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Improving the Long-Term Performance of Concrete Bridge Decks using Deck and Crack Sealers

June 2018

Nevada Department of Transportation
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Carson City, NV 89712

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16. Abstract

Maintaining bridge decks is a huge issue. It is critical to extend the life of a bridge deck as long as possible since bridge deck replacement is difficult, expensive, and it significantly disrupts the traveling public. For example, NDOT currently utilizes overlays, but effective use of sealants and deck treatments could delay overlays, save costs, and extend bridge deck life. The primary objective of the project will be to develop a bridge deck maintenance guide that focuses on weather conditions that are common in the desert southwest. This includes areas of extreme dry heat to mountainous regions with snow and deicing salts.

The primary focus of this research is to take the best practice from other states and determine the best implementation plan for the SOLARIS members. Therefore, the research will focus on reviewing the literature for current best practices. After collecting the literature, comparisons will be made between states in terms of bridge maintenance, construction practice, and deck conditions. An experimental phase will test these materials under accelerated conditions and then use test bridges to apply the knowledge in the field. The final step will be a comprehensive report that describes the work and provides recommendations for bridge deck maintenance.

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Final Report

June 2018

Improving the Long-Term Performance of Concrete Bridge Decks using Deck and Crack Sealers

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IMPROVING THE LONG-TERM PERFORMANCE OF CONCRETE BRIDGE DECKS USING DECK AND CRACK SEALERS

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Abstract

Many bridges are exposed to snow and ice during the winter. As snow and ice accumulate over the bridge's concrete deck, deicing salts are usually spread on the bridge deck to remove and dissolve the snow and ice. Deicing salts form a chloride solution that penetrate through the concrete and cause corrosion in reinforcing steel and deterioration in concrete. In order to decrease the chloride ingress into the concrete, sealers are applied over the concrete deck surface. It is critical to extend the life of the concrete bridge deck as deck replacement is very time consuming and expensive.

The primary objective of this project was to develop a guide for using deck and crack sealers. In this research, five deck sealers and six crack sealers were applied on two different type of concrete that are commonly used in Northern Nevada: American Ready-Mix and 3D Ready-Mix. The effectiveness and performance of commercially available deck and crack sealers were assessed by laboratory tests. The sealers were chosen according to criteria that are discussed in this report. Five deck sealers were subjected to three laboratory tests that were conducted at the University of Nevada, Reno (UNR), and a freeze/thaw test conducted in a company in Denver, Colorado. The specimens subjected to the freeze/thaw test were then sent back to UNR to complete testing. Six crack sealers underwent two laboratory tests conducted at UNR. All the tests were conducted according to ASTM, AASHTO, and NCHRP reports standards.

In order to report the effect of the sealers, a comparison was made between specimens covered with sealers and control specimens (i.e. specimens without any sealers). Also, a comparison was made between all the sealers together, and the sealers were assigned into different categories according to their performance. Each category has a certain score according to the test, and a total score for each sealer was calculated for all the tests. A recommendation is given for the sealers that gave the highest performance. The recommendation was not given for a certain sealer only, but for the chemical family and general properties for these sealers that gave the highest performance. Generally, all the deck sealers were effective in reducing the amount of chlorides ingress into the concrete. Silane sealers gave higher performance than siloxanes sealers, and water-based sealers gave a higher performance than solvent based sealers. Sealers with chemical family of Alkylalkoxy Silane gave higher performance among all the other sealers, and it is recommended to use sealer of Alkylalkoxy Silane and water-based sealer. Epoxies sealers provided higher performance for bond strength than methacrylate sealers. While for depth of penetration, methacrylate sealers could penetrate deeper into cracks because their viscosity is lower than the epoxies.

Acknowledgment

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Chapter 1 Introduction

1.1 Introduction

Infrastructure deterioration is a severe problem in the United States. In the winter when snow and ice start to accumulate on bridge decks, deicing salts are spread on the bridge desks to dissolve the snow and ice. Deicing salts are mixtures of sodium and calcium chlorides. Bridge deck concrete often has cracks. These cracks provide ingress for chloride ions to the reinforcement of the deck. When these salts react with ice, it starts to melt forming a chloride solution that penetrates through the cracks and pores in the concrete. The chloride solution causes corrosion in steel reinforcement. The corrosion increases the volume of steel reinforcement causing more cracks in the concrete, which allows more chlorides to penetrate through these cracks. Different values have been assigned that represent the level of chloride at which corrosion and deterioration occurs. Factors affecting the variation of these values include concrete mix design such as (water/cement ratios, admixtures, air content, supplemental material usage, density and age), coverage depths, type of reinforcing steel, use of epoxy coatings and other construction factors.In addition, the amount of carbonation and resultant change in the pH of the concrete affects the corrosion of concrete and reinforcing steel. These values are reported for corrosion; 1.2 lbs/yd3 (315 ppm) is the level where the chlorides start to initiate corrosion, 3.0 lbs/yd3 (790 ppm) is the amount of chloride that accelerate corrosion and >7.0 lbs/yd3 (1840 ppm) is the level that causes major corrosion and loss in the steel section . These values are calculated according to an average density of concrete of 3,800 lbs/yd3 (Newman, 2001).

Chloride ions can penetrate through the concrete in three different ways. First is capillary absorption which occurs when the concrete surface is subjected to continuous wetting and drying cycles. When chloride solution hits dry pavement it starts to penetrate into the pore structure of the concrete through capillary suction. Second is the hydrostatic pressure which is very rare on bridge structures, and this occur on concrete structures that are hydraulic or situated in the ocean under a hydrostatic pressure. The third method is diffusion and this is the most common and familiar method for chloride ion penetration.

In order to reduce these chlorides ingress in the concrete, deck and crack sealers are applied on the surface of the bridge deck. These sealers could be applied on a new constructed bridge as well as sealing existing cracks in a bridge deck to prevent chloride ion intrusion. Many concrete bridge decks in the United States are exposed to early age cracks within a short period of time after construction such as shrinkage cracks (Krauss and Rogalla, 1996). Crack sealers are usually used to penetrate, and seal an existing crackto prevent chloride ion ingress. These sealers are expected to seal fine cracks in a deck by creating an isolation layer that prevents saltwater solution from entering the concrete. Also, they must be able to withstand crack opening and closing due to thermal effects and deck movements. Currently available crack sealers products composed of three main chemical families which are High Molecular Weight Methacrylates (HMWM) resins, epoxy resins, and urethane resins among others. Deck sealers products are based on silane or siloxane and can either be water based or solvent. Deck sealers are used over the entire deck and help to prevent chloride intrusion over the entire surface and small cracks. Each sealer has specific properties to deal with specific problems.

1.2 Research objective

Nevada Department of Transportation "NDOT" currently utilizes overlays to repair deck and to seal decks, but effective use of sealers and deck treatments could delay overlays, save costs, and extend bridge deck life. The primary objective of the project was to develop a bridge deck guide for using deck and crack sealers. The primary focus of this research is to take the best practice from other states and determine the best implementation plan for the Nevada DOT and other states with similar climates such as New Mexico and Arizona. This could done by assess the effectiveness and performance of some of the commercially available deck and crack sealers.

1.3 Research plan

In order to achieve the research objective, previous research that was done on deck and crack sealers by other universities and states DOTs was studied. Then, an experimental program was developed that included different types of specimens and two different concretes that are available in Reno, NV: American Ready-Mix and 3D Ready-Mix. After that, sealers were identified and classified according to their properties and chemical family. Five sealers were chosen and were applied on the specimens in order to test them under different circumstances. Three experimental tests were conducted here at UNR on deck sealer specimens, and one was conducted in a company in Denver, Colorado and completed at UNR. For crack sealers, two tests were conducted here at UNR. All the tests were conducted according to ASTM, and AASHTO specs, and NCHRP Report series II and IV.

After all the tests were finished, the results were analyzed. A comparison was made between the sealers according to their performance, the sealers were assigned into three different categories, and each category has its own weighting score according to some statistical analysis "95% confidence interval". Finally, a recommendation was developed for the best-performed sealers and their chemical properties and family, so that sealers with similar chemical family and properties could be used on a new constructed bridge or an existing structure. The report is divided into different chapters. Chapter 2 discuss the literature review, the background of sealers, and the previous studies on sealers by other states DOTs. Chapter 3 is the identification and classification of sealers. Chapter 4 discuss the experimental work that was done. Chapter 5 and 6 discuss the test results and describes the recommendations for using deck and crack sealers. Finally, chapter 7 is the summary and conclusions for the report.

Chapter 2 Background/Literature Review

2.1 Introduction

In this chapter, the characteristic of deck and crack sealers and the different tests that were conducted on deck and crack sealers for evaluating their performance will be discussed. Moreover, a summary of different Department of Transportation (DOT) research on evaluating deck and crack sealers is presented.

2.2 Sealers background

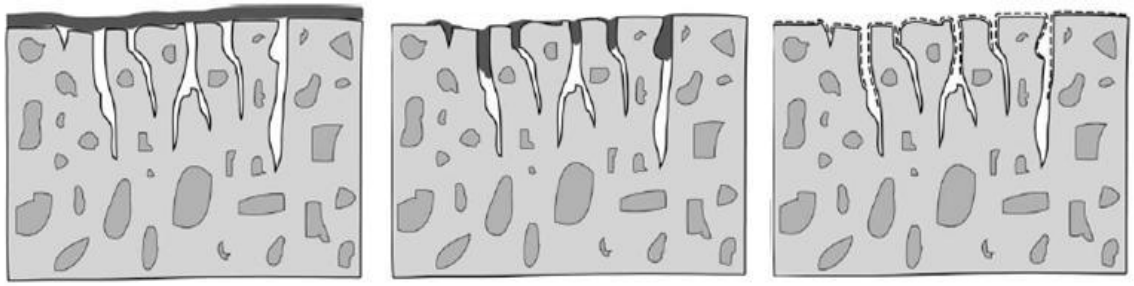
The usage of sealers are so beneficial on extending the service life of concrete bridge decks. Sealers help to prevent deterioration in the concrete and corrosion of the steel reinforcement. Corrosion of steel reinforcing results in expansion in concrete that causes cracking in the concrete as well as deterioration in steel and reduction in its area. These deicing salts are composed of different chemicals such as sodium chloride, calcium chloride, and magnesium chloride. In the winter, ice and snow could be melted by using deicing salts. As ice melts, it starts to react with the chlorides in the salts forming chloride solutions that penetrate through the concrete causing corrosion in the steel reinforcement and deterioration in the concrete. Water can penetrate the concrete through pores or void spaces by capillary action, and diffusion or most directly from seepage into surface cracks (Nielsen, J., Murgel, G., & Farid, A., 2011). Moisture inside the crack can cause damage to the concrete in the winter due to freezing and thawing cycles. When entrapped water in the crack converts to ice, its volume increase and hence this increase the volume of the concrete by 9% causing forces inside the concrete that leads to cracks in the concrete affecting the concrete durability. As chloride content increase, the risk of corrosion of reinforcement and deterioration in concrete increase. When the chloride content at the surface of the steel exceeds a certain limit, called the threshold value, corrosion will occur in the presence of water and oxygen. Federal Highway Administration (FHWA) studies found that a beginning limit of 0.20% total acid-soluble chloride by weight of cement could stimulate corrosion of steel reinforcement in bridge decks (Clear 1976). Work at the FHWA (Clear, K. C., & Hay, R. E., 1973) found that a range from 0.35 to 0.90 is the conversion factor from acid-soluble to water-soluble chlorides depending on the constituents of the concrete.

Limiting chloride ingress into concrete can extend the service life for bridge decks and enhance the deck durability. For new constructed bridges, the deck can be sealed with deck sealers immediately after construction to prevent the accumulation of chlorides, and to decrease the moisture penetration into the concrete preventing the formation of cracks due to the volumetric changes of the confined water in the pores. For existing bridges, the deck can be sealed to reduce the amount of chlorides that could be added to the already existing chlorides.

The following sections in this chapter define the classification for sealers and the primary main properties of the sealer. Further, a brief review is provided for the tests that will be used in evaluating the performance of the sealers.

2.3 Sealers classification

Concrete sealers are usually classified either a film formers or penetrating sealers. Penetrating sealers typically are classified as pore blocker or water repellent (Nielsen, J., Murgel, G., & Farid, A., 2011) ***Figure 2-1*** shows the different sealers classification.



(a) (b) (c)

Figure 2-1 Sealers Classification (a) Film Former coating Barrier (b) Pore Blocker (c) Water Repellent

2.3.1 Film formers “Barrier coating”

Film formers sealers are compounds with generally high molecular weight and high viscosity that would not be able to penetrate through the concrete decks. The main difference between film formers sealers and penetrating sealers is that penetrating sealers have low viscosity that allows them to “penetrate” into the concrete while a film former sealer forms an insulation layer over the surface. Film forming sealers can be used for sealing cracks in concrete as they could penetrate through large cracks. Examples of these compounds are linseed oil, epoxies and methacrylates. Their performance is reduced with time because of vehicle abrasion on the concrete deck. Very small aggregate can be placed on the top of these sealers to increase the skid resistance and hence enhance the friction between the vehicle and the sealers surface.

2.3.2 Pore blocker

Pore blockers are compounds that have low viscosity and small molecular size, so they could penetrate through the pores of concrete without leaving a measurable depth as a surface coating. Examples include lithium or sodium silicates and linseed oil in solvent. These silicates can be used to reduce the capillary suction for the pores.

2.3.3 Water repellent

Water repellent are a second type of penetrating sealers. When this type of sealers react with the cement paste, a coating is formed along the interior wall of the pores inside the concrete. This coating has a surface tension lower than the surface tension of chlorides, and this lead to reducing the penetration of chlorides into the pores. Examples of these compounds are silanes and siloxanes.

2.4 Water-based sealers and solvent-based sealers

Lowering volatile organic compound (VOC) content has been a popular topic lately, largely due to increasingly restrictive regulations across the country requiring lower VOC levels in various paint and coatings applications.

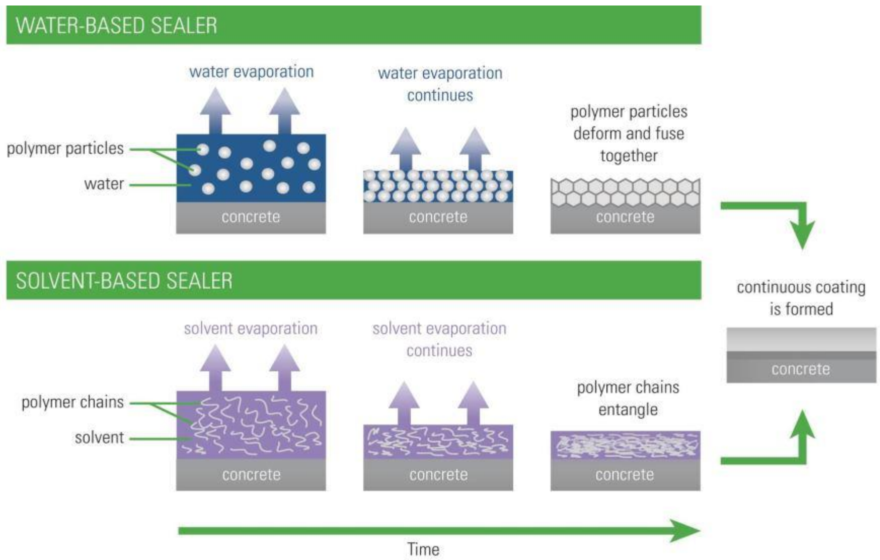
Concrete sealers are either are a water-based variety “lower VOC” or a solvent-based “high VOC”. Both water and solvent-based sealers act as a protective topcoats for concrete and are applied to the concrete surface after completing the curing process. The carrying agent of silane products can have a significant effect on the performance of the sealer. Solvent-based silanes are more commonly used than their water-based counterparts. This is because solvent-based products penetrate deeper into the concrete bridge deck. Many studies in the literature review support this notion (Pincheira 2005).

In the case of a water-based sealer, the polymer particles are scattered in water. When the sealer is applied to concrete, the water evaporates and the polymer particles move closer together and by continuing evaporation, the polymer particles begin to merge together, forming the coating.

With a solvent-based sealer, it is kind of different than water-based sealers where polymers are not scattered as separate particles, but the polymer and solvent form a continuous, clear polymer solution. When solvent evaporates from a solvent-based sealer, the polymer chains are fuse and entangle together. For both water- and solvent-based sealers, the water or the solvent evaporate and only the polymer remains on the concrete surface and this cause a shiny surface for the concrete. (http://www.concreteconstruction.net).

The appearance of water-based and solvent-based sealers after application and curing helps to distinguish between the two classifications of sealers. Solvent-based sealers usually penetrate concrete surfaces very well that result in a shining finish. Water-based sealers appear milky white after application and the polymer particles in the sealer scatter impact the visible light differently than the water in which they are scattered in. After curing, water-based sealers do not seem too glossier compared to solvent based sealer.

The finished performance properties of both type of sealers are similar and provide a long lasting good protection to newly finished or aged concrete surfaces. Water-based sealers are a good choice for the demand of a low-VOC, high-performance concrete sealer that is durable and easy to work with. ***Figure 2-2*** shows the difference between water-based sealers and solvent-based sealers.



http://www.concreteconstruction.net

Figure 2-2 Mechanism of water and solvent based sealers

From previous research and studies, the average solvent-based silane products had larger depths of penetration than water-based or siloxane products. The depth of penetration of solvent-based products ranged between 1.8 mm and 3.8 mm, while for water-based products their penetration depths range from 1.4 mm to 2.1 mm. When not exposed to freeze/thaw cycles, solvent-based products perform better than water-based products in reducing the ingress of chloride ions. When exposed to freeze/thaw cycles there was no clear difference between the performances of solvent-based and water-based. (Pincheira, J. A., & Dorshorst, M. A., 2005).

2.5 Deck sealers chemical family

The following subsections provide a brief review for the different chemical families of deck and crack sealers. The properties of these chemical families affect the performance of the sealer.

2.5.1 Linseed oil

Boiled linseed oil is an effective and affordable concrete floor sealer. Boiled linseed oil can be bought as linseed oil-mineral spirit compound or linseed oil emulsion. Linseed oil has many benefits such as sealing the moisture and making the concrete harder. Also, it lowers pH if used in new concrete floors.

Boiled linseed oil treated with mineral spirits can be used in many application such as treating new or old concrete floor, roads, sidewalks, curbs, parking ramps, floor, walkways, bridge decks and other similar concrete applications.

Nowadays, linseed oil is not classified or used as a penetrating sealer because it has a high molecular size and viscosity than does not allow its penetration into the pores of concrete. Therefore, it could be used as a temporary surface sealer.

2.5.2 Silanes and Siloxanes

Silanes and siloxanes are the most common penetrating sealers, and both of them are derived from the silicone family. Despite having the same chemical family, they have different performance. Silanes require a high pH to catalyze, while siloxanes are not dependent on substrate pH. This make siloxanes ideal for treating stucco, brick, and stone. Silanes are made up of molecules smaller than the molecules of siloxanes, and this make silanes penetrate deeper into the concrete than siloxanes. As a result, silanes give a better performance under abrasion and weathering. Because of this small molecular size of silanes, they are relatively volatile. Therefore, to compensate for the loss of evaporation of the reactive material during both application and curing, the solids content of a silane product should be high enough to reduce evaporation. Siloxanes, because they are less volatile, generally offer good water repellent performance at lower initial cost than do silanes. For concrete surfaces subjected to abrasive wear such as pavements and decks, treatment with a silane sealer will provide longer lasting protection. Regarding the color of the surface, treatment with silane sealers typically could not be detected by visual inspection.

Products with 100 percent solids have no carrying agent. Tests conducted on these products indicate slight advantages with an increased amount of solids. A test by (Soriano, 2002) showed that 100 percent silane absorbed slightly less water than the 40 percent silane products analyzed. Also, products with higher percent solids have larger penetration depth. (Basheer, 1998, and Soriano, 2002) all demonstrated 100 percent silanes to penetrate slightly deeper than 40 percent silanes.

In general, silane products are more commonly used than silane. This is most probably due to the lower performance of siloxane compared to the silane products.

2.6 Crack sealers chemical family

2.6.1 Epoxies

Epoxy sealers form a good protective film on the concrete surface, producing a finish that is hard, and effective against long-wearing and abrasion. They are also excellent water repellents. Epoxy sealer are used either in a flood coat as deck sealers or to seal individual cracks. The choice between sealing the entire deck (flood coat) and sealing individual cracks depends on the severity, amount of cracks and the state's preference. Most products impart a specular finish. Epoxy sealers are much harder than acrylics. Water-based epoxies adhere well to concrete and provide a clear finish. Moreover, water-based epoxies are nonporous so they do not allow moisture inside to escape so they should not be applied to surfaces that have any moisture problem. Most epoxies are composed of two component products that are mixed together before application on concrete surface and then rolled onto concrete. One of the drawbacks of epoxies is that that they require more deck preparation, long cure time, and the installation process is somewhat confusing and time consuming. They do last longer than an acrylic; there for a longer time is needed before they need to be reapplied.

Two laboratory studies by (Pincheira 2005, Sprinkel 1995) found that epoxy sealers were able to penetrate more into the entire depth. However, field studies demonstrated that the penetration depths of epoxy sealers were highly variable. Meggers (1998) found that two High Molecular Weight Methacrylate (HMWM) sealers penetrated deeper than the epoxy sealer studied. HMWN will be described in the next subsection.

In a study by Pincheira (2005) for Wisconsin DOT, he found that an epoxy sealer had the highest bond strength for hairline cracks (1/32 in.) and medium cracks (1/8 in.). While for wide cracks (1/5 in.), an epoxy and HMWM sealer performed the best. Pincheira noted that the epoxy and HMWM sealer exhibited poor freeze/thaw resistance. He recommended using the epoxy resin as Sikadur 55 SLV for the three-crack sizes.

2.6.2 High Molecular Weight Methacrylate

High molecular weight methacrylate (HMWM) is a monomer that has many of the characteristics and advantages of methyl methacrylate (MMA), such as the low viscosity, and the ability for curing over a wide range of temperatures. HMWM has low odor and a high flash point, which make it better than MMA. HMWM sealers are usually applied using a flood coat, which is spread over the entire deck because of their low viscosity that make them penetrate deeper into the cracks.

HMWM has an excellent performance for mechanical and durability properties and they bond well to the concrete. Also, it has been used to produce polymer concrete for overlays and other specialty applications.

. Due to the low viscosity of HMWM, it can penetrate very fine cracks as stated in many studies before (Pincheira 2005, Sprinkel 1995). HMWM has been used in many applications in the states especially for sealing cracks in bridges. The researchers noted that HMWM has been used widely in the United States including California, Kansas and Iowa by a lot of states DOT.

(Johnson, K., Schultz, A. E., French, C., & Reneson, J., 2009) condcted a survey and stated that HMWM sealers are the second most commonly used sealers by DOTs after epoxies, because of their low viscosity and their ability to penetrate deeper through the cracks. Some laboratory tests have found that the HMWM sealers were able to penetrate through the whole depth of the crack (Pincheira 2005, Sprinkel 1995). HMWM sealers penetrated deeper into cracks than epoxy sealers (Meggers 1998).

Through chloride ingress and corrosion laboratory testing on reinforced concrete samples, Meggers (1998) tested three HMWM sealers applied on reinforced concrete samples by chloride ingress laboratory tests, and found that these three sealers could protect the bridge for about eight, nine, and 11 years. The protection period of epoxy sealers was found to be 15 years.

2.7 Application procedures

In this section, the application procedures for both deck and crack sealers will be discussed according to what has been implemented in different states. Generally, deck and crack sealers are applied in a temperature range of 45F to 100F as specified by almost all the states.

2.7.1 Deck sealers

Before applying the deck sealers, the bridge has to be cleaned from any materials. This surface preparation is done by mainly two methods: sand/shot blasting or high water pressure. The contractors prefer to use the shot/sand blasting on bridges that have leftover curing compounds or overlays. The high-pressure water could be used but the deck has to left for two days drying period before applying the sealers. Also, compressed air could be used in the cleaning process but it is not a common method. On newly constructed bridge, no cleaning is required unless there are any dust or materials on the surface. There are different ways to apply the sealers over the bridge deck, such as spray bar mounted on the back of a truck, or by tank sprayer, roller, and brooms. Sealers are usually applied with two coats.

2.7.2 Crack sealers

The application of crack sealers is somewhat similar to deck sealers and includes cleaning the crack from any dust or any residual materials. The cleaning process could be done by either a shot/sand blasting or high water pressure or air pressure. Using sand/shot blasting is more familiar to contractors and more common in most of the states (Johnson, K., Schultz, A. E., French, C., & Reneson, J., 2009). Applying the crack sealer could be done by flooding a coat over the surface as deck sealers; this is done in the case of large number of cracks. It can also be applied by sealing individual cracks; this is done in case of having a limited number of cracks. Brooms or rollers do flood coat over the entire deck while sealing individual cracks is done by using handheld bottles or wheel carts. Drying period of two days are usually used in cases where moisture is present.

2.8 Time of applying the sealers

2.8.1 Deck sealers

Applying deck sealers immediately after construction is beneficial to reduce the ingress of chlorides from the early service life of the bridge. In a newly constructed bridge, the existing amount of chlorides is very low, so applying the sealers from the beginning will enhance in reducing future chloride in the concrete. Usually deck sealers are reapplied over the bridge deck after three to five years. Most of the states reapply the deck sealers after three to five years from applying.

2.8.2 Crack sealers

Time of application of crack sealers is different from deck sealers. Crack sealers are applied to a bridge due to the existence of cracks. Applying crack sealers immediately after construction is typically due to early age cracks caused by shrinkage of the concrete. For instance, Nebraska DOT applies a polymer sealer over the entire deck after the construction of any new bridge. The main purpose of this polymer sealer is to seal any early age cracks that could be formed on the deck surface. It was found that this polymer is very beneficial in extending the service life of bridge deck. (Johnson, K., Schultz, A. E., French, C., & Reneson, J., 2009).

2.9 Tests used for evaluating the performance of deck sealers

In this section, an overview is provided for the different laboratory tests that have been used in evaluating the performance of the deck sealers.

2.9.1 Rapid permeability by ASTM C 1202

The rapid permeability test method covers the determination of the electrical conductance of concrete to provide a rapid indication of its resistance to the penetration of chloride ions.
This test method consists of calculating the amount of electrical current passed through 50-mm thick slices of 100-mm nominal diameter cores or cylinders during a 6-h period. This test method determines the electrical conductance of concrete samples to provide a rapid indication of their resistance to chloride ion penetration by calculating the amount of charge passed through the concrete.

2.9.2 Saltwater absorption by NCHRP 244 series II

The saltwater absorption test determine the ability of the sealers to reduce the chloride ingress by calculating the change of weight that occurs in the concrete specimens before and after immersion in a sodium chloride solution; this test is based on the NCHRP 244 testing series II. All samples were tested for 7-days, 14-days, and 21-days saltwater absorption. The weight of each sample (W_{i0}) was measured before immersion in the solution. Samples were then immersed in 15 percent (by weight) sodium chloride solution maintained at laboratory temperatures and then weighed at 7-days, 14-days, and 21-days. Further details for the procedure of the test and calculation of SAR (Saltwater absorption ratio) are discussed in (section 4.1.7).

2.9.3 Chloride ion intrusion "AASHTO T259/T260"

The chloride ion intrusion test determines the ability of concrete and sealers in resisting the chloride ion ingress into the concrete. There are many factors that could affect the results slightly such as changes in the cement type and content, water/cement ratio, aggregate type and proportions, admixtures, treatments, curing and consolidation.
The standard describes the procedures for preparing the concrete specimens, including the application of concrete sealers. After applying the sealer, specimens are roughened by using sand blasting to simulate wear from vehicular traffic. Abrasion is not required and is neglected if the concrete or treatment is to be used on surface not subjected to vehicular wear. Dams are placed around the top edge of the specimens to be able to hold the water inside for 90 days of continuous ponding of a deicing solution. Following to the ponding stage, the specimens are wire brushed to remove any salts on the surface.
The procedures includes sample preparation, sample retrieving and the decomposition of concrete powder for determination of the chloride ion content. Equations for calculating the chloride ingress percent are presented in the AASHTO standards. This test method does not give an indication about the service life that could be expected from the tested concrete. More details for the procedures of this test will be discussed later in (section 4.1.4).

2.9.4 Freeze/thaw exposure "ASTM C666"

The ASTM C 666 test method determines the resistance of concrete specimens to rapidly repeating cycles of freezing and thawing in the laboratory. This test procedure can be used to determine the performance of the concrete and its resistance to freeze and thaw cycles. However, the test method is not intended to provide a quantitative measure of the length of service that may be expected from a particular type of concrete (Pincheira, Dorshorst, 2005). Two procedures can be used in this test: Procedure A - Rapid Freezing and Thawing in Water, and Procedure B - Rapid Freezing in Air and Thawing in Water. The specimens have to be completely surrounded by water during the thawing phase in both procedures. The only difference is for Procedure B specimens are surrounded only by air during the freezing phase of the cycle, while for Procedure A, specimens are surrounded by water during the freezing phase. Procedure A is better for tests relating to concrete bridge decks, to simulate actual decks that will usually be covered with ice "water" while they undergo freezing and thawing (Pincheira, Dorshorst, 2005).

2.10 Tests used for evaluating the performance of crack sealers

In this section, an overview is provided for the different laboratory tests that has been used in evaluating the performance of the crack sealers.

2.10.1 Bond strength test

There are no standard methods for determining the bond strength for crack sealers. A test was done that is similar to ASTM C 496 "A standard test for determining the splitting tensile strength of cylindrical concrete specimens". The test was applied by forming notches in the upper and lower surface of the specimens and then by putting two steel rods over the tested crack filled with sealer and then breaking it with the compressive strength test machine until failure. The applied load could be the strength of the sealer if the failure occurs in the sealers but it could be the strength of the specimen if the failure occur in the interface or in the concrete as will be shown later. The test was terminated the load dropped to 20% of the maximum load. Further details for the procedure of forming the cracks and determining the bond strength of the sealers are discussed in (section 4.2.8).

2.10.2 Depth of penetration test

The depth of penetration test is used to determine the ability of the sealers to penetrate through the crack depth with the required width of cracks. This test was conducted by visual inspection. If the sealer has a high viscosity, it will not penetrate sufficiently into the crack.

2.11 Previous DOTs research

Several Department of Transportations (DOTs) or universities have studied and conducted research on sealers, and studied the performance and the effective of different types of deck and crack sealers either through some laboratory or field tests. In this section, the conclusions of previous DOT research will be discussed.

2.11.1 Evaluation of concrete deck and crack sealers, Wisconsin DOT "Pincheira, J. A., & Dorshorst, M. A., 2005"

In this research, the main objective was to assess the performance of some of the commercially available concrete bridge deck and crack sealers. Thirteen deck sealers and ten crack sealers were chosen for this study. Two different laboratory tests, chloride ion intrusion test "90 days ponding" and depth of penetration test were used. Establishing a relationship between depth of penetration of the sealer and its performance in resisting the chloride ion intrusion was an objective in this research.
The study on crack sealers included a bond strength test and depth of penetration test. The deck and crack sealers were assigned into different categories according to their performance and compared. Sealers were assigned to category I, II, and III. I for the best performance, II for the moderate performance, and III for the least performance.

Main findings for deck sealers

- Silane products that are solvent based penetrated deeper than water-based or siloxane products. The depth of penetration of solvent-based products ranged between 1.8 mm and 3.8 mm; water-based products had penetration depths ranging from 1.4 mm to 2.1 mm.
- When not exposed to freeze/thaw cycles, the performance of solvent-based products in reducing the penetration of chloride ions was better than water-based products. Under exposure to freeze/thaw cycles, the performances of solvent- and water-based are not clearly differentiated
- Exposure to freeze/thaw cycles decreased the performance of most of the sealers in reducing chloride ion ingress.

Main findings for crack sealers

- All sealers studied penetrated through the full depth of the crack.
- For most sealers, the bond strength decreased, by increasing the crack width, and with exposure to freeze/thaw cycles.
- Sealers had similar performance for different crack width i.e., crack width did not have a dramatically effect on the performance of the sealer.

2.11.2 Alternative sealants for bridge decks, South Dakota DOT "Soriano, A., 2002"

The South Dakota DOT (SCDOT) project investigated concrete bridge deck crack and surface sealers, and their optimum application timing. The main objectives of this project were to determine if there were products that could give better performance than the products that SDDOT was using (i.e. linseed oil sealer and epoxy crack sealer) and determining the optimum time for applying the sealers.

Main findings for deck and crack sealers

- Application of crack and deck sealers after chloride ingress is not essential in extending bridge deck service lives, while slowing additional chloride and water penetration into the concrete could provide additional life to older bridges.
- Treating older bridge decks is not effective as treating these bridges prior to chloride ingress.
- Crack and deck sealers with viscosities less than 15 cp (centipoise) had good penetration (i.e. = 0.10 in.) into cracks and deck surface
- Linseed oil should be categorized as a membrane sealer not as a penetrating sealer because its molecular size is larger than the concrete pore openings.

2.11.3 Investigation of concrete sealer products to extend concrete pavement life: phase 1, Idaho DOT "Nielsen, J., Murgel, G., & Farid, A, 2011"

For the Idaho DOT study, five deck sealers were evaluated in the laboratory for different properties such as water vapor transmission, saltwater absorption, alkali resistance, depth of penetration, UV exposure and cyclic saltwater ponding, chloride content, and freeze/thaw resistance. The five treatments are silane, high molecular weight methacrylate (HMWM), epoxy, silane basecoat/HMWM topcoat, and silane basecoat/epoxy top coat. These sealers were applied in four different locations in Southwestern Idaho to initiate a long-term (four year) field evaluation of the treatments. According to the laboratory tests, the combination of silane basecoat and epoxy or HMWM topcoat gave the best performance among the tested sealers. Some tests were conducted between the five concrete sealer treatments and control samples to assess their performance. The tests were selected to simulate conditions similar to conditions that exist in Idaho such as UV exposure, freeze/thaw cycling and exposure to two different roadway deicing salts. Moreover, the same sealers were applied in the field at four sites in Southwestern Idaho to determine the long-term performance of the sealers.

Main findings for deck and crack sealers

- Dual treatment systems consisting of both silane as a base coat and an epoxy or HMWM as a top coat exhibited the best performance among the tested sealers for sealing decks and existing cracks.
- If the concrete pavement or bridge deck does not transmit water vapor through control surfaces then it is recommended to have a silane or a sealer that allows at least 35% of water vapor transmission relative to control samples.

2.11.4 Crack and concrete deck sealant performance, University of Minnesota DOT "Johnson, K., Schultz, A. E., French, C., & Reneson, J., 2009"

The objective of the Minnesota DOT project was to provide a guide regarding the use of bridge deck and crack sealers to extend the life of concrete bridge decks. The report studied the previous studies by other universities and DOTs, and a survey that focused on up to date studies in the field of deck and crack sealers. The main purpose of the survey was to determine common practices for using and applying these sealers in different States. Based on the performance of the sealers and the information collected from the previous studies and the survey, the best sealers and application practices were recommended for use in Minnesota and throughout the Midwest.

Main findings for deck sealers

- Based on the information from the literature review and the survey studied, silanes usually perform better than siloxanes in chloride ingress reduction and in penetration depth into the concrete; this may be because of the smaller molecular size of silanes than siloxanes.

- Solvent-based sealers tend to perform better than water-based sealers in both penetration depth into concrete and chloride ingress reduction.
- For a given type of carrying agent either solvent or water, products with higher solid content (i.e. 100% vs 40% solid content) gave a better performance in penetration and chloride ingress reduction than products with lower solids contents.
- The temperature of applying the sealers usually ranges from 40°F to 100°F Also, if there is any rainfall or the surface was cleaned by water, two days should be allowed for drying before applying the sealers.
- Water-based products are not suitable for reapplication.

Main findings for crack sealers

- Before applying the sealers, the cracks have to be cleaned and washed from any contaminated materials inside. The cleaning process could be either by power washers or by a compressed air. Although, two days as a drying period should be allowed for drying the crack and the surface before applying the sealers in case of using water in cleaning the surface, and three days drying period in case of any rainfalls.
- The laboratory studies found that all the sealers were able to penetrate into the whole crack depth in the concrete. For field investigation methyl methacrylate and HMWM, sealers gave the best performance in penetrating the whole crack depth. Krauss (1985) documented a case that an epoxy sealer failed to penetrate through the whole crack depth and after the failure, a HMWM was tested and was able to seal and penetrate through the whole depth. Meggers (1998) also conducted a study about the depth of penetration of HMWM and epoxy sealers and found that HMWM could penetrate deeper into the concrete that the epoxies.
- HMWM products are typically applied in a flood coat as deck sealers and epoxy products are generally applied to individual cracks. This means the extent of cracking, the number of cracks on the bridge deck, and their conditions are the main factors in determining whether to apply the sealers in a flood coat or to individual cracks. Flood coat for huge amount of cracks and applying the sealers to individual cracks for small number of cracks on the bridge Meggers (1998) suggests that crack sealers should have a viscosity lower than 500 cP, tensile strength above eight MPa, and tensile elongation greater than 10 percent.

2.11.5 Effectiveness of concrete deck sealers and laminates for chloride protection of new and in situ reinforced bridge decks in Illinois, Illinois DOT "Morse, K. L., 2009"

The Illinois DOT research project developed a study to assess the performance of concrete sealer and effect of laminate in protecting bridge deck concrete from chloride ion ingress. The study included the criteria for choosing products for evaluation, sample locations, sample depths, and duration of study. The results showed and explained the relative effectiveness of the various sealers and laminates and the durability of the studied products. The results for the durability study and the cost of each product was used to develop a relation between the cost and effectiveness for all the products.

Main findings for deck sealers

- Protective coat gave a better performance than all silanes and siloxanes. Dual treatment of both silane and siloxane together performed better than silanes and siloxanes alone.
- Water-based products may need to be used if environmental restrictions are present since the Environmental Protection Agency (EPA) imposed a VOC limits to 5 pounds per gallon or 600 grams per liter. The majority of the products evaluated were below the currently proposed limits (400 g/L) for waterproofing concrete/masonry sealers.

2.11.6 Evaluation of Bridge Deck Sealers, Colorado DOT "Liang, Y. C., Gallaher, B., & Xi, Y., 2014"

The Colorado DOT studied and evaluated the performance of deck sealers that are commonly used on bridge deck in the state. After reviewing the most recent research findings on deck sealers used by state DOTs, four sealer products were selected, that could be used by the Colorado Department of Transportation (CDOT), to assess their performance from different perspective. The performance was determined for a high molecular weight methacrylate (HMWM), two epoxies, and a silane for skid resistance, and their ability to reduce moisture and chloride ion penetration into concrete bridge decks. Four experimental parameters were chosen for conducting field tests on the selected sealers: skid resistance, temperature variation, moisture fluctuation, and chloride concentration profiles in concrete. Bridge structure E-17-QM (westbound US 36 to I-270 over I-25) was selected for the field study. Professional contractors installed the four sealers on the deck surface of Bridge E- 17-QM. The four sealers used in this study were:

- High molecular weight methacrylate (HMWM) - Sika Pronto 19- HMWM (2 components);
- Epoxy 1- Super low viscosity, low modulus epoxy;
- Epoxy 2 - Low Viscosity, high modulus epoxy.
- Silane - Tamms Baracade 244-Silane Sealer.

Eighteen integrated sensors were installed in the bridge decks in the five testing sections and at different depths for monitoring the internal temperature and relative humidity distributions in concrete. Concrete cores were taken at four periods during the project to test them for chloride ion ingress. The British Pendulum Tester (BPT) was used to measure the skid resistance of the concrete surface with and without sealers. The performances of the four sealers were ranked, according to their performance in the tests, from the four experimental parameters and cost perspective. A-Skid resistance, B-Internal temperature, C-Internal relative humidity, D- Chloride penetration, E-Cost

Main findings for deck sealers

- The sealers skid resistance for sealers were reduced compared to the control deck. After one year, most of sealers have lower skid resistance than the control deck, except the silane.
- Sealers applied on concrete decks generated higher temperature gradients in the decks than that of control decks; this increase in temperature gradient due to all sealers is very small and not effective in causing any deterioration in the concrete.
- No new moisture penetration was recorded into the concrete deck during the eight-month period. This gave an indication that the sealers were effective in blocking the moisture movement into and out of the concrete decks.

Chapter 3 Identification And Selection of Deck and Crack sealers

3.1 Introduction

This chapter includes the identification, review of different types of deck and crack sealers and also it includes the selection of the deck and crack sealers that were tested in this research. The selection depends on different criteria that will be discussed in this chapter. The selected deck and crack sealers have been approved to be tested by NDOT.

3.2 Choosing of sealers

Sealers for testing were chosen by looking at previous research, examining properties talking with supplier representatives, and final conversations with NDOT engineers. Some sealers were chosen from previous research, according to the sealer performance in different tests. Other sealers were chosen by searching about the sealers used to reduce the ingress of the chloride ion inside the concrete deck. Moreover, other sealers were chosen after meeting with representatives from different chemical companies during the Pacific Northwest Bridge Maintenance Conference held in Portland, Oregon in 2016.
A total of 12 deck sealers and 18 crack sealers were examined as part of the initial pool of sealers. Five deck sealers and six crack sealers were recommended to NDOT, and they were approved to be tested by NDOT. ***Table 3-1*** shows the different types of deck and crack sealers that were chosen before filtering into the tested sealers.
The deck sealers chosen were from five different companies, Sika, Proscoe, Advanced Chemical Tech., BASF, and ChemMasters. The crack sealers were chosen from five different companies, Sika, BASF, Advanced Chemical Tech, Chemmasters, and Transpo Industries.

Table 3-1: List of deck and crack sealers that were chosen before filtering

Sealer Name	Manufacturer
Deck Sealers	
ATS-100	Advanced Chemical Tech.
ATS-100 LV	Advanced Chemical Tech.
ATS-42 VOC	Advanced Chemical Tech.
Deck-Sil PS1700 Series	Advanced Chemical Tech.
MasterProtect H400	BASF
Aquanil Plus 40	ChemMasters
Aquanil Plus 100	ChemMasters
SpallGuard WB-10	ChemMasters
Saltguard WB	Prosoco
Saltguard	Prosoco
Sikagard 740 W	Sika
Sikagard 705 L	Sika
Crack Sealers	
EP-700 D	Advanced Chemical tech
MasterSeal 630	BASF
Duraguard HM Sealer	ChemMasters
Duraguard 401- 30 E	ChemMasters
EP100-SEAL	Echem
EP75-Seal	Echem
Five Star RSR PF-60	Five Star
Five Star RSR R-60	Five Star
Five Star RSR Easy Mix	Five Star
Five Star RSR PolyFix	Five Star
Five Star RSR EpoxyFix	Five Star
Sikadur Epoxy Broadcast	Sika
Sikadur 22, LO-Mod	Sika
Sikadur 22, LO-Mod FS	Sika
Sealate T-70	Transpo Industries
Sealate T-70 MX- 30	Transpo Industries
T-78 Polymer Crack Sealer	Transpo Industries
T-523	Transpo Industries

3.3 Identification of sealers

Sealers were compared with each other by chemical family, viscosity, volatile organic compound (VOC) and chloride reduction percentage. For example, sealers of silane or siloxane or silane/siloxane would be tested. Also, cracks sealers of epoxy and Methyl Methacrylate were chosen. Deck sealers mainly composed of silanes, siloxanes, and linseed oil. Linseed oil hasn’t been used because its performance was low compared to silanes and siloxanes. Linseed oil is a membrane sealer than a penetrating sealer (Soriano, A., 2002). That’s why linseed oil wasn’t chosen to be tested, and silanes and siloxanes are chosen. While for crack sealers, epoxies and methacrylate are the most common type of crack sealers and they have different properties and different viscosity, so they were chosen to be tested through different sealer.

For deck sealers, the viscosity of the sealers was one of the main issue that was taken into consideration. For instance, if the sealer has very high viscosity it won’t penetrate as much into the concrete so its performance won’t be good. Moreover, the depth of penetration, volatile organic compound (VOC), and Chloride reduction percentage stated by the manufacturer were main points of comparison between the sealers. The five deck sealers were chosen so that some sealers will be 100% active ingredient, other 40% active ingredient, and one 5% active ingredient. All the other sealers are the same percentage. Also, the depth of penetration of the selected sealers are the highest among the other sealers. This indicate that these sealers would give higher performance. Moreover, the chloride reduction percentage from different test, as AASHTO T260 or NCHRP report 244 series II, was the highest among the five selected sealers. Furthermore, the chosen sealers were chosen from different chemical family. Some of them are Alkylalkoxy Silane, water based and others are Alkytrialkoxy silane solvent based or water based as well. This could make a variety in testing different sealers.

For crack sealers, the viscosity of the sealers was very important as well as in the deck sealers. The sealers with lower viscosity were chosen. ***Figure 3-1*** shows the different viscosity for the sealers. The six selected sealers were chosen so that they define different range of viscosity. Also, the tensile properties and shear strength are the most important comparison points to compare between the sealers. The higher the bond strength, the better performance for the sealer. ***Table 3-2*** shows the different properties for the selected deck sealers used in testing. ***Table 3-3*** shows the different properties for the selected crack sealers used in testing.

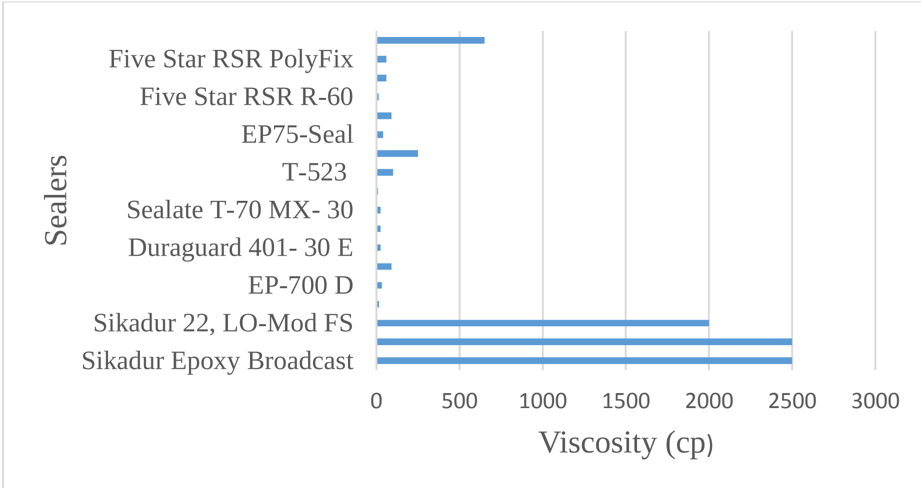


Figure 3-1 Different range of viscosity for eighteen crack sealers

Table 3-2: The different properties for the selected deck sealers for testing.

Product Name	Manufacturer	Chemical Family	Sealer type	Active Ingredient Content	Coverage rate Ft^2 /gal	VOC (g/l)	Depth of Penetration OHD L-34/40 (mm)	Water absorption without abrasion ASTM C 642	Chloride Reduction		
									ASHTO T259/ 260	NCHRP Report 244 Series II	NCHRP Report 244 Series IV
Sikagard 705 L	Sika	Silane, Water-Based	Alkylalkoxy Silane	100%	240-360	327	>10	0.06% (24 hrs) 0.1% (48 hrs)	82.6% at 1’’	88%	98%
Saltguard WB	Prosoco	Silane/ Siloxane water-Based	———	5%	50-300	<25	≤10	———	————	90%	88%
ATS-100	Advanced Chemical Tech.	Silane, Water-Based	Alkyltrialko-xysilane	100%	125-400	<350	10-15	0.3% 48 hours 0.8% 50 Days	96.7% @ 0.5 “ 96.4% @ 1”	89%	99%”
MasterProtect H400	BASF	Silane, water-based	Alkylalkoxy Silane	40%	100-200	<350	———	0.42% 48 hours 1.2% 50 Days	———	87%	99% South-ern Climate
Aquanil Plus 40	ChemMasters	Solvent, Based silane Sealer	Alkyltrialkxy silane	40%	100-150	<600	6.0	Reduction 95% 24 hours	84.8% 0.5” 89.4% 1”	89.9%	86.1 %

Table 3-3: The different properties for the selected crack sealers for testing.

Product Name	Manufacturer	Description	Viscosity (cps) ASTM D 2393	Tensile Properties ASTM D 638 (14 days)		Shear Strength (ASTM D 732) (psi) 14 days	Flexural Strength at 14 days (ASTM D-790)	Compressive Strength (psi)	Remarks
				Tensile Strength (psi)	Elongation at Break				
Sikadur 22, LO-Mod	Sika	Low Modulus, medium Viscosity and 100% Solid epoxy resin	2,500	2,200 **5,900**	1.1% **30%**	Mortar 1:5 3,300 **5,400**	4,300 **6,800**	28 days 7,850 at 73 F	Mortar 1:2.25 **Neat**
Sikadur 55 SLV	Sika	Super low viscosity, moisture-tolerant epoxy resin	105	7,100	10%	5,800	8,500	28 days 12,000 at 73 F	——
Duraguard HM Sealer	ChemMas-ters	Very low viscosity, high modulus, 100% solids epoxy	<90	7,000	3% - 7%	1,500	9,000	10,500	——
T-78 Polymer Crack Sealer	Transpo Industries	Low viscosity Methyl Methacrylate Resin System	5-10	8,100	5%	——	——	12,800	——
MasterSeal 630	BASF	Low viscosity, solvent-free, rapid reactive methacrylate	5-15	7,775	5%	——	11,900	12,800	Flexura l Strengt h tested by **(AST M D 638)**
KBP 204	KwikBond	high molecular weight methacrylate monomer composition	<25	>2000 7days	——	——	——	>3000 at 24 hours	——

Chapter 4 Experimental Program - Deck and Crack Sealers

4.1 Deck Sealers

4.1.1 Introduction

This chapter includes the laboratory experimental program used to assess the effectiveness and performance of some of the commercially available sealers for both deck and crack sealers. Details are provided for casting of specimens, test methods and testing procedures. All the test used were based on existing methods: ASTM, AASHTO, and NCHRP Report 244 series 2.

4.1.2 Laboratory experimental program overview

The primary objective of this task is to assess the performance of the chosen deck sealers, and their ability in reducing the penetration of the chlorides through the concrete. This task was accomplished by using different tests on five different deck sealers. Each test examined a different performance criterion of the sealers. The tests performed were as follow:

1- **Chloride Ion Intrusion "AASHTO T259/260":** Standard method test for resistance of concrete to chloride ion penetration.
2- **Freeze/thaw Exposure "ASTM C666":** Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing. This test used for testing the specimens in chloride ion intrusion test.
3- **Rapid Permeability "ASTM C1202":** Standard test method for electrical indication of Concrete's ability to resist chloride ion penetration.
4- **Saltwater Absorption "NCHRP report 244 series II":** A test used to measure the sealer's ability to limit the ingress of water and chlorides and is based on the NCHRP 244 testing series II.

The specimen's size were not the same for the tests. Some specimens were cylinders, others were small slabs. A number of samples were determined for each test, with different dimensions. The rapid permeability test used a 4 in. by 8 in cylinder. Slabs with dimensions 12 in. by 12 in. by 3 in. were used for chloride ion intrusion and saltwater absorption. For the freeze/thaw exposure tests, specimens with dimension 4 in. by 16 in. by 3 in. were used.
Tests included specimens that were:
Sealed and sandblasted before ponding with a sodium chloride solution for 90 days;
Sealed and immersed in sodium chloride solution for 21 days; and weighted after that.
Casting, preparation, and sealing of the concrete specimens, as well as the procedure of each test will be described further in this chapter.

4.1.3 Description of test specimens and application of sealers

Specimens were cast in January 2017. Two different concrete used in this research: American Ready-Mix and 3D Ready-Mix. The two kinds of concrete were of the same type “Portland cement concrete” but were from two different companies with different type of aggregate. Two types of concrete were used to see if sealers were equally effective for two types of concrete.

4.1.3.1 Concrete types

Table 4-1 and ***Table 4-2*** show the different characteristic of the American Ready-Mix and 3D Ready-Mix respectively.

Table 4-1 Characteristic and mix portions for one cubic feet of the American Ready-Mix

Materials	Description	Source	oz/yd	Abs.Vol(CF)	Weight(lb)
Coarse Aggregate	WNM#67	Western Nevada Materials		8.12	1.309
Coarse Aggregate	WNM#8 MA	Western Nevada Materials		1.53	248
Fine Aggregate	WNM Sand	Western Nevada Materials		7.36	1.196
Portland Cement	Type I/II	Lehigh		2.69	529
Mineral/admix	Class F-Fly Ash	Jim Bridger		1.23	176
Water	City		32 gal	4.34	271
Air Entrainer	NDOT Micro Air	BASF	10	0.01	1
Type A water reducer	NDOT Glenium 7500	BASF	50	0.05	3
Type A water reducer	NDOT Rheomne VMA 362	BASF	21	0.02	1
Type A water reducer	NDOT DELVO	BASF	21	0.02	1
Air				1.61	

Table 4-2 Characteristic and mix portions for one cubic feet of the 3D Ready-Mix

Material	Description/Source	Weight (lbs)	Volume (cu.Ft)
Cement	Nevada Type II	546	2.778
SCM	Nevada Class N Pozzolan	137	0.919
Coarse Aggregate	Dayton#67 stone	1434	8.839
Coarse Aggregate	Dayton#8 Stone	230	1.429
Fine Aggregate	Dayton Manufactured Concrete Sand	113	0.702
Fine Aggregate	Dayton Concrete Sand	1019	6.329
Water	33.1 gallons	276	4.423
Air Content	5.50%		1.485
Admixture	Eucon Air Entraining Admixture (0.45 oz/cwt)	3.1(fl oz)	0.003
Admixture	Eucon X15 (9oz/cwt) Initial	61.5(fl oz)	0.064
Admixture	Eucon 37(40z/cwt) Final	27.3(fl oz)	0.029

4.1.3.2 Casting and curing procedures

Casting of concrete occurred at the Large-Scale Structures Laboratory at University of Nevada, Reno. Slump tests and air content tests were conducted on the concrete during casting to make sure it met the criteria specified in ASTM C 143 and ASTM C 23. ***Figure 4-1*** show the slump and the air content tests applied during casting. Specimens were covered with plastic for 48 hours after casting and then transported to the curing room and left there for different days depending on the test specimen requirements. A compressive strength test was made after 7, 21, 28, and 133 "test date" days. ***Table 4-3*** shows the number of specimens used in each test. The same number of specimens were used in American Ready-Mix and in 3D Ready-Mix.

(a) **(b)**

Figure 4-1 Quality control tests for concrete **(a)** Slump test **(b)** Air content test

Table 4-3 shows the specimens size and no. of specimens used in each test

Test name	Test Method	Specimen size	Control specimens	Specimens with sealers
Chloride Ion Intrusion	AASHTO T259/260	Slab 12 in. by 12 in. by 3 in.	2	5
Freeze/thaw Exposure	ASTM C 666	Slab 16 in. by 4 in. 3 in.	1	5
Saltwater Absorption	NCHRP report 244 series II	Slab 12 in. by 12 in. by 3 in.	3	15
Rapid Permeability	ASTM C 1202	Cylinders 4 in. by 2 in	7	35
Bond Strength	ASTM C 496	Slab 8 in. by 4 in. 3 in.	0	10

4.1.3.3 Sealers application

The concrete age for the sealer application was different for each test. For the chloride ion intrusion test, sealers were applied on the 12 in. by 12 in. by 3 in. specimens after 14 days from casting. For the rapid permeability test, salt water absorption, and freeze/thaw test, sealers were applied after 28 days from casting. All the sealers air dried for 7 days before testing independent of the type of test. ***Figure 4-2*** shows the application of the sealers on some samples in the fume hood.

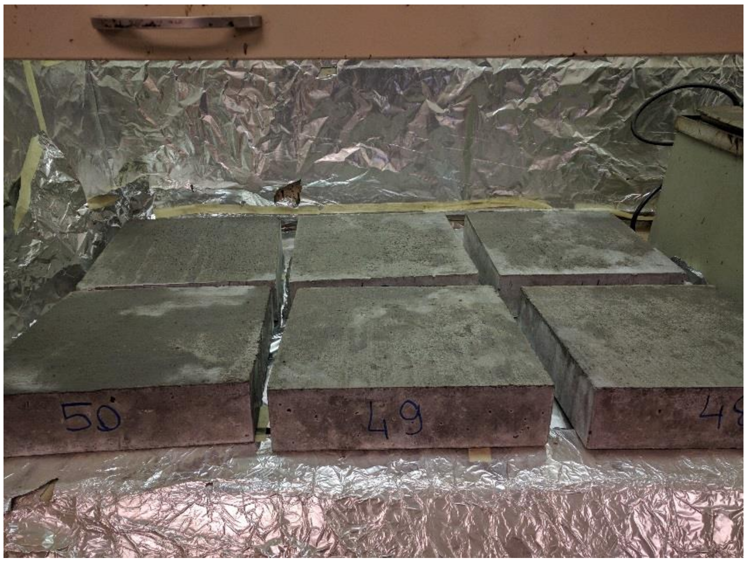


Figure 4-2 Application of sealers in flume hood

4.1.4 Chloride ion intrusion test “AASHTO T259/T260”

The chloride ion intrusion (90 days ponding test) is one of the test that have been performed on the deck sealers to assess the performance of each sealer and its ability in reducing the amount of chlorides that penetrates the concrete. The test was performed according to AASHTO T259 and AASHTO T260.

4.1.4.1 Specimen preparation and ponding

In this test, specimens were divided into two sets. The first set contains specimens that were not exposed to freeze/thaw cycles, and the second set contains specimens that have been exposed to freeze/thaw cycles. All the specimens followed the same preparation procedure. All the specimens were removed from the curing room after 14 days. After 14 days, the specimens were air dried until day 21. At 21 days, the sealers were applied, and the specimens were allowed to dry until day 28. At day 29, the specimens were sandblasted by 3.2 +- 1.6 mm (0.125 +- 0.0625 in.) of the slab surface to be similar to the bridge deck concrete that has been subjected to the wearing effect of vehicular traffic. The sandblasting was performed by a sandblaster equipment 20 lb. Pressurized Abrasive Blaster, and the abrasive material used was black aluminum oxide 70 grit, and the depth of the abraded surface was measured by a caliper in random locations to make sure that the required depth was removed. ***Figure 4-3*** shows the difference between a specimen before and after sandblasting.

(a) **(b)**

Figure 4-3 (a) Specimen before sandblasting **(b)** Specimen after sandblasting

Nineteen mm (0.75 in.) high dams were placed around the 12 in. by 12 in. by 3 in. specimens to prevent the leakage of the salt water used in ponding. The dam could be either expanded foam or plastic caulked by silicon to prevent the leakage of the saltwater solution. ***Figure 4-4*** shows the expanded foam dam around the specimens. All specimens returned back to the drying room for air drying till age 42 days.

Figure 4-4 Expanded foam around the edge of the specimen

After 42 days of curing, the specimens were covered by 3 percent sodium chloride solution for 90 days and stored in a separate shed. The saltwater depth was 0.5 in. above the surface of the specimens. The specimens were covered by plastic tarpaulin to eliminate the evaporation of water. ***Figure 4-5*** shows the specimens covered with plastic. "About once a week, which is approximately eleven times the solution was added to the specimens whose water level decreased. After 90 days of ponding, the solution was removed from the specimens, and the specimens were wire-brushed to remove the salt crystal from the surface. Then, using a rotary hammer the samples were extracted from the specimens immediately.

Figure 4-5 Specimens with saltwater solution covered with plastic covers

4.1.4.2 Samples retrieving

For each sealer, two samples for each condition were tested. Samples were retrieved from the holes in each specimen within two different depth ranges. The first depth range was 1.6 mm to 13 mm (0.0625 in. to 0.5 in.), and the second depth range was 13 mm to 25 mm (0.5 in. to 1.0 in.). The samples were retrieved using rotary hammer and a depth indicator. Three holes were formed in each specimen. The sample had to be about 3 grams of powder. From each hole, about 10 grams of powder were extracted to form two samples per hole or more if it was needed. ***Figure 4-6*** shows the location of holes.

Figure 4-6 Locations of holes in a specimen

All samples had to pass a 0.300 mm (No.50) sieve. One specimen was used for each sealer and for the control (unsealed) specimen one specimen was used as well, 3 holes were extracted from each specimen, and two samples from each hole. The rotary hammer, drills and spoons used were washed with alcohol and distilled water after the retrieving of each samples and then wiped to prevent the contamination of the chlorides between different samples.

4.1.4.3 Equipment and reagents used

The amount of chlorides was determined by using a Cole Palmer chloride ion selective electrode. The measurements were done with the electrode and connected to Fisher Scientific accumet AE150 millivolt meter and digital data display.
Different reagents were used in this test for the sample decomposition. Sodium chloride NaCl with 0.01 Normality was used. The sodium chloride solution was prepared by getting a mass of approximately 0.5844 g of NaCl reagent, dissolve in a 1-L of distilled water and mix them together. Silver nitrate $AgNO_3$ with 0.01 Normality was used. The silver nitrate solution was prepared by obtaining the mass of 1.7 g of reagent $AgNO_3$ mixed with 1-L of distilled water. Concentrated Nitric Acid HNO_3 (sp gr 1.42) was used. Methyl orange indicator was used.

4.1.4.4 Sample decomposition

AASHTO T260 specify two procedures for decomposition, either acid-soluble chloride ion content or water-soluble chloride ion content. Both procedures use the same chemicals and equipment but with different techniques. This research used the water-soluble chloride ion content.

The first step was to obtain approximately 3.0 g of concrete powder for each sample to nearest 0.001 g. The weighed powders were transferred to a beaker of 150 ml or 250 ml. Distilled water was added to the beaker until it reached 60-70 ml. The beaker was covered and brought to boil on a hot plate and magnetic stirrer using a small magnet for 5 min and left for 24 hours in an HCI fume-free atmosphere.

The boiled liquid was filtered in a beaker through double filter paper (Whatman No. 41 and 42). Sufficient hot distilled water was added to cover any residue left in the beaker and then filtered into the beaker. 1-2 drops of methyl orange indicator were added to the filtered liquid, then concentrated HNO_3 was added while continuous stirring on a magnetic stirrer until a permanent pink color was obtained. ***Figure 4-7*** shows some samples with pink color after addition of nitric acid and methyl orange.

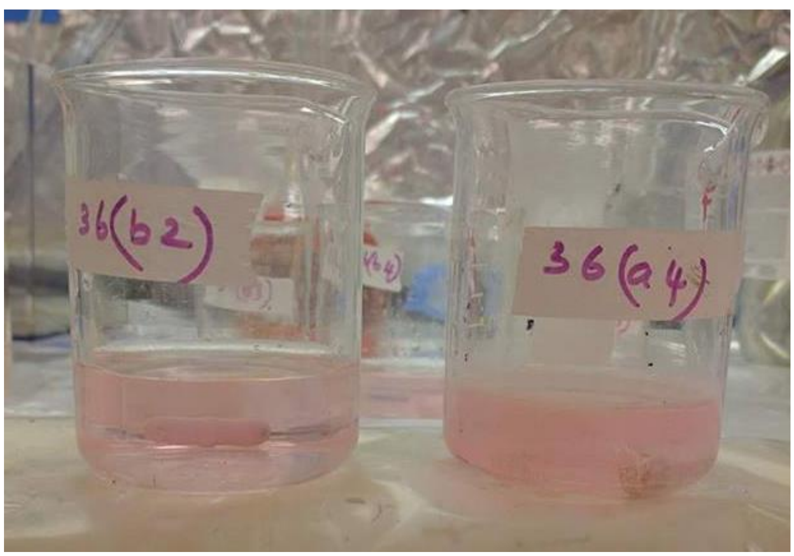


Figure 4-7 Samples after being acidic with nitric acid and methyl orange indicator

Three alternate methods are specified by AASHTO T260 for the analysis of the given results of the electrode. The method used in this research was Potentiometric Titration.

4.1.4.5 Potentiometric titration

The electrode first was filled with the 10% KNO_3 solution and then calibrated. Three solutions of ionic selective electrode (ISA) solution were made for calibration: 1 ppm, 10 ppm and 100 ppm. According to the manufacture, the electrode was calibrated to 200 mv for 1 ppm, 150 mv for 10 ppm, and 90 mv for 100 ppm. After calibration, the electrode was immersed in distilled water to measure the equivalence point of the distilled water.

The electrode was removed from the distilled water and wiped carefully then immersed in the sample's beaker. 4.00 ml of 0.01 normality of NaCl was added to the sample beaker, while swirling carefully on a magnetic stirrer. $AgNO_3$ solution with normality 0.01 was added gradually, the amount was recorded that brought the electrode measurement to below 40 mv of the equivalence point determined in distilled water. Standard 0.01 normality solution in 0.10 mL increments was added and the millivolt meter reading was recorded after each addition. The titration was continued until the millivolt meter reading was at least 40 mV past the approximate equivalence point. The end point of titration was usually near the approximate equivalence point in distilled water and can be determined by plotting the volume of $AgNO_3$ solution versus the millivolt meter reading. The end point for the $AgNO_3$ solution correspond to the point of the inflection of the resultant smooth curve (i.e. the biggest difference between two consecutive readings. ***Figure 4-8*** shows the combination of the beaker-electrode-burette-millivolt meter during the chloride ion analysis titration.

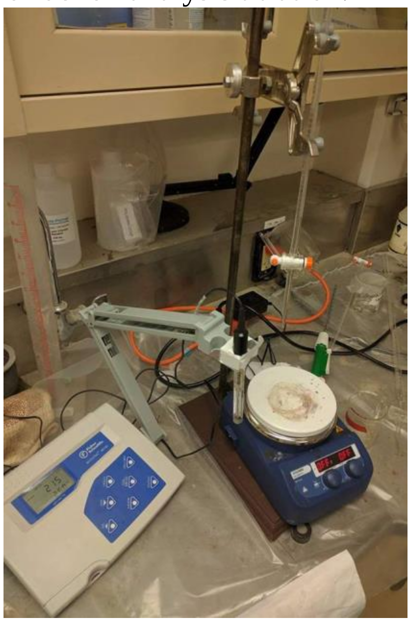


Figure 4-8 Electrode-burette-millivolt meter used for chloride ion analysis titration

4.1.4.6 Data collection

As stated before, from each hole 10 grams of material was extracted and two samples each 3 grams samples were tested from each hole and 4 grams are excessive in case that we need to test any sample again. The two samples from each hole gave very close number for the amount of silver nitrate added as shown in the following figures where the two samples from the same hole have very similar amount of chlorides. ***Figure 4-9*** and ***Figure 4-10*** shows the titration curves for two samples taken from two different holes.

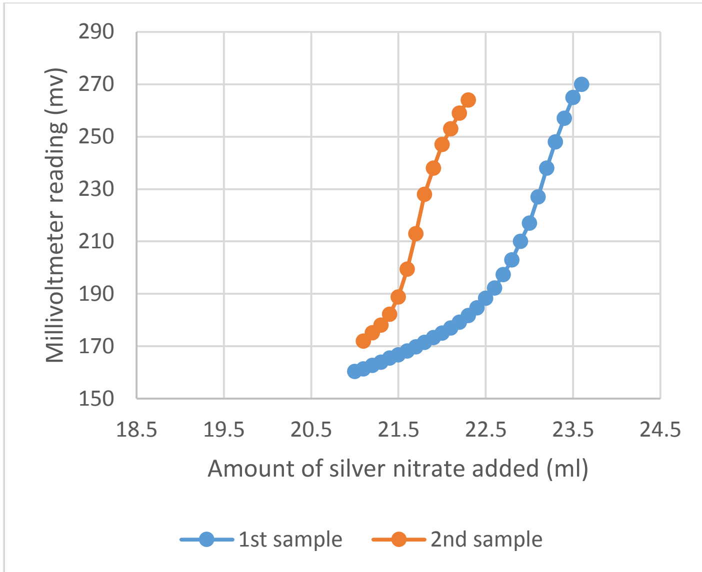


Figure 4-9 Two titration curves for two samples from the same hole

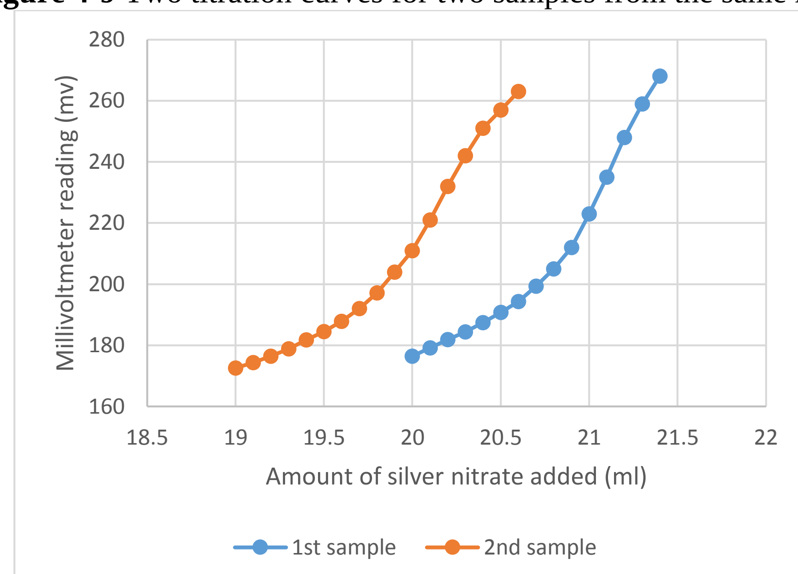


Figure 4-10 Two titration curves for two samples from the same hole

The end point of the silver nitrate solution has been determined either by the inflection of the curve or the biggest difference between two consecutive readings, then the percentage of chloride ion was calculated from Equation 4-1:

$$Cl^{-}\% = (3.5453(V_1N_1 - V_2N_2))/W \qquad \text{Equation 4-1}$$

Where:
V_1: end point of $AgNO_3$ in mL,
N_1: normality of $AgNO_3$ (almost 0.01),
W: actual mass of concrete sample in grams,
V_2: volume of NaCl solution added in mL (4 mL),
N_2: normality of NaCL solution,

In order to make comparison easier, the chloride percentage was converted to pounds of chloride ion per cubic yard of concrete by the following Equation 4-2:

$Cl^- / yd^3 = Cl^- \% * (UW/100)$ Equation 4-2

Where UW is the unit weight of concrete per cubic yard and taken as 4050 lb/yd^3 for normal structural mass concrete when the actual unit weight is unknown. ***Figure 4-11*** shows a sample curve for one of the tested samples.

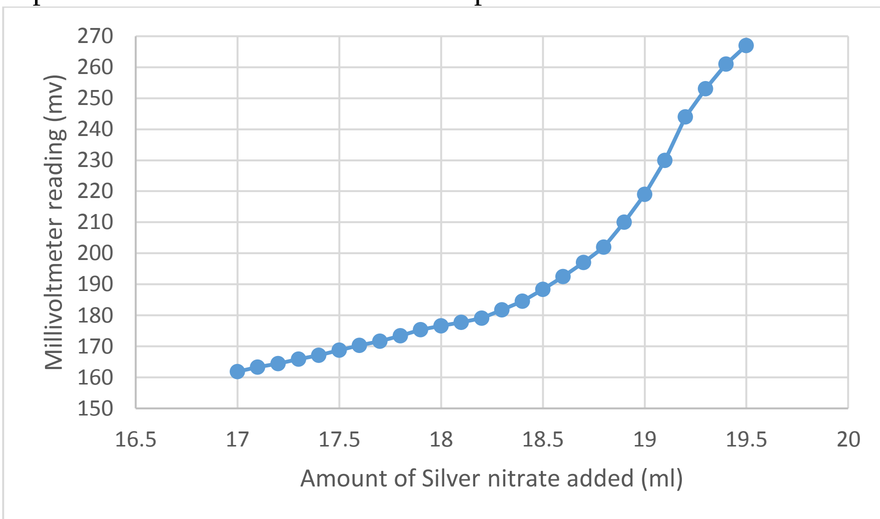


Figure 4-11 Sample titration curve for unsealed specimen

4.1.5 Freeze/thaw exposure "ASTM C 666"

In order to understand the behavior of the sealers in reducing the amount of chlorides penetrated into concrete when exposed to freeze/thaw cycles, some specimens were exposed to freeze/thaw cycles and tested with the chloride ion intrusion test. For each concrete type, the American Ready-Mix and the 3D Ready-Mix, one specimen for each sealer and two specimens as control specimens were sent to a CTL Thompson company in Denver, Colorado to be tested under freeze/thaw cycles. The test was done according to ASTM C 666, and the test was finished after 300 cycles. After completing the tests, the specimens were shipped back to the University of Nevada, Reno. The durability for the concrete were calculated for both concrete. Specimens were placed in the sodium chloride solution (3%) for 90 days, and then the same procedures for the chloride ion intrusion was repeated.

4.1.6 Rapid permeability test "ASTM C1202"

This is an indirect testing method commonly used to measure the permeability of concrete, ASTM C 1202 ("Standard test method for electrical indication of concrete's ability to resist chloride ion penetration"). The result of this testing method was related to the electric conductivity of saturated concrete, which can be correlated to the chloride permeability of saturated concrete (Stanish et al. 1997).

4.1.6.1 Specimen preparation

Specimens used for this test were cylinders "4 in. by 8 in." and then were cut into smaller samples according to the standard specifications. For each cylinder specimen, the cutting machine in the laboratory cut a "4 in. by 2 in." slice. This test was done twice. First one within 30 to 40 days concrete age, 10 days to finish testing all the specimens, and the second one was done after an age of 120 days. The purpose of doing the test at different ages was to assess the impact of concrete age on performance. The porosity decreases with time as concrete becomes denser. After cutting the specimens into 4 in. by 2 in. disks, the specimens were coated with plasti dip around its circumference while filling any apparent hole in the coating. The plasti dip is an air dry, specialty rubber coating, insulating, and non-slip. This coating was used to prevent the leaking of any of the electrical current during the test.

The university laboratory has the instrument to perform this test on but it would take more time because the test has to be performed manually. The research team to talk with professional testing company that has a digital instrument; this allowed the testing to proceed much faster.

4.1.6.2 Test Procedure

Sealer was applied on concrete types after day 28. Five different sealers were applied on both concrete. Twenty-four specimens were tested at the age of 30-40 days and 18 were tested after 120 days. At the age of 30-40 days, four concrete specimens for each of the five sealers were tested, plus four specimens with no sealer act as a control specimen to compare the amount of chlorides penetrated the concrete without sealers and with sealers. At the age of 120 days, three concrete specimens for each sealer plus three concrete specimens without any sealer were tested.

Test was done by passing an electrical current through the concrete cylinder. Two solutions were used for this test. Sodium chloride with 3 % weight and sodium hydroxide with 0.03 normality. The test is done on two separate days. First day, the specimens were put in a vacuum desiccator for three hours under pressure 50 mmhg and then immerse in water for additional hour under the same pressure and left for 18 +/- 2 hours till the next day, then it was ready to be tested. ***Figure 4-12*** shows the vacuum desiccator used in removing air from the specimens. The next day the test was conducted and terminated automatically after 6 hours.

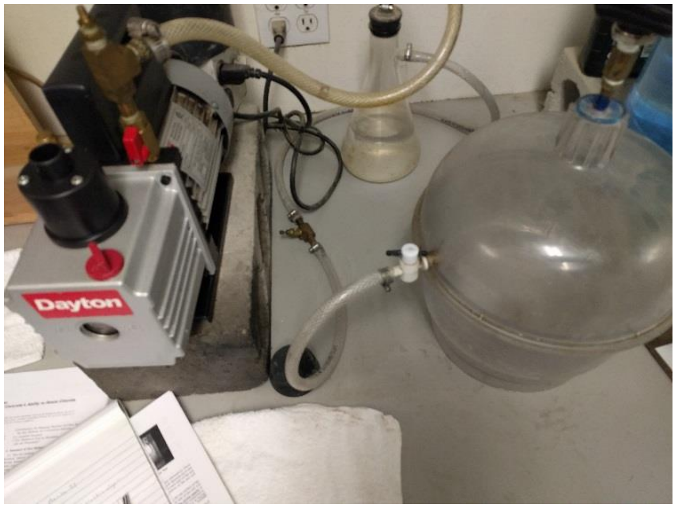
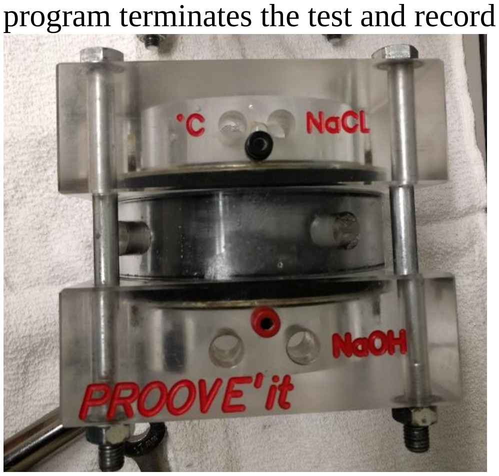
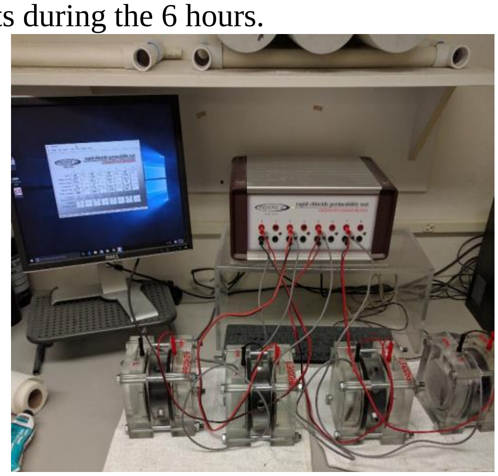


Figure 4-12 Rapid chloride permeability test setup

The next day, the specimens were ready for testing. Each specimen was put between two cells: one contained the sodium chloride solution and the other cell contain the sodium hydroxide solution. The cell containing sodium chloride solution was attached to the negative terminal of the power supply. The cell containing sodium hydroxide was attached to the positive terminal of the power supply. Lead wired from the cell to the power supply had temperature recording in order to terminate the test if the temperature exceeded 65°C. ***Figure 4-13*** shows typical cell and test setup for the specimens with cells, lead wire, power supply and program used for recording the data. After 6 hours the program terminates the test and record all the results during the 6 hours.



(a)



(b)

Figure 4-13 (a) Typical tested specimen **(b)** Rapid chloride permeability test setup

4.1.7 Saltwater absorption "NCHRP Report series II"

The Saltwater absorption test method is used for determining sealer's ability to limit the ingress of water and chlorides and is based on the NCHRP 244 testing series II. In this study, only the gravimetric determination of absorption was tested. Specimens used for

this test were small slabs 12 in. by 12 in. by 3 in. For each sealer, three specimens were tested and three specimens without any sealers were tested as a control specimen.
Sealers were applied on concrete specimens after 28 days after casting. All the specimens were weighted after applying the sealers (W_0). A sodium chloride solution (15 percent by weight) was used to immerse the specimens. Specimens were immersed in the solution and put on small wooden sticks, so that water will cover the specimens from all sides. ***Figure 4-14*** shows the immersion of the specimens in a plastic bucket filled with the solution.

Figure 4-14 Immersion of specimens in a plastic bucket filled with water

Specimens were removed after 7 days, rinsed, toweled and weighted (W_7). The weight gained was calculated using Equation 4-3

$\Delta W_{i7} = (W_{i7}d - W_{i0}) / (W_{i0})$ Equation 4-3

Where,
ΔW_{i7}: Weight gained during 7 days of immersion
W_{i0}: Weight at 0 days
The mean weight, which is the average of the three tested specimens for each type of sealer and control, were calculated. The saltwater absorption Ratio (SAR) was calculated representing the ratio between the absorption of sealed specimens to unsealed specimens, as in Equation 4-4.

$SAR_7\% = \Delta W_{i7\ sealed} / \Delta W_{i7\ unsealed} * 100$ as percent at7 days Equation 4-4

Where,
SAR_7: saltwater absorption ratio at 7 days
$W_{i7\ sealed}$: mean weight of three sealed specimens at 7 days
$W_{i7\ unsealed}$: mean weight of three unsealed specimens at 7 days
The specimens were then returned to the saltwater bath. Then at day 14 and at day 21, the specimens were removed out from the saltwater, rinsed, toweled, and then weighted (W_{14}) and (W_{21}). The weight gain at 14 days and 21 days were calculated using equations (4-5) and (4-6).

$\Delta W_{i14} = (W_{i14} - W_{i0}) / (W_{i0})$ Equation 4-5
$\Delta W_{i21} = (W_{i21} - W_{i0}) / (W_{i0})$ Equation 4-6

The SAR was calculated for both 14 and 21 days using Equations 4-7 and 4-8:

$SAR_{14}\% = \Delta W_{i14\ sealed} / \Delta W_{i14\ unsealed} * 100$ as percent at 21 days Equation 4-7
$SAR_{21}\% = \Delta W_{i21\ sealed} / \Delta W_{i21\ unsealed} * 100$ as percent at 21 days Equation 4-8

4.2 Crack sealers

4.2.1 Introduction

This section includes the experimental program for laboratory test used to assess the effectiveness and performance of some of the commercially available crack sealers. Details on casting of specimens, test methods and procedure are provided.

4.2.2 Laboratory test overview

Six crack sealers were used in this study by applying two tests to assess the performance of the crack sealers. These two tests are depth of penetration test, to examine the penetration of the sealers through the required crack width, and bond strength test, to assess the ability of the sealers to fill and glue the crack till breaking. Depth of penetration will be tested by visually inspection, and bond strength test was applied with a procedure similar to that used for obtaining the splitting tensile strength of cylindrical concrete specimens. To achieve this goal, concrete specimens with dimension 4 in. by 16 in. by 3 in. were cast and cured. Every specimen was cut into two halves to form a specimen with dimension 4 in. by 8 in. by 3 in. Cracks were formed in specimens with dimension of 4 in. by 8 in. by 3 in. with the required width, then filled with the sealers and tested after two weeks.

4.2.3 Description of test specimens

Specimens of dimension 4 in. by 16 in. by 3 in. were cast and then cut into 4 in. by 8 in. by 3 in. specimens. Sufficient number of specimens were casted to be tested after applying six sealers on two different crack widths.

4.2.4 Casting and curing

The same two concrete mixes as used for the deck sealer were used for crack sealer: American Ready-Mix and 3D Ready-Mix. Concrete specimens were left in the curing room (100% humidity) for 3 months till the scheduled testing date.

4.2.5 Cracking of the specimens

Before applying the sealers in the cracks, the cracks had to be formed with the required width. In order to form the cracks, a notch in the upper and lower surface of the specimens was formed using a cutting sawing machine with depth 1/4 in. and width 5/8 in. as shown in ***Figure 4-15.***

Figure 4-15 Notches in the upper and lower surface of the specimens

Steel rods were used in the upper and lower notch to concentrate the load over the notch. The specimens were then placed in the testing machine to be loaded and to form the crack as shown in ***Figure 4-16***. Instead using method consistent with the Wisconsin DOT, the crack could have been formed by cutting the specimens into two halves using a cutting sawing machine. In this case the crack will be very smooth, therefore the crack would need to be roughen in order to similitude a real crack surface; this type of crack would be better more consistent, so the modes of failure between all the sealers would be according to the same crack pattern. To be consistent with the Wisconsin DOT; this research used the method of forming a crack using rods and notches.

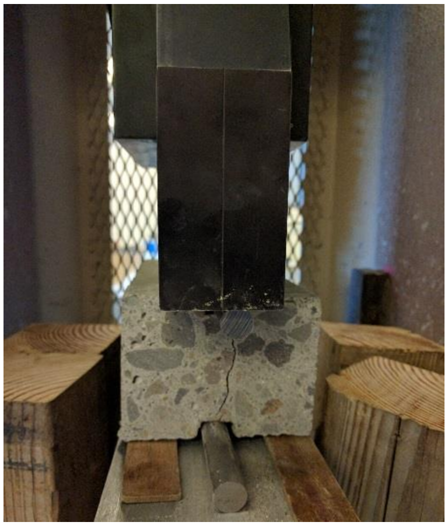


Figure 4-16 Test setup used for cracking the specimens

4.2.5.1 Formation of crack width

Two cracks width were used in the research. These crack widths were 0.09 inch and 0.15 inch. In order to form the cracks with the required width, aluminum foil was wrapped to the required thickness and placed at the two ends of the specimens using C-clamps; this forced the crack width to be the same as the aluminum foil thickness, as shown in ***Figure 4-17.*** The crack width was measured at the end of the specimens to make sure that the required width was obtained. Some adjustment was made either by changing the number of foil layers or changing the C-clamps pressure until the required width was achieved.

Figure 4-17 Specimens clamped to form the required width

After the specimens were clamped to the required crack width, silicone caulk was used to seal the ends and the underside of the specimens to prevent the leakage of the sealers after applying. Also, the silicon was put on the upper side on the edges so that the silicon would act as a dam to prevent the leakage of the sealers. ***Figure 4-18*** shows the specimens after being caulked with silicon from beneath and the sides.

Figure 4-18 Specimens after being sealed with silicone caulk

4.2.6 Sealers application

After the silicone caulk was dried according to the manufacturers' recommendation, sealers were applied inside the cracks. Each sealer from the six sealers was applied in two specimens, one with crack width 0.09 in. and the other with 0.15 in. Total twelve specimens of American Ready-Mix were sealed, and the same for the 3D Ready-Mix.
The sealers were applied in the fume hood and left for 14 days till testing. Before testing two inches were cut from both ends of the specimen by the cutting machine to use them in the depth of penetration test and the remaining part of each specimen – approximately 4 inches by 3.5 inches - was used in the bond strength test.

4.2.7 Depth of penetration test

The purpose of this test was to see how deeply each sealer would penetrate through the cracks, depending on the viscosity of each sealer, and to determine if any voids or parts the sealers couldn't penetrate by visually examining the two cross sections with the naked eye. Two inches were cut from both edges of the specimens as shown in ***Figure 4-19*** and were visually inspected. The remaining part of the specimens "3.5 in. by 4 in. by 3 in." were used in bond strength test.

Figure 4-19 Cross section of a specimen filled with crack sealer

4.2.8 Bond strength test

The bond strength test was studied by a test procedure similar to ASTM C 496 "Splitting Tensile Strength of Cylindrical Concrete Specimens". After 14 days from applying the sealers, concrete samples were cut 2 inches from both ends for the depth of penetration test and the remaining part were used for this test.

4.2.8.1 Breaking of the specimens and the loading rate

Specimens were placed in a machine similar to that used in forming the crack. Two steel rods were placed along the notches in the upper and lower face of the specimens. The load was applied along these steel rods to make sure the uniform distribution of the load. ***Figure 4-20*** shows the test setup.

Figure 4-20 Setup used to test the bond strength of the crack sealer specimens

The load rate used was approximately equal to that stated by the ASTM C 496. The loading rate in the specification is 100 to 200 psi/min. The loading rate used in the experiment was load control rate equal to 550 lb/10 sec. The specification stated that the splitting tensile strength of the specimen is T =2P/πld where p is the load, l is the length of the specimen and d is the diameter. Since the specimens used are not cylindrical but rectangle, d used in this equation was 3 inches and l was 3.5 inches, and the T was 200 psi/min. By applying this equation, the p obtained was 550 lb/ 10sec. The load was compared to 10 sec, so that it could be applicable to control the rate in the machine. The maximum load reached by the machine was the bond strength for the specimen. The test was terminated when the load decreased to 20% of the maximum load or until the specimens completely crush. Test data were collected included the bond strength of each specimen with a certain sealer and the mode of failure for the specimens. The modes of failure could be either concrete failure, sealer failure or interface failure. A combination of two failures mode could also happen. The bond strength reported is not necessarily the bond strength of the sealer but strength at which the specimen failed. If this failure was in the sealer, the reported strength is the shear strength of the sealer. If the failure is in the interface, then this is the bond strength. If the failure is in the concrete, then the bond strength of the sealer is known to be at least that equal to the concrete shear strength.

Chapter 5 Test Results And Discussion - Deck Sealers

5.1 Introduction

In this chapter the results of the tests that were conducted for deck sealers will be presented and discussed. As stated in Chapter 4, four tests were done on the deck sealers, and two tests were done on the crack sealers. Crack sealer results will be discussed in the next chapter. For deck sealers, results of rapid chloride permeability (Section 5.2), saltwater absorption (Section 5.3), and chloride ion intrusion for specimens with and without exposing to freeze/thaw (Section 5.4) are presented and discussed. The results from these tests are then discussed and the sealers are ranked and classified into different categories according to their performance (Sections 5.5 to 5.8).

5.2 Rapid permeability test "ASTM C1202"

As stated in Chapter 4, the rapid permeability test was conducted on two concrete types and at two different stages. The first stage was after a concrete age of 30 to 40 days and the other stage was after 120 to 130 days. The performance of the sealers was different for both stages and both concretes as well. The results of this test were related to the amount of charge passed through the specimens. From the average charge amount, the permeability class can be defined. The following tables show the results for both the American Ready-Mix and 3D Ready-Mix at the two stages. The dashed cells in the table mean that these cells were neglected in the calculations. The results were neglected because the test was terminated automatically during the test because of the high temperature of the specimens and the cells. Also, out of the average of the tested cells, some few results were not included according to ASTM E 177-14 (2013) precision and bias procedure. Bias is defined as a systematic error that contributes to the difference between the mean of a large number of test results and an accepted reference value. ***Figure 5-1*** and ***Figure 5-2*** show the mean results and the 95% confidence interval for the control specimens and the five sealers for American Ready-Mix, and 3D Ready-Mix respectively for stage 1 "after 30 days". Where the 95% confidence interval was calculated based on the mean plus/minus 1.96 x standard deviation over the square root of the number of samples. Table 5-1 shows the chloride ion penetrability based on charge passed according to ASTM C 1202 Standard Test Method for Electrical Indication of Concrete Ability to Resist Chloride Ion Penetration.

Table 5-1 Chloride ion penetrability according to charge passed

Charge passed (coulombs)	Chloride Ion Penetrability
>4000	High
2,000 – 4,000	Moderate
1,000 – 2,000	Low
100 – 1,000	Very Low
<100	Negligible

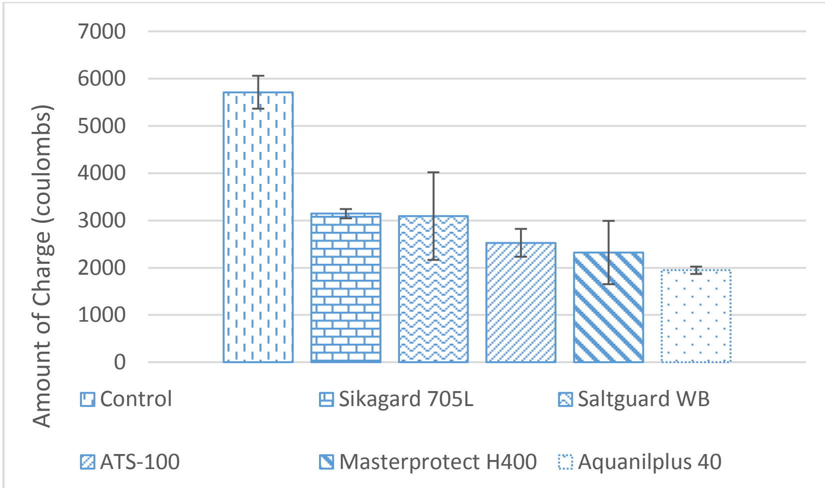


Figure 5-1 Mean and 95% confidence interval for American Ready-Mix specimens after 30 days

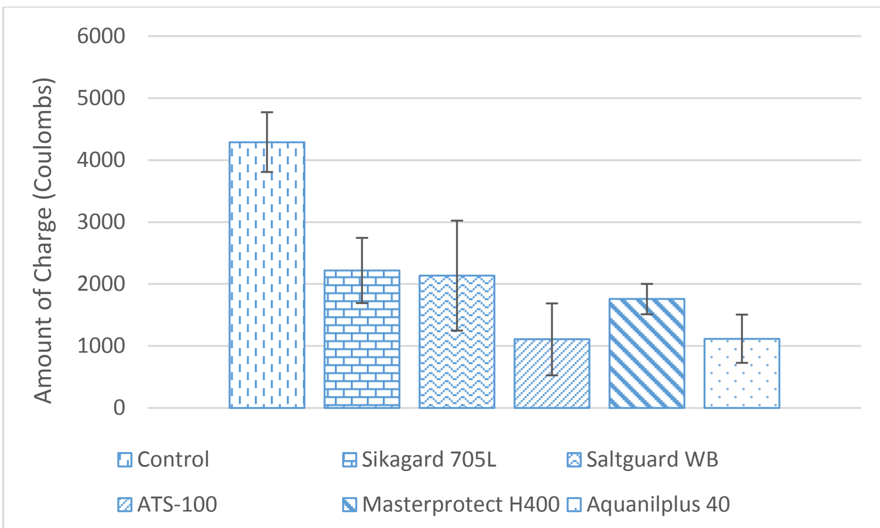


Figure 5-2 Mean and 95% confidence interval for 3D Ready-Mix specimens after 30 days

***Table* 5-2** shows the results for the different sealers applied on the concrete from American Ready-Mix at stage 1 (30-40 days of age) and stage 2 (120-130 days of age). For stage 2, the amount of charges passed for Aquanil plus 40 specimens were very high while all the other sealers were very low which is expected to have a few amounts of charges passed after 120 days; so, the results for Aquanil plus 40 doesn't make any sense and it was neglected.

Table* 5-3** shows the results for the different deck sealers applied on the concrete from 3D Ready-Mix at stage 1 (30-40 days of age) and stage 2 (120-130 days of age). The results in the following tables are based on the average value of the charge passed not the value of upper or the lower interval for the 95% confidence level, hence the permeability class is assigned according to the average. ***Table 5-4 shows the different penetrability "permeability" class for both concretes after 30 days of age according to the 95% confidence interval. In stage 2, specimens sealed with MasterProtect H400 were neglected because the tests were terminated due to these specimens reaching high temperatures. The discussion of all the results will be shown in (Section 5.5).

Table 5-2 Results of rapid permeability test for American Ready-Mix at both stages

	30 days		120 days	
Sealer	**Average charges passed**	**Permeability class**	**Average charges passed**	**Permeability class**
Control	5713	High	5786	High
Sikagard 705 L	3146.5	Moderate	134.67	Very Low
Saltguard WB	3091.7	Moderate	330.7	Very Low
ATS-100	2527.75	Moderate	152	Very Low
MasterProtect H400	2320.25	Moderate	181	Very Low
Aquanil Plus 40	1947.25	Low	----	----

Table 5-3 Results of rapid permeability test for 3D concrete at both stages

	30 days		120 days	
Sealer	**Average charges passed**	**Permeability class**	**Average charges passed**	**Permeability class**
Control	4289.3	High	3918	Moderate
Sikagard 705 L	2220.5	Moderate	142.5	Very Low
Saltguard WB	2136.3	Moderate	474	Very Low
ATS-100	1107.25	Low	260.5	Very Low
MasterProtect H400	1757.25	Low	----	----
Aquanil Plus 40	1115	Low	149.5	Very Low

Table 5-4 Permeability class for both concretes after 30 days of age according to the 95% confidence interval

Concrete	Specimens	Average	Highest Interval	Lowest Interval
American Ready-Mix	Control	High	High	High
	Sikagard 705 L	Moderate	Moderate	Moderate
	Saltguard WB	Moderate	High	Moderate
	ATS-100	Moderate	Moderate	Moderate
	MasterProtect H400	Moderate	Moderate	Low
	Aquanil Plus 40	Low	Moderate	Low
3D Ready-Mix	Control	High	High	Moderate
	Sikagard 705 L	Moderate	Moderate	Low
	Saltguard WB	Moderate	Moderate	Low
	ATS-100	Low	Low	V.Low
	MasterProtect H400	Low	Low	Low
	Aquanil Plus 40	Low	Low	V.Low

5.3 Saltwater absorption test "NCHRP report series II"

In saltwater absorption test, the weight of the specimens with each sealer was measured before immersion in solution and then weighed after 7 days, 14 days, and 21 days of immersion in 15% saltwater solution. The weights were used to calculate the saltwater absorption ratio (SAR), Equation 4-3 to Equation 4-8.

Table 5-5 shows the SAR % for the 7 days, 14 days, and 21 days for the American Ready-Mix specimens. ***Table 5-6*** shows the SAR % for the 7 days, 14 days, and 21 days for the 3D Ready-Mix specimens. ***Figure 5-3*** and ***Figure 5-4*** show the mean weight and 95% confidence interval for American Ready-Mix and 3D Ready-Mix. ***Figure 5-5*** shows the SAR% for both concrete along the days.

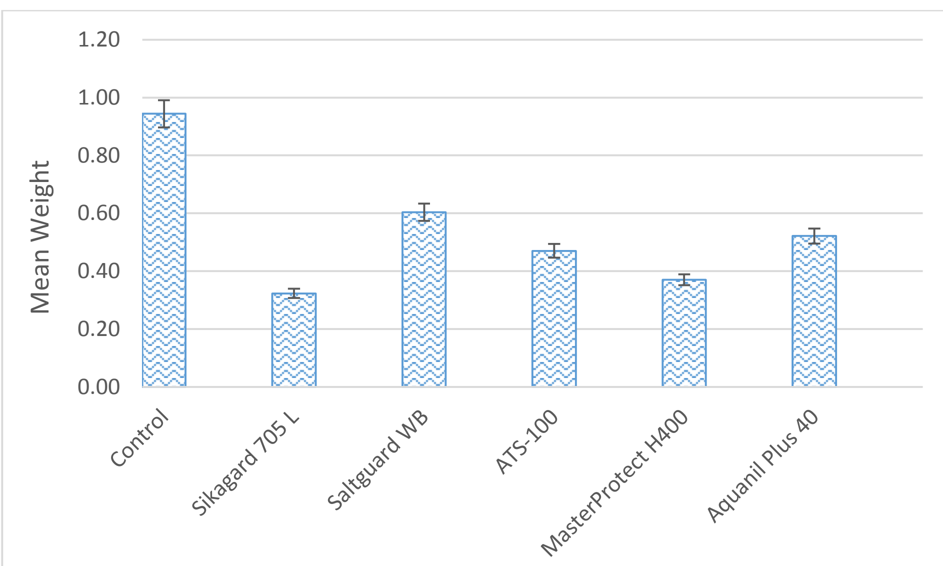


Figure 5-3 Mean Weight and 95% confidence interval for American Ready-Mix specimens

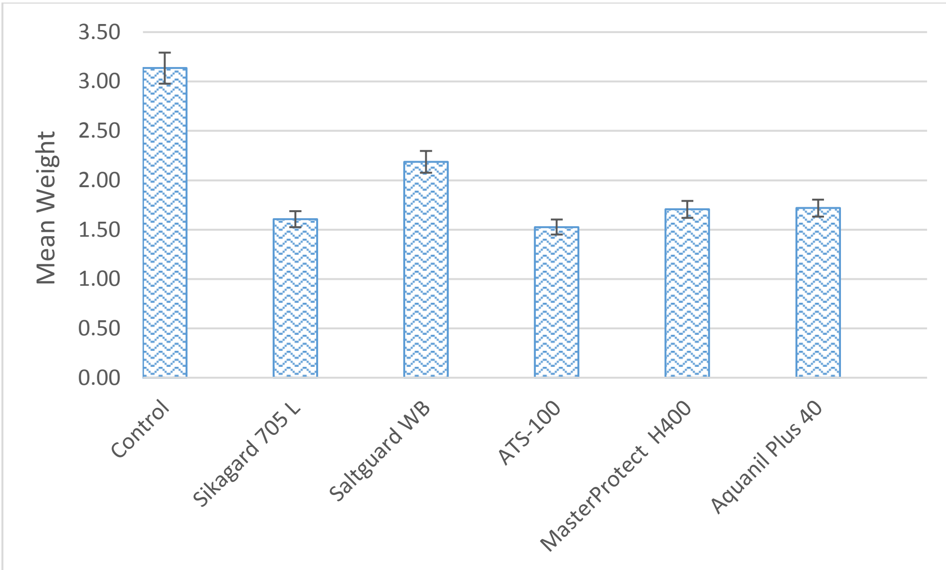


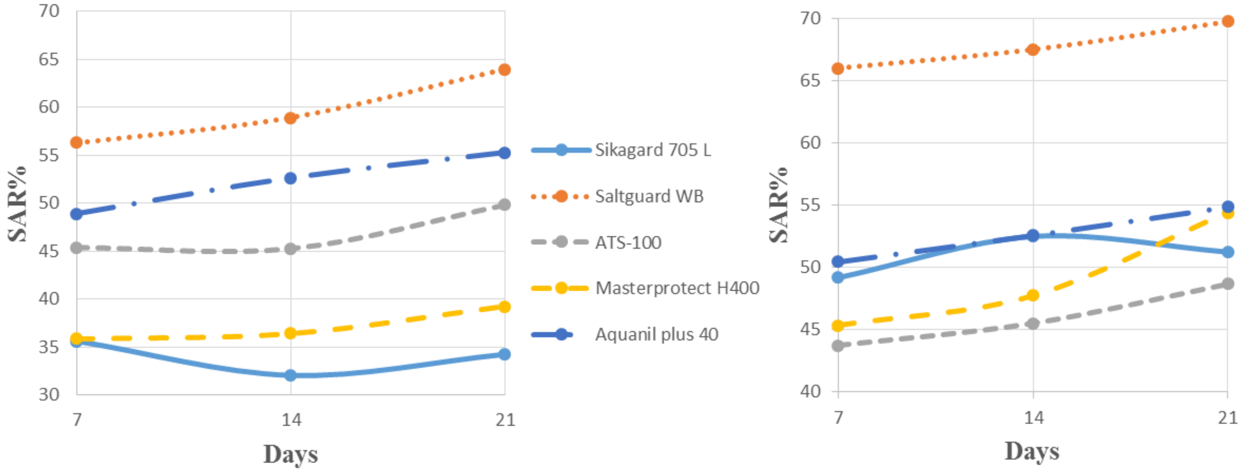
Figure 5-4 Mean Weight and 95% confidence interval for 3D Ready-Mix specimens

Table 5-5 Results for the saltwater absorption test for American Ready-Mix

Sealers	SAR_7 %	SAR_{14} %	SAR_{21} %
Control	100	100	100
Sikagard 705 L	35.619	32.033	34.232
Saltguard WB	56.297	58.933	63.954
ATS-100	45.367	45.252	49.812
MasterProtect H400	35.830	36.392	39.209
Aquanil Plus 40	48.885	52.613	55.248

Table 5-6 Results for the saltwater absorption test for 3D Ready-Mix

Sealers	SAR_7 %	SAR_{14} %	SAR_{21} %
Control	100	100	100
Sikagard 705 L	49.176	52.477	51.226
Saltguard WB	65.961	67.469	69.730
ATS-100	43.728	45.510	48.678
MasterProtect H400	45.342	47.720	54.389
Aquanil Plus 40	50.442	52.558	54.824



(a) **(b)**

Figure 5-5 SAR% for deck sealers applied on (a) American Ready-Mix (b) 3D Ready-Mix

5.4 Chloride ion intrusion test "AASHTO T259/T260"

For the chloride ion test, some specimens were not exposed to freeze/thaw cycles, and a second set up specimens was exposed to freeze/thaw cycles.

5.4.1 Without exposure to freeze/thaw "freeze/thaw"

Samples were taken to determine the amount of chlorides in the concrete. Two samples from each hole, with three holes per specimens, were collected. The same procedures were done on specimens of American Ready-Mix and 3D Ready-Mix.

Detail for AASHTO T260 were provided in (Section 4.1.4.) Equation 5-1 was used to calculate the amount of chlorides that penetrated through the concrete. Then the percentage of this concrete was converted to lbs/yd3 by multiplying the percentage by (UW/100) to see the effect of chlorides on a large scale. UW is the unit weight of concrete per cubic yard and taken as 4050 lb/yd3 for normal structural mass concrete when the actual unit weight is unknown. ***Table 5-7*** shows the chloride amounts absorbed by the control specimens and different types of sealers applied on American Ready-Mix. ***Table 5-8*** shows the chloride amounts absorbed by control specimens and different types of sealers applied on 3D Ready-Mix. For all the specimens, the mean chloride ingress was calculated and the standard deviation for all the sealers and control specimens, then a 95% confidence interval was calculated.

$Cl^{-}\% = (3.5453(V_1N_1 - V_2N_2))/W$ Equation 5-1

Table 5-7 Chlorides values for sealers applied on American Ready-Mix specimens not exposed to freeze/thaw

Sealers	Amount of Chloride absorbed (lb./yd³)				
	First hole	Second hole	Third hole	Average	Standard deviation
Control unponded	0.525	0.572	0.476	0.516	0.064
	0.476	0.429	0.62		
Control ponded	9.107	9.342	10.609	10.045	0.894
	11.36	10.75	9.107		
Sikagard 705L	2.99	3.123	2.225	2.984	0.803
	2.11	2.891	4.566		
Saltguard WB	4.788	9.94	7.511	7.254	2.214
	5.211	5.727	10.345		
ATS-100	5.493	6.887	4.245	6.149	1.589
	5.142	5.901	9.227		
Masterprotect H400	3.096	2.916	3.436	3.713	0.863
	3.092	5.27	4.468		
Aquanil Plus 40	7.042	7.981	8.591	7.793	0.623
	7.605	8.497	7.042		

Table 5-8 chlorides values for sealers applied on 3D Ready-Mix specimens not exposed to freeze/thaw

Sealers	Amount of Chloride absorbed (lb./yd^3)				
	First hole	**Second hole**	**Third hole**	**Average**	**Standard deviation**
Control unponded	0.516	0.516	0.376	0.533	0.116
	0.516	0.704	0.704		
Control ponded	6.184	5.868	5.232	5.779	0.40
	5.241	5.962	6.19		
Sikagard 705L	2.779	3.24	3.129	2.932	0.451
	2.272	2.548	3.627		
Saltguard WB	5.465	5.716	5.784	6.191	0.719
	6.662	5.952	7.571		
ATS-100	5.257	4.483	4.085	5.022	0.612
	6.008	5.057	5.246		
Masterprotect H400	3.157	4.256	3.063	3.431	0.581
	2.938	2.938	4.237		
Aquanil Plus 40	7.149	8.103	9.151	7.340	1.721
	9.151	6.196	4.29		

Figure 5-6 and ***Figure 5-7*** shows the average and the 95% confidence interval for the control and five sealers specimens for both American Ready-Mix and 3D Ready-Mix w/o exposure to freeze/thaw cycles.

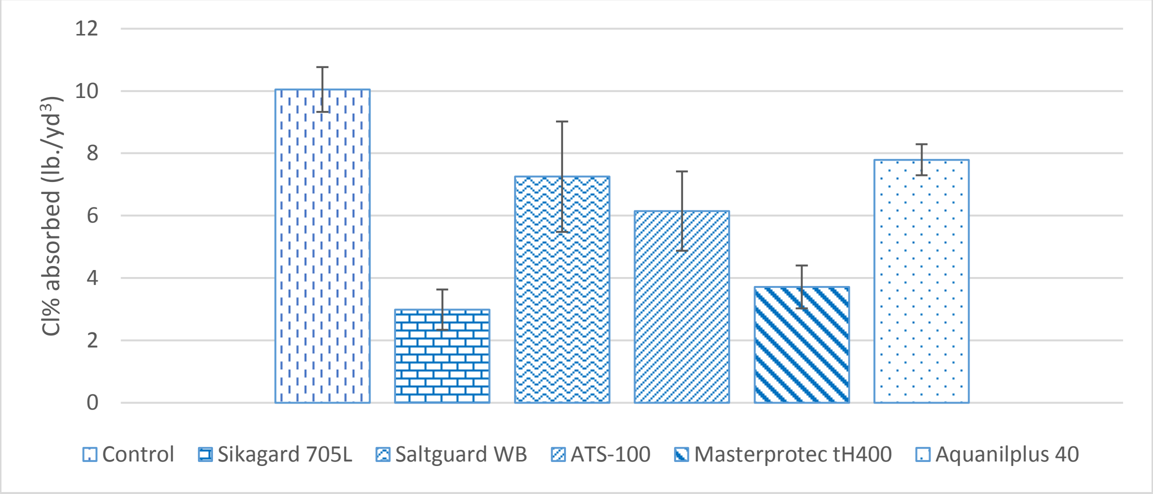


Figure 5-6 95% confidence interval for American Ready-Mix specimens w/o exposure to freeze/thaw cycles

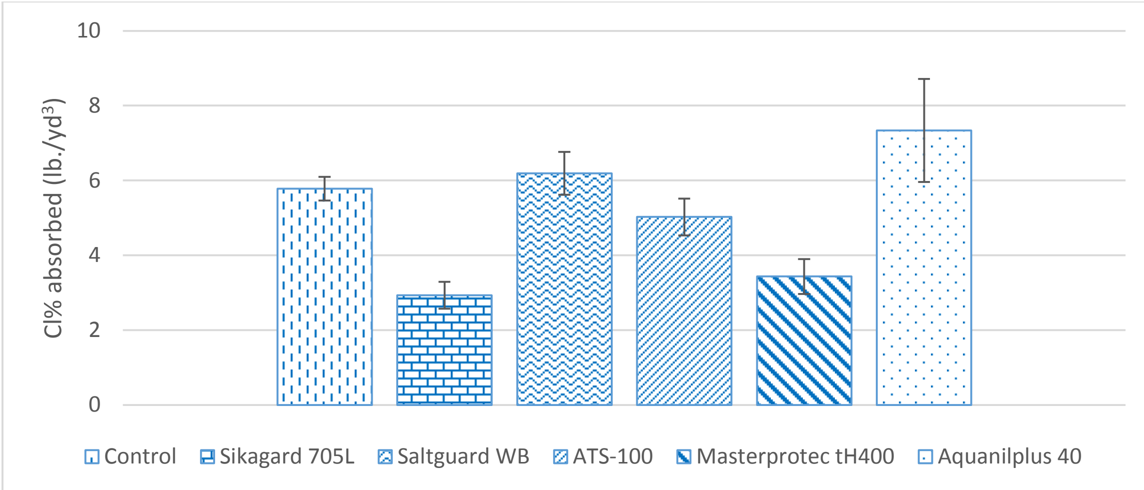


Figure 5-7 95% confidence interval for 3D Ready-Mix specimens w/o exposure to freeze/thaw cycles

5.4.2 With exposure to freeze/thaw "ASTM C 666"

Seven specimens from American Ready-Mix and seven specimens from 3D Ready-Mix were sent to CTL Thomson Company in Denver, Colorado. The specimens were exposed to 300 cycles of freeze/thaw. The weight, and the resonant frequency of each specimen were recorded in the company and sent to UNR Lab. Calculations at UNR were made in order to calculate the relative dynamic modulus of elasticity, and the durability of each specimen. After the specimens were shipped back from the company to UNR, the chloride ion intrusion test was conducted on these specimens with the same procedure as chloride ion intrusion w/o exposing to freeze/thaw cycles. ***Table 5-9*** shows the durability of American Ready-Mix and 3D Ready-Mix specimens after exposing to freeze/thaw cycles. More detailed calculations are found in Appendix A.

Table 5-9 Durability factors for American Ready-Mix and 3D Ready-Mix specimens.

Concrete	Sealers	Modulus of Elasticity % (Average of 300 cycles)	Durability factor %
American Ready-Mix	Control	96.3	96
	Control	100.3	100
	Sikagard 705L	98.9	99
	Saltguard Wb	98.9	99
	ATS-100	98.8	99
	Masterprotect H400	94.8	95
	Aquanil Plus 40	96.6	97
3D Ready-Mix	Control	93.4	93
	Control	104.2	104
	Sikagard 705L	100	100
	Saltguard Wb	101.1	101
	ATS-100	97.8	98
	Masterprotect H400	102.1	102
	Aquanil Plus 40	103	103

Table 5-10 shows the chloride amounts absorbed by control specimens and different types of sealers applied to the American Ready-Mix samples.

Table 5-10 Chlorides values for sealers applied on American Ready-Mix specimens exposed to freeze/thaw

Sealers	Amount of Chloride absorbed (lb./yd^3)				
	First hole	Second hole	Third hole	Average	Standard deviation
Control ponded	10.397	9.539	7.917	7.941	1.683
	7.631	6.916	5.246		
Sikagard 705L	4.00	1.812	2.623	2.654	1.026
	1.192	3.911	2.385		
Saltguard WB	1.24	1.908	1.669	1.701	0.284
	2.00	1.955	1.431		
ATS-100	1.908	1.812	1.192	1.637	0.250
	1.669	1.431	1.812		
Masterprotect H400	3.577	1.908	1.86	2.742	0.913
	1.812	3.243	4.05		
Aquanil Plus 40	2.154	6.105	5.246	4.4605	4.379
	1.335	5.246	6.677		

For the specimens of 3D concrete ready-mix, some samples gave very high numbers and are completely irrelevant and far away from the expected range in comparison to the other samples from the same specimens, and according to ASTM bias these samples were rejected. ***Figure 5-8*** and ***Figure 5-9*** show the average and the 95% confidence interval for the control and five sealers specimens for both American Ready-Mix and 3D Ready-Mix w/o exposure to freeze/thaw cycles.

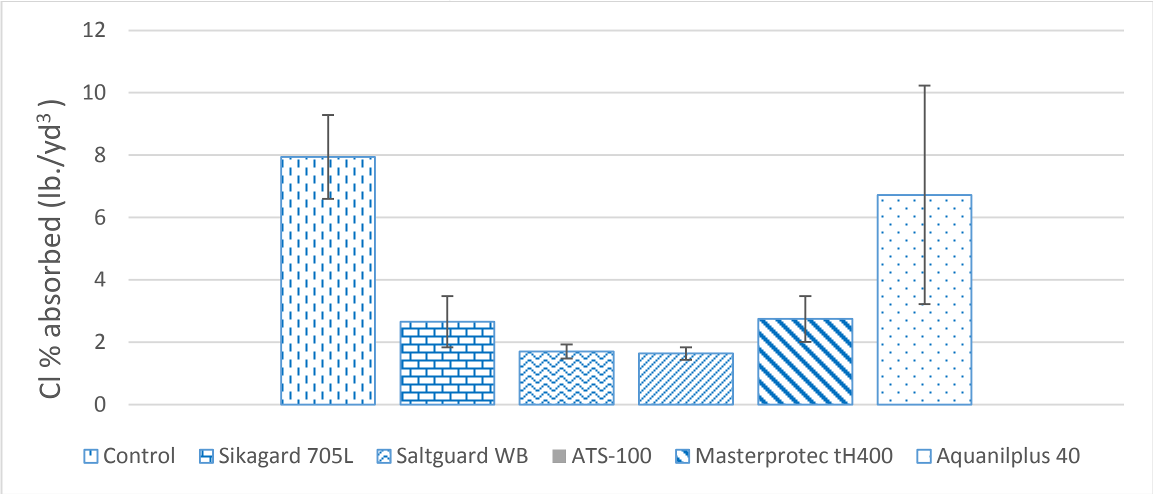


Figure 5-8 95% confidence interval for American Ready-Mix specimens w/o exposure to freeze/thaw cycles

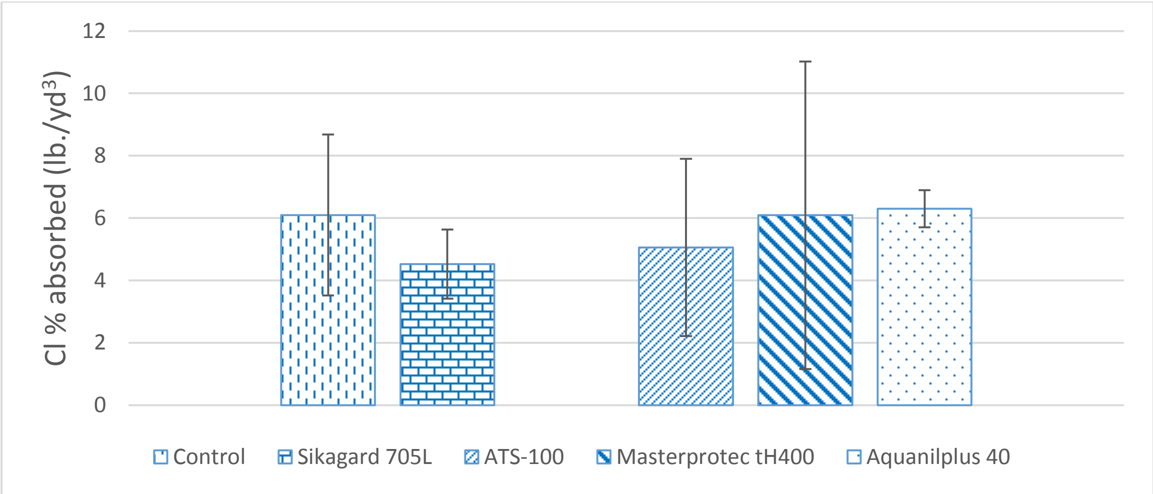


Figure 5-9 95% confidence interval for 3D Ready-Mix specimens w/o exposure to freeze/thaw cycles

Table 5-11 Chlorides values for sealers applied on 3D Ready-Mix specimens exposed to freeze/thaw

Sealers	**Amount of Chloride absorbed (lb./yd^3)**				
	First hole	**Second hole**	**Third hole**	**Average**	**Standard deviation**
Control ponded	3.196	4.531	12.878	6.097	3.228
	4.769	4.293	6.916		
Sikagard 705L	6.057	2.623	6.20	4.522	1.38
	3.672	5.246	3.339		
Saltguard WB	----	----	----	----	----
	----	----	----		
ATS-100	7.631	2.826	2.385	5.055	3.553
	9.062	3.339	----		
Masterprotect H400	5.246	7.393	----	----	6.616
	5.628	----	----		
Aquanil Plus 40	7.154	5.962	7.154	6.295	0.744
	5.008	6.057	6.439		

After calculating the average amount of chlorides absorbed for each specimen sealed with a sealer, a ratio between the average amount of chloride absorbed for each sealer and for the control ponded specimen was calculated to see the effect of the sealers compared to the control specimen in reducing the chloride ingress. For instance, the ratio for Sikagard 705L to the control ponded in the American Ready-Mix specimens that are not exposed to freeze/thaw is 0.297. This means that Sikagrad 705L sealer was able to absorb about 30% from the chlorides absorbed by control ponded specimens and was able to reduce 70% from the chlorides absorbed by the ponded specimens. ***Table 5-12*** shows the ratio of the absorbed chlorides from the sealers to the control specimens.

Table 5-12 Ratio of amount of chloride absorbed for sealers to control ponded specimens

Concrete	Sealer	Ratio of amount of chloride absorbed	
		Not exposed to freeze/thaw cycles	Exposed to freeze/thaw cycles
American Ready-Mix	Control ponded	1.0	1.0
	Sikagard 705L	0.297	0.334
	Saltguard WB	0.370	0.345
	ATS-100	0.612	0.206
	Masterprotect H400	0.722	0.214
	Aquanil Plus 40	0.776	0.562
3D Ready-Mix	Control ponded	1.0	1.0
	Sikagard 705L	0.507	0.742
	Saltguard WB	0.594	0.450
	ATS-100	0.869	0.829
	Masterprotect H400	1.071	N/A
	Aquanil Plus 40	1.270	1.032

Figure 5-10 and ***Figure 5-11*** show a comparison graph between the ratios of the absorbed chloride for the five sealers to the control ponded specimen, when exposed to freeze/thaw cycles, and when not exposed to freeze/thaw cycles for both American Ready-Mix and 3D Ready-Mix respectively.

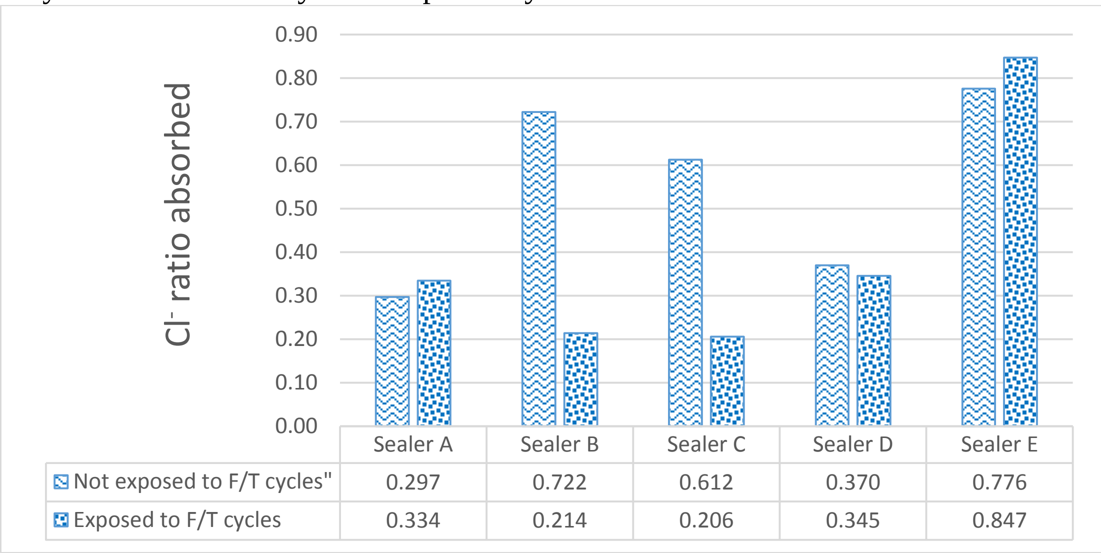


Figure 5-10 Ratio of chlorides absorbed for the five sealers with the ponded control specimen for American Ready-Mix

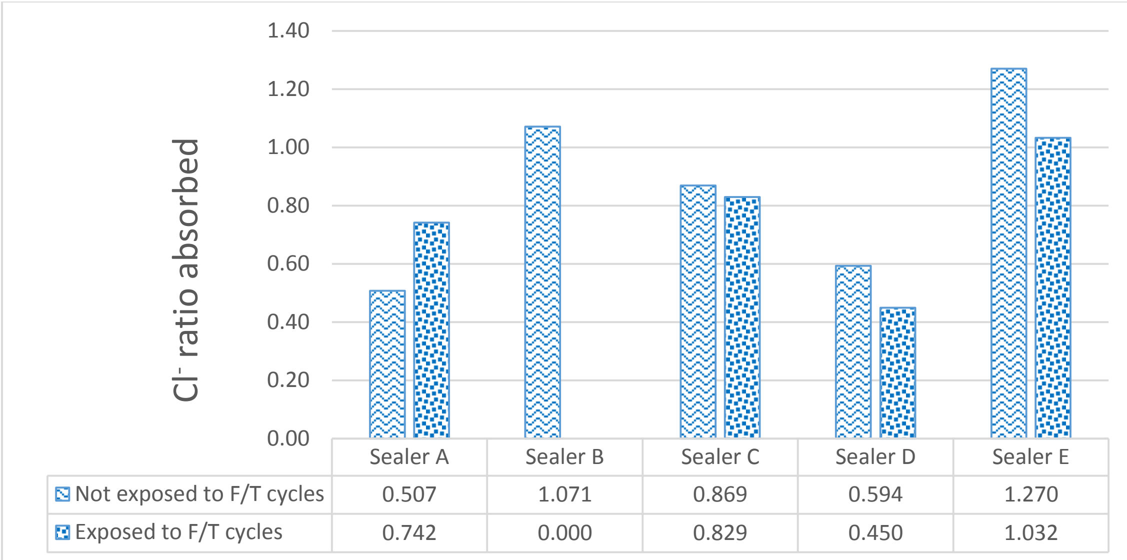


Figure 5-11 Ratio of chlorides absorbed for the five sealers with the ponded control specimen for 3D Ready-Mix

5.5 Discussion of tests results

5.5.1 Rapid permeability test

This test was conducted on five deck sealers and on two types of concrete, American Ready-Mix and 3D Ready-Mix. The tests were conducted at two different stages: 30 days and 120 days. The behavior of both concretes was different during the two stages.

For the first stage, 30 days, the amount of charge that passed through the concrete was much higher in both concrete compared to the amount of charge passed during the second stage, 120 days. This is because the concrete in its early age hasn't become dense yet, and it contains a lot of pores that allows a lot of charge to pass. While, at the later age, 120 days, the concrete has become denser, more mature, and the number of voids and pores decrease, so the amount of charge that passes was lower than the charge that passes in the first stage, 30 days.

Moreover, the 3D concrete seems to have less pores, and better performance in the first stage. The charge that passed through the 3D concrete specimens was lower than that passed through the American Ready-Mix**.** For stage 2, both concrete became dense so there is no significant difference between the amounts of charge that passed through the specimens of both concrete. The less pores in 3D concrete could be because of the type of aggregate used. The aggregate used in the 3D concrete is Dayton #67 stone and #8 stone while in American Ready-Mix is Western Nevada Materials "WNM" #67 and #8. Both of the concretes have the same aggregate size, but different producer.

For the sealers, in general, all the sealers were very effective in reducing the amount of charge that passed through the concrete. This means that the sealers made an insulation layer that reduces the chlorides ingress.

For stage 1, 30 days, **Aquanil Plus 40**, **Masterprotect H400**, and **ATS-100** gave the highest performance among all the sealers in both American Ready-Mix and 3D Ready-Mix.While, for stage 2, 120 days, the performance of all sealers were almost the same and in the same permeability class, very low, which is below 1000 charge. However, **Sikagard 705L** is the highest one among all sealers in this stage.
As mentioned in (section 5.2), the 95% confidence interval was applied on the control specimens and specimens covered with sealers. The weighted score for the sealers performance was according to the average charge passed, however for the best performance sealers as Sikagard 705L and Masterprotect H400 the lowest interval are either the same as the average category or even a better category. For example, using the Sikagard 705L in American Ready-Mix, the average was moderate while the lowest interval was category low; this means that using the 95% confidence interval data, the performance of the sealer could be in the low category.
This test can be conducted with limited error (i.e. limited human error) because not much work is done by hand, and most of the test is related to connecting the specimens to two cells, instruments, and a computer. This is why this test had the highest weight when comparisons were made between sealers as will be discussed later in this chapter.

5.5.2 Saltwater absorption

The saltwater absorption ratio for 7, 14, and 21 days were calculated for specimens sealed with five sealers for both concrete. **Sikagard 705L** and **Masterprotect H400** were the lowest SAR % for 7, 14, or 21 days for American Ready-Mix. This gives an indication that these two sealers were good in preventing the concrete in absorbing many salts, which increase the specimen weight.
ATS-100, Sikagard 705L and Masterprotect H400 were the lowest SAR % for 7, 14, or 21 days for 3D concrete. **Aquanil plus 40** and **Saltguard WB** didn't perform well in this test. This test was straight forward with limited opportunity for error, because this test is only calculating the specimen's weight before immersing and after immersing in the saltwater solution for different days; this test was given a high weighting when making comparisons between sealers as will be shown later in this chapter.

5.5.3 Chloride ion intrusion test

As mentioned before, this test was conducted twice. One for specimens that were not exposed to freeze/thaw cycles, and other for specimens that were exposed to freeze/thaw cycles on both American Ready-Mix and 3D Ready-Mix.
For both concrete, the American Ready-Mix and the 3D Ready-Mix, when not exposed to freeze/thaw cycles, **Sikagard 705L** and **Masterprotect H400** absorbed the least amount of chlorides among the five sealers. These two sealers showed the best performance among all the sealers. **Figure *5-8*** shows the average test results and the 95% confidence intervals. **Aquanil plus 40** showed the lowest average performance in this test. In **Figure *5-11***, **Aquanil plus 40** shows a chloride ingress ratio that is greater than one, which means that the chloride ingress is greater than the chloride ingress for control specimens. As shown in **Figure *5-8***, **Aquanil plus 40** has the largest 95% confidence interval; this is

because the standard deviation was largest for this sealer. For **Aquanil plus 40** the lowest portion of the 95% confidence interval provide a ratio that is below one.

When the specimens were exposed to freeze/thaw cycles, **Sikgard 705L** gave a lower performance than when not exposed to freeze/thaw cycles. While all the other sealers gave a higher performance; this could be a questionable issue that the sealers performed better when exposed to freeze/thaw cycles. A recommendation for additional research is to study the behavior of sealers when exposed to freeze/thaw cycles on many specimens to have more data, so that more definite conclusions can be established. Among all the sealers, **ATS-100** and **Masterprotect H400** performed the best in American Ready-Mix specimens. For 3D Ready-Mix specimens, **Saltguard WB** gave the highest performance.

5.6 Sealers performance categories

After finishing all the test, the sealers were classified into different categories according to their performance. These categories are I, II, and III. Category I is for the best performance, for sealers that gave absorption values below the average, Category III is for the lowest performance, for sealers gave absorption values above average, and Category II in between, for sealers that gave values around the average. Sealers are classified separately in each test according to the results of each test.

.. The saltwater absorption test, rapid chloride permeability “120 days” test, and chloride ion intrusion test without exposure to freeze/thaw were given the highest score (weight) because they provide important information about sealer performance and have low probability of error after the 95% confidence interval study. The scores for these tests are 45, 30, and 15 for categories I, II, and III respectively. While for rapid permeability test “30 days” and the chloride ion intrusion test with exposure to freeze/thaw were given a score 30, 20, and 10 for categories I, II, and III respectively. The rapid permeability test “30 days” had a low 95% confidence interval but because the concrete was not mature this will affect the results and not be as representative as what will be found in the field. Therefore this test was given a a lower weight when comparing the performance of the different sealers. For the chloride ion intrusion test with exposure to freeze/thaw, the 95% confidence interval was very high, therefore the test was given a lower weight.

After giving a certain score for each sealer according to its performance category and according to the test conducted, a total score was given to each sealer as an overall score according to the average score for the sealers in each test; this will provide an overall measure of how each of the sealers performed.

Table* 5-13** and ***Table 5-14 show the classifications of sealers according to their categories in different tests, and the scores for the American Ready-Mix specimens and 3D Ready-Mix specimens respectively. ***Table 5-15*** show the total score for each sealer for both American Ready-Mix and 3D Ready-Mix, and ***Figure 5-12*** shows a corresponding graph to these total scores of sealers.

Table 5-13 Classification of sealers into different categories according to their performance for American Ready-Mix

Test	Sealer	Performance Category	Score
Chloride ion intrusion "not exposed to freeze/thaw"	Sikagard 705 L	I	45
	MasterProtect H400		
	ATS-100	II	30
	Saltguard WB	III	15
	Aquanil plus 40		
Chloride ion intrusion "exposed to freeze/thaw"	ATS-100	I	30
	Saltguard WB		
	Sikagard 705 L	II	20
	MasterProtect H400		
	Aquanil plus 40	III	10
Rapid Chloride Permeability "30 days"	Aquanil plus 40	I	30
	Sikagard 705 L	II	20
	Masterprotect H400		
	ATS-100		
	Saltguard WB		
Rapid Chloride Permeability "120 days"	Sikagard 705 L	I	45
	MasterProtect H400		
	ATS-100	II	30
	Saltguard WB		
	Aquanil plus 40	NA	NA
Saltwater absorption 21 days	Sikagard 705 L	I	45
	MasterProtect H400		
	ATS-100	II	30
	Aquanil plus 40		
	Saltguard WB	III	15

Table 5-14 Classification of sealers into different categories according to their performance for 3D concrete

Test	Sealer	Performance Category	Score
Chloride ion intrusion Without exposed freeze/thaw	Sikagard 705 L	I	45
	MasterProtect H400		
	ATS-100	II	30
	Saltguard WB	III	15
	Aquanil plus 40		
Chloride ion intrusion exposed to freeze/thaw	MasterProtect H400	I	30
	ATS-100	II	20
	Sikagard 705 L		
	Aquanil plus 40	III	10
	Saltguard WB	NA	NA
Rapid Chloride Permeability "30 days"	Aquanil plus 40	I	30
	MasterProtect H400		
	ATS-100		
	Saltguard WB	II	20
	Sikagard 705 L		
Rapid Chloride Permeability "120 days"	Sikagard 705 L	I	45
	MasterProtect H400		
	ATS-100		
	Saltguard WB	II	30
	Aquanil plus 40	NA	NA
Saltwater absorption 21 days	Sikagard 705 L	I	45
	Aquanil plus 40		
	ATS-100	II	30
	MasterProtect H400		
	Saltguard WB	III	15

Table 5-15 Total score for all the sealers

Concrete	Sealer	Total Score
American Ready-Mix	Sikagard 705 L	175
	MasterProtect H400	175
	ATS-100	140
	Saltguard WB	110
	Aquanil plus 40	85
3D Ready-Mix	Sikagard 705 L	175
	MasterProtect H400	180
	ATS-100	155
	Saltguard WB	80
	Aquanil plus 40	100

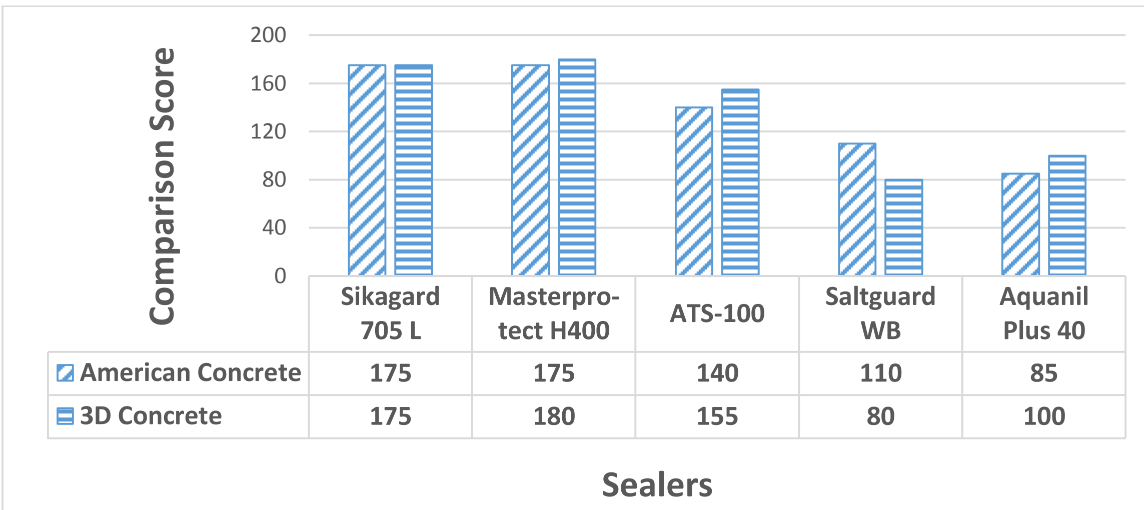


Figure 5-12 Graph for the total score and comparison between all the sealers

5.7 Sealers discussions

- **Sikagard 705 L** is a low viscosity, penetrating sealer, 100% Alkylalkoxy Silane, water based.
- **MasterProtect H 400** is a 40% Alkylalkoxy Silane penetrating sealer, water-based.
- **ATS-100** is a penetrating sealer, 100% Alkyltrialkoxy Silane, water-based.
- **Aquanil Plus 40** is a penetrating, chemically reactive Alkyltrialkoxy Silane 40% solids, solvent based Silane sealer.
- **Saltguard WB** is a penetrating sealer, 5% silane/siloxane, water-based sealer.

According to the total score for all the sealers, **Sikagard 705 L** and **Masterprotect H400** gave the highest performance after all the tests. These two sealers are Alkylalkoxy Silane, penetrating sealers, water based. The water-based sealers gave better performance than the solvent-based sealers. Therefore, the primary recommendation from this project for deck sealers is to use sealers that are Alkylalkoxy Silane and water-based sealer.

There is no significant relation between the percentage of active ingredient of the sealers and its performance in this study. However, from previous research, there is a significant relation between the depth of penetration and the performance of the sealers. Among the tested five sealers, **Sikagard 705 L** had the biggest depth of penetration (>10 mm) according to the manufacturer. The more the depth of penetration, the better the performance of the sealer in reducing the chloride ingress in the concrete.

Moreover, the water-based sealers are friendlier to the environment than the solvent based, due to the lower Volatile organic compound (VOC) in the water-based sealers. The difference between the water-based sealers, and the solvent-based sealers are discussed before in chapter 2: Literature Review.

According to the manufacturer, the chloride reduction for **Sikagard 705 L and Masterprotect H400** were the highest according to NCHRP Report 244 series II and series IV. No information was provided from the manufacturer about the viscosity of these sealers, but as seen by visual inspection, all the sealers were liquid with a very low viscosity.

In general, all the sealers were effective in reducing the amount of chlorides penetrated into the concrete compared to the control specimens, but one sealer could give higher performance in a particular test compared to another. Finally, based on the laboratory tests, **Sikagard 705 L**, **and Masterprotect H400**, and any water-based sealer made of Alkylalkoxy Silane, with bigger depth of penetration, usually >10 mm is recommended to Nevada Department of Transportation (NDOT) to be used in newly constructed bridge.

5.8 Sealers cost perspective

A comparison was made between all the sealers from a cost perspective. Moreover, the equipment, and labor cost are different from one project to another, from one state to another, and also depend on the size of the project. Roughly according to contractors that were contacted, the application of sealers for a 10,000 ft^2 cost about 30 cents per ft^2 for labor and applications only. ***Table 5-16*** shows the cost for sealer's application

Table 5-16 Coverage rate (ft^2/gal) and cost for 5 gallons for five deck sealers

Sealers	Coverage rate (ft^2 / gal)	Cost per 5 gallon "Material"	Labor and equipment cost	Total cost for 10K ft^2 bridge
Sikagard 705L	240 to 360	$330	About 40 cents per ft^2	$6310
Masterprotect H400	100 to 200	$135		$5755
Saltguard WB	200 to 300	$150		$5875
ATS-100	200 to 300	$165		$5200
Aquanil plus 40	100 to 150	$250		$7500

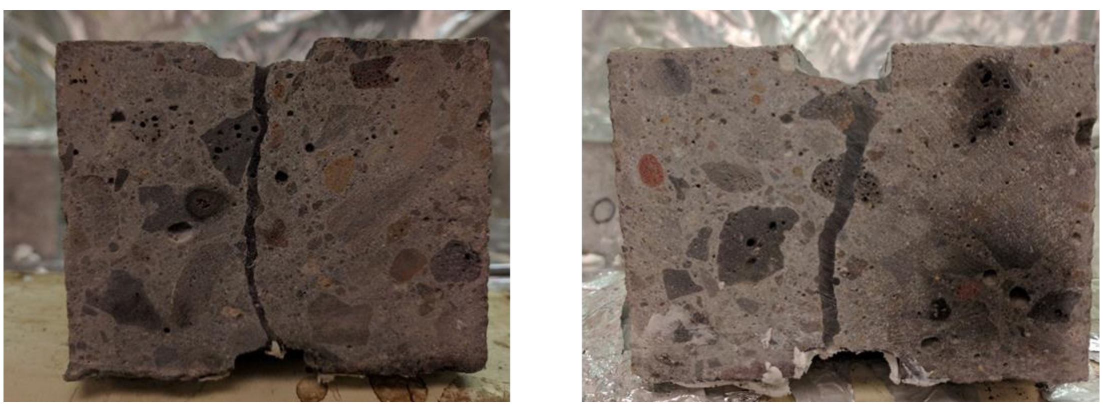
Chapter 6 Test Results And Discussion- Crack Sealers

6.1 Introduction

In this chapter, test results for the crack sealers experiments will be presented and discussed. The two tests that were conducted and will be discussed are depth of penetration test (Section 6.2) and bond strength test (Section 6.3). The sealers will be ranked according to their performance in (Section 6.4).

6.2 Depth of penetration test

The depth of penetration test was examined by visually inspection with the naked eye for the concrete specimens. Two cross sections were cut from the edge of the specimens used in bond strength test whose dimensions are 8 in by 4 in by 3 in and then examined. For all the specimens, the crack sealers penetrated through the whole depth of the concrete specimen approximately 2.5 inches without any voids independent of the crack width. ***Figure 6-1*** shows cross sections for specimens with a full penetration of the crack sealers for the two different crack widths that were investigated.



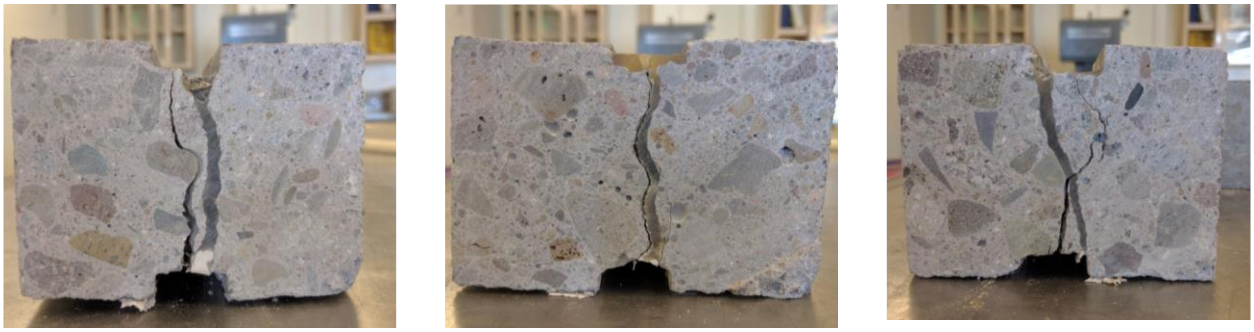
(a) **(b)**

Figure 6-1 Full penetration for a crack sealer in a crack of (a) 0.09 in (b) 0.15 in

6.3 Bond strength test

Six crack sealers were tested to compare their performance in sealing the concrete cracks. Both American Ready-Mix and 3D Ready-Mix were sealed with six sealers and then tested. For each sealer and for both concrete types, two specimens were tested (0.09 in and 0.15 in).

Different modes of failure were noticed for the specimens. Modes of failure were: concrete failure, sealer failure and interface failure. Some specimens failed with two different modes combined together. ***Figure 6-2*** shows different mode of failure for the crack and the concrete.



(a) (b) (c)

Figure 6-2 Modes failures for crack sealers (a) Concrete Failure (b) Interface Failure (c) Concrete and Sealer failure

6.3.1 Narrow Crack width (0.09 in.)

The results for the bond strength test for the American Ready-Mix varied from 680 lbs to 8155 lbs. The results for the 3D Ready-Mix varied from 2040 lbs to 7130 lbs. ***Table 6-1*** shows the bond strength and mode of failure for American Ready-Mix for 0.09 in. and ***Table 6-2*** shows the bond strength and mode of failure for 3D Ready-Mix for 0.09 in.

Sikadur 55 SLV gave the highest bond strength among the six sealers in both American Ready-Mix and 3D Ready-Mix specimens. **T-78 Polymer** gave the lowest bond strength among the six sealers in American Ready-Mix while **KBP 204** gave the lowest strength in 3D Ready-Mix. ***Figure 6-3*** shows a graph for the bond strength for different sealers used to seal the American Ready-Mix concrete for a crack width 0.09 in, and

Figure 6-4 shows a graph for the bond strength for different sealers used to seal the 3D Ready-Mix of a crack width 0.09 in

Table 6-1 Bond strength and mode of failure for American Ready-Mix for 0.09 in.

	Sealer	**Bond Strength (lbs)**	**Mode of Failure**
American Concrete	Duraguard HM Sealer	6545	Concrete
	Sikadur 55 SLV	8155	Concrete & Interface
	Sikadur 22, LO-MOD	4320	Concrete
	MasterSeal 630	7715	Interface
	KBP 204	5205	Concrete & Interface
	T-78 Polymer	680	Interface

Table 6-2 Bond strength and mode of failure for 3D Ready-Mix for 0.09 in.

	Sealer	**Bond Strength (lbs)**	**Mode of Failure**
3D Concrete	Duraguard HM Sealer	4145	Concrete
	Sikadur 55 SLV	7130	Concrete
	Sikadur 22, LO-MOD	4680	Concrete & Interface
	MasterSeal 630	2570	Concrete
	KBP 204	2040	Interface
	T-78 Polymer	5065	Concrete

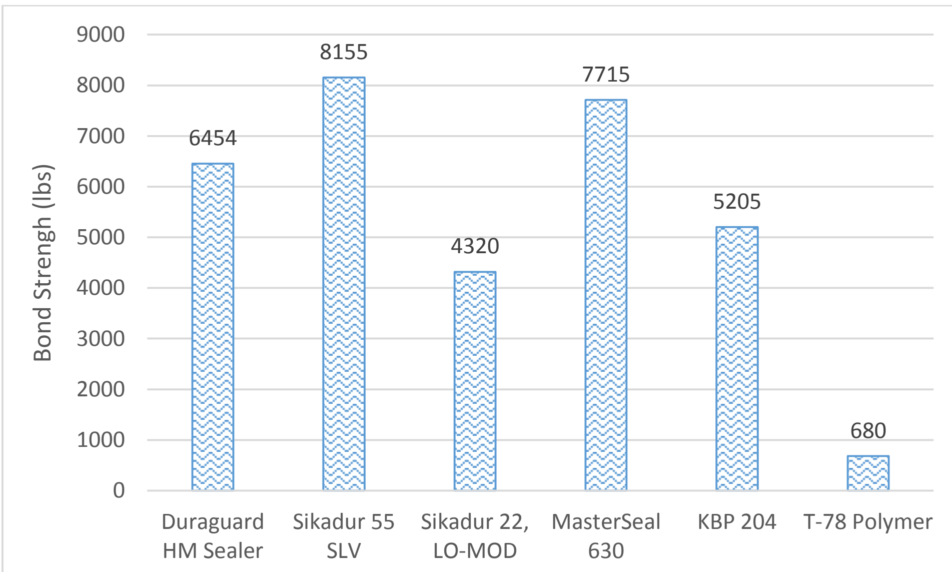


Figure 6-3 Bond strength for American Ready-Mix for 0.09 in.

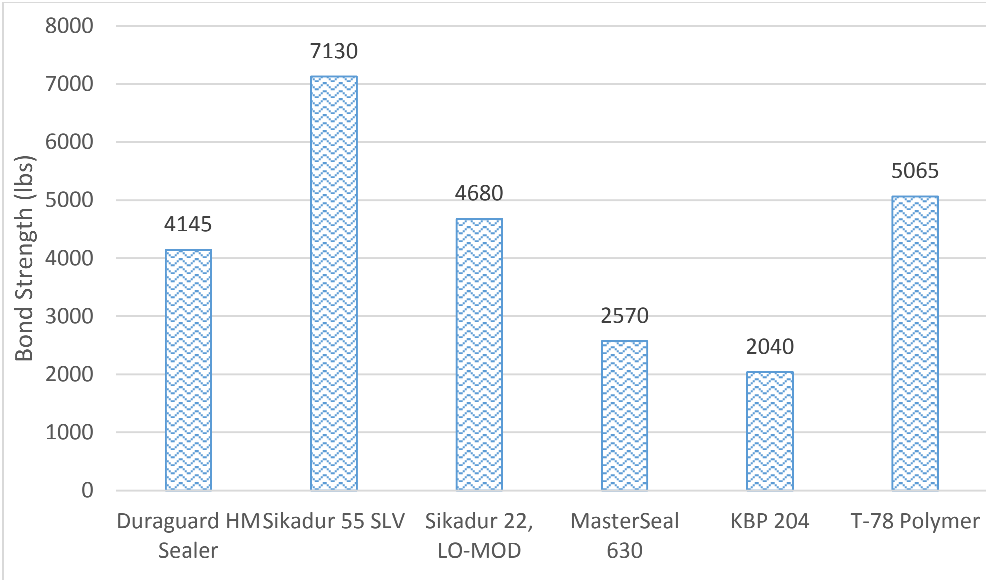


Figure 6-4 Bond strength for 3D Ready-Mix for 0.09 in.

6.3.2 Wide Crack width (0.15 in.)

The results for the bond strength test for American Ready-Mix specimens varied from 1485 lbs to 6980 lbs. The results for the 3D Ready-Mix specimens varied from 905 lbs to 5480 lbs. ***Table 6-3*** shows the bond strength and mode of failure for American Ready-Mix for 0.15 in. **Table *6-4*** shows the bond strength and mode of failure for 3D Ready-Mix for 0.15 in. **Duraguard HM Sealer** and **Sikadur 55 SLV** gave the highest bond strength among the six sealers in both American Ready-Mix and 3D Ready-Mix specimens. **T-78 Polymer** gave the lowest bond strength among the six sealers in both American Ready-Mix and in 3D Ready-Mix. ***Figure 6-5*** shows a graph for the bond strength for different sealers used to seal the American Ready-Mix for a crack width 0.15 in, and ***Figure 6-6*** shows a graph for the bond strength for different sealers used to seal the 3D Ready-Mix for a crack width 0.15 in.

Table 6-3 Bond strength and mode of failure for American Ready-Mix for 0.15 in.

	Sealer	Bond Strength (lbs)	Failure
American Concrete	Duraguard HM Sealer	6980	Concrete
	Sikadur 55 SLV	5815	Concrete
	Sikadur 22, LO-MOD	4580	Concrete & Interface
	MasterSeal 630	2825	Interface
	KBP 204	2210	Interface
	T-78 Polymer	1485	Concrete & Interface

Table 6-4 Bond strength and mode of failure for 3D Ready-Mix for 0.15 in.

	Sealer	**Bond Strength (lbs)**	**Failure**
3D Concrete	Duraguard HM Sealer	5480	Concrete
	Sikadur 55 SLV	3545	Concrete
	Sikadur 22, LO-MOD	3315	Concrete & Sealer
	MasterSeal 630	2135	Interface
	KBP 204	1580	Interface
	T-78 Polymer	905	Interface

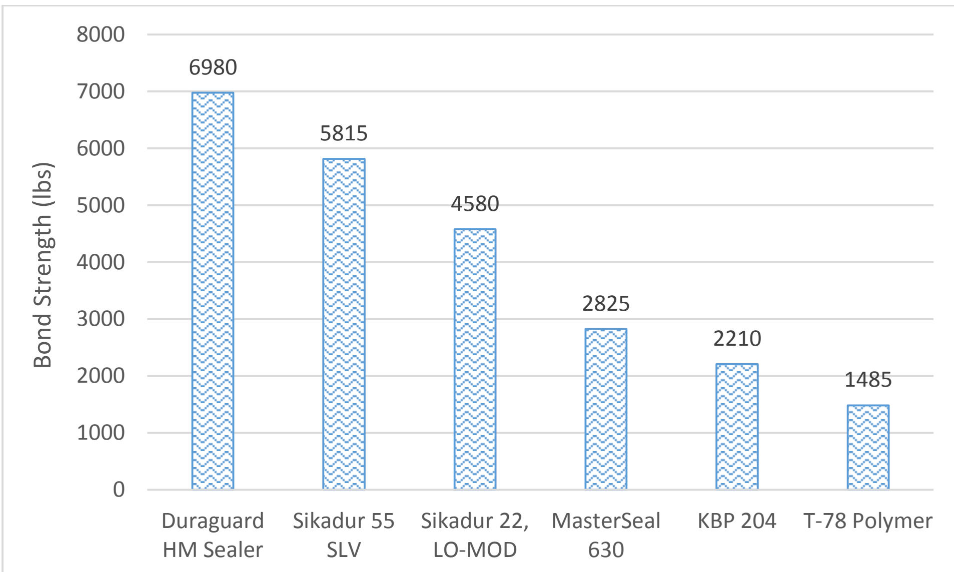


Figure 6-5 Bond strength for American Ready-Mix for 0.15 in.

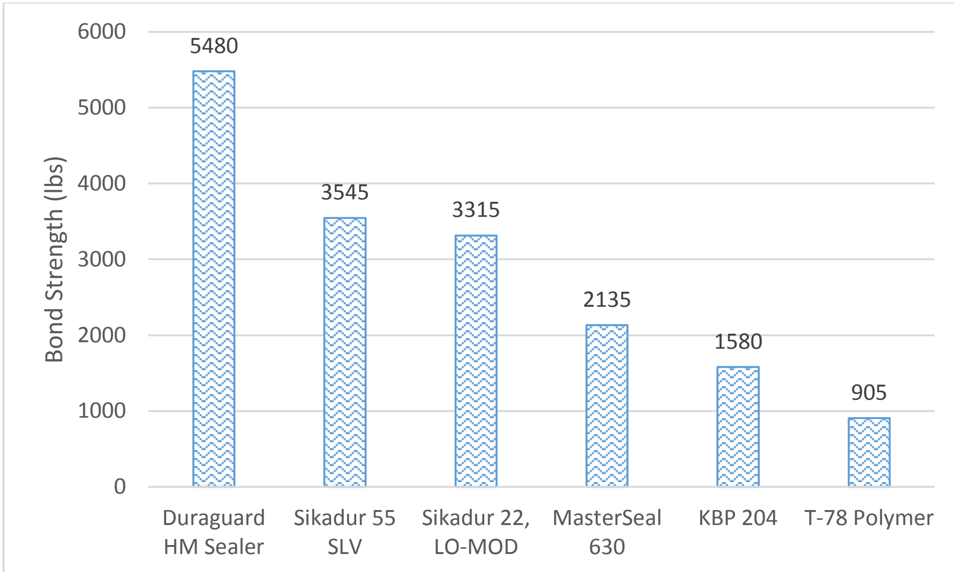


Figure 6-6 Bond strength for 3D Concrete for 0.15 in.

6.4 Discussion of test results

6.4.1 Effect of viscosity of sealers

Among the six tested sealers, some sealers are more viscous than the others. All the tested sealers penetrated through the whole depth of the crack either for 0.09 in. or 0.15 in.; this indicated that all the tested sealers have a good range of viscosity that should be able to penetrate through small cracks. Viscosity of the sealers is such an important point of comparison between sealers. It is critical that the sealer be able to penetrate through the whole depth. The viscosity of the sealers was one of the main criteria for the section of the sealers that were tested sealers. As mentioned in (section 3.3), sealers that were selected have a viscosity in the range of 10 to 100 cps and other sealer in the range of 2000 cps, which was found to be sufficient in the tests, conducted.

6.4.2 Failure mode

Three main failure modes occurred in the breaking of the specimens. Concrete failure, sealer failure and interface failure. Also, some specimens have combined modes of failure

(i.e. concrete and interface failure or concrete and sealer failure). Concrete failure occurred in specimens that used sealers that had high bond strength. The specimens with lower bond strength sealers displayed interface failure. Concrete failure is the preferred mode of failure because this means that the sealer adhered enough (i.e. good bond between the sealer and the concrete) to the concrete and the sealer was strong enough to withstand the high bond stress. Thus, sealers that fail with concrete failure could be a good indication for a high bond strength.

As the crack width increased, concrete failures became less common, and the most common failures are a combination between concrete and interface failures. Also, when the amount of sealer is increased within a specimen and this occur when the crack width is increased, this weakens the area between the crack and the sealer compared with the surrounding concrete. The amount of the sealer enclosed is large enough to withstand the strength and stiffness of the cross section. Therefore, interface failure and/or sealer failures can be expected to occur with increasing crack width.

6.4.2.1 For narrow crack width (0.09 in.)

Sikadur 22, LO-MOD in 3D Ready Mix, **Sikadur 55 SLV**, and **KBP 204** in American Ready-Mix displayed concrete & interface failure, however they were expected to have only concrete failure due to their high bond strength despite the large bond strength. **Masterseal 630** in American Ready-Mix had an interface mode of failure despite the high bond strength while a concrete failure mode in 3D Ready-Mix. **Sikadur 55 SLV** gave the highest bond strength in both American Ready-Mix and 3D Ready-Mix. Among the American Ready-Mix specimens, **T-78 polymer** gave the lowest bond strength and among the 3D Ready-Mix specimens, **KBP 204** gave the lowest bond strength.

6.4.2.2 For wide crack width (0.15 in.)

Only **Sikadur 22, LO-MOD**, in American Ready-Mix that displayed concrete & interface failure despite the high bond strength value. In both concrete, **Duraguard HM**, **Sikadur 55 SLV, and Sikadur 22, LO-MOD** gave higher bond strength, while the other three sealers, **MasterSeal 630**, **KBP 204**, and **T-78 Polymer** gave the lower bond strength. The latter three sealers are formulated, high molecular weight methacrylate monomer composition.

6.4.3 Sealers discussion

- Duraguard HM is 100% solids, high modulus epoxy sealer with a very low viscosity.
- Sikadur 55 SLV is a 100% solids, epoxy crack sealer with a very low viscosity.
- Sikadur 22, LO-MOD is Lo-Mod is a 2-component, 100% solids, moisture-tolerant, epoxy resin binder with medium-viscosity.
- MasterSeal 630is a very low viscosity, low surface tension, solvent-free, rapid curing reactive methacrylate resin.
- KBP 204is a formulated, high molecular weight methacrylate monomer composition, and low viscosity penetrant.
- T-78 Polymer is a very low viscosity, low surface tension, rapid curing methacrylate reactive resin.

6.4.4 Sealers performance evaluation

Based on the above results and discussion, the performance of the sealers could be presented as A, B, C for best, moderate, and lowest performance respectively. ***Table 6-5*** shows the ranked sealers from best to lowest performance according to their bond strength. The average bond strength for all the sealers was assigned to category B, above average is A, and below average is C.

Epoxies materials gave higher bond strength than methacrylate, while methacrylate have lower viscosity and it could penetrate more in the cracks. Therefore, if the bond strength is more important than depth of penetration, epoxies materials are recommended to be used. While, if the depth of penetration is more important than bond strength, methacrylate materials have to be used.

Table 6-5 Performance evaluation of different crack sealers

Narrow crack (0.09 in.)			**Wide crack (0.15 in.)**		
Sealer	**Concrete type**	**Performance**	**Sealer**	**Concrete type**	**Performance**
Sikadur 55 SLV	American Ready-Mix	A	Duraguard HM Sealer	American Ready-Mix	A
MasterSeal 630			Sikadur 55 SLV		
Duraguard HM Sealer		B	Sikadur22,LO-MOD		
KBP 204			MasterSeal 630		B
Sikadur22,LO-MOD			KBP 204		
T-78 Polymer		C	T-78 Polymer		C
Sealer	**Concrete type**	**Performance**	**Sealer**	**Concrete type**	**Performance**
Sikadur 55 SLV	3D Ready-Mix	A	Duraguard HM Sealer	3D Ready-Mix	A
Sikadur22,LO-MOD		B	Sikadur 55 SLV		B
Duraguard HM Sealer			Sikadur22,LO-MOD		
T-78 Polymer			MasterSeal 630		
MasterSeal 630		C	T-78 Polymer		C
KBP 204			KBP 204		

Chapter 7 Summary and Conclusions

7.1 Summary

Deck and crack sealers are a good solution for reducing the chloride ingress into concrete. These chlorides come mainly from the reaction of the deicing salts with snow and ice. Deck and crack sealers have been used in different states, but currently the Nevada Department of Transportation use overlays to protect decks and extend life, not sealers. The usage of sealers could be critical and useful in extending bridge deck life, and reducing the time and cost for replacing the deck.

The primary objective of this research was to develop a guide for using deck and crack sealers in Nevada and the surrounding states. This includes areas of extreme dry heat to mountainous regions with snow and deicing salts. The primary focus of this research was to take the best practice in the use of deck and crack sealers from other states, conduct additional experiments and analysis, and determine the best implementation plan. The research objective was achieved through four main tasks. The first one was the literature review; the background of sealers was studied to understand the behavior of the sealers and chemical properties and chemical families. Moreover, research done by other states DOTs regarding deck and crack sealers and their behavior was studied. The second task was to plan the experimental program including the types of tests to conduct, the number of specimens needed, and the specimen's dimensions. The third task was the laboratory tests: some of them were conducted at UNR and one was conducted in Denver, Colorado and completed at UNR. All the tests were according to AASHTO, ASTM, and NCHRP series II and IV. Finally, the performance of all the sealers was discussed based on the laboratory test results, assigned into different categories according to their performance, and application recommendations were made. Also, 95% confidence interval study was done for the precision and bias of the results for all the tests..

The experimental program was conducted on two types of concrete, American Ready-Mix, and 3D Ready-Mix. Twelve deck sealers were initially examined, and five were chosen to be tested. Eighteen crack sealers were discussed, and six crack sealers were chosen to be tested. The sealers were chosen according to different criteria as stated before and with the acceptance by NDOT.

7.2 Deck sealers tests observations

Generally, all the deck sealers were effective in reducing the amount of chlorides ingress into the concrete. Some sealers gave a higher performance than the other in one or more tests.

7.2.1 Rapid chloride permeability test

- Concrete become more mature with time, so the amount of charge that passes decreases.

- For stage 1, after 30 days, **Aquanil plus 40**, **Masterprotect H400**, and **ATS-100** gave the highest performance among all the sealers in both concrete mixes.
- For stage 2, after 120 days, the performance class for all sealers were the same, very low, which is below 1000 coulomb. However, Sikagard 705L was the lowest one among all sealers in this stage.
- The weighted score for this test was assigned according to the permeability class for the average amount of charge passed.

7.2.2 Saltwater absorption test

- **Sikagard 705L** and **Masterprotect H400** had the lowest SAR % for all days, 7, 14 and 21 days for both concretes investigated.

7.2.3 Chloride ion intrusion test

- For both concretes, when not exposed to freeze/thaw cycles, **Sikagard 705L** and **Masterprotect H400** gave the highest performance.
- **Aquanil plus 40** had the lowest performance among all the sealers, however the lowest interval showed some protection against chlorides.
- For the specimens exposed to freeze/thaw cycles, **Sikgard 705L** gave a lower performance than no exposure to ` cycles.
- When exposed to freeze/thaw cycles, for American Ready-Mix concrete specimens, **ATS-100** and **Masterprotect H400** gave the highest performance.
- When exposed to freeze/thaw cycles, for 3D Ready-Mix concrete specimens, **Saltguard WB** gave the highest performance.

7.3 Deck sealers discussion

- Silane sealers gave higher performance than siloxanes sealers.
- According to the laboratory tests, water-based sealers provided higher performance.
- Water based sealers are friendly from environmental perspective, because their Volatile Organic Compound (VOC) are lower than solvent based sealers.
- The higher the depth of penetration, the better performance for the sealers in reducing the chlorides ingress into the concrete.
- **Sikagard 705 L and Masterprotect H400** were the highest according to the manufacturer for absorbed chloride for NCHRP Report 244 series II and series IV.

7.4 Crack sealers tests observations

7.4.1 Depth of penetration test

- All the sealers were able to penetrate through the cracks depth whether the width was 0.09 inch or 0.15 inch.
- The viscosities of the tested sealers were good for the narrow and wide cracks.

7.4.2 Bond strength test

- For narrow crack width 0.09 inch, **Sikadur 55 SLV** gave the highest bond strength for both concretes.
- For wide crack width 0.15 inch, **Duraguard HM Sealer** and **Sikadur 55 SLV** gave the highest bond strength for both concretes.
- The mode of failure for **Sikadur 55 SLV** in the American Ready-Mix concrete with a 0.09 inch crack was concrete & interface failure, while the failure mode for **Duraguard HM Sealer** and **Sikadur 55 SLV** in both concretes and both crack widths was concrete failure.
- Width of the crack did affect the mode of failure.
- As the amount of sealer was increased within a specimen, the area enclosing the crack and sealer becomes weaker in comparison with the surrounding concrete. Therefore, a larger number of interface and/or sealer failures can be expected occur with increasing crack width.

7.5 Crack sealers discussion

- Epoxies sealers gave higher performance for bond strength than methacrylate.
- The viscosity of all the sealers were good for penetrating the whole depth of both 0.09 in. and 0.15 in. cracks.
- In general the viscosity of methacrylate was lower than the epoxies, so they could penetrate deeper through very narrow cracks.
- Modes of failure is important in determining the behavior and performance of the sealer.
- Concrete failure is better than sealer failure or interface failure because this gives an indication about the level of bond between concrete and sealer.
- If the bond strength is more important than depth of penetration, epoxies sealers are a very good choice.
- If the depth of penetration is more important than the bond strength, methacrylate sealers are a very good choice.

- The number of cracks defines the application of the sealers. A large number of cracks can be sprayed with sealer, but small number of cracks can be injected individually.

7.6 Conclusions

a) Generally, all the deck sealers were effective in reducing the amount of chlorides ingress into the concrete. Silane sealers gave higher performance than siloxanes sealers, and water-based sealers gave a higher performance than solvent based sealers. Water-based sealers are more environmentally friendly because of the low volatile organic compound (VOC).
b) The higher the depth of penetration of the sealer, the better performance of the sealers in reducing the chlorides ingress into the concrete.
c) Sealers with chemical family of Alkylalkoxy silane gave higher performance among all the other sealers, and it is recommended to use sealer of Alkylalkoxy silane and water-based sealer.
d) Epoxies sealers provided higher performance for bond strength than methacrylate sealers. While for depth of penetration, methacrylate sealers could penetrate deeper into cracks because their viscosity is lower than the epoxies.
e) According to a research done in Colorado DOT in 2014, all the sealers reduced skid resistance compared to the unsealed deck, so it is necessarily to use high friction surface treatments or aggregates on the top of the sealers to make the surface rough and increase the skid resistance.

7.7 Recommendations for future testing

a) A detailed study need to be done on sealers exposed to freeze/thaw cycles to understand the behavior of these sealers under exposure to these cycles.
b) A study between the sealers and the commonly used overlays is needed. This study should distinguish between the performances of the sealers versus the overlays over time.
c) Alkyltrialkoxysilane which is the chemical family of Aquanilplus 40 gave a poor performance in one of the laboratory tests and better performance in another test. This sealer need to be studied under different conditions to assess its performance.
d) Sikagard 705L gave the best performance in chloride ion intrusion test, while its performance was poor after exposing to freeze/thaw cycles. The chemical family of Sikagard 705L is Alkylalkoxy silane which gave the best performance throughout all the tests except for the freeze/thaw cycles.

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Appendix A: Sample calculation for Durability Factor calculation for three American Ready-Mix specimens

Specimen 1

Date	Period Cycles	Weight (lbs)	Resonant Frequency 1	Selected Fundamental Frequency	Cumulative Cycles
03/01/17	0	16.930	1679	1679	0
03/08/17	36	16.930	1677	1677	36
03/15/17	36	16.940	1652	1652	72
03/22/17	36	16.960	1650	1650	108
03/29/17	36	16.970	1648	1648	144
04/05/17	36	16.975	1644	1644	180
04/12/17	36	16.925	1641	1641	216
04/19/17	36	16.905	1645	1645	252
04/26/17	36	16.890	1647	1647	288
05/03/17	36	16.835	1649	1649	324

Date	Period cycles	Cumulative cycles	Weight (lbs) #1	Resonant Frequency #1	Relative Dynamic Modulus of Elasticity #1
03/01/17	0	0	16.930	1679	100
03/08/17	36	36	16.930	1677	99.8%
03/15/17	36	72	16.940	1652	96.8%
03/22/17	36	108	16.960	1650	96.6%
03/29/17	36	144	16.970	1648	96.3%
04/05/17	36	180	16.975	1644	95.9%
04/12/17	36	216	16.925	1641	95.5%
04/19/17	36	252	16.905	1645	96.0%
04/26/17	36	288	16.890	1647	96.2%
05/03/17	36	324	16.835	1649	96.5%
				Average at 300 cycles:	96.3%
				Durability Factor	**96%**

Specimen 2:

Date	Period Cycles	Weight (lbs)	Resonant Frequency 1	Selected Fundamental Frequency	Cumulative Cycles
03/01/17	0	16.670	1625	1625	0
03/08/17	36	16.665	1622	1622	36
03/15/17	36	16.665	1626	1626	72
03/22/17	36	16.705	1624	1624	108
03/29/17	36	16.715	1618	1618	144
04/05/17	36	16.665	1614	1614	180
04/12/17	36	16.635	1613	1613	216
04/19/17	36	16.625	1615	1615	252
04/26/17	36	16.620	1616	1616	288
05/03/17	36	16.575	1616	1616	324

Date	Period cycles	Cumulative cycles	Weight (lbs) #1	Resonant Frequency #1	Relative Dynamic Modulus of Elasticity #1
03/01/17	0	0	16.670	1625	100
03/08/17	36	36	16.665	1622	99.6%
03/15/17	36	72	16.665	1626	100.1%
03/22/17	36	108	16.705	1624	99.9%
03/29/17	36	144	16.715	1618	99.1%
04/05/17	36	180	16.665	1614	98.7%
04/12/17	36	216	16.635	1613	98.5%
04/19/17	36	252	16.625	1615	98.8%
04/26/17	36	288	16.620	1616	98.9%
05/03/17	36	324	16.575	1616	98.9%
				Average at 300 cycles:	98.9%
				Durability Factor	**99%**

Appendix B: Sample calculation for Durability Factor calculation for three 3D Ready-Mix specimens

Specimen 1:

Date	Period Cycles	Weight (lbs.)	Resonant Frequency 1	Selected Fundamental Frequency	Cumulative Cycles
03/01/17	0	15.960	1457	1457	0
03/08/17	36	15.925	1443	1443	36
03/15/17	36	16	1461	1461	72
03/22/17	36	16.015	1461	1461	108
03/29/17	36	16.02	1462	1462	144
04/05/17	36	16.02	1459	1459	180
04/12/17	36	16.025	1456	1456	216
04/19/17	36	16	1455	1455	252
04/26/17	36	15.950	1457	1457	288
05/03/17	36	15.875	1458	1458	324

Date	Period cycles	Cumulative cycles	Weight (lbs.) #1	Resonant Frequency #1	Relative Dynamic Modulus of Elasticity #1
03/01/17	0	0	15.960	1457	100
03/08/17	36	36	15.925	1443	98.1%
03/15/17	36	72	16	1461	100.5%
03/22/17	36	108	16.015	1461	100.5%
03/29/17	36	144	16.02	1462	100.7%
04/05/17	36	180	16.02	1459	100.3%
04/12/17	36	216	16.025	1456	99.9%
04/19/17	36	252	16	1455	99.7%
04/26/17	36	288	15.950	1457	100.0%
05/03/17	36	324	15.875	1458	100.1%
				Average at 300 cycles:	100.0%
				Durability Factor	**100%**

Specimen 2:

Date	Period Cycles	Weight (lbs.)	Resonant Frequency 1	Selected Fundamental Frequency	Cumulative Cycles
03/01/17	0	15.505	1565	1565	0
03/08/17	36	15.495	1557	1557	36
03/15/17	36	15.565	1563	1563	72
03/22/17	36	15.570	1565	1565	108
03/29/17	36	15.555	1566	1566	144
04/05/17	36	15.550	1568	1568	180
04/12/17	36	15.550	1569	1569	216
04/19/17	36	15.545	1571	1571	252
04/26/17	36	15.545	1572	1572	288
05/03/17	36	15.460	1576	1576	324

Date	Period cycles	Cumulative cycles	Weight (lbs.) #1	Resonant Frequency #1	Relative Dynamic Modulus of Elasticity #1
03/01/17	0	0	15.505	1565	100
03/08/17	36	36	15.495	1557	99.0%
03/15/17	36	72	15.565	1563	99.7%
03/22/17	36	108	15.570	1565	100.0%
03/29/17	36	144	15.555	1566	100.1%
04/05/17	36	180	15.550	1568	100.4%
04/12/17	36	216	15.550	1569	100.5%
04/19/17	36	252	15.545	1571	100.8%
04/26/17	36	288	15.545	1572	100.9%
05/03/17	36	324	15.460	1576	101.4%
				Average at 300 cycles:	101.1%
				Durability Factor	**101%**

Appendix C: Report calculation for amount of charge passed through one of the sealers in rapid chloride permeability test for American Ready-Mix after 30 days

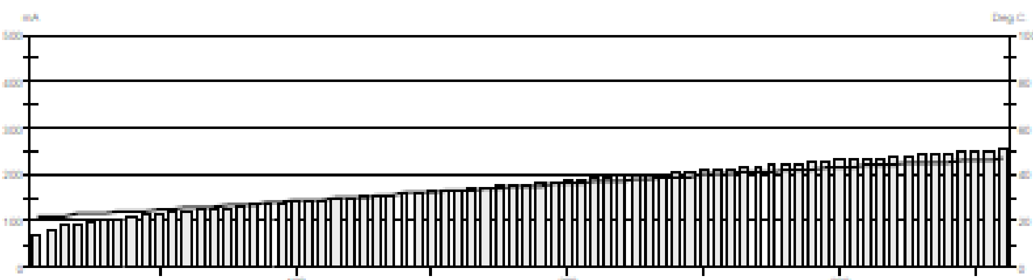
PROOVE it

ASTM C 1202-10

CME CONSTRUCTION MATERIALS ENGINEERS, INC.

Test report

Voltage Used:	60
Testing time:	06:00 hour
Charge passed:	3790
Adjusted Charge passed:	3288
Permeability class:	Moderate
Instrument number:	011503
Channel number:	2
Report date:	2/17/2017
Testing by:	---
Reference:	---
Sample diameter:	102
Comment:	---



Time	°C	mA	Time	°C	mA	Time	°C	mA	Time	°C	mA
00:05	22	71.1	01:35	28	137.9	03:05	35	178.6	04:35	41	217.9
00:10	22	83.2	01:40	29	139.8	03:10	35	181.3	04:40	42	220.0
00:15	22	88.7	01:45	29	142.3	03:15	36	183.4	04:45	42	222.4
00:20	23	93.7	01:50	29	144.7	03:20	36	186.4	04:50	42	224.9
00:25	23	98.1	01:55	30	147.2	03:25	36	188.6	04:55	43	226.8
00:30	23	101.8	02:00	30	150.0	03:30	37	191.3	05:00	43	228.8
00:35	24	105.4	02:05	30	152.1	03:35	37	193.5	05:05	43	230.8
00:40	24	108.6	02:10	31	154.0	03:40	37	195.9	05:10	44	232.4
00:45	24	111.9	02:15	31	155.8	03:45	38	197.1	05:15	44	234.7
00:50	25	114.7	02:20	32	158.3	03:50	38	199.1	05:20	44	236.9
00:55	25	117.7	02:25	32	161.4	03:55	39	201.5	05:25	45	238.7
01:00	26	119.9	02:30	32	163.5	04:00	39	203.7	05:30	45	240.8
01:05	26	122.5	02:35	33	165.6	04:05	39	206.2	05:35	45	242.5
01:10	26	125.2	02:40	33	167.4	04:10	40	209.0	05:40	45	244.2
01:15	27	127.8	02:45	33	170.6	04:15	40	210.3	05:45	46	247.1
01:20	27	130.4	02:50	34	171.8	04:20	40	212.0	05:50	46	249.6
01:25	27	133.1	02:55	34	174.9	04:25	41	214.3	05:55	46	250.7
01:30	28	135.5	03:00	35	177.1	04:30	41	215.8	06:00	47	251.2

Appendix D: Report calculation for amount of charge passed through one of the sealers in rapid chloride permeability test for American Ready-Mix after 120 days

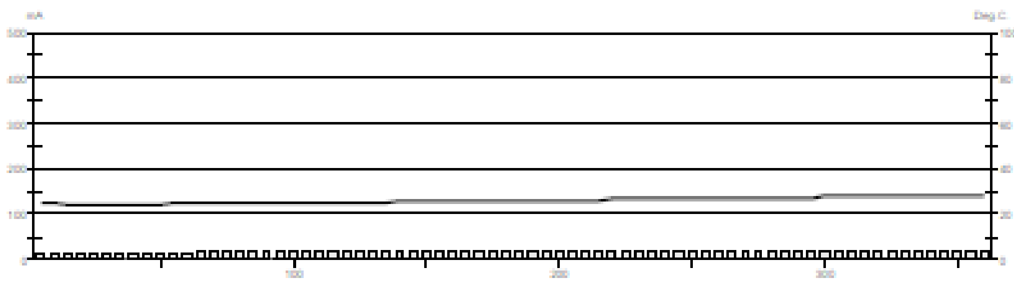
PROOVE it

ASTM C 1202-10

CME CONSTRUCTION MATERIALS ENGINEERS, INC.

Test report

Voltage Used:	60
Testing time:	06:00 hour
Charge passed:	365
Adjusted Charge passed:	317
Permeability class:	Very Low
Instrument number:	011503
Channel number:	5
Report date:	5/24/2017
Testing by:	---
Reference:	---
Sample diameter:	102
Comment:	---



Time	°C	mA	Time	°C	mA	Time	°C	mA	Time	°C	mA
00:05	25	13.0	01:35	25	15.2	03:05	26	17.0	04:35	27	18.8
00:10	25	13.2	01:40	25	15.2	03:10	26	17.0	04:40	27	18.9
00:15	24	13.4	01:45	25	15.3	03:15	26	17.1	04:45	27	19.0
00:20	24	13.5	01:50	25	15.3	03:20	26	17.2	04:50	27	19.1
00:25	24	13.7	01:55	25	15.4	03:25	26	17.3	04:55	27	19.2
00:30	24	13.8	02:00	25	15.5	03:30	26	17.4	05:00	28	19.3
00:35	24	14.0	02:05	25	15.6	03:35	26	17.5	05:05	28	19.4
00:40	24	14.1	02:10	25	15.7	03:40	27	17.6	05:10	28	19.5
00:45	24	14.2	02:15	25	15.9	03:45	27	17.8	05:15	28	19.7
00:50	24	14.3	02:20	26	16.1	03:50	27	17.8	05:20	28	19.8
00:55	25	14.4	02:25	26	16.1	03:55	27	17.9	05:25	28	19.9
01:00	25	14.5	02:30	26	16.2	04:00	27	18.0	05:30	28	20.0
01:05	25	14.6	02:35	26	16.3	04:05	27	18.1	05:35	28	20.0
01:10	25	14.7	02:40	26	16.4	04:10	27	18.3	05:40	28	20.2
01:15	25	14.8	02:45	26	16.4	04:15	27	18.3	05:45	28	20.3
01:20	25	14.9	02:50	26	16.5	04:20	27	18.5	05:50	28	20.3
01:25	25	15.0	02:55	26	16.7	04:25	27	18.6	05:55	28	20.4
01:30	25	15.1	03:00	26	16.8	04:30	27	18.7	06:00	28	20.5

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