curing compound, moreover to evaluate any potential negative impacts when penetrating sealers were applied adjacent to the sawn joint. As observed in Figure 4.7, the control concrete had moderate scaling. Figure 4.8 shows the performance after 50 cycles for all of the "A" concrete sealer types. All of the penetrating sealers provided an improvement in deicer scaling, even considering the application over the PAM curing compound. Performance was better when the sealers were applied to the 7-day old concrete versus the younger concrete timed 30 minutes after sawing activities. The complete performance evaluation for both the "A" and "FA" concrete is shown in Table 4.16 where 0 – no scaling, 1 – very slight scaling, 2 – slight to moderate scaling, 3 – moderate scaling, 4 – moderate to severe scaling, and 5 – severe scaling (ASTM, 2012).

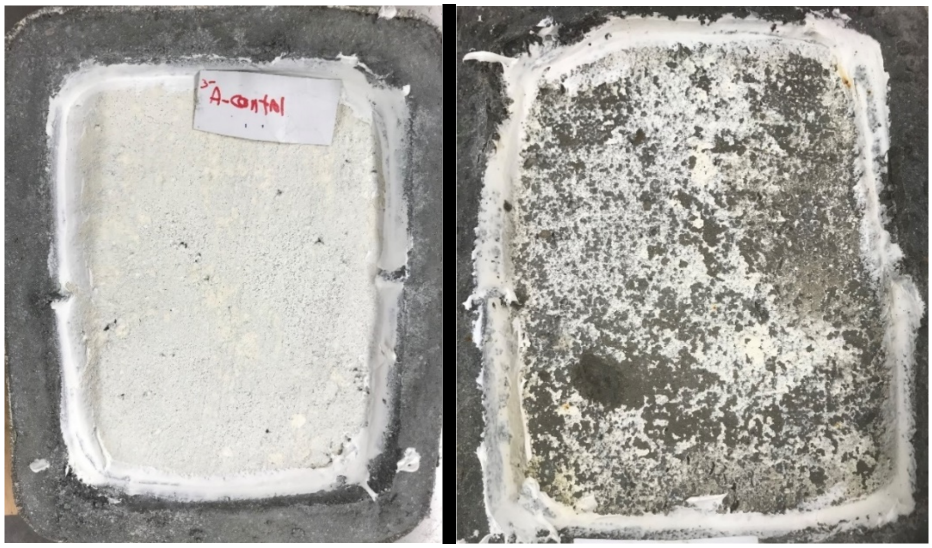


Figure 4.7 “A” Control Deicer Scaling Performance (Left 0 cycles-0, Right 50 cycles-3)

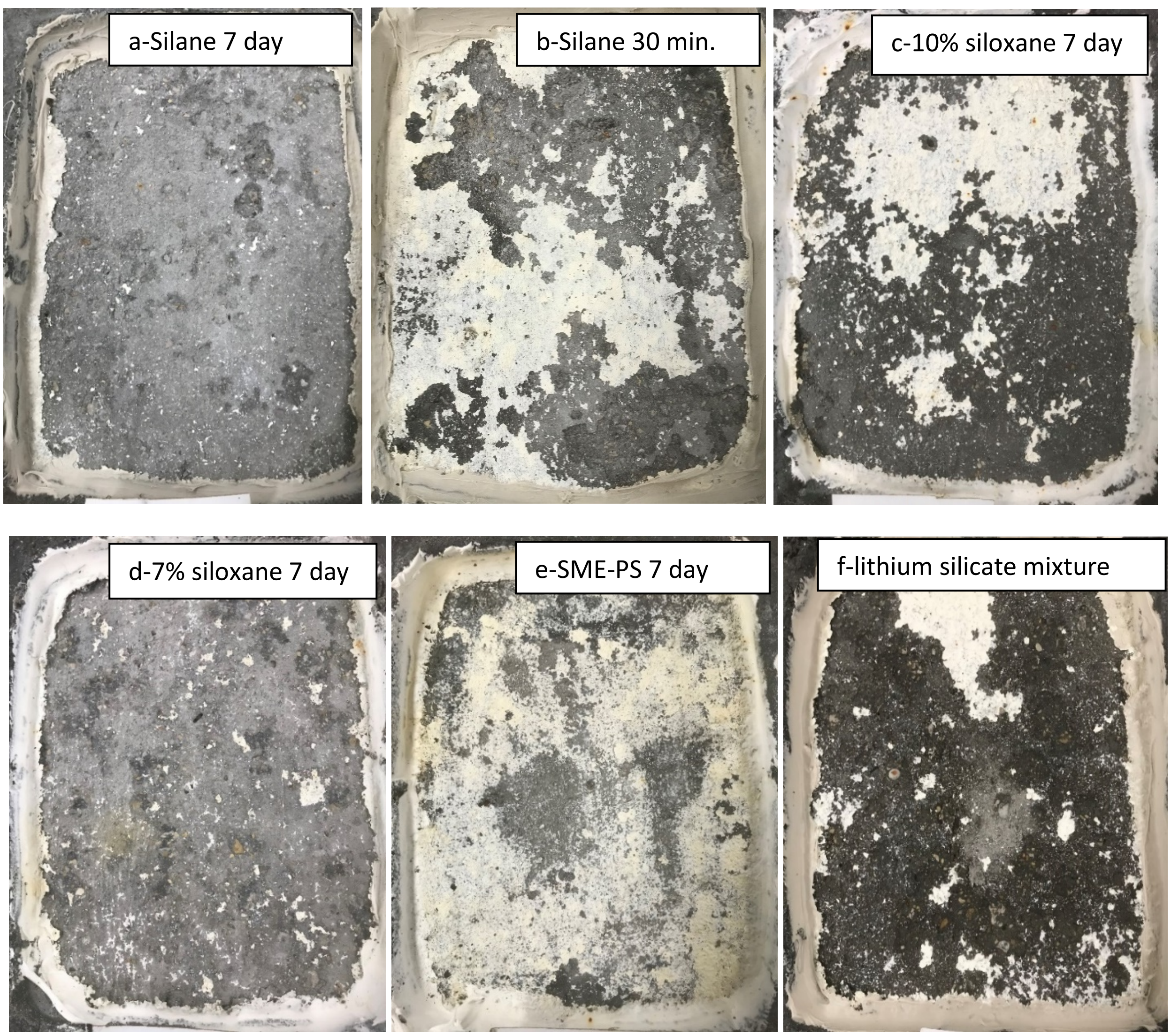


Figure 4.8 Deicer Scaling Performance of Wis “A” Concrete (50 cycles)

Table 4.16 Deicer Scaling Rating after 50 Freeze/Thaw Cycles

Treatment	"A"	"FA"
Untreated Control (PAM)	3	3
40% silane applied after 7 days	1-2	2
40% silane applied 30 min. after sawing	2	2
10% Siloxane mixture applied after 7 days	1-2	1
7% Siloxane mixture applied after 7 days	2	2-3
SME-PS applied after 7 days	1	1-2
Lithium Silicate mixture applied 30 min.	4-5	2

4.3.3 Evaluation of Application Rate and Technique

During laboratory application several important observations were made for the different products. An application rate of 200 sf/gal was easily achieved by a pump sprayer and resulted visually in complete coverage. An application rate of 100 sf/gal was not easily achieved using a pump sprayer as the amount of sealer was not easily maintained on the surface. A disposable foam brush was used to achieve the 100 sf/gal which involved balancing the sealer to the surface using surface tension. In practice, and especially to a vertical surface, 100 sf/gal would not be an appropriate application rate. Oppositely, the 400 sf/gal application rate was difficult to achieve uniform coverage and require more practice by the applicator to achieve good results. As observed in the following results, the 400 sf/gal application rate had the highest absorption variability.

The research team also conducted several trials on parking lots to test the sprayer and find the best combination of nozzle type, opening size, and speed to achieve the most uniform coverage of the targeted 150-200 sf/gal recommended for field application. However, none of them was able to visually reveal the results until a lab setup using masonry blocks was invented. As shown in Figure 4.9, 12 masonry blocks (8in. x 8 in. x 8 in.) were carefully lined together with 0.2 in. gap to simulate the joint saw cut. The same operator applied the pump sprayer with different combinations. The masonry blocks were then opened to show the depth and uniformity of the coverage. Weight of the sprayer before and after were taken to calculate the quantity.

Fan nozzles and cone nozzles were tested. Application rates of 0.1, 0.2, and 0.5 gallon per minute (GPM) were evaluated. Two passes application means first placing the nozzle in contact with joint surface for the first pass, then lift the nozzle up to cover about 3 inches on both sides of the joint for the second pass. Three passes application means pointing the fan nozzle toward one side of the joint face, followed by pointing the fan nozzle toward the other side of the joint face, and finally lift the nozzle up to cover about 3 inches on both sides of the joint for the third pass. Fan nozzle at 0.5 GPM was not uniform and created waste at the bottom. Fan nozzle at 0.2 GPM did not cover enough depth, neither did the cone nozzle at 0.1 GPM. Compared to fan nozzle, cone nozzle had better coverage and faster speed. Among all combinations, the cone nozzle at 0.2 GPM with 2 passes application demonstrated the best coverage and application speed, and therefore was adopted as the spraying process in the field for this study.

Trial applications using masonry blocks were easy to setup and convenient to evaluate effectiveness. Contractors are recommended to use this method to test their sprayer system and application method.

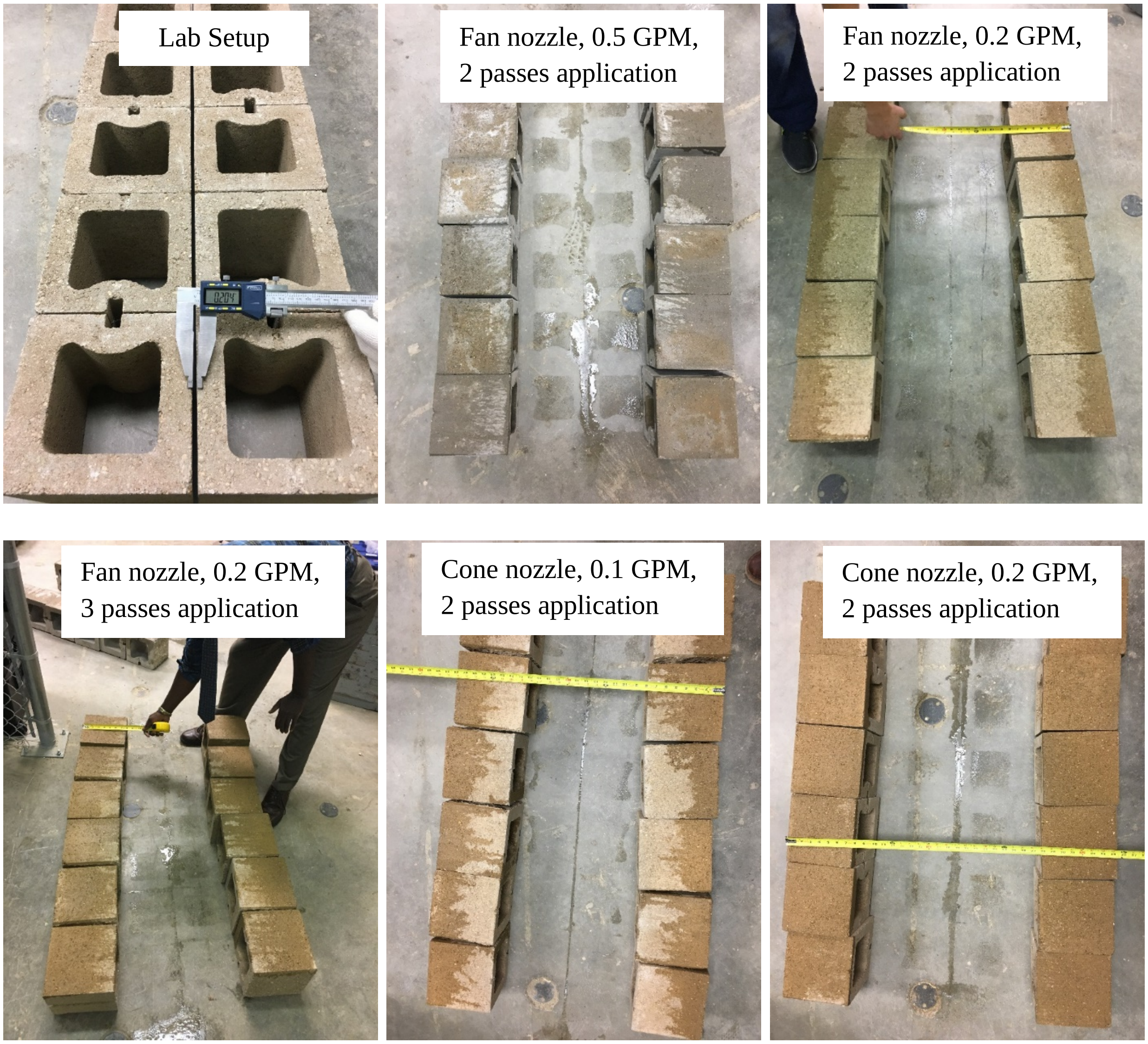


Figure 4.9 Coverage of Joint Face using Different Types of Nozzle and Opening Size

4.4 Summary

This chapter summarized the results of the laboratory investigation. An initial investigation (Phase I) studied the influence of application rate and moisture condition on absorption of a control mortar. Phase II expanded WisDOT “A” and “FA” concrete testing to a variety of basic characterization and performance measures. The following are the notable findings from the laboratory investigation:

1) In general, an increase in application rate provided a reduction in absorption. Two application of any sealer provided a reduction in absorption over a single application at any application rate.

2) In general, applying a sealer in moist condition resulted in a reduction in absorption because the sealer was blocked from penetrating into the concrete by the fluid-filled pores. Depth of penetration was greatest when sealer was applied in dry condition.

3) The two concrete mixtures “A” and “FA” produced in the laboratory had good air systems and material properties consistent and acceptable for highway paving in Wisconsin.

4) Chloride penetration was significantly reduced by the silane, SME-PS, and PAM treatments. A reduction was not observed for the siloxane mixtures applied to dry concrete or the lithium silicate applied 30 minutes after sawing.

5) All penetrating sealers applied to concrete samples resulted in decreased absorption and extension of time to critical (85%) saturation. PAM curing compound used as a sealer did not extend time to critical saturation.

6) Absorption tested on the lithium silicate densifying chemical showed a significant mass gain (3 days for “FA” and 12 days for “A”) during the initial absorption period indicating the formation of additional hydration products.

7) All of the penetrating sealers provided improved deicer scaling performance except for the lithium silicate solution applied to the “A” concrete 30 minutes after sawing activities. Sealers applied to the 7 day old, dry concrete had the best performance.

8) A coverage rate of 200 sf/gallon provides complete wetting at an application rate of 0.2 GPM with two passes using a cone nozzle. An application rate of 100 sf/gallon was difficult to apply to a horizontal surface and would result in excessive runoff when attempted on a vertical joint. An application rate of 400 sf/gallon did not result in full wetting.

9) Contractors are suggested to use the masonry block setup to test their sprayer system and application method. This method can visually verify the uniformity of coverage.

Chapter 5 – Field Study

5.1 Introduction

Based on the results of laboratory tests, a field project was selected to implement the recommended practice and compare its field performance. The site was on project 1007-11-74, located in the southbound of I-39/90 corridor between E Church Rd and CTH A (log mile 1897+75 ~ 1871+75).

The site contains three replicas, each with 50 joints (four sealer types and one control). Figure 5.1 shows the experimental design and numbering of joints. Concrete of this section was poured on 9/28/2018 and sealers were applied on 10/18/2018 (the 20th day). To keep the process consistent, the spraying process was operated by the same person for all joints using a 3.5-gallon industrial concrete sprayer. Through laboratory trials, the best method to provide a uniform coverage of 150~200 sf/gal was a two-pass application using cone nozzle at 0.2 gallon per minute (GPM): placing the nozzle in contact with joint surface for the first pass, then lift the nozzle up to cover about 3 inches on both sides of the joint for the second pass. The coverage was closely managed by weighing the sprayer before and after each section; Appendix D lists the record of field application. Four different pump sprayers were used for the four types of sealer to avoid cross contamination.

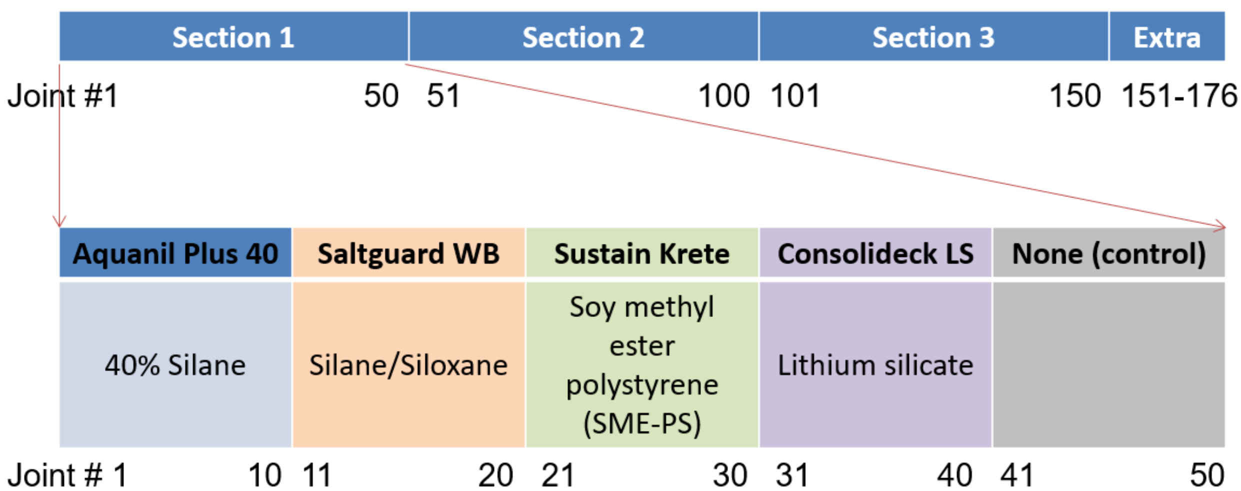


Figure 5.1 Experimental Design of Field Study

Figure 5.2 shows the appearance of joint right after the spraying of sealers. Aquanil Plus 40 is clear, colorless, but with petroleum solvent odor since it is solvent based 40% Silane. Joint appears wet after application but cannot tell the difference after it dries. SaltGuard WB is an odorless white liquid. The wet appearance disappears after it dries. SME-PS is pale yellow liquid with mild odor. It is very light (specific gravity =0.88) so wind blows it easily. The joint appears wet and does not "dry out". Lithium silicate is a clear, colorless, odorless liquid. The wet appearance disappears quickly.

The section was opened to traffic on 10/23/2018, 5 days after the application of sealers. Four site visits were conducted since the opening. All joints were in good condition. Hence, 15 core samples (5 types * 3 sections) were collected from the site on 10/3/2019 (near one year of service). Laboratory tests were then conducted on these samples to evaluate sealers' performance.

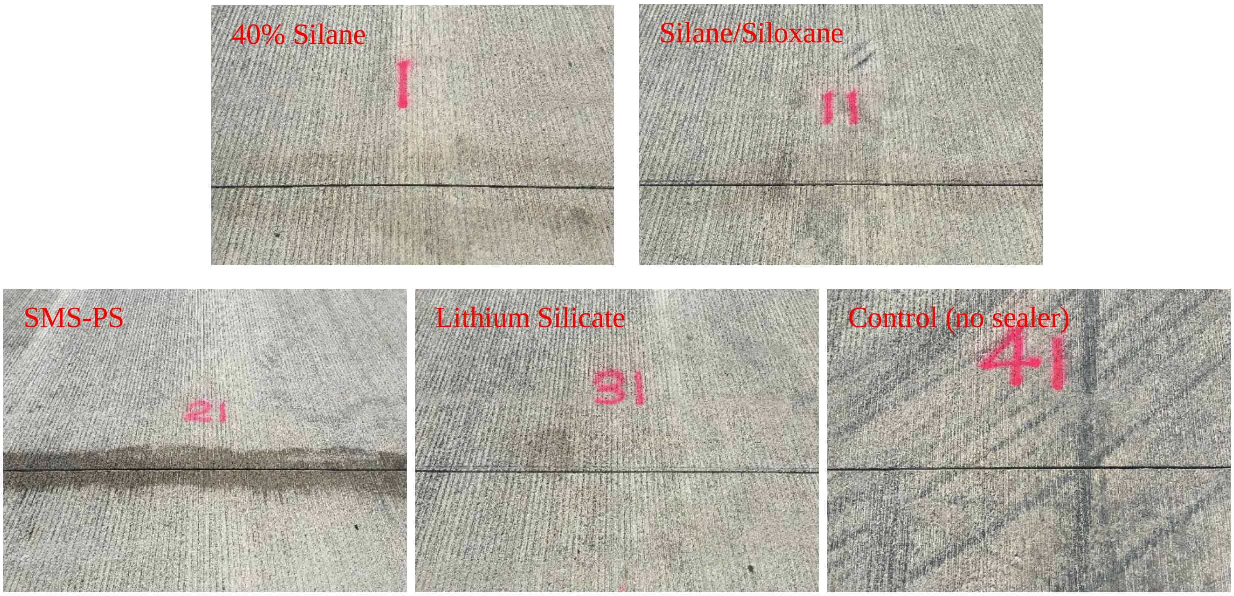


Figure 5.2 Appearance of Joints Right After Sealer Applied

5.2 Analysis of Field Performance

After the opening of traffic, initial performance of all joints was collected using WisDOT's multi-function vehicle on 10/24/2018. Follow-up field visits were conducted on 2/13/2019, 5/14/2019, and 8/2/2019. Only visual inspection from the shoulder were performed without traffic control.

The initial pavement images show that all joints in the main lane were in excellent condition. However, 90% of joints had visible spalling in the white pavement marking strip area, which is most likely due to the grinding process in preparing for the recessed white marking. It is recommended for WisDOT to explore the formation of recessed pavement marking groove using modified screed bar on plastic concrete, a cost-effective method investigated by Colorado DOT (Outcalt, 2004).

There was no visible distress in the main lane area on 2/13/2019 (113 days of service since opening to traffic). Spalling in the recessed white marking strip was visible but with no sign of further deterioration.

On 5/14/2019 (202 days of service since opening to traffic), no major distress in transverse joints was observed. However, 14 cases of small spalling were found, most of them near the white marking strip, as shown in Figure 5-3. Among the 14, there were 5 sealed with 40% silane, 5 with SME-PS, 2 with silane/siloxane, 1 with lithium silicate, and 1 without penetrating sealer. Due to the consistent location of the spalling, it is highly suspected that these spalling are related to the milling process for the recessed white marking.

The 3rd visit of the field study site was conducted on 8/2/2019 (283 days of service). There was no major distress in transverse joints in the study area. However, 23 cases of minor spalling were observed, most of them near the white marking strip, as shown in Figure 5.4. Among the 23, there were 4 associated with sections sealed with 40% silane, 8 with SME-PS sections, 3 with silane/siloxane sections, 2 with lithium silicate sections, and 6 for sections without any penetrating sealer. A close-up picture Figure 5.5 taken during the coring time shows the detail of the spalling.

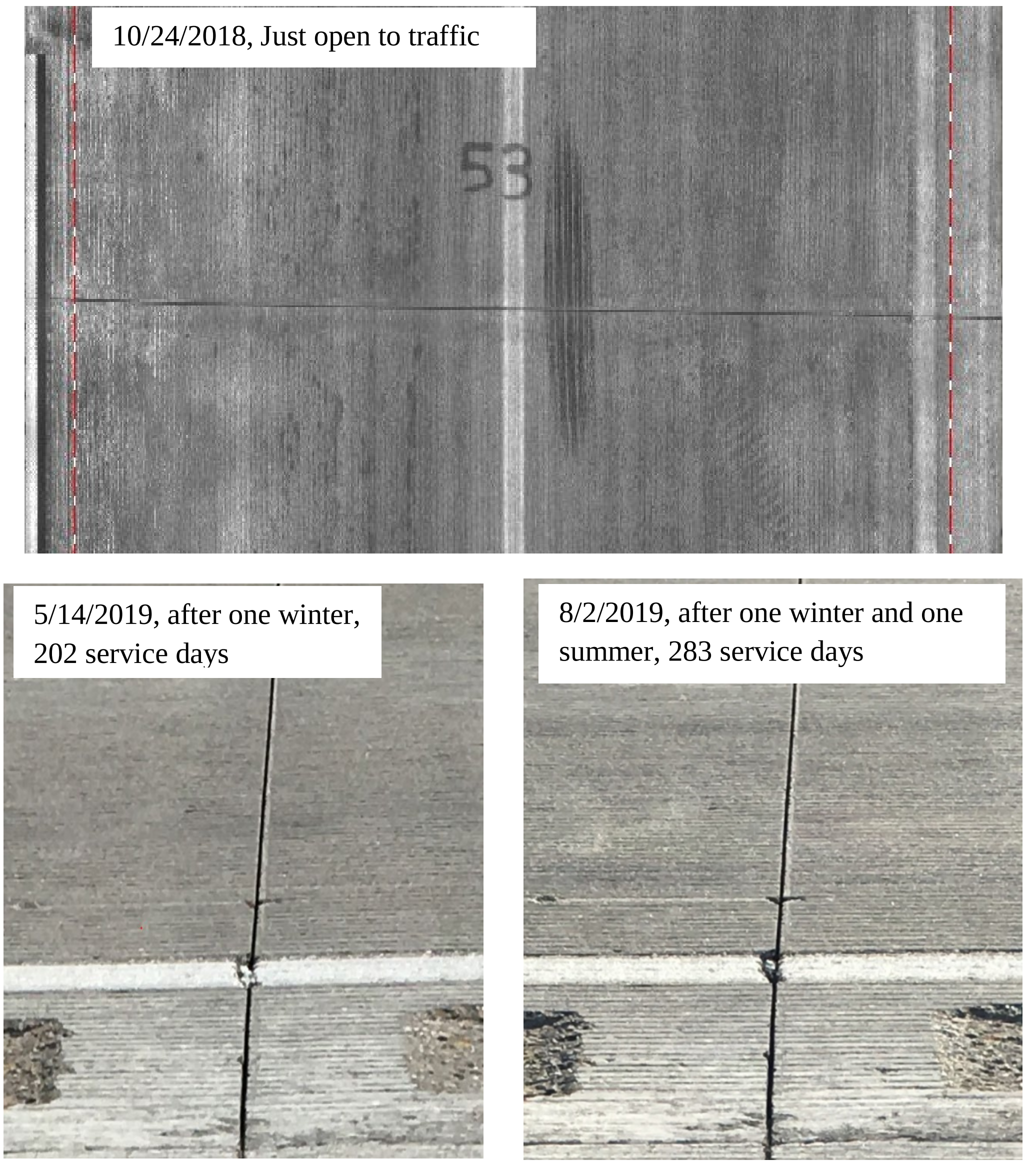
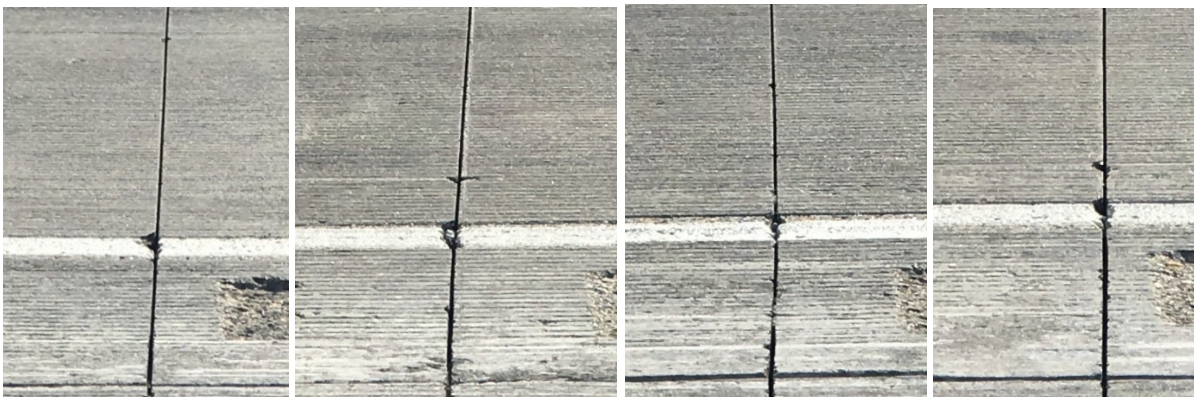


Figure 5.3 Field Performance of Joint #53



Joint #104 (Control) Joint #53 (40% Silane) Joint #63 (Silane/Siloxane) Joint #72 (SME-PS)

Figure 5.4 Examples of small spalling observed during the August site visit

Figure 5.5 Close-up of small spalling at Joint #104

5.3 Laboratory Test of Field Core Samples

After one year in service, fifteen 4-inch-diameter core samples were removed from non-adjacent slabs and transported to the laboratory for testing. It was observed that all core samples were quite dirty with salt and tire residue. Figure 5.6 shows an untreated core in the as-received condition on the left and after cleaning in an ultrasonic bath on the right. All cores were visually similar in the as-received condition. After cleaning the core samples treated with silane (Figure 5.7) and SME-PS had less black residue than the siloxane mixture or lithium silicate mixture.

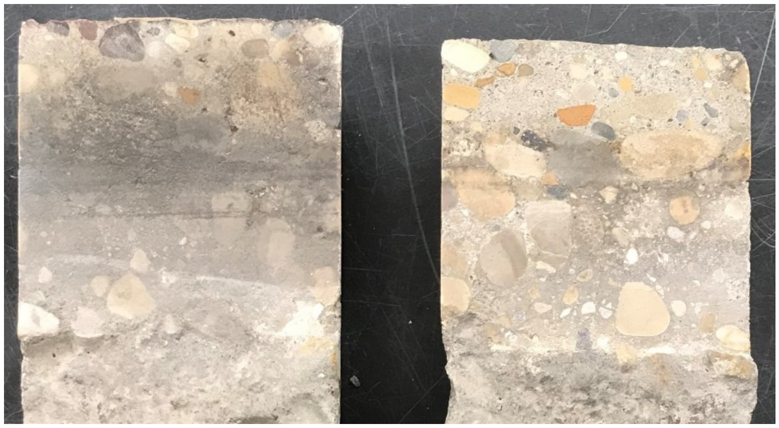


Figure 5.6 Untreated core samples (left) as received and (right) after cleaning

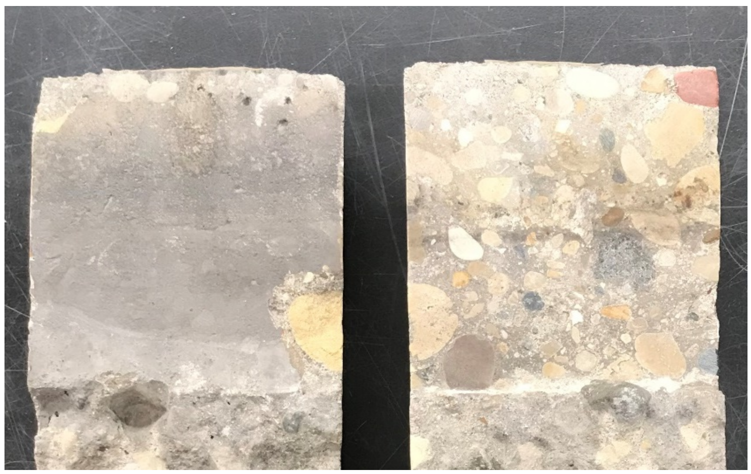


Figure 5.7 Silane-treated core sample (left) as received and (right) after cleaning

5.3.1 Contact Angle Test

Same as the contact angle testing in Chapter 3, contact angle was measured in triplicate 1 cm from the pavement surface, in the middle third of the core, on mortar portions using 20 micrograms of deionized water. The average contact angle results in both the as-received (dirty) condition and after cleaning (clean) are shown in Table 5-1. The contact angle of the control specimens indicated the untreated samples possessed a hydrophobic surface, likely from a combination of the polishing action of the saw and high strength, low permeability concrete. An increase in contact angle was observed for the two hydrophobic agents (silane and siloxane mixture) with no difference to the control of the SME-PS and lithium silicate mixture.

Table 5.1 Contact Angle of the I-39 Core Samples

ID	θDirty	θClean	COV Dirty	COV Clean
Untreated Control	98	104	7.4%	1.1%
Silane	117	134	6.4%	5.3%
SME-PS	78	93	40.8%	30.0%
Siloxane mixture	113	121	0.5%	7.9%
Lithium Silicate mixture	111	96	9.1%	2.6%

There is no report of contact angle of concrete joints in the literature. For reference, the contact angle test on bridge decks and surface coating in the literature is listed below:

- Contact angle for normal concrete was around 35° for samples without siloxane treatment and greater than 60° for samples treated with siloxane. This test was made on bridge deck concrete with different ages in Oklahoma (Ley, Materer, & Apblett, 2011).
- Michigan (Attanayaka, Ng, & Aktan, 2002) reported the contact angle increased from 49.5° to 77° after the silane application.
- The untreated concrete surface is inherently hydrophilic with a contact angle of 40°. Two surface coatings turned the concrete surface somewhat hydrophobic with contact angle up to 90°. Note again the concrete and test were designed for bridge decks (Dang et al., 2014).
- Contact angle is 40.15° for the standard sample (concrete made from lightweight-aggregates with sewage sludge) at time t=0 which reduced to 14.16° within 40 minutes (Barnat-Hunek et al., 2015). The same sample coated with water-based solution of methylosilicaon resin in potassium hydroxide had a contact angle of 105.47° at t=0 and 91.76° at t=40 minutes.
- Contact angle is 61.7° for uncoated concrete samples, 77.5° for epoxy coated samples, and 96.1° for samples coated with epoxy resin nano-composites modified with 0.3% graphene oxide by weight (Zheng et al., 2020).
- The uncoated concrete exhibited a rough but uniform surface. The contact angle is 72.9° for uncoated concrete. When a superhydrophobic coating using rice husk ash dispersed in ethanolic solution containing fluoroalkyl silane, the contact angle increased to 152.3° (Husni et al., 2017)

Contact angle is influenced by a variety of factors such as surface roughness and contamination, surface homogeneity, modulus of elasticity of the analyzed material, type of the measurement liquid, size of measurement liquid droplets, moisture, or ambient temperature (Law & Zhao, 2016). It is very likely that the sawcut process has polished the concrete joint surface similar to Figure 5-8, resulting to a hydrophobic surface. The joint surface of all core samples from the field study was very smooth.

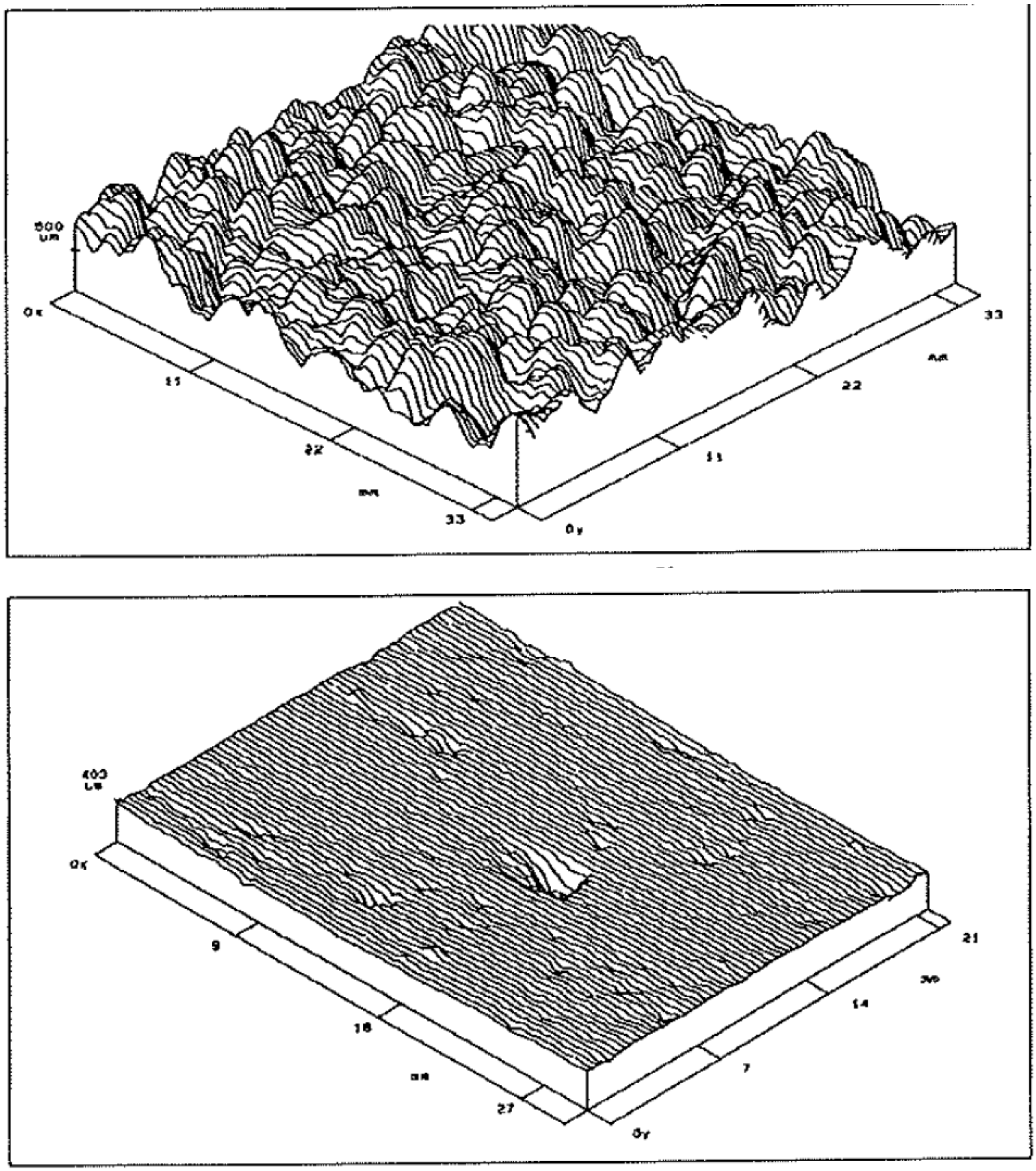


Figure 5.8 3D visualization of (a) sandblasted and (b) polished concrete profile (Courard, 2000)

In addition to initial contact angle, measurements were taken over the first two minutes. The change in contact angle with time for the dirty samples is shown in Figure 5.9. The surface contamination caused a rapid wicking of the water droplet and rapid reduction in contact angle indicating the lack of cleanliness in the joint reduces hydrophobicity. The contact angle performance with time of the clean samples is likewise shown in Figure 5.10 where all samples were classified as hydrophobic (θ>90°) initially, but only the silane and siloxane samples kept hydrophobic after 120 seconds.

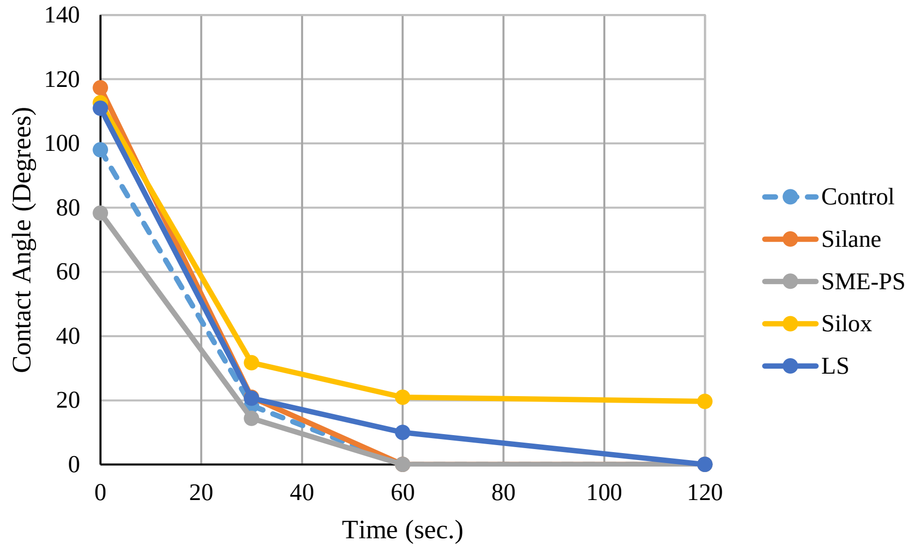


Figure 5.9 Change in Contact Angle with Time for the As-Received (Dirty) Core Samples

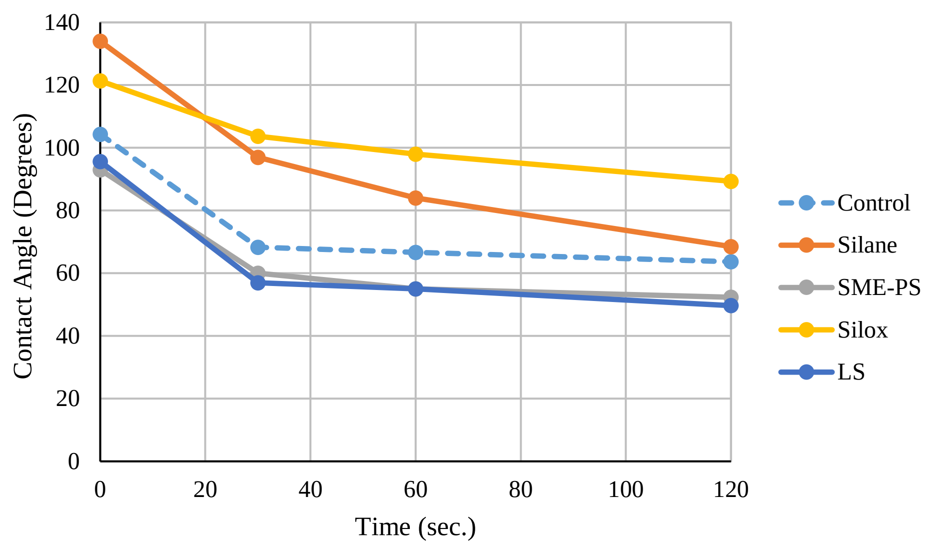


Figure 5.10 Change in Contact Angle with Time for the Cleaned Core Samples

5.3.2 Absorption Test

Absorption was measured according to ASTM C1585 on all core samples followed by saturation test to determine the degree of saturation by the previously mentioned RILEM method (Fagerlund, 1977). The core sample saturation results are shown in Figure 5.11. No difference in degree of saturation was observed with all samples between 80% and 85% saturated after 15 days of testing.

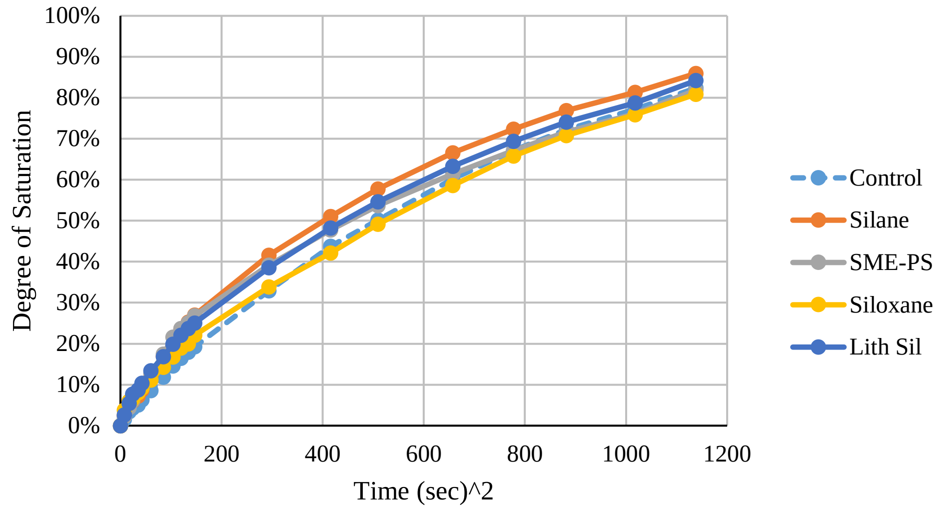


Figure 5.11 Absorption Performance of I-39 Core Samples

5.3.3 Depth of Penetration Test

Depth of penetration testing was performed on the core samples after absorption testing followed by slow drying in an environmental chamber at 50% RH. Testing followed the procedure described in Chapter 4. No measurable or observable penetration occurred for any of the core samples or treatments. A wetted control sample (Core #45) is shown in Figure 5.11. As expected for the untreated concrete, no hydrophobic or water-repellent zone can be observed. A similarly wetted sample treated with silane sealer (Core #55) is shown in Figure 5.12. Unexpectedly, no penetration was observed. All other samples had similar appearance.

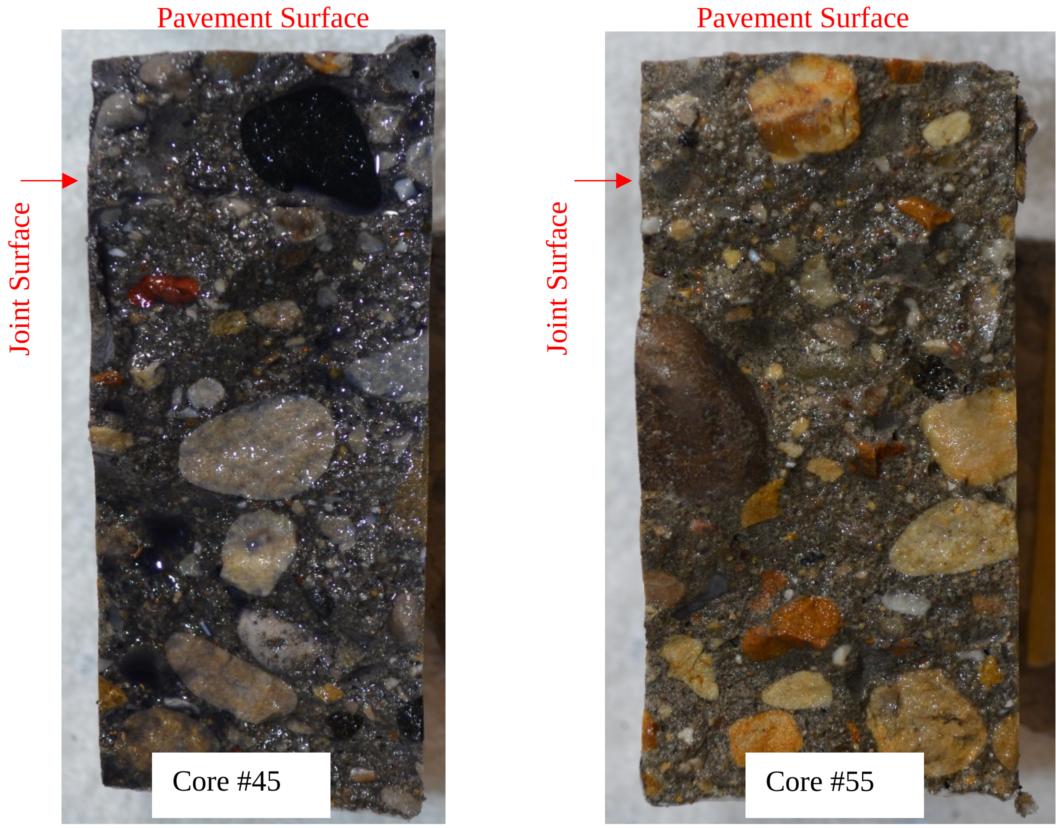


Figure 5.12 Depth of Penetration of Core Samples from I-39

5.3.4 Discussion

It is unexpected to observe the absence of sealer in the field study section. Intuitively normal concrete is hydrophilic; hence the question is not whether penetrating sealer will be absorbed but how much will be absorbed in vertical applications (Weiss et al., 2016).

To address this "surprise", all laboratory tests were first reconducted to rule out any error in the test process. The results as presented above were confirmed.

Since the mechanism of penetrating sealer is for materials to penetrate into concrete pores and coat pore walls rendering them hydrophobic, sealer should be applied on dry concrete surface. According to the project record, concrete of the field study section was paved on 9/28/2018. Joints were powerwashed on 10/16. Joints were further cleaned using a pressured air hose, then sealer applied on 10/18. It was a sunny day with air temperature above 40°F (Figure 5.13). There were two days for the joint to dry after powerwashing and no rain during the two days. There was no rain within 12 hours after the sealer application. The section was not open to traffic until 10/23, five days after the sealer application. With this information (Table 5.2), it was believed that the concrete was not saturated when the sealer was applied.

Table 5.2 Daily weather data for 2018 October (NOAA, 2018)

Date	Temperature				HDD	CDD	Precipitation	New Snow	Snow Depth
	Maximum	Minimum	Average	Departure					
2018-10-01	55	49	52.0	-2.4	13	0	2.05	0.0	0
2018-10-02	56	51	53.5	-0.5	11	0	T	0.0	0
2018-10-03	84	55	69.5	15.9	0	5	T	0.0	0
2018-10-04	65	41	53.0	-0.2	12	0	0.00	0.0	0
2018-10-05	58	45	51.5	-1.3	13	0	0.27	0.0	0
2018-10-06	56	50	53.0	0.6	12	0	0.69	0.0	0
2018-10-07	52	49	50.5	-1.5	14	0	0.65	0.0	0
2018-10-08	79	52	65.5	13.9	0	1	0.11	0.0	0
2018-10-09	81	63	72.0	20.7	0	7	0.06	0.0	0
2018-10-10	72	47	59.5	8.6	5	0	0.94	0.0	0
2018-10-11	47	38	42.5	-8.0	22	0	T	0.0	0
2018-10-12	42	31	36.5	-13.7	28	0	0.00	0.0	0
2018-10-13	49	27	38.0	-11.8	27	0	0.00	0.0	0
2018-10-14	51	34	42.5	-7.0	22	0	0.04	T	0
2018-10-15	43	32	37.5	-11.6	27	0	0.01	T	0
2018-10-16	57	36	46.5	-2.3	18	0	0.00	0.0	0
2018-10-17	50	31	40.5	-8.0	24	0	0.00	0.0	0
2018-10-18	58	27	42.5	-5.6	22	0	0.00	0.0	0
2018-10-19	55	48	51.5	3.7	13	0	0.04	0.0	0
2018-10-20	48	27	37.5	-9.9	27	0	T	T	0
2018-10-21	49	22	35.5	-11.6	29	0	0.00	0.0	0
2018-10-22	63	30	46.5	-0.2	18	0	0.00	0.0	0
2018-10-23	53	31	42.0	-4.4	23	0	0.00	0.0	0
2018-10-24	53	27	40.0	-6.0	25	0	0.00	0.0	0
2018-10-25	50	36	43.0	-2.7	22	0	0.00	0.0	0
2018-10-26	52	40	46.0	0.7	19	0	T	0.0	0
2018-10-27	49	39	44.0	-1.0	21	0	0.01	0.0	0
2018-10-28	49	43	46.0	1.4	19	0	0.10	0.0	0
2018-10-29	52	40	46.0	1.8	19	0	T	0.0	0
2018-10-30	57	41	49.0	5.2	16	0	0.39	0.0	0
2018-10-31	58	37	47.5	4.1	17	0	0.00	0.0	0
Sum	1743	1219	-	-	538	13	5.36	T	-
Average	56.2	39.3	47.8	-1.1	-	-	-	-	0.0
Normal	58.9	38.8	48.9	-	505	4	2.40	0.5	-

Note: Daily maximum, minimum and average temperature (degrees F), average temperature departure from normal (degrees F), heating and cooling degree days (HDD, CDD) (base 65), precipitation, snowfall and snow depth (inches)

Figure 5.13 A clear day when the sealer was applied on the field study section

The research team is also confident the contractor did not accidently seal this section because verbal confirmation was received from the crew members during the site visit. The start and end of the test section were clearly identified on the pavement with paint marking. In addition, it is worth mentioning that, except SME-PS, the contact angle test results are consistent among the three replica sections (COV as low as 0.5%). Therefore, there is plenty of confidence that the laboratory test results are correct.

There are three reasons to explain the absence of penetrating sealer in the field study:

1. The concrete on this project is high-performance concrete with high strength (average 28-day flexural strength 955 psi, Appendix G) and low permeability, which had a low chance of absorption to start with.
2. The joint saw-cutting process polished the concrete and reduced the permeability.
3. Penetrating sealer applied on a vertical and hydrophobic surface resulted in the liquid material flowing downward along the vertical surface without much penetration into the concrete.

It should be clarified that the absence of penetrating sealer in the field study section does not invalidate the effectiveness of penetrating sealer in reducing the ingress of water and deicing chemicals. The laboratory tests in this study as well as many others in the literature proved that penetrating sealer can significantly reduce the absorption of water. The caution raised by this field study is that penetrating sealer may not provide its intended function for low permeability concrete or when it cannot be practically applied to a vertical surface. A quantitative study would be necessary to investigate at what permeability level the sealer would be ineffective. For accessible vertical surfaces such as building wall, bridge parapet, and other structures, multi-passes may be needed to achieve the required coverage rate (Ohio DOT, 2005). Applying sealers with brush or roller is recommended by the manufacturer. However, these methods are difficult to apply on joint surface of concrete pavement.

It should also be pointed out that the absence of sealer was only observed on one project. As shown in Chapter 3, the presence of sealer was verified on three projects ranging from 2 to 8 years of service. Only with more laboratory tests and field studies on high-performance concrete, can a conclusive statement be drawn.

5.4 Summary

The best practice recommended from laboratory study was implemented on a test section on I-39. Five combinations with three replicas were executed.

1) One year of field performance showed good performance on all joints except for some spalling in the white marking strip area, which is most likely due to the grinding process in preparing for the recessed white marking.
2) A total of 15 core samples were removed after one year of service for lab testing. All core samples were hydrophobic with contact angle exceeding 90°. The samples treated with silane and siloxane had higher contact angle than the control, SME-PS, and lithium silicate mixture.
3) No difference in time to critical saturation was observed between the core samples. No penetration depth was observed for any of the core samples.
4) After ruling out the reason of testing error and saturated concrete during sealing, the absence of sealer was contributed to three possible reasons: (a) high-performance concrete has very low permeability, (b) the polished concrete after saw-cutting is hydrophobic, and (c) application to a vertical surface may not result in an effective coverage since much of the sealer can be lost by flowing downward along the vertical surface.
5) Penetrating sealer may not provide its intended function for low permeability concrete or when it cannot be practically applied to a vertical surface.
6) Further studies are needed to make a firm conclusion on at what permeability level the sealer would be ineffective.

Chapter 6 – Conclusions and Recommendations

6.1 Summary and Conclusions

The objectives of this project were to: (1) evaluate the concrete sealers used to date and their application methods employed to determine if sealing concrete pavement saw cut faces is effective; (2) assess the work done to date to determine if the goal of longer lasting concrete pavement joints is being achieved; and (3) develop standard specification language for applying penetrating sealers to concrete pavement saw cuts along with construction inspection guidelines.

Based on site visits, tests of laboratory samples and core samples from field study, the following conclusions are reached:

1) Although there was no visual detection of the presence of sealers in in-service pavements (at 2, 6, and 8 years of service) previously treated with sealers, laboratory tests proved the presence and functionality through contact angle, absorption, and penetration depth measurements.

2) The depth of penetration ranged from 1.46 mm (0.06 inch) to 11.75 mm (0.46 inch), with an average of 5.14 mm (0.20 inch). Penetration depth seemed to depend on concrete strength; less penetration was associated with high-performance concrete.

3) A general trend of decreasing effectiveness with years of service was observed. However, when compared with the samples without sealer, more than half of the joints with sealer are still performing better in terms of contact angle and absorption after 8.2 years of service.

4) Laboratory study found that sealer is more effective (in terms of water absorption and penetration depth) when applied on dry concrete.

5) All penetrating sealers applied to concrete samples resulted in decreased absorption and extension of time to critical (85%) saturation. For the "FA" concrete, the silane applied in dry condition extends the time to critical saturation 8 times longer than the control sample without silane, indicating silane's capability of extending the service life of concrete.

6) All penetrating sealers evaluated in this project improved deicer scaling performance except for the lithium silicate solution applied to the "A" concrete 30 minutes after sawing activities. Sealers applied to the 7-day old, dry concrete had the best performance.

7) All joints are performing well in the field study section after one year of service.

8) Core samples from the field study section were hydrophobic with contact angle exceeding 90°. There was no difference in time to critical saturation and no sign of sealer presence in the penetration depth test.

9) The absence of sealer in the field study section was attributed to three possible reasons: (a) high-performance concrete has very low permeability, (b) the polished concrete after saw-cutting is hydrophobic, and (c) vertical surface is challenging for effective coverage.

10) Penetrating sealer may not provide its intended function for low permeability concrete or when it cannot be practically applied to a vertical surface.

6.2 Recommendations

1) The effectiveness of penetrating sealer on horizontal surfaces is well established in the laboratory tests and in the literature. Therefore, there is no doubt that bridge decks can be protected by the application of penetrating sealers.

2) Whenever possible, multiple applications of sealer should be encouraged since it provided more reduction in absorption over a single application.

3) Penetrating sealer should be applied on dry concrete after at least 7-day of curing.

4) Among the four products tested in this study, silane and SME-PS were more effective than siloxane and lithium silicate.

5) Before further confirmation of field study, it does not seem effective to apply penetrating sealer on saw cut joint faces of high-performance concrete due to the difficulty of sufficient coverage and penetration.

6) Application of penetrating sealer on joints of regular concrete is effective. The following language is recommended to be added into WisDOT Standard Specification.

415.3.7.1 General

(7) Treat sawed surfaces of transverse and longitudinal joints with a penetrating sealer found on the Department approved products list for Concrete Protective Surface Treatments. Prepare surface by pressure washing all saw slurry from sawed joints and allow to dry thoroughly prior to application of sealer. Apply the product directly to the interior of the sawed joint. Apply additional passes in 10 to 15 minutes to achieve the required coverage rate. Do not use the broadcast spray method of application.

7) Contractors are suggested to use the masonry block setup to test their sprayer system and application method. This method can visually verify the uniformity of coverage.

8) Future studies are recommended to investigate the relationship between sealer effectiveness and concrete permeability/strength.

9) Conduct a long-term performance study of the field test sections to measure effectiveness of the sealer treatments.

10) Research is also needed to find quick and reliable methods to test the moisture content of concrete and to quality control the sealer application on site.

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Appendices

A. Laboratory Testing Results and Statistical Analysis of I-94, I-41, and I-39 Core Samples

Table A.1 Contact Angle of Field Cores

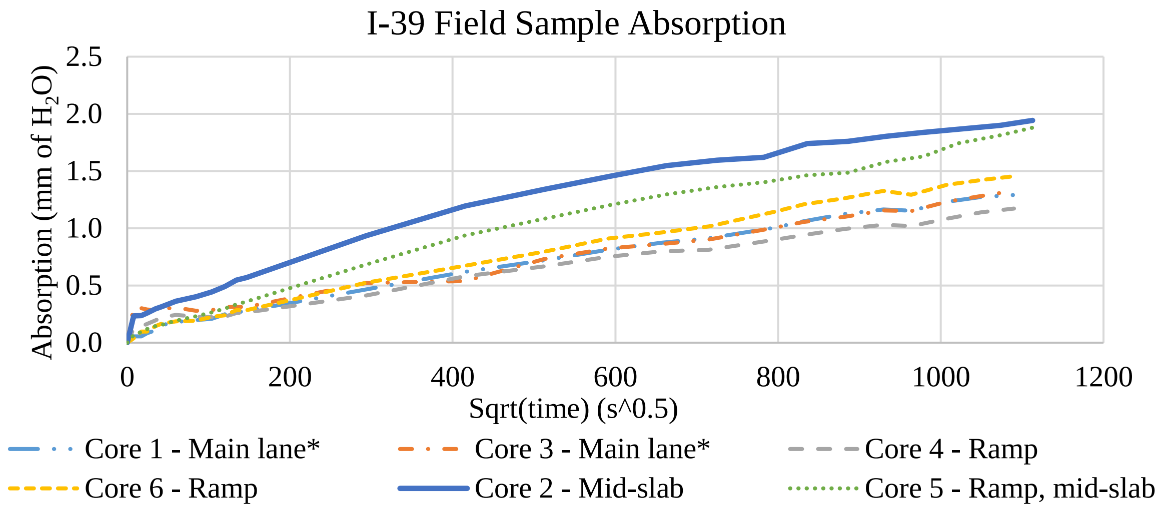
Core #	Sample No.	Contact angle °	Notes	Sealer	Construction Date	Coring Date	Age (yr)	Project
1	01-1	49.50	Main lane	Yes	8/24/2016	8/13/2018	2.0	I-39
1	01-2	97.30	Main lane	Yes	8/24/2016	8/13/2018	2.0	I-39
2	02-1	38.10	Mid-slab	No	8/24/2016	8/13/2018	2.0	I-39
2	02-2	36.60	Mid-slab	No	8/24/2016	8/13/2018	2.0	I-39
3	03-1	35.30	Main lane	Yes	8/24/2016	8/13/2018	2.0	I-39
3	03-2	38.30	Main lane	Yes	8/24/2016	8/13/2018	2.0	I-39
4	04-1	55.00	Ramp	No	8/24/2016	8/13/2018	2.0	I-39
4	04-2	37.40	Ramp	No	8/24/2016	8/13/2018	2.0	I-39
5	05-1	30.00	Ramp, mid-slab	No	8/24/2016	8/13/2018	2.0	I-39
5	05-2	41.30	Ramp, mid-slab	No	8/24/2016	8/13/2018	2.0	I-39
6	06-1	7.30	Ramp	No	8/24/2016	8/13/2018	2.0	I-39
6	06-2	22.70	Ramp	No	8/24/2016	8/13/2018	2.0	I-39
7	07-1	53.60	Good joint	Yes	7/16/2010	8/20/2018	8.2	I-94
7	07-2	55.00	Good joint	Yes	7/16/2010	8/20/2018	8.2	I-94
8	08-1	14.80	Spalled joint	Yes	7/16/2010	8/20/2018	8.2	I-94
8	08-2	34.80	Spalled joint	Yes	7/16/2010	8/20/2018	8.2	I-94
9	09	47.70	Mid-slab	No	7/16/2010	8/20/2018	8.2	I-94
10	10-1	59.00	Good joint	Yes	7/16/2010	8/20/2018	8.2	I-94
10	10-2	15.70	Good joint	Yes	7/16/2010	8/20/2018	8.2	I-94
11	11-1	56.60	Spalled joint	Yes	7/16/2010	8/20/2018	8.2	I-94
12	12-1	55.60	Spalled joint	Yes	7/16/2010	8/20/2018	8.2	I-94
12	12-2	58.30	Spalled joint	Yes	7/16/2010	8/20/2018	8.2	I-94
13	13-1	74.40	Good joint	Yes	6/7/2012	8/22/2018	6.3	I-41
13	13-2	49.20	Good joint	Yes	6/7/2012	8/22/2018	6.3	I-41
14	14-1	77.00	Spalled Joint	Yes	6/7/2012	8/22/2018	6.3	I-41
14	14-2	22.10	Spalled joint	Yes	6/7/2012	8/22/2018	6.3	I-41
15	15	58.70	Mid-slab	No	6/7/2012	8/22/2018	6.3	I-41
16	16-1	34.70	Good joint	Yes	6/7/2012	8/22/2018	6.3	I-41
16	16-2	56.00	Good joint	Yes	6/7/2012	8/22/2018	6.3	I-41
17	17-1	54.70	Spalled joint	Yes	6/7/2012	8/22/2018	6.3	I-41
17	17-2	43.70	Spalled joint	Yes	6/7/2012	8/22/2018	6.3	I-41

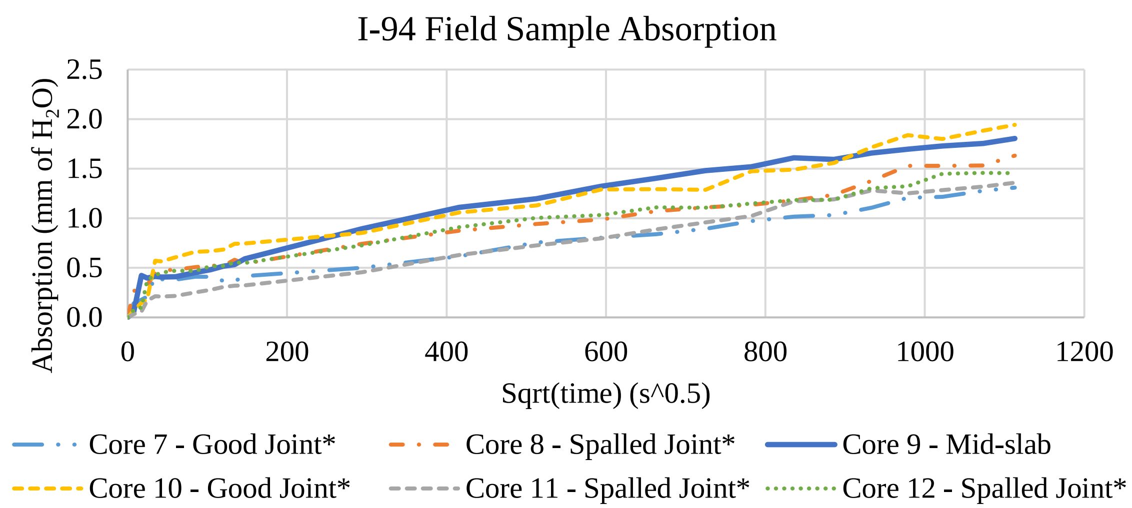
Table A.2 14-day Absorption of Field Cores

Core Number	Average 14 day Absorption (mm)	Notes	Sealer	Construction Date	Coring Date	Age (yr)	Project
1	1.29	Main lane	Yes	8/24/2016	8/13/2018	2.0	I-39
2	1.94	Mid-slab	No	8/24/2016	8/13/2018	2.0	I-39
3	1.32	Main lane	Yes	8/24/2016	8/13/2018	2.0	I-39
4	1.17	Ramp	No	8/24/2016	8/13/2018	2.0	I-39
5	1.88	Ramp, mid-slab	No	8/24/2016	8/13/2018	2.0	I-39
6	1.45	Ramp	No	8/24/2016	8/13/2018	2.0	I-39
7	1.31	Good joint	Yes	7/16/2010	8/20/2018	8.2	I-94
8	1.63	Spalled joint	Yes	7/16/2010	8/20/2018	8.2	I-94
9	1.80	Mid-slab	No	7/16/2010	8/20/2018	8.2	I-94
10	1.94	Good joint	Yes	7/16/2010	8/20/2018	8.2	I-94
11	1.36	Spalled joint	Yes	7/16/2010	8/20/2018	8.2	I-94
12	1.46	Spalled joint	Yes	7/16/2010	8/20/2018	8.2	I-94
13	1.49	Good joint	Yes	6/7/2012	8/22/2018	6.3	I-41
14	0.99	Spalled Joint	Yes	6/7/2012	8/22/2018	6.3	I-41
15	2.54	Mid-slab	No	6/7/2012	8/22/2018	6.3	I-41
16	1.01	Good joint	Yes	6/7/2012	8/22/2018	6.3	I-41
17	1.00	Spalled joint	Yes	6/7/2012	8/22/2018	6.3	I-41

Table A.3 Depth of Penetration of Field Cores

Core No.	Test No.	Depth (mm)	Core#	Notes	Sealer	Construction Date	Coring Date	Age (yr)	Project
1-1	1	2.22	1	Main lane	Yes	8/24/2016	8/13/2018	2.0	I-39
1-1	2	2.03	1	Main lane	Yes	8/24/2016	8/13/2018	2.0	I-39
3-1	1	2.43	3	Main lane	Yes	8/24/2016	8/13/2018	2.0	I-39
3-1	2	2.44	3	Main lane	Yes	8/24/2016	8/13/2018	2.0	I-39
14-1	1	4.82	14	Spalled Joint	Yes	6/7/2012	8/22/2018	6.3	I-41
14-1	2	4.6	14	Spalled Joint	Yes	6/7/2012	8/22/2018	6.3	I-41
16-1	1	7.84	16	Good joint	Yes	6/7/2012	8/22/2018	6.3	I-41
16-1	2	6.03	16	Good joint	Yes	6/7/2012	8/22/2018	6.3	I-41
17-1	1	4.94	17	Spalled joint	Yes	6/7/2012	8/22/2018	6.3	I-41
17-1	2	6.26	17	Spalled joint	Yes	6/7/2012	8/22/2018	6.3	I-41
C07-1	1	3.47	7	Good joint	Yes	7/16/2010	8/20/2018	8.2	I-94
C07-1	2	5.95	7	Good joint	Yes	7/16/2010	8/20/2018	8.2	I-94
C08-1	1	1.76	8	Spalled joint	Yes	7/16/2010	8/20/2018	8.2	I-94
C08-1	2	3.48	8	Spalled joint	Yes	7/16/2010	8/20/2018	8.2	I-94
C10-1	1	11.75	10	Good joint	Yes	7/16/2010	8/20/2018	8.2	I-94
C10-1	2	9.86	10	Good joint	Yes	7/16/2010	8/20/2018	8.2	I-94
C11-1	1	6.01	11	Spalled joint	Yes	7/16/2010	8/20/2018	8.2	I-94
C11-1	2	8.49	11	Spalled joint	Yes	7/16/2010	8/20/2018	8.2	I-94
C12-1	1	1.46	12	Spalled joint	Yes	7/16/2010	8/20/2018	8.2	I-94
C12-1	2	2.28	12	Spalled joint	Yes	7/16/2010	8/20/2018	8.2	I-94
C13-1	1	7.65	13	Good joint	Yes	6/7/2012	8/22/2018	6.3	I-41
C13-1	2	7.22	13	Good joint	Yes	6/7/2012	8/22/2018	6.3	I-41





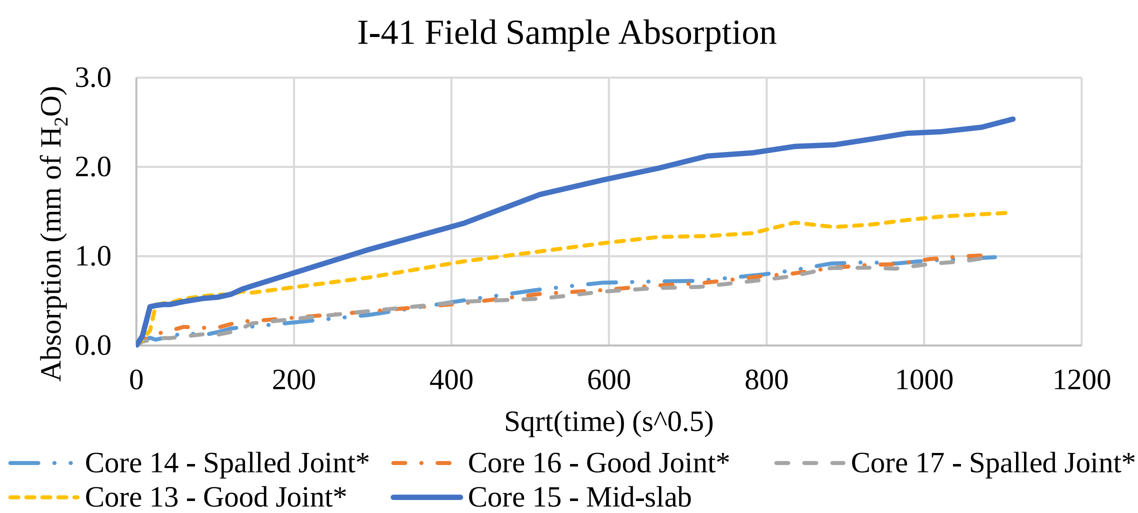


Figure A.1 Absorption of Core Samples from I-94, I-41, and I-39

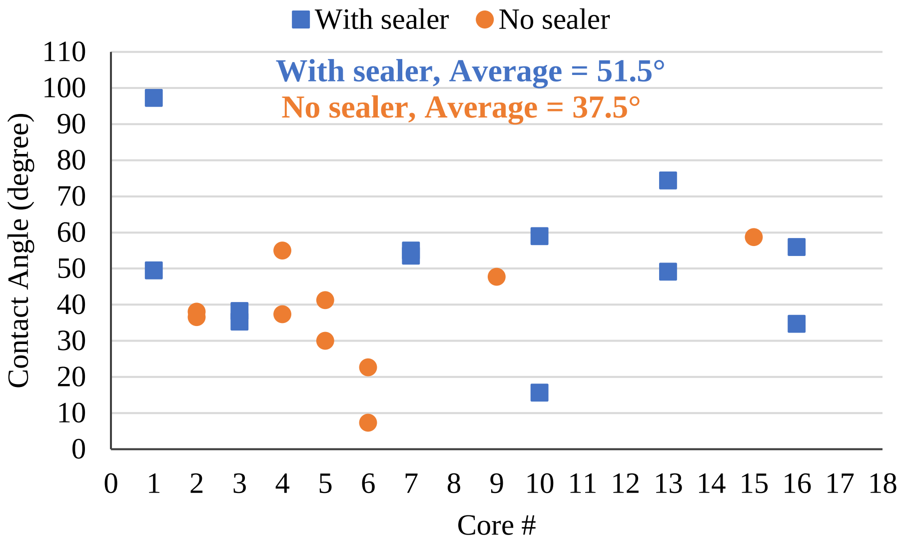


Figure A.2 Contact Angle of Core Samples from I-94, I-41, and I-39

Table A.4 Analysis of Variance of Contact Angle with and without Sealer

Anova: Single Factor						
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*	*Std.Dev.*	
No sealer	10	374.8	37.5	229.19	15.14	
With sealer	12	618	51.5	429.55	20.73	
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	1072.148	1	1072.15	3.16	0.09	4.35
Within Groups	6787.736	20	339.39			
Total	7859.884	21				

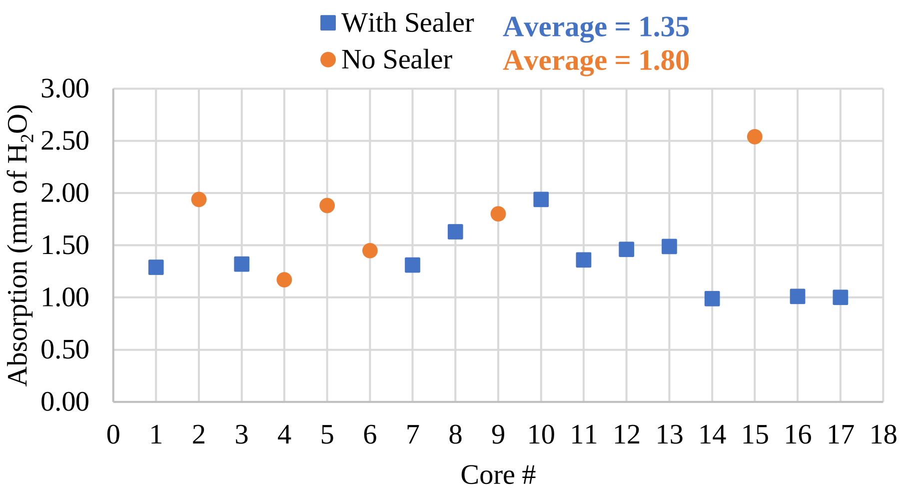


Figure A.3 Absorption of Core Samples from I-94, I-41, and I-39

Table A.5 Analysis of Variance of Absorption with and without Sealer

Anova: Single Factor						
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*	*Std.Dev.*	
With Sealer	11	14.8	1.35	0.08	0.29	
No Sealer	6	10.78	1.80	0.22	0.47	
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.79	1	0.79	6.16	0.03	4.54
Within Groups	1.92	15	0.13			
Total	2.72	16				

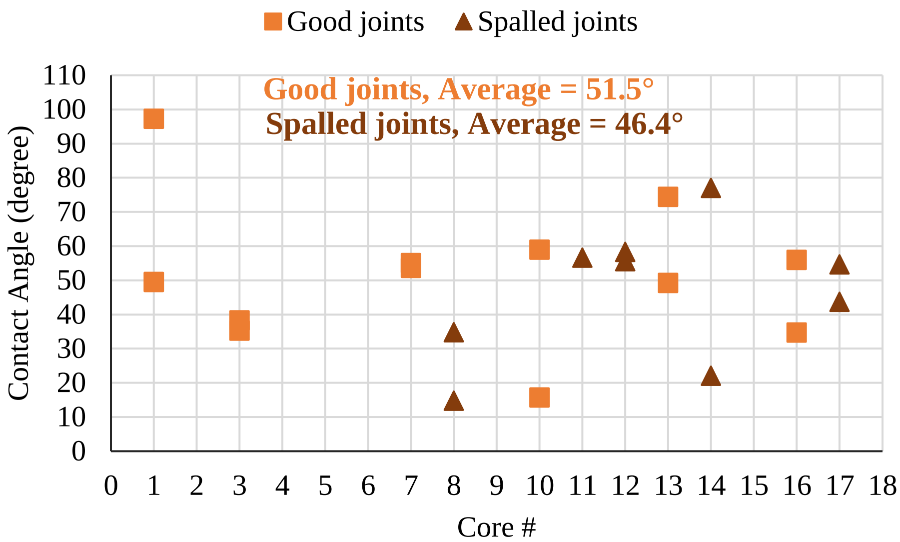


Figure A.4 Contact Angle of Good Joints and Spalled Joints from I-94, I-41, and I-39

Table A.6 Analysis of Variance of Contact Angle (Good Joints vs. Spalled Joints)

Anova: Single Factor						
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*	*Std.Dev.*	
Good	12	618	51.5	429.55	20.73	
Spalled	9	417.6	46.4	383.30	19.58	
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	133.77	1	133.77	0.33	0.57	4.38
Within Groups	7791.50	19	410.08			
Total	7925.27	20				

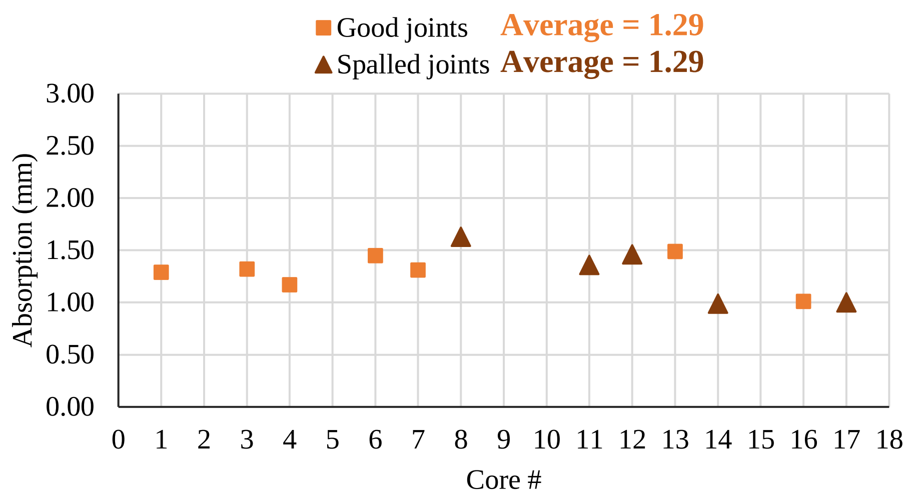


Figure A.5 Absorption of Good Joints and Spalled Joints from I-94, I-41, and I-39

Table A.7 Analysis of Variance of Absorption (Good Joints vs. Spalled Joints)

Anova: Single Factor						
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*	*Std.Dev.*	
Goog joints	7	9.04	1.29	0.03	0.16	
Spalled joints	5	6.44	1.29	0.08	0.28	
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	3.42857E-05	1	3.42857E-05	0.00071	0.98	4.96
Within Groups	0.483165714	10	0.048316571			
Total	0.4832	11				

B. PCC Mix Design with Optimized Gradation for Laboratory Study

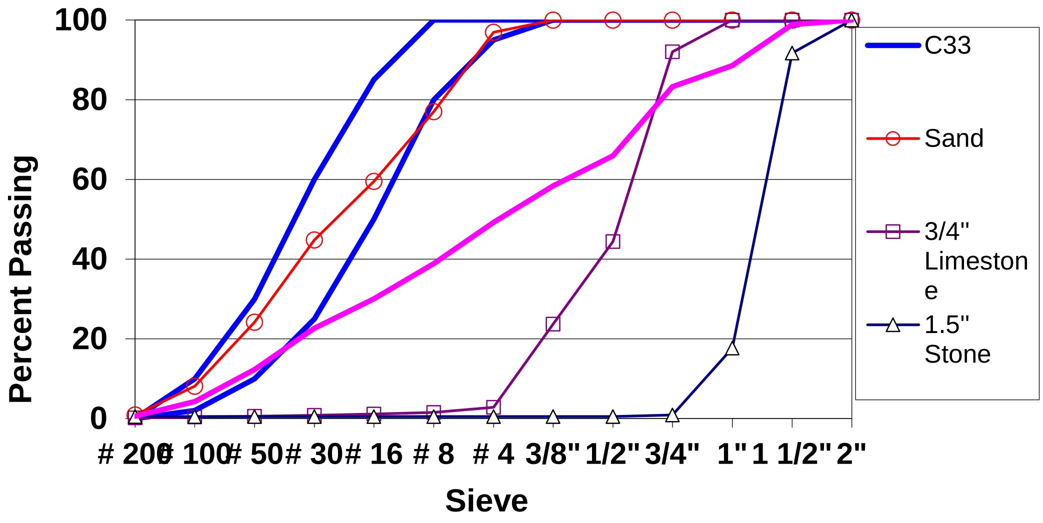


Figure B.1 Aggregate Gradations

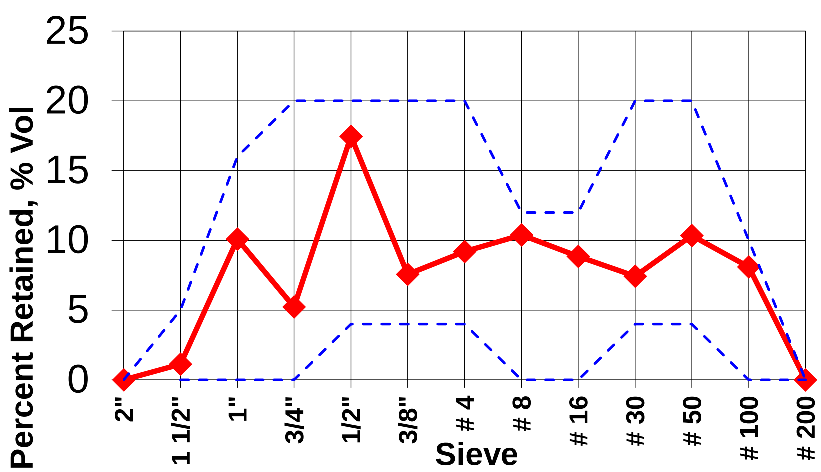


Figure B.2 Tarantula Curve Combined Aggregate Gradation

C. UM-KC Laboratory Study Results

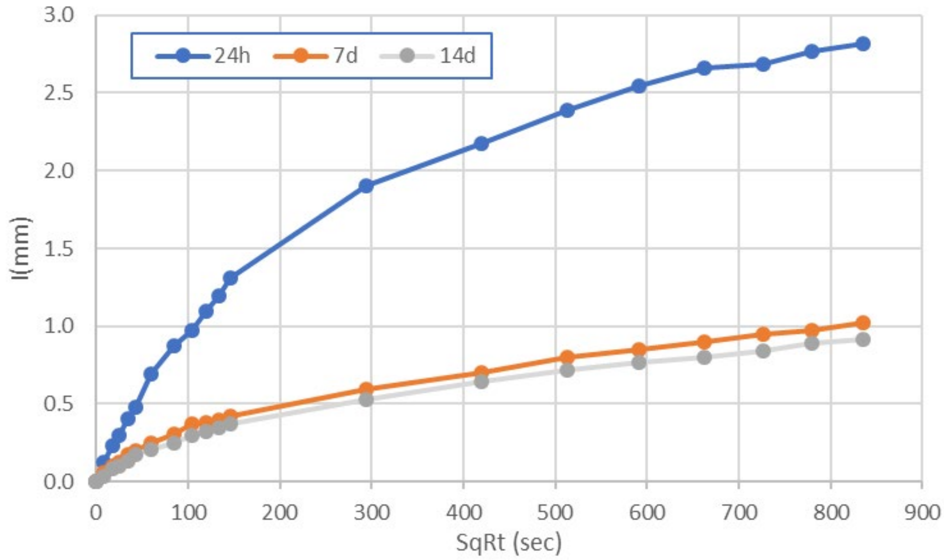


Figure C.1 Phase I Mortar Absorption Results as a Function of Curing Time (Times shown are length of moist curing before the prerequisite 14d drying time required by ASTM C1585 prior to testing)

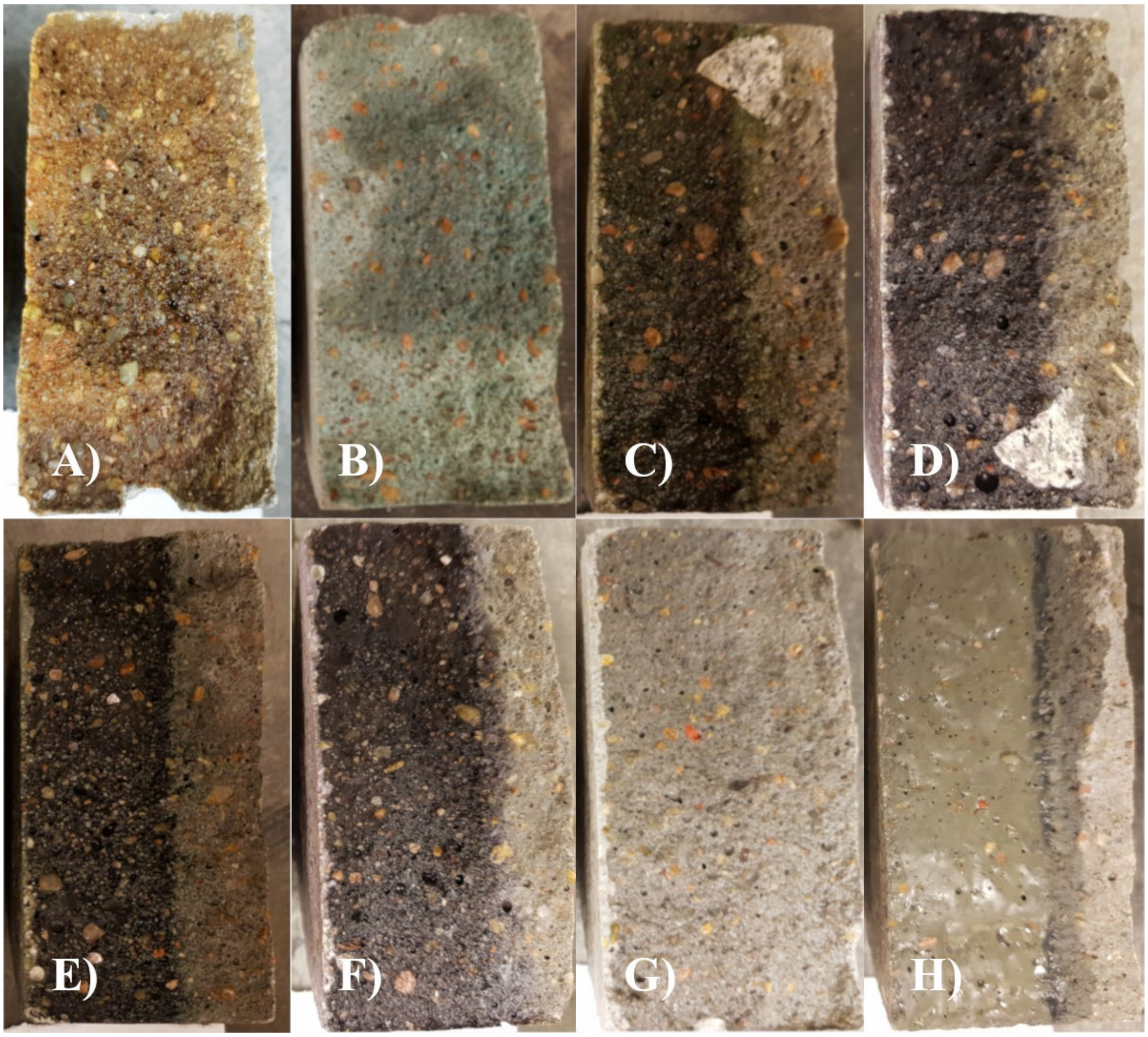


Figure C.2 Preliminary Dye Testing for Depth of Penetration (A) Cola AS, B) Azure Blue AS, C) Green Apple LRD, D) Navy Blue LRD, E) Dark Green PRD, F) Navy Blue PRD, G) Blue FC, H) Antique Gray WB

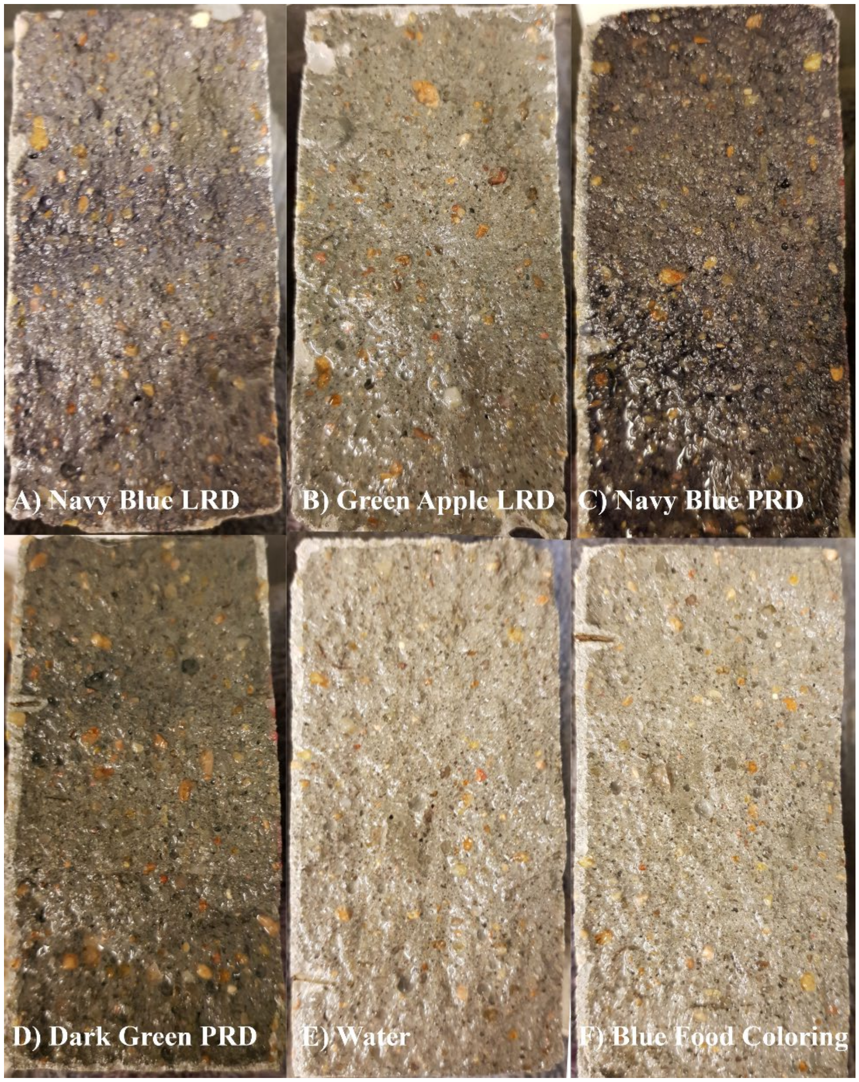


Figure C.3 Secondary Dye Testing for Depth of Penetration

Figure C.4 FA Control after 50 Cycles

Figure C.5 FA Silane applied dry after 50 Cycles

Figure C.6 FA Silane applied moist after 30 minutes after 50 Cycles

Figure C.7 FA SME-PS applied dry after 50 Cycles

Figure C.8 FA Lithium Silicate mixture applied moist after 30 minutes after 50 Cycles

D. Record of Sealer Application in the Field Study

Paving date: 9/28/2018, Main lane, sealer applied at 20th day, cone nozzle, 0.2 GPM, 2 round application

Date	Time	Starting Joint #	Ending joint #	Sealer Type	Main Chemical	Sp.Gr.	Unit Wt. (lb/gal)
18-Oct	10:30am	1	10	Aquanil Plus 40	40% Silane	0.84	6.93
18-Oct		11	20	SaltGuard WB	Silane/Siloxane	0.997	8.24
18-Oct		21	30	CSH Sustain Krete	SME-PS	0.88	7.34
18-Oct		31	40	Consolideck LS	Lithium Silicate	1.1	9.20
18-Oct		41	50	None			
18-Oct		51	60	Aquanil Plus 40	40% Silane	0.84	6.93
18-Oct		61	70	SaltGuard WB	Silane/Siloxane	0.997	8.24
18-Oct		71	80	CSH Sustain Krete	SME-PS	0.88	7.34
18-Oct	2:00pm	81	90	Consolideck LS	Lithium Silicate	1.1	9.20
18-Oct		91	100	None			
18-Oct	3:30pm	101	110	Aquanil Plus 40	40% Silane	0.84	6.93
18-Oct		111	120	SaltGuard WB	Silane/Siloxane	0.997	8.24
18-Oct		121	130	CSH Sustain Krete	SME-PS	0.88	7.34
18-Oct		131	140	Consolideck LS	Lithium Silicate	1.1	9.20
18-Oct		141	150	None			
18-Oct		151	160	Aquanil Plus 40	40% Silane	0.84	6.93
18-Oct	6:00pm	161	170	Aquanil Plus 40	40% Silane	0.84	6.93

Starting Joint #	Ending joint #	Initial Wt. (lb)	After Wt. (lb)	Net Wt. (lb)	Vol. (gal.)	Coverage (sq.ft.)	Unit Coverage (sq.ft./gal.)	Notes
1	10	27.88	22.26	5.62	0.81	130	160	clear, colorless, Petroleum Solvent Odor
11	20	31.58	24.20	7.38	0.90	130	145	white liquid, odorless
21	30	27.66	21.42	6.24	0.85	130	153	Pale yellow liquid, mild odor, very light, wind blows it easily
31	40	32.82	24.84	7.98	0.87	130	150	Clear, colorless, odorless liquid
41	50							
51	60	22.26	16.06	6.20	0.89	130	145	
61	70	24.20	16.42	7.78	0.94	130	138	
71	80	21.42	14.40	7.02	0.96	130	136	
81	90	24.84	16.74	8.10	0.88	130	148	
91	100							
101	110	26.52	20.44	6.08	0.88	130	148	
111	120	30.74	23.16	7.58	0.92	130	141	
121	130	28.46	21.52	6.94	0.95	130	137	
131	140	22.58	14.6	7.98	0.87	130	150	
141	150							
151	160	28.4	22.54	5.86	0.85	130	154	0.2 GPM nozzle, 3 rounds application
161	170	22.54	15.78	6.76	0.98	130	133	0.5 GPM nozzle, 2 rounds application (both perpendicular to joints)

E. One Year Performance of Field Study on I-39

Date of Concrete Construction: 9/28/2018 Date of Sealer Application: 10/18/2018
Date of Opening to Traffic: 10/24/2018 Date of 1st Site Visit: 2/13/2019
Date of 2nd Site Visit: 5/14/2019, 12 small spalls were observed in the following joints

Joint #	Sealer Type	Main Chemical
53	Aquanil Plus 40	40% Silane
104	Aquanil Plus 40	40% Silane
106	Aquanil Plus 40	40% Silane
137	Consolideck LS	Lithium Silicate
71	CSH Sustain Krete	SME-PS
72	CSH Sustain Krete	SME-PS
73	CSH Sustain Krete	SME-PS
76	CSH Sustain Krete	SME-PS
127	CSH Sustain Krete	SME-PS
42	None	
65	SaltGuard WB	Silane/Siloxane
69	SaltGuard WB	Silane/Siloxane

Date of 3rd Site Visit: 8/2/2019, 23 small spalls were observed in the following joints

Joint #	Sealer Type	Main Chemical
53	Aquanil Plus 40	40% Silane
102	Aquanil Plus 40	40% Silane
104	Aquanil Plus 40	40% Silane
106	Aquanil Plus 40	40% Silane
85	Consolideck LS	Lithium Silicate
137	Consolideck LS	Lithium Silicate
71	CSH Sustain Krete	SME-PS
72	CSH Sustain Krete	SME-PS
73	CSH Sustain Krete	SME-PS
76	CSH Sustain Krete	SME-PS
77	CSH Sustain Krete	SME-PS
120	CSH Sustain Krete	SME-PS
126	CSH Sustain Krete	SME-PS
127	CSH Sustain Krete	SME-PS
41	None	
42	None	
43	None	
44	None	
45	None	
91	None	
63	SaltGuard WB	Silane/Siloxane
65	SaltGuard WB	Silane/Siloxane
69	SaltGuard WB	Silane/Siloxane

F. Laboratory Testing Results of I-39 Core Samples

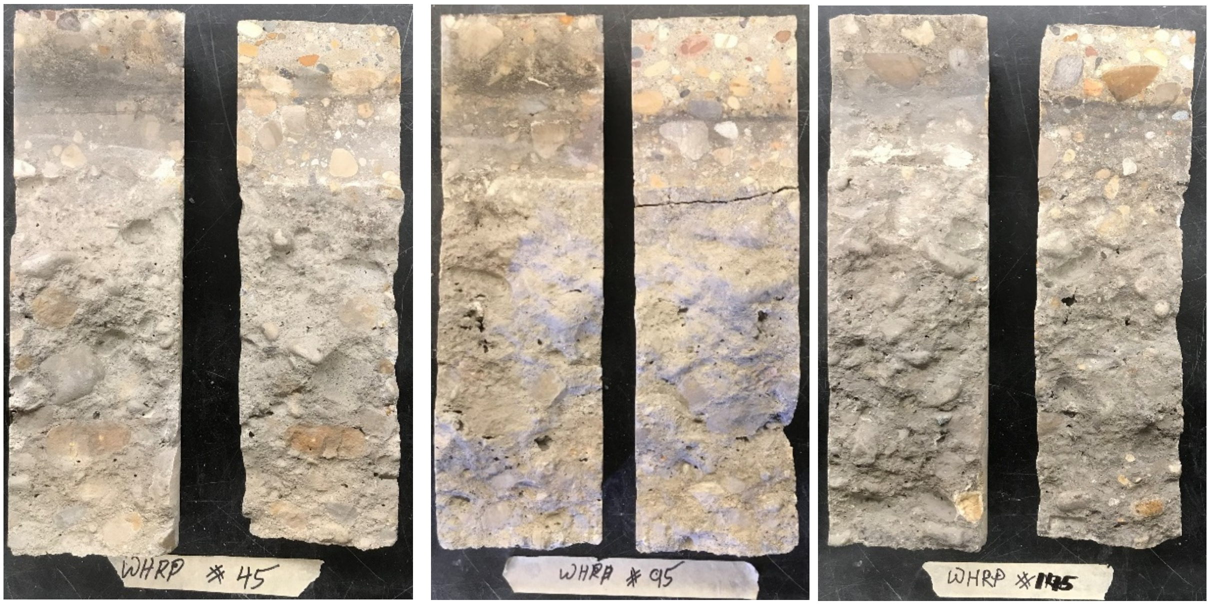


Figure F.1 I-39 Control Core Samples, as-received left, cleaned right

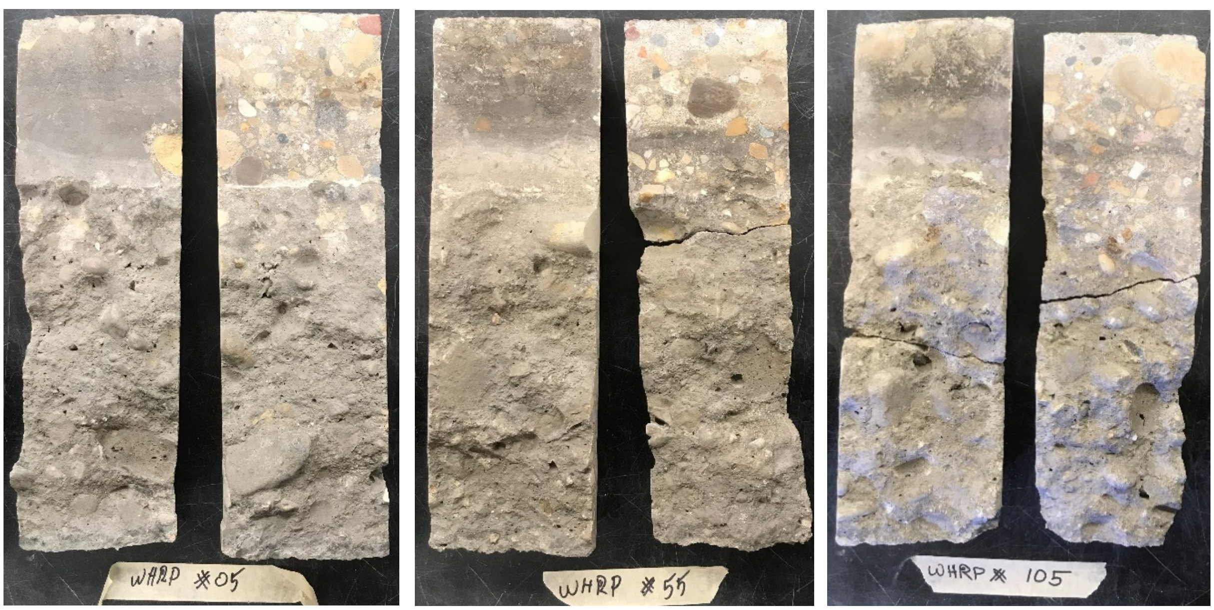


Figure F.2 I-39 Silane-Treated Core Samples, as-received left, cleaned right

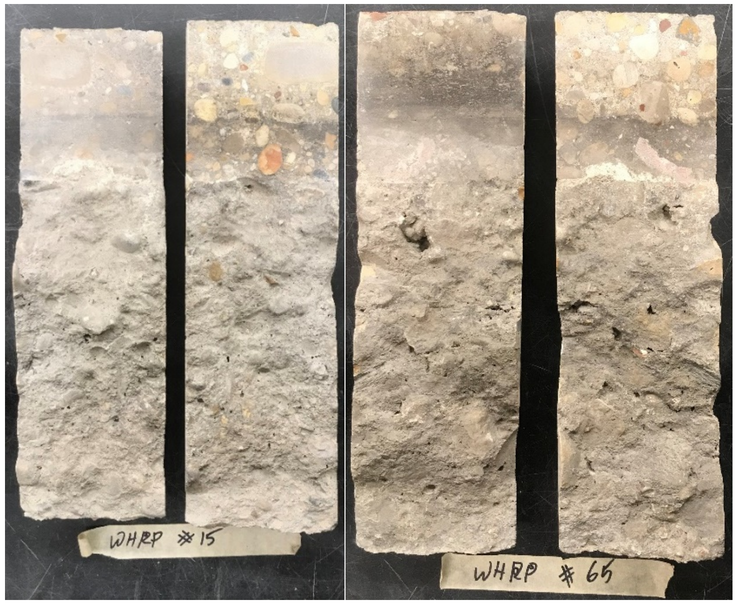


Figure F.3 I-39 Siloxane Mixture-Treated Core Samples, as-received left, cleaned right

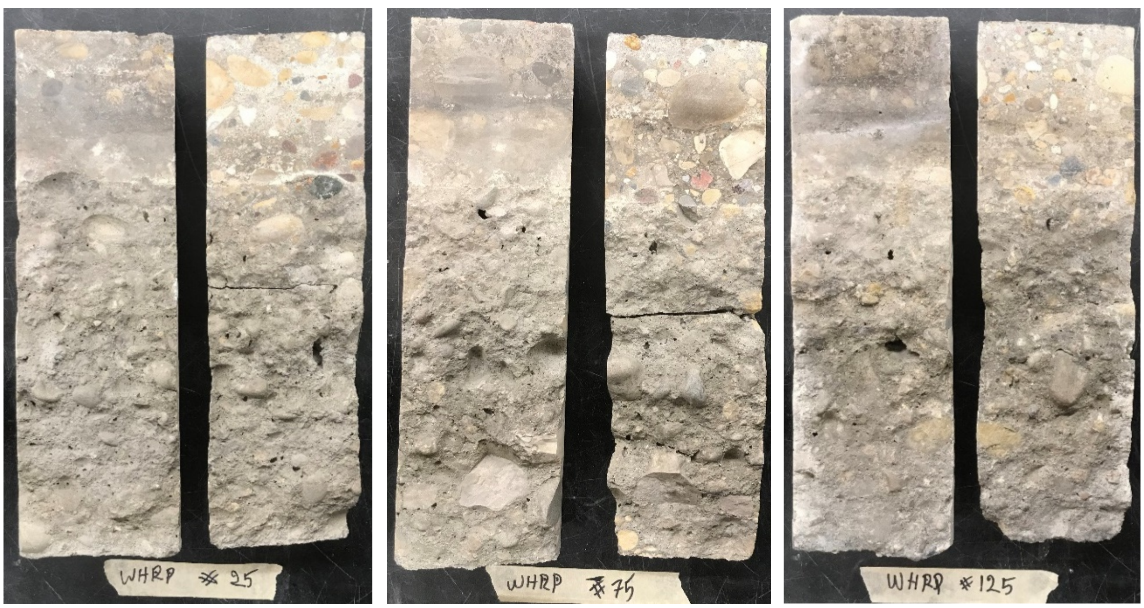


Figure F.4 I-39 SME-PS Treated Core Samples, as-received left, cleaned right

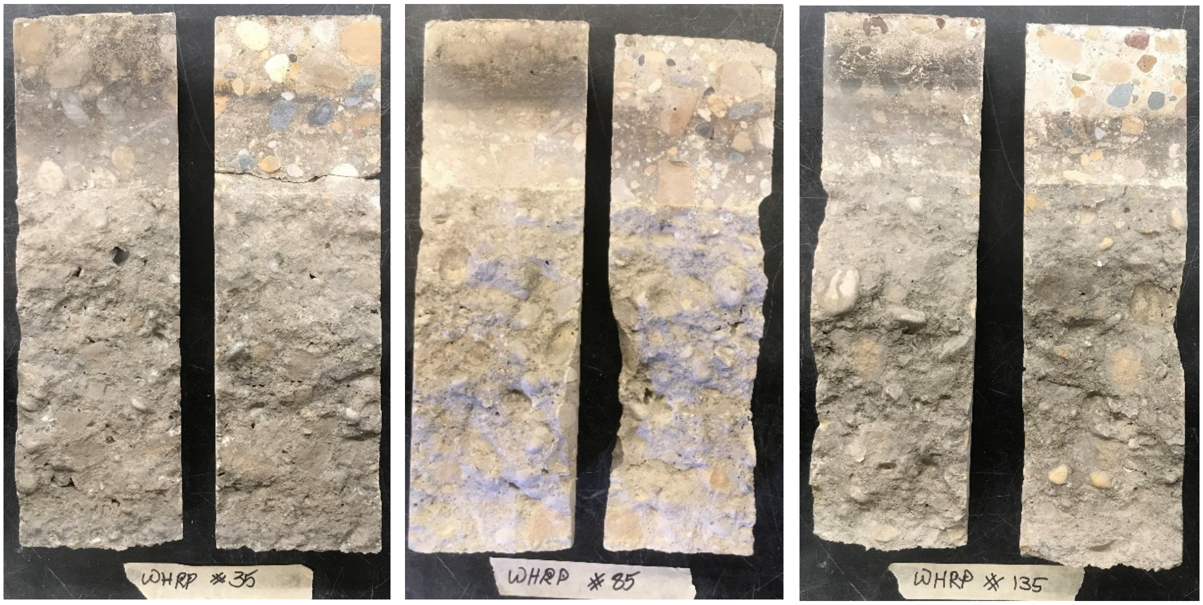


Figure F.5 I-39 Lithium Silicate Mixture-Treated Core Samples, as-received left, cleaned right

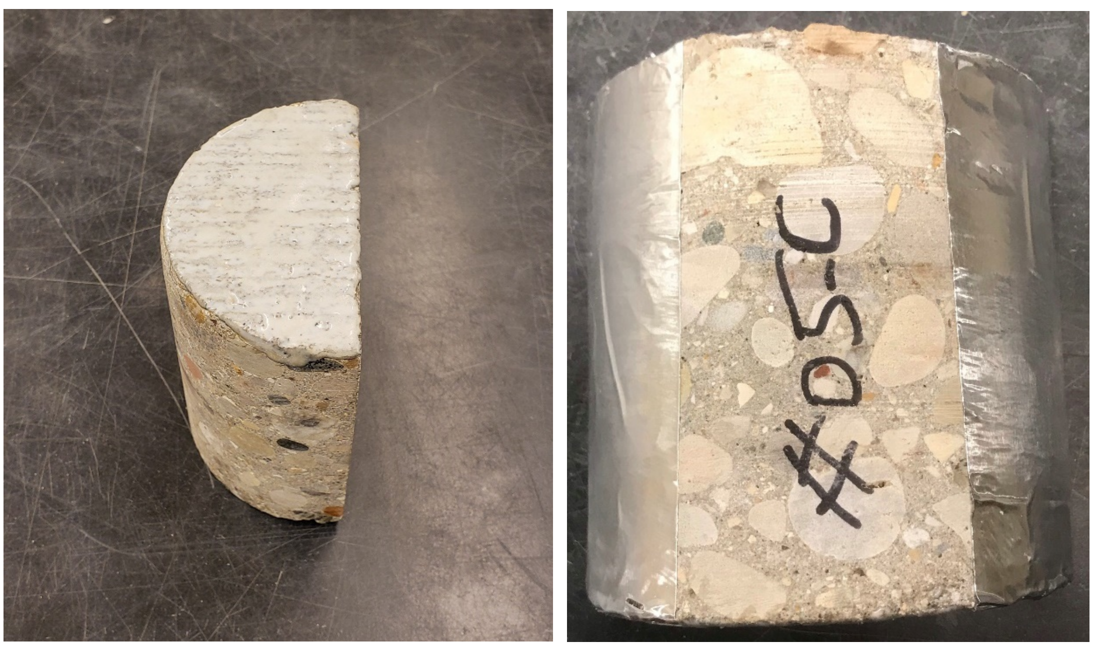


Figure F.6 Preparation of Core Samples for Absorption Testing, epoxy-coating surface (left) and aluminum tape on shoulders and exposed top (right)

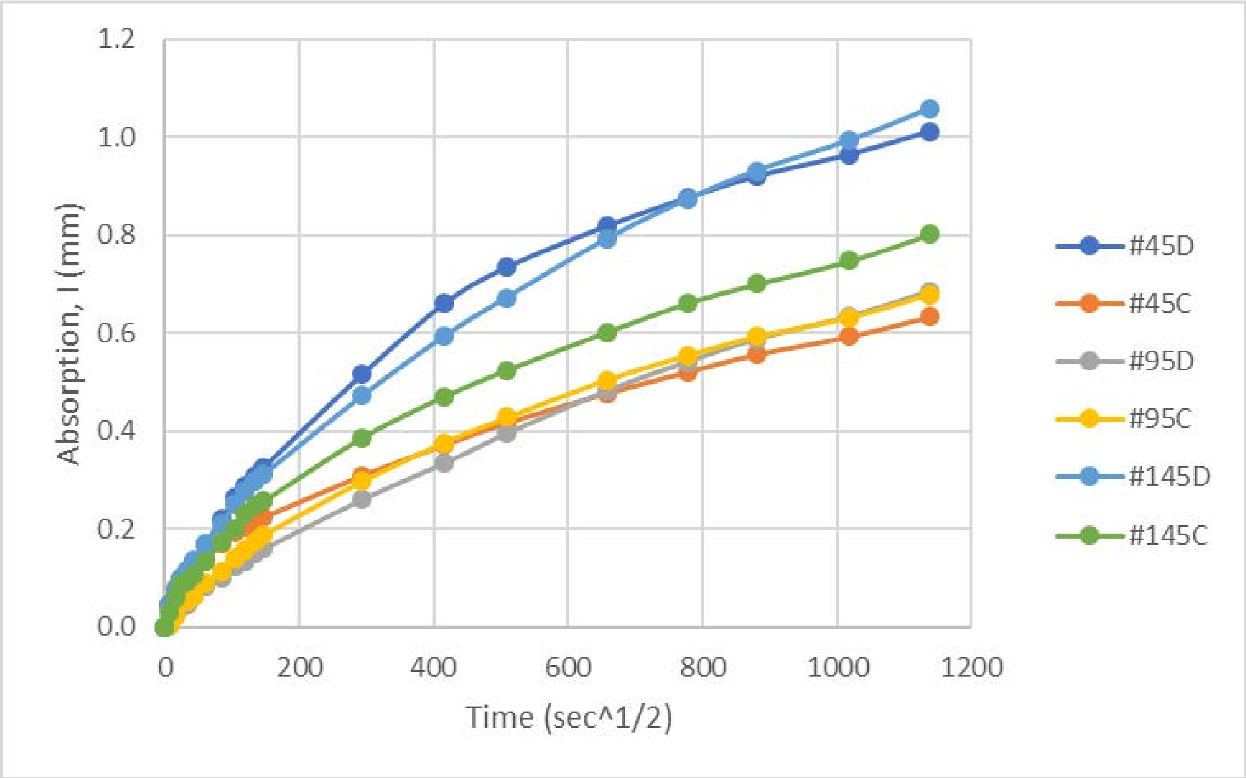


Figure F.7 I-39 Untreated Control Core Absorption

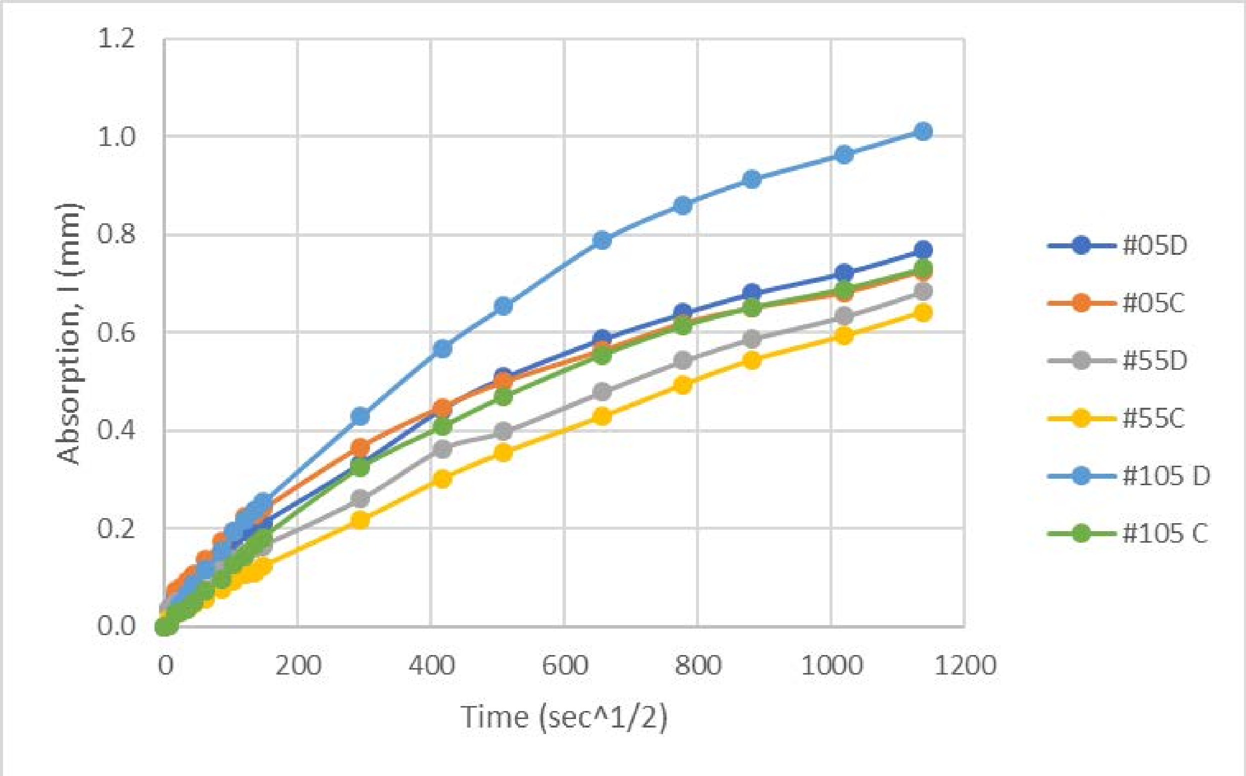


Figure F.8 I-39 Silane-Treated Core Absorption

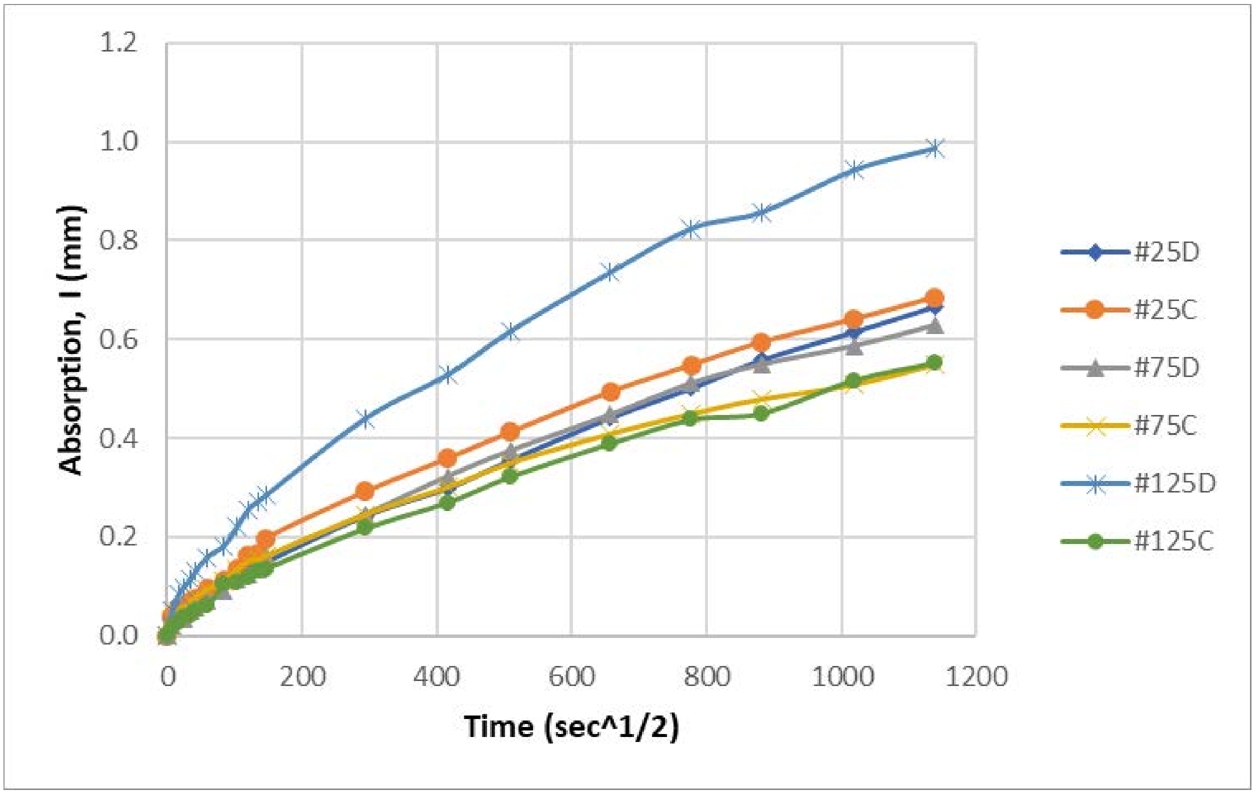


Figure F.9 I-39 SME-PS-Treated Core Absorption

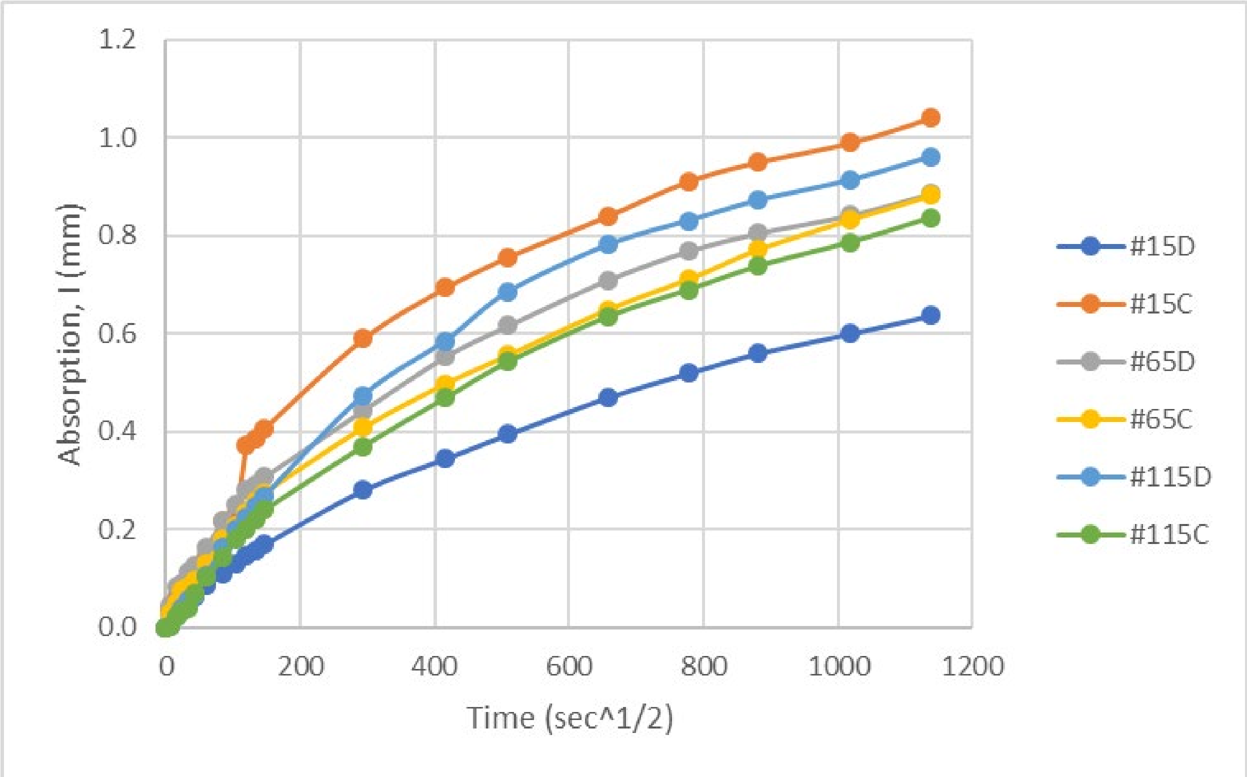


Figure F.10 I-39 Siloxane Mixture-Treated Core Absorption

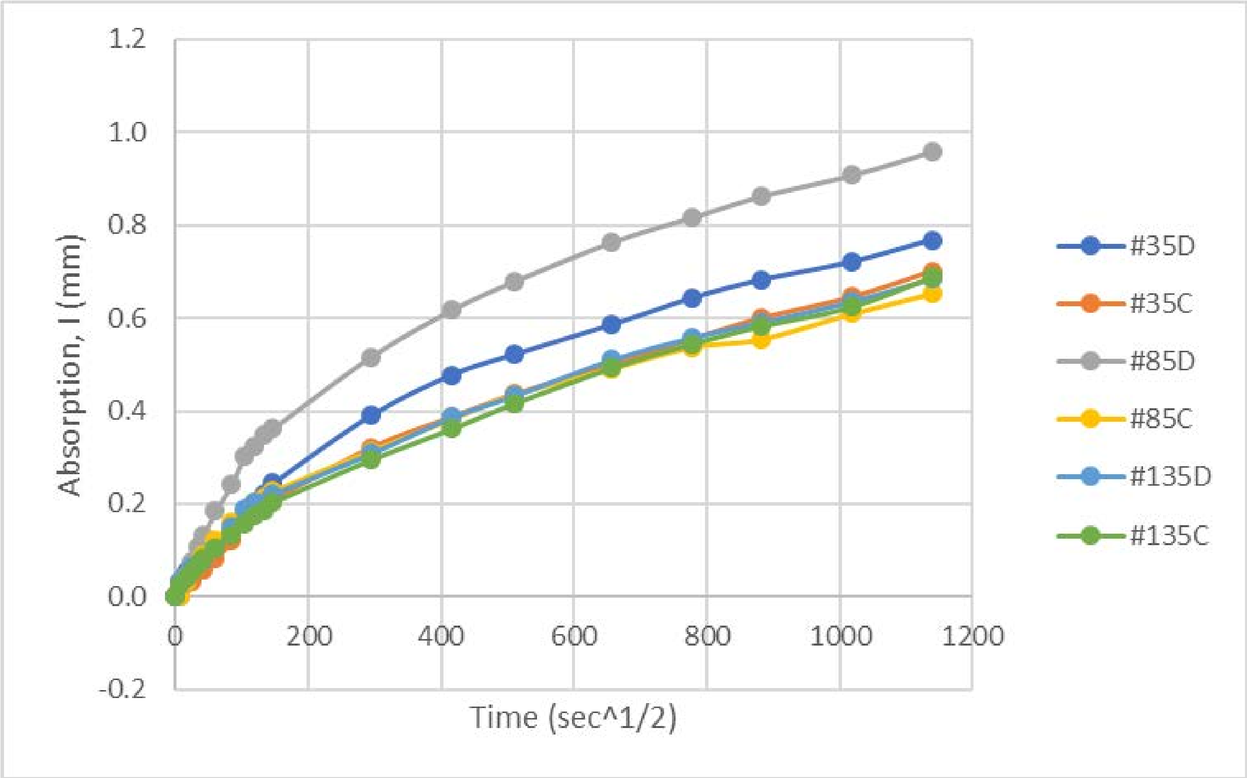


Figure F.11 I-39 Lithium Silicate Mixture-Treated Core Absorption

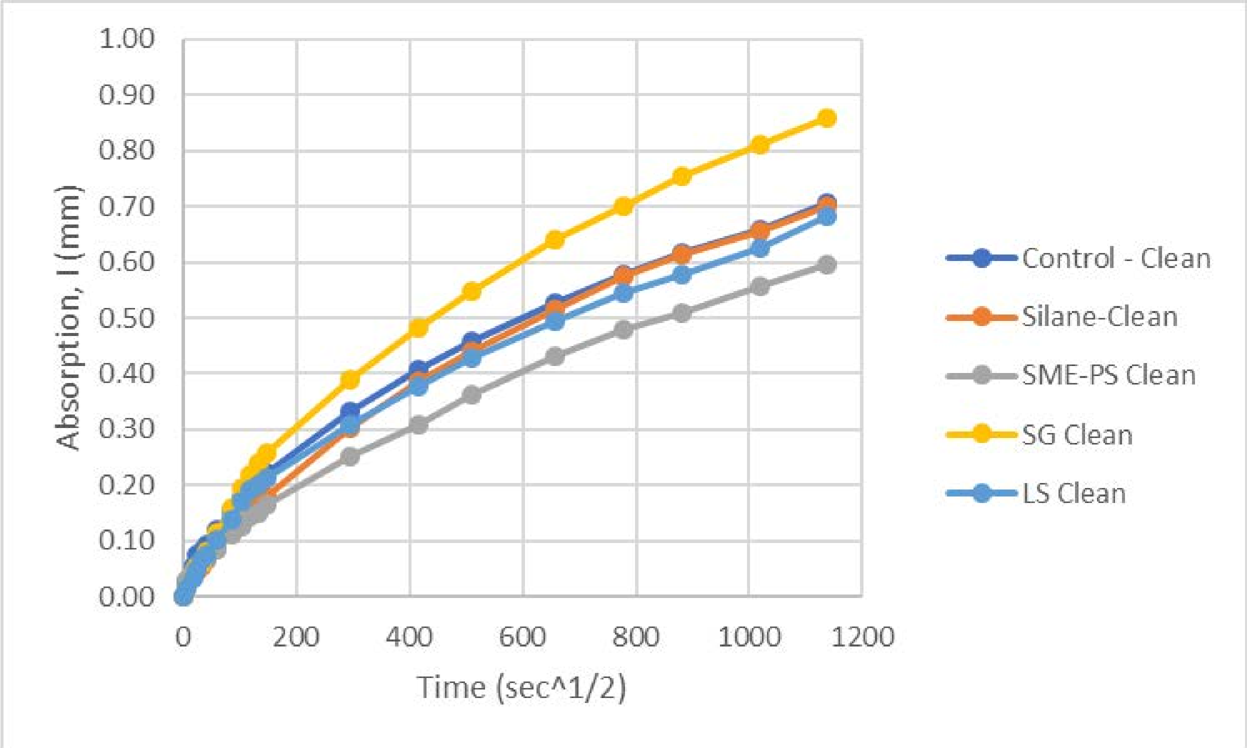


Figure F.12 I-39 Average Clean Core Absorption

G. Quality Control Result of Concrete in the Field Study Section

Test Number: 095.526 - 133 - 0072 - 2018

Materials Laboratory Testing System Tests On:
Concrete Flexure Strength
Type: QV - QUALITY VERIFICATION

55-53-017-PIT
HURD PIT

Lab Site
Behnke Materials Engineering
Site 1
1209 Elmwood Ave
Beloit, WI 53511

Main Project ID: 1007-11-74
Illinois State Line - Madison
S.Dane Cty Line To E.Church Rd,Sb
IH 39, Dane County

Qty Represented:
Units Represented:

Date Received:	**Date Tested:**	**Date Sampled**
10/01/18	10/26/18	09/28/18
	By: Steve Osborne / 106006	By: Timothy Schmidt / 102785

Source: 55-53-017-PIT : HURD PIT **Legal Desc:** NW, SW, Section: 15, T: 4 N, R: 12, E **County:** ROCK

SPECIFICATION: AASHTO T22

Grade: A-FA **Cement:** Content: 365 **Class:** AE

● Fly Ash ○ Pozzolan
Content: Content: 156
Source: ST. MARYS LABADIE
Class: C

Slag: Content:
Source:
Grade: 100
Lot: 217 **Sublot:** 217B

Aggregate Sources:
Fine: HURD PIT
Course: LATHER
Other: PRAIRIE AVE CONCRETE

Brand/Mill: St. Marys-Charlevoix,MI
Type: 2

Sample Location: STA: 1869+24 SB (12"LT-38'LT)
Concrete Supplier: Trierweiler - Portable

Admixtures:

	Brand and Trade Name	Dosage Rate
1	Polychem SA	4.00
2	Dynamon SX	4.00
3	Polychem 400 NC	3.00

133 Flexural Strength of Concrete Beams

Beam Number	Avg Width	Avg Depth	Length	Max Load	Modulus of Rupture	Age (Days)	Exclude Beam
0567	6.13	6.02	18.00	10961	885	28	Y
Point of Fracture	Within the middle third of span length						
0566	6.12	6.01	18.00	12071	985	28	
Point of Fracture	Within the middle third of span length						
0565	6.13	6.02	18.00	11395	925	28	
Point of Fracture	Within the middle third of span length						
				Beam Avg	955		

Total Aggregate: 3,170 **Fine Aggregate:** 41 % **Slump:** %

Net Air: 6.1 %

Lab certifies strength is per ASTM C39. Other data not certified. Conical break unless otherwise noted.

Verified Date: 10/26/2018 **Verified By:** SIGNE REICHELT

H. Synopsis of Literature Review

Sealers for Pavement Joint Durability

(Golias et al., 2012)

Soy methyl ester–polystyrene (SME-PS) is derived from soybeans and has demonstrated an ability to reduce fluid absorption in concrete when used as a topical treatment. The focus of this research is on evaluating the effectiveness of SME-PS at increasing the durability of concrete, especially in a freeze–thaw environment. This work examines the influence of SME-PS for reducing water absorption, freeze–thaw durability, and the ingress of chlorides ions.

It was observed that the penetration depth of SME-PS is dependent on concrete moisture level, size of PS molecules, and time. As the concrete moisture level increases, the amount of SME-PS that can be absorbed will decrease. As the chain length of PS increases, the amount of SME-PS absorbed will decrease. SME-PS reduced damage from freezing and thawing. After 300 cycles, the untreated samples had a relative elastic modulus of 55% compared to the 85% of the SME-PS-treated samples.

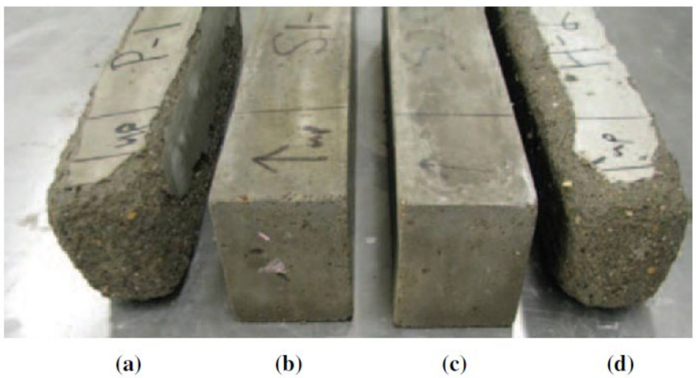


FIGURE 7 Freeze–thaw samples after 280 cycles: (*a*) plain, (*b*) SME-PS, Dose 1, (*c*) SME-PS, Dose 2, and (*d*) SBS. Untreated (plain) samples and SBS-treated samples show significant cover loss. SME-PS-treated samples show no visual damage.

Testing Methods of Concrete Sealers

(Sudbrink, 2011)

This work establishes and evaluates some important non-destructive laboratory and field techniques that can be used to determine the presence and effective lifespan of silane treatments. four different non-destructive techniques are investigated including Micro X-ray Fluorescence (μ-XRF), the 4-Point Wenner Probe, a brominated-dye, and a chlorine-based dye. All four techniques are then compared to determine which technique is most effective in determining the presence and depth of penetration of silane in concrete. By comparing with laboratory tests, it was concluded that

- the use of the Four-Point Wenner Probe to determine the presence of silane in the field needs further development.
- the brominated dye also needs further development for determining the presence of silane.
- the chlorine-based dye was the best method to use to determine the presence of silane.

(Nielsen, 2011)

To select the best surface applied concrete sealing product, a series of tests is recommended.

a) Water vapor transmission test: Does the sealer exhibit at least a 35% vapor transmission relative to control samples if water vapor transmission is a concern?
b) Saltwater absorption test: Can the sealer limit water absorption by 75% relative to control samples?
c) Sandblast samples and repeat saltwater absorption test: Can the sealer limit water absorption by 75% relative to control samples?
d) Chloride content test: Can the sealer limit chloride ingress by 75% relative to control samples?
e) Alkali resistance test: Does the sealer's saltwater absorption increase after alkali exposure?
f) Depth of penetration: If a penetrating sealer, does the sealer have an average penetration depth >3.8 mm?
g) UV weathering and cyclic saltwater ponding: Does the sealer exhibit visual deterioration and does it reduce chloride content by 75% relative to control samples?
h) Freeze-thaw resistance: Does the sealer reduce saltwater absorption by 75% relative to control samples after 300 cycles of freezing and thawing?

(Wells et al., 2017)

In evaluating three new concrete sealers intended for bridge deck protection, the Kentucky Transportation Center (KTC) conducted four laboratory tests:

- Chloride content at different depth after 90 days of salt ponding in accordance with AASHTO T-259 "Standard Method of Test for Resistance of Concrete to Chloride Ion Penetration" & AASHTO T260 "Standard Method of Test for Sampling and Testing for Chloride Ion in Concrete and Concrete Raw Materials". Specimen size was 10"x10" x 4".
- Water absorption test in accordance with ASTM D6489 "Standard Test Method for Determining the Water Absorption of Hardened concrete With a Water Repellant Coating". Specimen size was 2.0" x 4.0" (diameter x length) core.
- Adhesion test ASTM 7234 "Standard Test Method for Pull-off Adhesion Strength of Coatings on Concrete Using Portable Pull-Off Adhesion Testers".
- Depth of penetration test according to KTC-SOP-24 "Depth of Penetration of Concrete Sealer"

(Sudbrink et al., 2017)

Sudbrink et al. uses micro X-ray fluorescence (μXRF) to image the presence of silane coatings in field samples and the changes made to the paste chemistry. Micro X-Ray fluorescence (μXRF) is a powerful, non-destructive technique that can provide data on chemical composition and position within concrete. μXRF uses polycapillary optic to focus X-rays to a spot size of approximately 50 μm in diameter. Images are created by moving the sample in a raster pattern under a stationary Xray beam. These images are sensitive to trace (0.1% by weight or lower) level elements, and they are ideal for tracking small changes in chemistry. There are many advantages that μXRF has over other imaging techniques due to the large spot size and the high energy levels. Because of this, μXRF can rapidly investigate large areas and requires minimal sample preparation. The method was applied on cylindrical samples approximately 12.5 mm (0.5 inch) diameter and 25 mm (1 inch) height were taken from various in-service bridge decks in Oklahoma. The study proved the possibility of using μXRF to determine the presence of silane and quantitatively show the depth of its penetration by showing a change in the sulfur and potassium concentrations in the treated portion of the concrete. Figure ** shows an example of this method be applied to a sample treated with silane and another sample without silane.

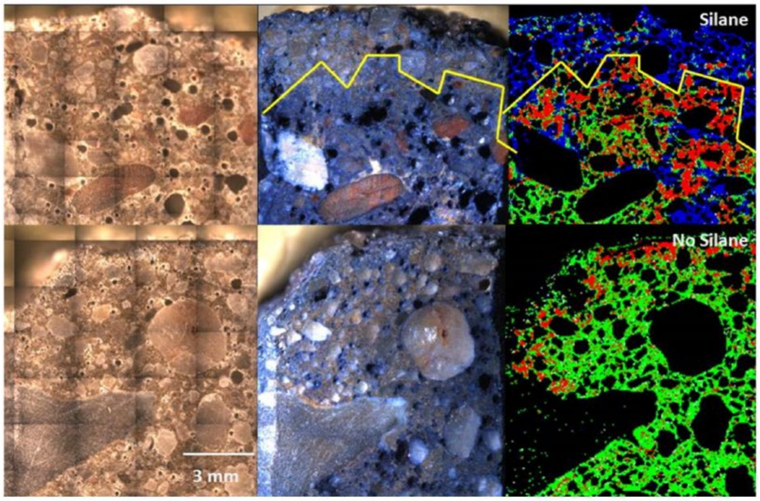


Fig. 9. Example of comparing a sample that contains silane to a sample that does not. (Top left) optical image of sample containing silane (top middle) optical image of sample containing silane stained with dye (top right) cement paste cluster map for sample containing silane (bottom left) optical image of sample not containing silane (bottom middle) optical image of sample not containing silane stained with dye (bottom right) cement paste cluster map for sample not containing silane. Note: The average sulfur concentration level for different colors in paste cluster map is provided in Table 2.

Field Performance of Penetrating Sealers

(Hagen, 1995)

The objective was to evaluate the effectiveness of various concrete sealers at reducing chloride penetration into a bridge deck with a low slump concrete overlay. 16 difference sealers were tested. Drill dust samples were collected annually for three years and analyzed for chloride content. Effectiveness was interpreted as reducing the penetrating of chloride ions from deicing chemicals into concrete deck while causing no detrimental effects to the deck surface or to the concrete appearance. It was found that

(1) The best penetrating sealers appear to provide protection for about three years.
(2) In terms of effectiveness, a water-based silane > two solvent-based silanes > a siloxane.
(3) Surface-type (film-forming) sealers were generally ineffective after one year. Therefore, abrasion resistance test is recommended for candidate sealers in the future.

(Nielsen, 2011)

In this study, five different surface applied concrete sealer treatments were evaluated in the laboratory for water vapor transmission, saltwater absorption, alkali resistance, UV exposure and cyclic saltwater ponding, penetration depth, and freeze-thaw cycling resistance. In addition, the same treatments were applied at four different field sites near Boise, **Idaho** to instigate a long term field evaluation of surface applied concrete sealers in Idaho. The treatments consisted of: (i) an epoxy, (ii) a silane, (iii) a high molecular weight methacrylate (HMWM), (iv) a base coat of silane with a top coat of epoxy, and (v) a base coat of silane with a top coat of HMWM.

In the laboratory tests, the best performance for saltwater absorption, alkali resistance, and freeze-thaw cycling was obtained by dual treatments consisting of a silane base coat followed by an epoxy or HMWM top coat. Only the silane sealer exhibited a consistently measurable depth of penetration and was the only sealer that exhibited greater than 35% vapor transmission ability relative to control samples.

The duration of the initial phase of this study was insufficient for the analysis of the long-term (4 years +) performance of the field site applications.

(Sudbrink, 2011)
This work establishes and evaluates some important non-destructive laboratory and field techniques that can be used to determine the presence and effective lifespan of silane treatments. Core samples were taken from various bridges in the state of **Oklahoma** to be tested in the laboratory. it was concluded that the useful lifespan of a silane treatment on a concrete bridge deck is 5-6 years. There does appear to be a reduction in the effectiveness of silane after being in service after nine years of service of about 30% of the bridges. Because only a few samples were investigated between these periods it is difficult to comment on the exact loss in effectiveness of the silane. It is recommended that silane either be reapplied or no longer expected to resist outside chemicals after 9 years of service.

(Liang et al., 2014)
Four sealer products that could potentially be used on highway bridge decks by the **Colorado** Department of Transportation (CDOT) were evaluated. Skid resistance, temperature variation, moisture fluctuation, and chloride concentration profiles in concrete were selected as the four experimental parameters for evaluating the performance of the four sealers. Results showed that

1) Silane is better than the other sealers in terms of skid resistance. It was very close to the bare deck right after the installation and better than the bare deck after one year.
2) The sealers can slow down the thermal conduction process in concrete decks.
3) After the application of the four sealers, there is no new moisture penetration into the concrete decks from moisture precipitation (rain and snow) during the eight-month period.
4) The silane can block the penetration of chloride ions to a certain extent, but not as effective as epoxy-type sealers.

(You et al., 2018).
Silane/Siloxane seal is not a practice by Michigan DOT. Research (Attanayaka, Ng, & Aktan, 2002) in Michigan has shown silane and siloxane to be effective treatments against moisture and chloride penetration on bridge decks, and MDOT approves these treatments when they meet the requirements of NCRP Report 244. It is currently not well understood how long the hydrophobic nature of the sealant will remain under traffic but current thoughts are that the sealant will need to be reapplied every 2 to 3 years.

Selection Procedure of Penetrating Sealers for Bridge Decks
(Attanayake et al., 2006)
The major parameter controlling the effectiveness of penetrating sealants as a means of protecting concrete bridge deck surface is the depth of penetration. The penetration depth however depends on several factors such as sealer type, concrete porosity, moisture content, and prevailing weather conditions. Therefore, it was recommended to collect samples from deck concrete and conduct impreganation experiment with sealer candidate for possible substrate moisture and environmental conditions at the field. The sealer should penetrate more than 6 mm during a required time period. If this criteria is met,

NCHRP Report 244 Test (Series-II) should be conducted to check whether the sealer can reduce chloride content by 80% and salt water absorption by 75%. Finally the sealer should satisfy the abrasion test following Alberta Department of Transportation's procedure.

In addition, authors calculated silane penetration depth against time using common values of concrete permeability, moisture content, and silane viscosity. As shown in Figure **, 6-mm depth of penetration is achieved by ponding the deck between time periods of 45 sec. and 12 min. For longer ponding durations, the amount of sealant evaporation will be greater and needs to be considered for cost-effectiveness.

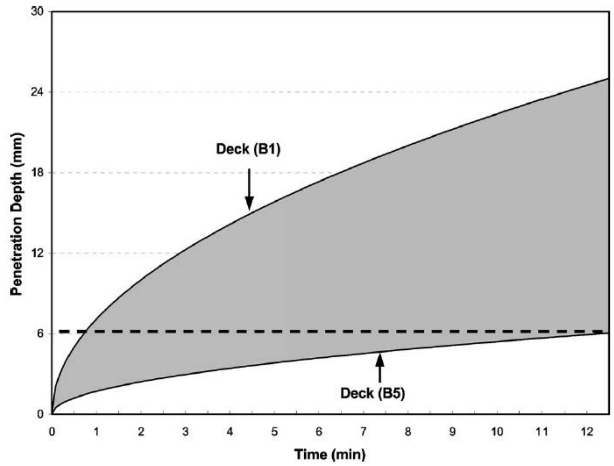


Fig. 4. Silane penetration depth against time

Sealer to Mitigate ASR

(Deschenes et al., 2017)

A study in Arkansas applied silane on concrete barrier that exhibited moderate to severe damage (different from many previous studies with only minimal to moderate damage). Researchers placed instruments to monitor strain and internal relative humidity on several sections where different sealers were applied. After 3 years of performance monitoring, silane-treated sections exhibited a reduction in expansion as compared to the untreated control sections for all damage levels. Silane also produced a measurable reduction in internal RH for sections of minimal damage.

Surface Sealers for Concrete Hydraulic Structures

(Mirza et al., 2011)

This research program was aimed at studying the performance of sealers on the downstream face of dams, including their mode of application and their compatibility with different surface states and climatic conditions. The ultimate goal was to minimize the water saturation of concrete downstream of the dams, which would eventually lead to desaturation of the concrete surface, forcing its degree of saturation to be lower than the critical value. This improvement would enhance the durability of dams, and improve their performance against the actions of the various deleterious agents.

A total of 60 products from 23 manufacturers were selected for the laboratory tests. Results showed that

- The different commercial sealers which appeared to be the most promising products from the point of view of the characteristics sought (water absorption, vapour transmission) belong to the silane family followed by the siloxane family. The performance of other sealers (boiled linseed oil, epoxies, urethanes and cement-based products) tested was poor.

- Reducing the temperature for sealer application and curing does not seem to have any major effect on the performance of silane- and siloxane-based sealers.
- Silane- and siloxane-based sealers show better performance in the presence of 15% salt (NaCl) solution compared to a solution of pH 5.