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EVALUATION OF BRIDGE DECK SEALERS

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16. Abstract
This study focuses on the evaluation of bridge deck sealers commonly used on highway bridge decks and their relative performance. After reviewing the most up-to-date research findings on chemical sealers used by state DOTs, four sealer products that could potentially be used by the Colorado Department of Transportation (CDOT) were selected for evaluation. High molecular weight methacrylate (HMWM), two epoxies, and a silane were assessed for their skid resistance and ability to block or slow down moisture and chloride ion penetration into concrete bridge decks. Bridge structure E-17-QM (westbound US 36 to I-270 over I-25) was selected for the field study. The four sealers were installed on the deck surface of Bridge E-17-QM by professional contractors on 06/02/2010. Skid resistance, temperature variation, moisture fluctuation, and chloride concentration profiles in concrete were selected as the four experimental parameters for evaluating the performance of the four sealers. 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 for chloride concentration profiles. The British Pendulum Tester (BPT) was used to measure the skid resistance of the concrete surface with and without sealers. From the analysis and comparisons of the test data, the performances of the four sealers were ranked in terms of the four experimental parameters.

Implementation
Without further long-term data, the use of sealers is recommended as a viable short-term protection system. If CDOT chooses to use a long-term bridge deck sealing system, HMWM is recommended over the other sealers. Eligible bridge decks should be selected based on the assessment of percent deck deterioration, estimated time to corrosion, deck surface condition, and concrete quality.

17. Keywords	18. Distribution Statement
skid resistance, chloride ion penetration, moisture penetration, British Pendulum Tester (BPT), high molecular weight methacrylates (HMWMs), epoxies, silanes	This document is available on CDOT's website http://www.coloradodot.info/programs/research/pdfs

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EXECUTIVE SUMMARY

Many old bridges and some new bridges suffer excessive deterioration on the surface of their decks. Although some substances such as deicing salts, graffiti and oil might cause damage or disfigure concrete surfaces, deicing salts are the most destructive material among them. Much of the deterioration is caused by the penetration of water and chloride ions from deicing chemicals into the concrete. Over the past several decades, several hundred different concrete sealers have been used to seal cracks on concrete decks. The sealers were applied in an attempt to seal the surface and prevent or to slow down the penetration of water and chloride ions. This research project on the performance of concrete deck sealers has two specific objectives:

(1) To determine the ability of various sealer products to stop the intrusion of chloride-laden moisture into concrete bridge decks.
(2) To determine if the sealer products impact skid resistance of deck surfaces.

An extensive literature review was conducted on the features and performance of different chemical sealers. Based on the literature review, four sealer products were selected for evaluation of their skid resistance and their ability to block or slow down the moisture and chloride ion penetration into concrete bridge decks. The four sealers are:

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

Bridge structure E-17-QM (westbound US-36 to I-270 over I-25) was selected for the field study. The four sealers were installed on four sections of bridge deck. Another section of the deck was used as the reference section. Skid resistance, temperature variation, moisture fluctuation, and chloride concentration profiles in concrete were selected as the four experimental parameters for evaluating the performance of the four sealers. 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 for chloride concentration

profiles. The British Pendulum Tester (BPT) was used to measure the skid resistance of the concrete surface with and without sealers.

From the analysis and comparisons of the test data, the performance of four sealers can be ranked in terms of the four parameters.

(1) Skid resistance

Silane is better than the other sealers in terms of skid resistance. It was very close to the bare deck right after the installation and better than the bare deck after one year. The skid resistance of Epoxy 1 is not good.

(2) Internal temperature

The sealers can slow down the thermal conduction process in concrete decks. All sealers generated higher temperature gradients in the decks than that of unsealed deck. However, the increase of temperature gradient due to all sealers is very small, not enough to create any damage in the concrete.

(3) Internal relative humidity

After the application of the four sealers, there is no new moisture penetration into the concrete decks from moisture precipitation (rain and snow) during the eight-month period. Therefore, the sealers are effective to block moisture movement into and out of the concrete decks.

(4) Chloride penetration

HMWM, Epoxy 1, and Epoxy 2 can effectively block the penetration of chloride ions from the sealed surface. The silane can block the penetration of chloride ions to a certain extent, but not as effective as the other three sealers. After one year on the bridge deck, Epoxy 1 and Epoxy 2 are not as effective as a year ago. HMWM is still quite effective after one year, and appears to be more durable than the other three sealers.

In summary, the sealers tested in the project have no have adverse thermal effect and they are effective in blocking moisture penetration. HMWM and Epoxy 1 have better skid resistance. HMWM, Epoxy 1, and Epoxy 2 can effectively block the penetration of chloride ions, and HMWM is more durable to resist chloride penetration. Therefore, HMWM achieved the overall best performance among the four sealers.

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1. CHEMICAL SEALERS AND TESTING METHODS

Chemical sealers applied on the top of concrete bridge decks are used by many state Departments of Transportation (DOTs) for waterproofing new and existing bridge decks. Chemical sealers can be categorized as deck sealers and crack sealers. There are many different types of chemical sealers including silanes, HMWMs, siloxanes, epoxy, methacrylate, and other potential sealer products.

There are two parts to the literature review in this report (Chapter 1 and Chapter 2). In the first part (this chapter), basic information is reviewed on sealers that have been used by DOTs in the United States and on the testing methods that have been and could been used for testing sealers. In the second part, the research work is reviewed in detail on the projects conducted for evaluating the performance of chemical sealers.

1.1 Introduction

Many old bridges and some new bridges suffer excessive deterioration on the surface of their decks. Although some substances such as deicing salts, graffiti and oil might cause damage or disfigure concrete surfaces, deicing salts are the most destructive material among them. Much of the deterioration is caused by the penetration of water and chloride ion from deicing chemicals into the concrete. Deicing chemicals, which are generally mixtures of sodium chloride, calcium chloride, magnesium chloride, and corrosion inhibitors are commonly used in the winter season on bridge decks. As ice melts, the chloride ions in deicing chemicals mix with water to form a chloride solution, which remains on the surface of bridge decks. Although some bridges built in the last 15 to 25 years already have the sealer coating system applied on their decks, chloride ions may still penetrate into the decks through existing cracks, and then induce the corrosion of the steel substructure or rebar in the concrete. The chloride-induced corrosion of rebar in concrete structures is an electrochemical process and it has been reviewed extensively and will not be reviewed here.

The existing cracks in bridge decks provide a convenient avenue for chloride ions and water to penetrate concrete and thus speeding up the corrosion of rebar. In addition to the corrosion damage, moisture stays inside cracks and contributes to the deterioration of concrete during freeze-thawing cycles. As the water in the cracks freezes into ice, the volume of ice is about 9% larger than the volume of water and the volumetric mismatch forces the concrete apart.

The American Concrete Institute (ACI) identifies that the cracks, with a width larger than 0.18 mm, must be sealed by crack sealers or must be protected by a system for prohibiting chloride ions from penetrating into the decks (American Concrete Institute Manual of Practices 1997). Crack sealers can penetrate into and seal cracks and thus block the pathway for moisture and chloride penetration. The rates of penetration of sealers into cracked concrete depend strongly on the crack width and viscosity of the sealer (type of sealer). It was found that a crack with a width of 0.3 mm to 0.64 mm allows a silane solution to flow through the cracked concrete swiftly (John and Wenzlick 2007).

Over the past several decades, several hundred different concrete sealers have been used to seal large cracks. The sealers were applied in an attempt to seal the surface and prevent or to slow down the penetration of water and chloride ions. Each sealer has specific properties to deal with specific problems. In order to verify the permeability of concrete and performance of the sealers, various test procedures were proposed and some of them were adopted as standard testing methods. In this chapter, a brief introduction on various sealers will be provided first, and followed by a review on the selected testing methods.

1.2 Deck Sealers and Crack Sealers

1.2.1 HMWMs

HMWMs (high molecular weight methacrylates) are adhesives composed of methacrylate monomers (Meggers 1998). Curable methacrylate adhesives were first developed in West Germany in the late 1960s. Curing of the methacrylate monomers is accomplished by adding an initiator and a promoter to create an oxidation–reduction chain reaction. An intermediate free radical allows the monomer to build a high molecular weight polymer (Damico 1990).

The California Department of Transportation (Caltrans) began the use of HMWM resin for sealing cracks in bridge decks in 1981 (Krauss 1985). Caltrans treated the first bridge deck with a topical application through the use of squeeze bottles. HMWM resin was batch mixed and applied to each crack individually. The method successfully treated cracks as deep as 76 mm. Caltrans had developed a specification. The application of the material has been adopted in part, or whole, by a number of Departments of Transportation, including the Kansas Department of Transportation. Another example is the Mississippi River Bridge at Keokuk, Iowa that was completed and opened to traffic in November 1985 by the Iowa DOT. HMWM was applied to the bridge deck for the first time in October 1986. The Iowa DOT adopted the Caltrans specification, with some changes to reflect the Iowa climate. However, leakage occurring soon after the first application indicated that the cracks had not been sufficiently sealed, although the flow had been reduced. A second application of the material was done in November 1987. In June 1988, the leakage was further reduced by the second application (Marks 1988).

Recently, HMWM has been frequently used as a crack sealer on some state-owned bridges (Rahim et al. 2007). In these states, a thorough review of previous research regarding the effectiveness of concrete bridge deck sealers has been done in conjunctions with a nationwide survey investigating sealer effectiveness. Rahim et al. (2007) have also reviewed practices for using methacrylate as a crack/surface sealer and developed guidelines concerning the use of HMWM along with other potential sealers.

HMWM sealers appeared to be effective in penetrating into the existing cracks in bridge decks due to their extremely low viscosity and low surface tension. A wide range of application temperature was reported in the literature. However, a preferred range of application temperature between 45 and 85ºF was recommended. It was also recommended that HMWM sealer be applied every 4-5 years or as recommended by a bridge inspection team. For areas not subjected to deicing chemicals or a chloride-laden environment, the use of HMWM as a crack sealer can help restore the structural bond strength, but only for narrow and contaminant free cracks.

1.2.2 Epoxy

Epoxy adhesives are perhaps the most versatile of structural adhesives. Various formulations can create epoxies with a wide range of physical properties (Behm and Gannon 1990).

The New Jersey Highway Authority used epoxy as a bridge deck sealer on several structures as early as 1959 and 1960 (Goldberger, 1961). The initial application in 1959 was completed mostly by hand and was relatively expensive. After the application of the epoxy material, a layer of crushed emery was spread on the fresh epoxy to create a skid resistant surface. It should be noted that application rates and procedures developed in 1961 are very similar to those in use today. There is minimal information available as to the effectiveness of the material used to seal the decks or the longevity of the treatment.

1.2.3 Linseed oil

In the past several years, some departments of transportation have experienced problems with large amounts of cracking on some concrete bridges. Various concrete sealer products have been used to seal cracks. Linseed oil was one of the crack sealers used for scaling bridge decks, and it was also listed in the standard specifications (John and Wenzlick 2007). But, the application of linseed oil has not been as common as other sealers such as epoxy.

1.2.4 Silanes and siloxanes

Silanes and siloxanes are deck sealers produced by silicone industry. These materials are derivatives of silicone with molecules small enough to penetrate and bond to the concrete, creating a hydrophobic layer in the treated region. Since they penetrate the concrete and do not create a continuous membrane, they do not provide an impenetrable physical barrier, but rather reduce water inflow by inducing a chemical repulsion of the concrete to water (Aitken and Litvan 1989). Silanes and siloxanes are usually supplied as a solution or as a suspension in a solvent.

1.2.5 Other sealer products and additives

Above sections provided a review on the sealers used on concrete decks. There are many other types of sealer products that have been used on asphalt pavement and steel structures, which will not be reviewed in detail. A brief introduction will be provided for readers' convenience.

Crude tar and coal tar have been an important component of seal coating for the past 50 years (Heydorn 2007a, 2007b). Asphalt emulsion sealer is one of the asphalt-based sealers that have been used. It has been the primary alternative to coal tar for many years. Products that blend asphalt and coal tar are also available. The handling and use of these products is determined by which ingredient dominates the blend. Blended sealers generally take longer to cure than either 100% asphalt or 100% coal tar products. For example, Arizona Department of Transportation (ADOT) sought an alternative to using asphalt for a roadway rehabilitation project in Yavapai County (James Information Media 2003). By mixing recycled asphalt pavement

(RAP) with a polymer-modified asphalt surface sealer (PASS), they found a combined RAP/PASS method that enabled them to meet the ADOT's minimum stability requirements in an inexpensive way.

In 1997, the North and South Grand Island Bridges (a steel structure), near Niagara Falls, New York, were repaired by a coating system that features several layers of coatings (Scranton Gillette Communications 1998). The first one was Zinc Clad IV, which is an organic two-component polyamide epoxy zinc-rich coating. Its low volatile organic compound (VOC) level and wide curing temperature range of 40 to 120 °F at 85% relative humidity combined with 85% zinc dust pigment in its dried film has made zinc clad IV ideal for this type of application. In addition, Zinc Clad IV has exhibited years of proven corrosion resistance on other similar structures.

There are other sealer products used commercially or still in the process of laboratory test, such as:

(1) Lithium hydroxide (Krauss et al. 2006).
(2) Methacrylate (Krauss et al. 2006).
(3) Methyl Methacrylate (Chang 1992).
(4) Asphalt/rock composite material (Bose and Li 2002).
(5) Styrene acrylic-modified cementitious coating (Technology Publishing Company and Steel Structures Painting Council 2000).
(6) Aliphatic acrylic-modified polyurethane (Scranton Gillette Communications 1998).
(7) Urethane (Transportation Research Record 1995).
(8) Acrylics (Damico 1990).

Additives are often added to sealers to enhance the performance of the sealers in terms of better flexibility, toughness, chemical resistance, and overall longevity. Specifications that delineate the proper ratios of various components are important for the optimum performance of seal coats.

1.3 Tests for Evaluating Deck and Crack Sealants

Our literature review showed that there are no standard testing methods for the effectiveness of deck and crack sealers. Some of the existing testing methods can be indirectly used for testing deck and crack sealants. There are different considerations in evaluating the chemical sealants. For example, tests that measure chloride ion intrusion can be used for evaluation of the performance of deck sealers. Modified versions of the splitting tensile strength of concrete cylinders and the scaling tests provide methods for evaluating the bond strength and durability of the sealers.

1.3.1 Chloride Ion Intrusion Test - AASHTO 259

AASHTO T 259 ("Standard method of test for resistance of concrete to chloride penetration") is a testing method which determines resistance of concrete specimens to chloride ion penetration. This method is also called 90-day salt solution ponding test. This method was designed for concrete without sealant, but it can be used to test for the effectiveness of a sealant applied on a concrete specimen. When a chloride profile (chloride concentrations at different depths) is obtained from a concrete sample sealed by a sealant, it includes the effects of chloride resistances of the sealant as well as the resistance of concrete. In order to separate the two effects, a control concrete sample without the sealant should be used. The difference in the two chloride concentration profiles obtained from concrete samples with and without the sealant will unveil the chloride resistance of the sealant. This test may be used for both deck and crack sealant. When it is used for crack sealant, the control sample should be a sample with a similar crack.

1.3.2 Rapid Chloride Permeability Test - ASTM C 1202

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 is actually related to the electric conductivity of saturated concrete, which can be correlated to the chloride permeability of saturated concrete (Stanish et al. 1997). Similar to AASHTO 259, this test can be performed on concrete samples with sealant. A control concrete sample without the sealant should be used. The difference in the two test results obtained from concrete samples with and without the sealant will unveil the chloride resistance of the sealant. This test may be used for both deck and crack sealant.

1.3.3 Bond Strength of Crack Sealants

In addition to the resistance the chloride ion penetration into concrete structures under service condition (with both traffic and environmental loadings), bond strength is sometime an important property for crack sealants. There are no standard methods for determining the bond strength of crack sealants. The splitting cylinder test to measure the tensile strength of the concrete (ASTM C 496 “Standard test method for splitting tensile strength of cylindrical concrete specimens”) may be used to obtain a relative comparison of the bond strength of sealants. In this case, a concrete cylinder can be cut along the diameter and the two parts can be glued together by the sealant. Then, the splitting tensile test can be conducted on the cylinder with the load applied in the direction of cut diameter. The measured tensile stress may be used as an indicator for the bond strength of the sealant. Another method for testing the bond strength is ASTM D 4541-09el (the pull-off test). This test can be done on a two-layered concrete slab. The two layers are glued together by the sealer.

1.3.4 Scaling Test

ASTM C 672 test (“Standard test method for scaling resistance of concrete surfaces exposed to deicing chemicals”) can be used to determine the resistance to scaling of a horizontal concrete surface exposed to freezing and thawing cycles in the presence of deicing chemicals. The test procedure is intended to be used for evaluating the surface resistance to scaling by visual examination. It may be used for concrete with a sealant, and the test result can be considered to be an indication of the durability of sealant.

1.3.5 Depths of sealant penetration - OHD L-40

OHD L-40 is a testing method used by the Oklahoma Department of Transportation for determining depth of penetration of water repellent treatment solutions into Portland cement concrete (Oklahoma DOT 2003). Specimens used in this test procedure are 4 in. diameter cores approximately 4 in. in length retrieved from a concrete surface that has been treated with a penetrating water repellent solution. The cores are split through the sealed surface and immersed in a solution of Sulfonazo III and water, which is capable of staining only the untreated concrete. The cores are then rinsed with water and photographed, and the area of penetration is outlined. Using the specimen width and scale of the photograph, the average depth of penetration can be calculated. This method can be used to detect the penetration depth of a deck sealer. It can also be used for a crack sealer when a concrete core with a crack is split through the crack.

2. PERFORMANCE OF CHEMICAL SEALERS

In the past 25 years, many comprehensive studies were conducted by state DOTs on the performance of chemical sealers. In this chapter, several comparative studies involving field and/or lab experimental study are reviewed. They compared the performances of various types of sealers in the lab tests and in the field studies. It should be pointed out that there are many reports in the literature on this topic, and some of them are not included in this chapter such as the report by Rahim and Jansen (2006) to the California Department of Transportation.

2.1 The Texas Study (Curra 1990)

An evaluation of representatives of the most popular types of concrete bridge deck sealers was conducted using a two-pronged approach (Curra 1990): performance testing via accelerated weathering coupled with water immersion, and indirect testing using instrumental and analytical techniques. The goal of the comparative study was to assess the ability of the sealers to protect embedded reinforcing steel from corrosion and to develop an effective test procedure for screening commercial products: silanes, siloxanes, water-based epoxy, polyester, silicate, and linseed oil.

The silanes and siloxanes group performed the best in all phases of testing. Linseed oil performed nearly as well. However, some questions were raised concerning its long term durability due to its limited depth of penetration and to the reactivity of the linseed oil in the alkaline environment of fresh concrete.

2.2 The Indiana Study (Chang 1992)

Research was conducted to evaluate generic types of sealer and coating systems for use on non-wearing concrete surfaces in Indiana (Chang 1992). Although significant variations exist among six generic classes of coating systems subject to accelerated weather, water absorption and vapor transmission, and rapid chloride ion permeability tests; certain generic chemical formulations of coating systems appear to exhibit comparatively better performance than others.

The epoxies were comparatively better barriers to chloride and water absorption but deteriorated and discolored slightly in the accelerated weathering test. The penetration sealers (silanes, silicone, and siloxanes) were relatively good in terms of their ability to resist water and chloride absorption and showed little sign of deterioration in the weathering test. The products that were combinations of the above materials did not perform as well as the penetration sealers. The urethane and methyl methacrylate did not perform consistently across all tests.

2.3 The Kansas Study (Meggers 1998)

The Kansas Department of Transportation (KDOT) conducted a comparative study for the performance of HMWM and epoxy (Meggers 1998). During the summer of 1991, eight bridges, through six operating districts of KDOT, were selected for sealer testing. Bridges were chosen to cover a wide range of geographic and climatic regions. In addition to the location, the bridges chosen also had a significant amount of deck cracking. The structures had a variety of substructures, and several had bridge deck wearing surfaces.

Two types of HMWM sealers and one epoxy sealer were chosen to be applied to the bridge decks. A third HMWM sealer was added to the laboratory portion of the study. The three HMWM materials had different elongation, strength, and viscosity. The epoxy sealer was a special low viscosity material developed for flood coat crack sealing. The physical properties of the sealers were listed in Table 2.1 (Meggers 1998).

Table 2.1 Significant Material Properties (Meggers 1998)

Sealer	Viscosity Pa.s	Tensile Strength (MPa)	Tensile Elongation Percent
Epoxy	0.3-0.5	29.3	9.9
HMWM A	0.01-0.025	2.8	30
HMWM B	0.07-0.15	8.3	10
HMWM C	0.025	2.8	1.9

The objective of the study was to determine the feasibility of using HMWM and epoxy sealers for crack sealing and repair of old serviceable bridges. However, the results of the field portion of the study were inconclusive. Chloride concentration levels of the sealed sections and the control sections were inconsistent. In some cases, the sealed portions of the bridge deck had higher chloride concentration increases than the control section. This indicated that the sealers may trap chloride in the system and actually worsen the conditions. The penetration data indicated that the extremely low viscosity HMWM A sealer may have been more effective in penetrating the cracks than the other two sealers. The HMWM A sealers did not show any greater ability to prevent an increase in chloride concentration.

The optimum sealer would be the one with a relatively low viscosity so it can better seal the crack. It was concluded that although a sealer may not fully penetrate or completely seal a crack, it is still be beneficial. Any reduction in the amount of water and chloride intrusion into a bridge deck has the potential to slow down the corrosion and reduce freeze-thawing damage.

2.4 The Iowa Study (Krauss and Boyd 1999)

Crack analysis and repair trials were performed on the City Island Bridge over the Mississippi River for the Iowa DOT in 1999 (Krauss and Boyd 1999). Concrete cores were removed from the bridge and examined. Chloride ion tests were performed to investigate the depth of chloride ion penetration. The cracks included in the study ranged from 0.3 to 0.7 mm wide. The depth of penetration of the sealant materials ranged from 1 to 8 mm.

The researchers concluded that the HMWM and epoxy resins used on the bridge were unable to penetrate cracks adequately to structurally bond the cracks. However, the problem was not due to the sealers but due to the fact that the cracks were filled with an extensive amount of dirt and debris, which appeared to inhibit penetration of the HMWM and epoxies selected for evaluation. On the other hand, silanes and overlay system appeared to be viable to seal cracks and extend the service life of decks. Silanes were able to penetrate and coat the inside of cracks, providing a hydrophobic layer to depths between 35 to 55 mm (Krauss and Boyd, 1999). The researchers acknowledged, however, that it is unknown whether silanes can effectively prevent water infiltration into cracks when subjected to truck traffic service loads and bridge deflection.

2.5 The Wisconsin Study (Pincheira and Dorhorst 2005)

The Wisconsin Department of Transportation conducted a comparative study in 2005 for the performance of several commonly used deck sealers. The study compared the effectiveness and relative performance of commercially available concrete deck and crack sealants (Pincheira and Dorhorst 2005). Thirteen deck sealants and ten crack sealants were selected and tested under laboratory conditions that simulated the exposure to deicing salts and freeze-thawing cycles. Conclusions of the study are described below.

Deck sealants, solvent-based, and silane products had larger depths of penetration than water-based and siloxane products. Also, when not exposed to freeze-thawing cycles, solvent-based products were generally able to reduce the ingress of chloride ions better than water-based products. Under exposure to freeze-thaw cycles, however, there was no clear distinction between the performances of solvent-based and water-based products.

For crack sealants, including HMWM resins, epoxy resins, and urethane resins, all sealants were able to penetrate the full depth of the crack designed for this study, 2.5 inches. For most sealants, the bond strength decreased, and the failure mode changed with increasing crack width and with exposure to freeze-thawing cycles. Also, reductions in bond strength under freeze-thawing cycles varied widely depending on the product and the crack width considered.

2.6 The Missouri Study (John and Wenzlick 2007)

The Missouri Department of Transportation (MoDOT) conducted a comparative study in 2007 for the performance of linseed oil, silicate, and silane (John and Wenzlick 2007). Linseed oil was used as a scaling prevention treatment material by MoDOT. Linseed oil is the only concrete sealer listed in Missouri's Standard Specifications, and is used for resistance to scaling on new bridges. Although linseed oil has been considered as the best surface scaling preventer tested by MoDOT, it is not good as a crack sealer.

The objective of the study was to come up with the testing methods to qualify concrete sealer products. Sealers that have been used already by maintenance or construction: reactive silicates, silanes, and siloxanes were compared to linseed oil for scaling prevention. They were also tested on cracked concrete to establish their effectiveness in sealing cracks. Testing information is listed in Table 2.2 (John and Wenzlick 2007) along with the four different penetrating sealers that were tested, including linseed oil and a control test sections (unsealed concrete).

From the Salt Solution Ponding Test (AASHTO T259), the test data showed the uncoated samples had a lower value than any of the penetrating type sealers and were equal to linseed oil. From the Scaling Resistance of Concrete Surfaces Test (ASTM C672), none of the sealers tested had a rating of zero except for linseed oil. From the Rapid Chloride Permeability Tests (AASHTO T277), all samples but one tested in the "Moderate" range even for the uncoated control sample. The only sealer that seemed to have a positive effect was the Silane 55 averaging a reading of 2880 C and being on the low end of the "moderate" rating.

Table 2.2 Tests Performed in MoDOT Research Investigation of Concrete Sealers

Test No.	Description
Test1: AASHTO T259	Resistance of Concrete to Chloride Ion Penetration
Test2: ASTM C672	Standard Test Method for Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals
Test3: AASHTO T277	Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration
Test4: ASTM C642	Standard Test Method for Density, Absorption, and Voids in Hardened Concrete
Test5 Modified AASHTO T259	Crack Sealer Test

From the Crack Sealing Test (AASHTO T259 Modified), linseed oil performed well although the specimen had small crack widths with 0.0767 mm average crack width. The specimen treated by Silane 55 had crack width of 0.050 mm, which was the smallest crack, and the treated crack never leaked. The reactive silicates did not perform well on this test and the specimens had the largest average crack widths at 0.187 mm and 0.3 mm. The ACI suggestion is that a crack larger than 0.18mm is large enough for chloride ions to intrude into concrete. Therefore, linseed oil and Silane 55 passed the test.

2.7 The Illinois Study (Morse 2009)

The Illinois Department of Transportation (IDOT) conducted a comparative study in 2009 for the performance of various deck sealers (Morse 2009). The research project developed a protocol to evaluate concrete sealers and laminates effectiveness in protecting bridge deck concrete from chloride ion ingress. The protocol developed includes criteria for selecting products for evaluation, sample locations, sample depths, duration of study as well as the method of analysis of the chloride ions present in the concrete dust collected. The research found that a water-based silane/siloxane mixture demonstrated the best durability over the 5 year study. While one water-based sealer performed slightly better than the others, solvent-based sealers perform better overall than the water-based counterparts in this research.

3. RESEARCH PLAN AND EXPERIMENTAL PARAMETERS

This research project has two specific objectives:

(1) To determine the ability of various sealer products to block the intrusion of chloride-laden moisture into concrete bridge decks.
(2) To determine if the sealer products impacts skid resistance of deck surface.

These objectives are different from those reviewed in the first two chapters (penetration depth of crack sealers, for instance). Field experimental study is the main research method. CDOT identified the highway bridge structure E-17-QM as the bridge to be used for the field evaluation. The bridge was built in 1998 and is part of the interchange of U.S. 36, I-270, and I-25. It is located at the end of I-270 connecting U.S. 36 to Boulder. The structure consists of two traffic lanes and one shoulder lane. It is 841 feet long with 6.6-foot-deep steel box girders. Access inside the box girders is achieved by walking up the paved slope and entering through a hatch. Fig 3.1 is the bird’s eye view of the testing section on E-17-QM. Figs 3.2 through 3.4 show the structure of this bridge.

Fig 3.1 Bird’s eye view on Bridge E-17-QM

Fig 3.2 Side view of Bridge E-17-QM

Fig 3.3 One shoulder lane and two traffic lanes of Bridge E-17-QM

Fig 3.4 A hatch beneath the bridge for accessing the steel box girder

Based on the literature review mentioned above, four sealers were chosen. They represent four categories of commonly used sealers.

(1) HMWM: Sika Pronto 19- HMWM (2 components).
(2) Epoxy 1: Super low viscosity, low modulus epoxy.
(3) Epoxy 2: Low Viscosity, high modulus epoxy.
(4) Silane: Tamms Baracade 244-Silane Sealer.

The four sealers were installed on the bridge decks the evening of June 2, 2010. Traffic detour was started at approximately 9:00 pm, and the entire installation and testing process continued for the whole night.

Prior to installing sealer products on the bridge deck, the concrete substrate was inspected. There were no major contaminants at the location of surface cracks and there were no major cracks on the surface of concrete decks. For surface preparation, in general, the manufacturer's recommendations were followed. The sealers were installed by professional contractors hired by the sealer manufacturers or suppliers. The decks were washed and power swept to remove all dirt, sand, clay and other debris prior to applying the sealers (Fig 3.5). Proper chemical solutions were used to form the sealer products (Fig. 3.6), placed on deck surfaces (Fig. 3.7). Finally, fine sand was spread on the surface (Fig. 3.8). Figs 3.5 - 3.8 show the installation process of the sealers.

Fig 3.5 Cleaning the deck surface

Fig 3.6 Mixing chemical solutions

Fig 3.7 Sealer application

Fig 3.8 Spreading fine sand on the top of decks

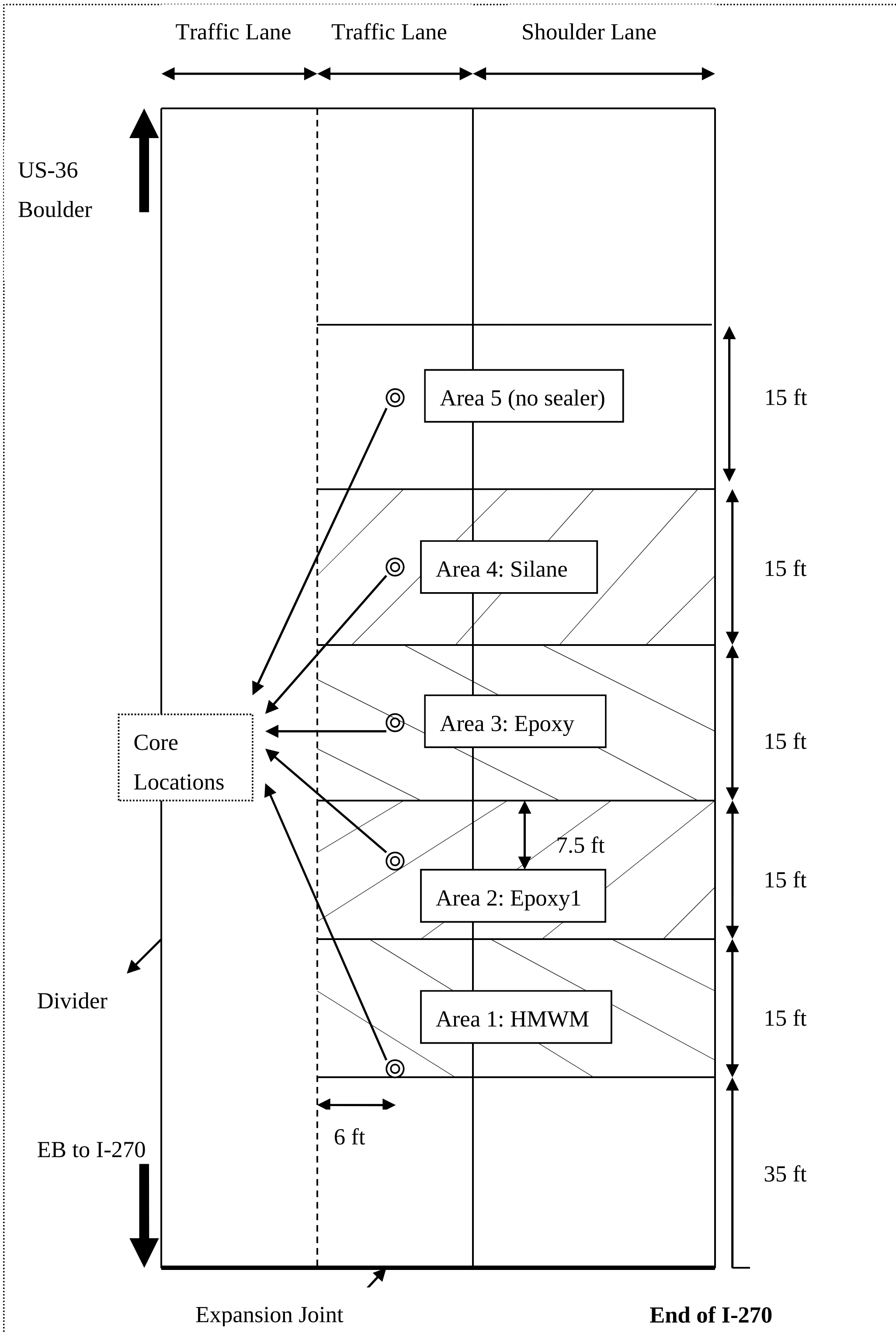

Fig 3.9 The five test sections on Bridge E-17-QM

The longitudinal direction of one traffic lane was divided into five testing areas (sections). Each area is 15-feet long occupying the full traffic lane next to the shoulder. Areas 1-4 were sealed by using the selected sealer products and Area 5 was not sealed, and it was used as the reference area (section) to compare the performance with the four sealers. The five locations for the sealers are shown in Fig 3.9.

The chemical sealers' performance was evaluated by four experimental parameters: skid resistance, internal temperature, internal pore relative humidity in the concrete, and chloride concentration profiles in concrete. These four parameters were selected based on the research needs of this project. The internal temperature, relative humidity, and chloride concentration are essential to evaluate the ability of the sealers to block the intrusion aggressive deicers. The bond strength and sealer penetration depth as described in chapter 1 were not considered as the control parameters of the project and thus were not tested. The skid resistance tests were done by CDOT on-site, and the chloride concentration profiles were obtained by the research team at CU-Boulder using concrete cores taken from each testing area on bridge decks. Moisture and temperature measurements were monitored by integrated sensors installed by the research team of CU-Boulder in each testing area at different depths of the bridge deck to show the vertical distributions of both internal moisture content and temperature.

Based on the four parameters measured during the project, the performance of the four sealers were compared and ranked. Details about the four parameters will be discussed in the next sections of this chapter and the test results will be discussed and analyzed in the following chapters.

3.1 Skid Resistance

3.1.1 Background

Skid resistance deficiency is a major concern for the highway construction industry and management agencies. A high percentage of these accidents are due to driver's error, however, the condition of highways has a significant effect. In regards to traffic accident rates and safety, one of the most influential factors is the skid resistance of the roadway surface (Piyatropoomi et al 2008).

Skid resistance is a technical term for the cumulative effects of snow, ice, water, loose material and the road surface on the traction produced by the wheels of a vehicle. Road slipperiness is measured either in terms of the friction between a freely-spinning wheel and the ground or vehicle braking distance which is related to the coefficient of friction between the tire and the road. Skid resistance of a roadway surface is developed when vehicle tires are fully or partially prevented from rolling under lubricated conditions and start to slide along a pavement surface. When a sealer is applied on a roadway surface, the skid resistance of the surface could change. For this reason, the skid resistance was selected as one of the four parameters to evaluate the performance of the sealers.

3.1.2 Test apparatus and test methods

There are different standards and corresponding test apparatus that can be used to measure skid resistance. The following is a brief description of some commonly used methods.

Yaw Mode Method (Mu-meter)

- Two smooth treaded tires mounted on a trailer
- The wheels are turned in equal but opposite angles to the direction of travel.
- The sliding force is measured to find the angle for peak sliding force.
- Test is conducted on wet pavement.

Stopping Distance Method: ASTM E445 (Locking 4 wheels) and ASTM E303 (Locking diagonal wheels)

- Lock all four wheels (ASTM E445) or diagonal wheels (ASTM E303).
- Determine distance for the vehicle to stop.
- Compute Stopping Distance Number.

Slip Mode Method (Swedish Road Research Skid meter):

- Measures the friction experienced as brake is gradually applied.
- Maximum friction occurs at the critical slip.

Portable Field Tester – ASTM E303 British Pendulum Tester (BPT)

- A small rubber shoe is attached to the end of a pendulum.
- The pendulum is dropped against the pavement surface to be tested.
- British Pendulum Number (BPN) is read from the drag pointer after each drop.

Locked-wheel trailer– ASTM E 274-97

- This test uses a standard test tire mounted on a specially designed trailer.
- A standard amount of water is applied ahead of the tire while moving.
- The tire is locked while the vehicle maintains a constant speed, usually 40 mph (65 kph), and the resistance between the tire and the wet pavement is measured.
- The force required to slide the tire is divided by the wheel load and multiplied by 100. The results are expressed as a skid number (SN) or friction number (FN).

3.1.3 British Pendulum Tester

The British Pendulum Tester (BPT) was selected from the four previously mentioned tests for evaluating the skid resistance of sealed concrete surface in this project. The BPT is a stationary type of skid testers. It comprised a support frame that can be leveled on the road. Attached to the support frame is a swinging arm, at the bottom of which is a spring loaded ASTM rubber measuring foot. This swinging arm, when released from a fixed point, sweeps across the surface underneath. The skid resistance of the surface determines how far the arm swings up on the follow-through. The arm also moves a measuring that gives a value on the attached scale. Fig 3.10 and Fig. 3.11 show the BPT purchased and used for this project.

Fig 3.10 British Pendulum Tester

The test method described in ASTM E303 (1993, reapproved 2013), *Standard Test Method for Measuring Surface Frictional Properties Using the British Pendulum Tester*, uses the BPT to measure the frictional properties of the micro texture. The result from the BPT is the British pendulum number (BPN), which relates to skid resistance obtained in the field.

The advantages of this approach are that it is portable, has a low initial cost, and can test in different orientations. Also, the instrument gives a direct measurement of the friction between a skidding tire and wet road surface. It provides us with a practical means of obtaining reliable scientific evidence on which to take the appropriate measures to reduce skidding. Disadvantages include that test results from coarse (macro) texture are questionable, and it can only simulate low-speed skidding and it requires laborious calibration.

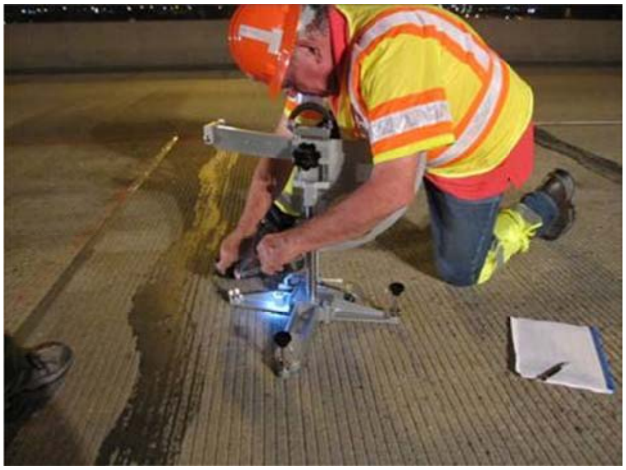

Fig 3.11 CDOT engineer conducting a skid resistance test

For this research project, we use a BPT to take measurements when sealers were initially applied and again one year later. The purpose of the first measurement is to determine which sealer product can provide the best skid resistance immediately after installation and prior to traffic loading. From the second measurement, we can gather information on the skid resistances of the sealed surfaces after one year traffic loading. According to ASTM E303-93 (reapproved 2013), the greater the friction between the slider and the test surface, the more the swing is retarded, and the larger the BPN reading. In another word, a slippery surface produces readings close to zero, and an anti-slip surface impedes the motion of the pendulum arm, giving results further from zero, thus a high BPN indicates higher skid resistance.

3.2 **Integrated Thermal and Moisture Sensors and Data Logger**

3.2.1 Integrated sensors for temperature and moisture measurement

An integrated sensor was used in the project to measure pore relative humidity and temperature in concrete (SHT7X by Sensiron). The sensor is connected to a data logger and a computer so the relative humidity and the temperature in concrete can be continuously recorded.

In each of the five testing sections on the bridge, the research team installed multiple integrated sensors at different depths. The five sections are shown in Fig. 3.9: Section 1 for HMWM, Section 2 for epoxy 1, Section 3 for epoxy 2, Section 4 for Silane, and Section 5 for bare deck (no sealer). The objective was to obtain the vertical profiles of moisture and temperature distribution inside each testing section of concrete decks (Fig 3.7). Comparing the recorded results, the effectiveness of the sealers was determined.

It is important to evaluate the penetrations of moisture into concrete using the moisture concentration profiles (distribution) instead of a single data point, because data might scatter at a single point in concrete which may lead to confusing conclusions.

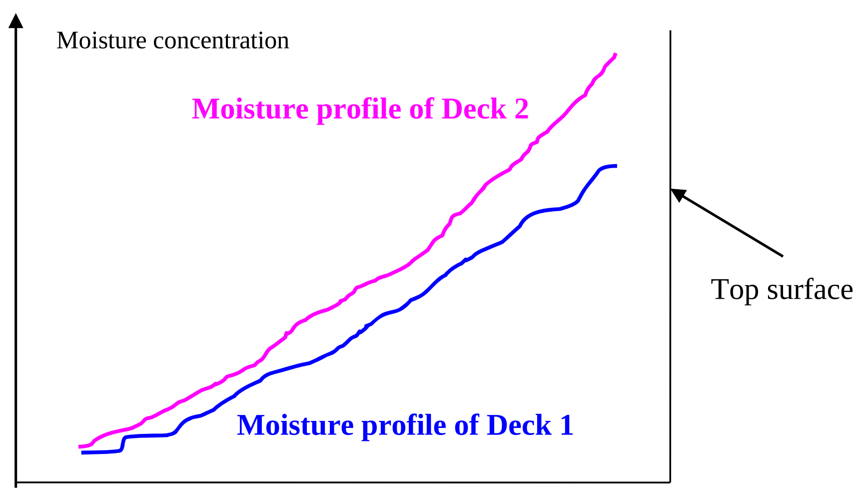

Fig 3.12 Continuous wet condition on the top surface of bridge decks

For example, when considering two concrete decks both under continuous wet conditions on the top surface, two moisture profiles obtained from the two decks may look like those shown in Fig 3.12. Profile 1 has lower concentration than Profile 2, and we may conclude that the permeability of the concrete of Deck 1 is lower than that of Deck 2. However, under the complicated service condition (or the condition of first wet and then dry on the top surface), the two profiles in Fig 3.12 may change to those shown in Fig 3.13. At some depths especially in the shallow part of the concrete, the moisture in Deck 1 maybe higher than Deck 2 because the moisture penetrates faster into the concrete of higher permeability when the top surface is wet, and the moisture also diffuses out of the concrete faster when the top surface is dry. In this case, if we only use one sensor, different conclusions would be reached on the permeability of the concretes depending on the location of the single sensor.

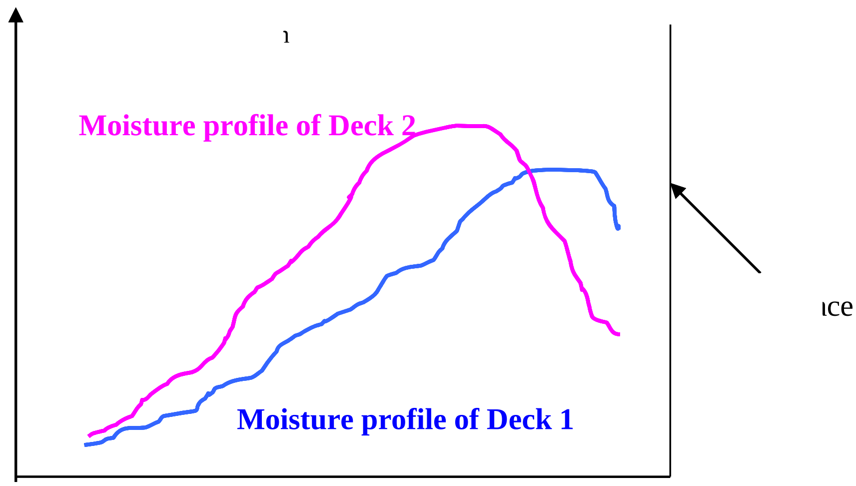

Fig 3.13 Condition of first wet and then dry on the top surface

Although the example shown above is for evaluating the permeability of concrete, it can also be used for evaluating the permeability of concrete covered by a chemical sealer. All sensors were installed from underneath the decks inside the steel box girder, and the holes were drilled upwards into decks for installing the sensors (Fig 3.14).

Fig 3.14 Integrated sensors installed in the deck.

The total depth of the bridge decks is approximately 9.5 in and the written numbers next to sensors in Fig 3.14 represent the drilling distances. For example, the third number from the left, 6.5 in means that the depth of the sensor is 3 inches from the top surface. The variation of internal moisture and temperature in deck is mainly caused by the environmental conditions at the surface of the bridge deck. All comparisons and analysis of those readings are based on the distance from the deck surface to the location of the sensors.

3.2.2 Data logger

The data logger (EK-H3)/evaluation kit, designed for the sensor SHT7X, was used for the data acquisition. The data logger allows for simultaneous reading of 20 sensors. 18 sensors were installed in the five testing sections on the bridge. The instrumentation is shown in Fig 3.15 and Fig 3.16.

Fig 3.15 Sensor wiring from inside of the steel box girder

Fig 3.16 The data logger recording data for the integrated sensors

The data acquisition system was set up to take monthly readings for one year. Based on these readings, the resistance of the chemical sealers to moisture penetration was analyzed. At the same time, the internal temperature variations in the concrete decks were also recorded to analyze the thermal effect on the moisture and chloride penetration into concrete decks.

3.3 Chloride Concentration Profiles in Concrete Decks

The main function of the chemical sealers is to block or slow down the penetration of chloride ions. Concrete cores were taken from bridge decks four times as detailed in Table 3.3. The first time was six months before the installation of sealer products, and the chloride profiles from Section 1 through 4 can be considered to be the initial chloride concentration profiles. The second time was on the same day after the installation of sealer products. The third and fourth measurements represent the results six-month and one-year after the initial application of sealers.

Table 3.3 Dates for taking concrete cores from the bridge decks

	Date	**No. of cores taken**	**Deck surface condition**
1	11/04/2009	4	No sealer
2	05/26/2010	5	Before sealer application
3	11/16/2010	5	Six months after sealer application
4	05/04/2011	5	One year after sealer application

Concrete cores (4 inches in diameter) were taken from test sections to determine chloride contents at different depths with an interval of 0.25 in below the surface following ASTM C1218M-99. Fig 3.17 shows the process of taking concrete cores from bridge decks.

Fig 3.17 Taking concrete cores from bridge decks

4. TEST RESULTS - SKID RESISTANCE

4.1. Test Results

The skid resistance tests were performed on 06/02/2010 and 05/04/2011 by the BPT. Details about the measurements are described below and the test results are shown in Tables 4.1 - 4.2. Details for the first test, measurement 1:

(1) Tested dry (no rain, no water).
(2) Sections 1 and 2 were very oily.
(3) Section 2 was not completely set.
(4) All tests were done in the area of the right wheel path.
(5) The changing lane width made the wheel path very vague and not well defined.
(6) Tests were done with the pendulum traveling in the direction of traffic.

Table 4.1 Skid resistance of measurement 1

06/02/2010 (the same day as the application of sealers)	Average
Area 1 (HMWM)	86.35
Area 2 (Epoxy 1)	57.4
Area 3 (Epoxy 2)	96.1
Area 4 (Silane)	96.15
Area 5 (No sealer)	100.7

Table 4.2 Skid resistance of measurement 2

05/04/2011	Readings					Average
Area 1 (HMWM)/1	72	70	71	70	70	73.9
/2	78	77	77	77	77	
Area 2 (Epoxy 1)/1	60	59	59	58	57	61.2
/2	63	64	64	64	64	
Area 3 (Epoxy 2)/1	90	89	89	89	89	82.9
/2	78	77	76	76	76	
Area 4 (Silane) /1	92	92	93	93	94	91.2
/2	88	89	90	90	91	
Area 5 (No sealer)/1	89	88	88	88	88	88
/2	87	88	88	88	88	

Details for the second test, measurement 2:

(1) Tested with water.
(2) All tests were done in the area of the right wheel path.
(3) The changing lane width made the wheel path very vague and not well defined.
(4) Tests done with the pendulum traveling in the direction of traffic.

4.2. Analysis

The ranking of these four sealer products right after application and after one year's usage are shown in Table 4.3 and Table 4.4. In general, a high skid resistance number represents a high skid resistance. For example, in Table 4.3, Epoxy 1 has a number 57.1, which is the lowest among all readings, and thus Epoxy 1 has the lowest skid resistance right after the installation, and thus it was ranked No. 5 in terms of skid resistance in Table 4.3.

Table 4.3 Ranking for Skid resistance of measurement 1

Sealer	Epoxy1	HMWM	Epoxy2	Silane	No sealer
Number	57.4	86.35	96.1	96.15	100.07
Ranking	5	4	3	2	1

Table 4.4 Ranking for Skid resistance of measurement 2

Sealer	Epoxy1	HMWM	Epoxy2	No sealer	Silane
Number	61.2	73.9	82.9	88	91.2
Ranking	5	4	3	2	1

From the rankings in the two tables, we can obtain the following conclusions:

(1) From Table 4.3, most readings from the four areas with sealers are smaller than the reading from the area without sealer, which means that the sealers reduced the skid resistance.
(2) From Table 4.4, most readings from the sealed sections are smaller than the reading from the area without sealer, except Silane which is slightly higher than No sealer. This means that the skid resistances of sealed sections are not better or just comparable to the bare deck after some wearing from traffic.
(3) Silane has the highest skid resistance among the four sealers. It was very close to the bare deck right after the installation and better than the bare deck after one year.

5. TEST RESULTS – INTERNAL TEMPERATURES

From the installed sensors in bridge decks, internal temperatures and moistures were recorded. The temperature distribution in concrete has two possible adverse effects: the generation of thermal stresses and swelling due to freeze/thaw cycles. The purpose of temperature monitoring is to determine the effect of sealers on the internal temperature distribution in concrete, and to see if there are any adverse effects such as excessive thermal stress caused by the applied sealers. The temperature records were analyzed and compared in four different ways:

(1) Comparisons between daytime and nighttime.
(2) Comparisons for hourly readings in five testing areas.
(3) Comparisons at different depths.
(4) Comparisons for bimonthly readings.

5.1. Comparisons Between Daytime and Nighttime

The trend in all five areas between daytime and nighttime is consistent. The temperature decreases during the day time and increases at the nighttime. Figs 5.1 through 5.5 show the trend for sealed and unsealed areas. The two curves in the range of 40 to 50°C were recorded during daytime at 3:00 pm. The two curves in the range of 20 to 30°C were recorded during nighttime at 1:00 am. They were all recorded in the summer 2010. The temperature difference at different depths is important to observe. Since the sealers were applied at the top surface, the temperature variation in the shallow part of the deck may be affected by the sealers.

The sampling time of 3:00 pm was selected based on our experience of monitoring temperature variation in concrete structures. Usually, the environmental (air) temperature reaches the maximum at noon or at 1:00 pm, and the internal temperature in the concrete reaches the maximum with about a two-hour delay. Similarly, the sampling time in the night was selected at 1:30 am for the internal temperature in concrete to reach the minimum.

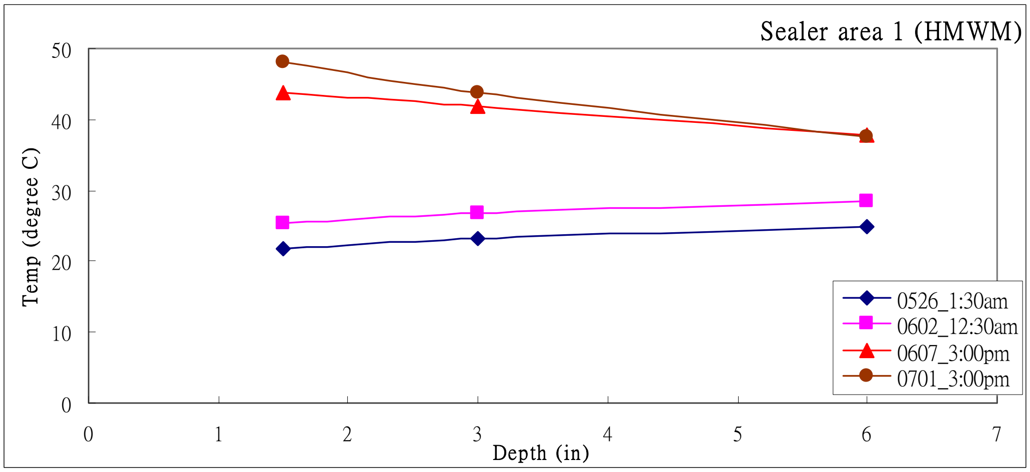

Fig 5.1 Comparison of the internal temperatures at daytime and nighttime (HMWM)

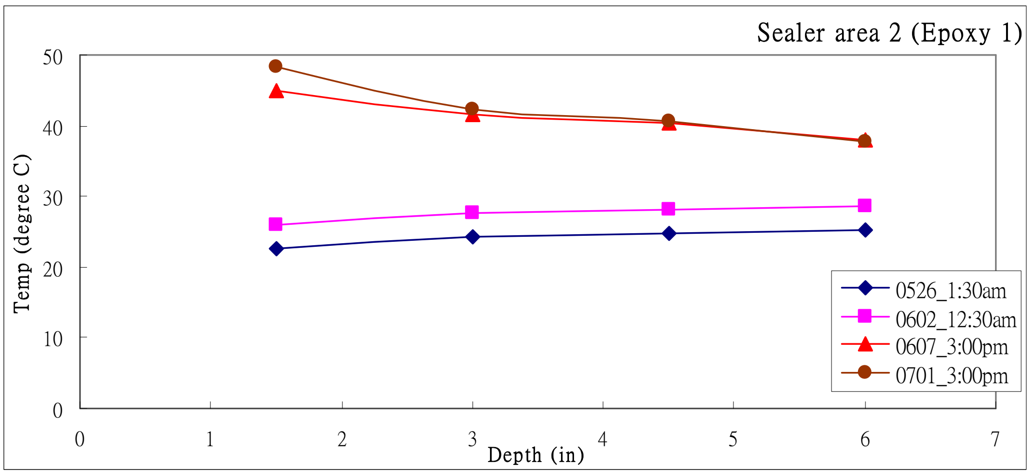

Fig 5.2 Comparison of the internal temperatures at daytime and nighttime (Epoxy 1)

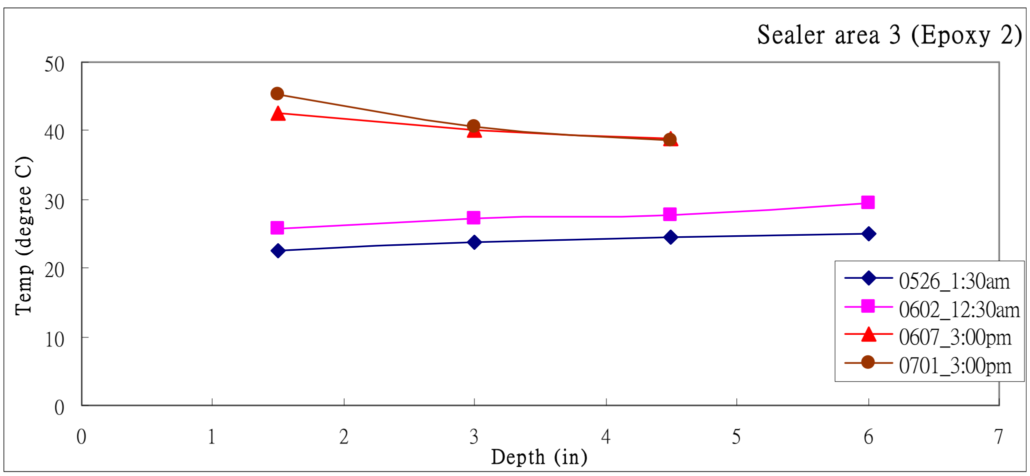

Fig 5.3 Comparison of the internal temperatures at daytime and nighttime (Epoxy 2)

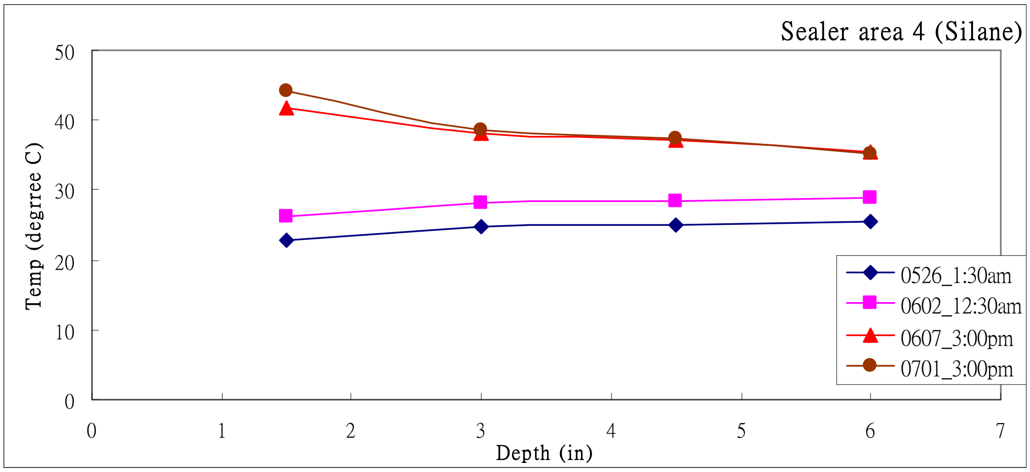

Fig 5.4 Comparison of the internal temperatures at daytime and nighttime (Silane)

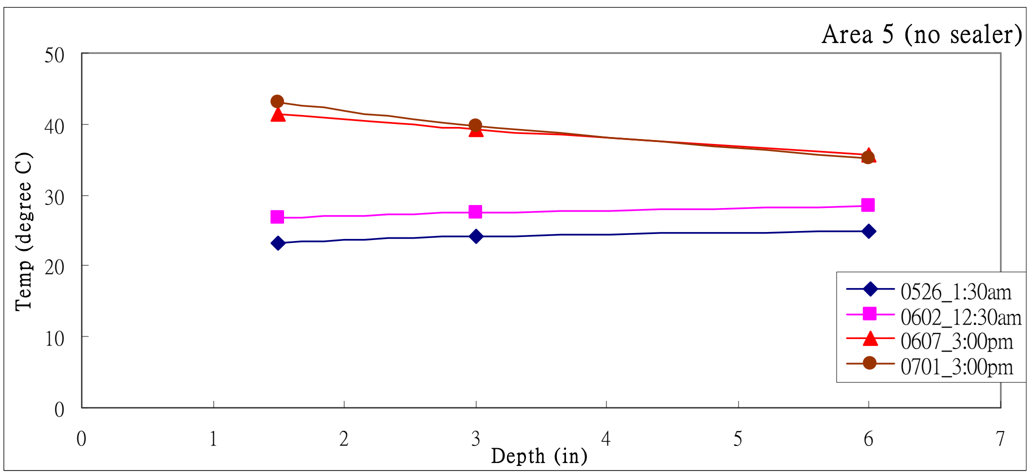

Fig 5.5 Comparison of the internal temperatures at daytime and nighttime (no sealer)

From Fig. 5.1 to Fig. 5.5, the only difference between the curves is the temperature variation near the surface. Between the depth of 1.5 in. and 3.0 in., there is a 5 to 8°C difference in the sealed areas (Sections 1 – 4) and just 2°C difference in unsealed area (see Fig. 5.5 for the testing section 5). This indicated that the sealers can slow down the heat conduction, but its effect is limited to the shallow surface. At deeper locations, such as 3 and 6 inches, there are no significant temperature differences among these five testing areas.

5.2. Comparisons for Hourly Readings in Five Testing Areas

Figs 5.6 - 5.10 show hourly readings for the five testing areas over a 24-hour period starting from 3:31 pm on 11/30/2010. Again, the temperature difference at different depths is important.

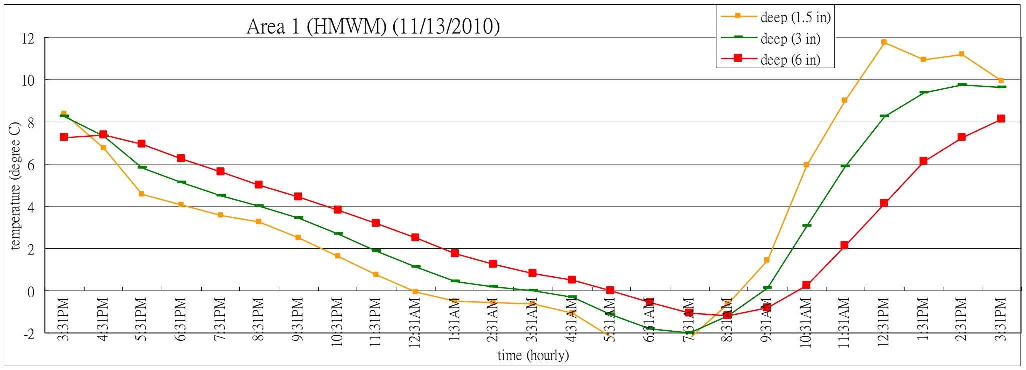

Fig 5.6 Comparison of temperature variations at different depths over 24 hrs. (HMWM)

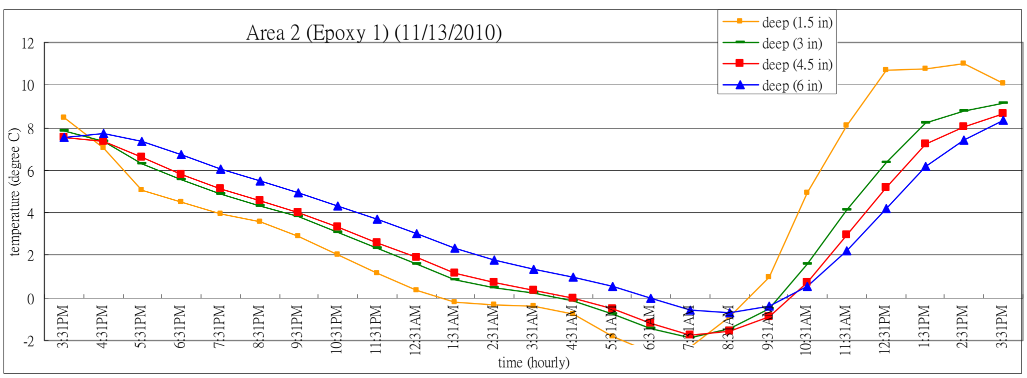

Fig 5.7 Comparison of temperature variations at different depths over 24 hrs. (Epoxy 1)

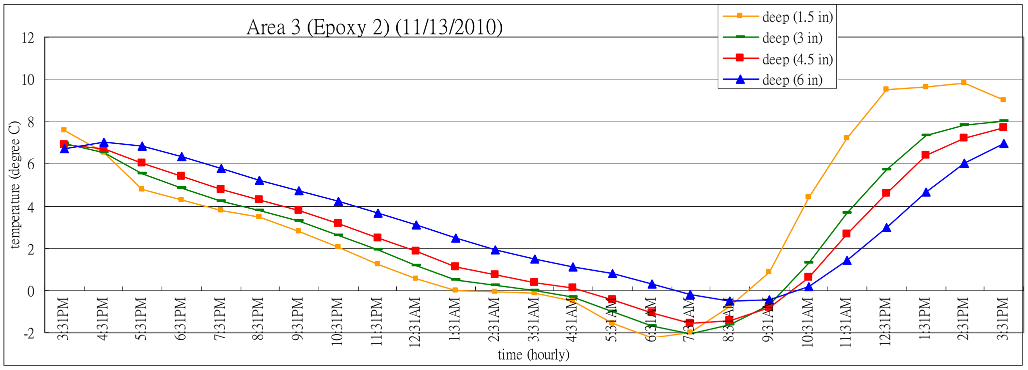

Fig 5.8 Comparison of temperature variations at different depths over 24 hrs. (Epoxy 2)

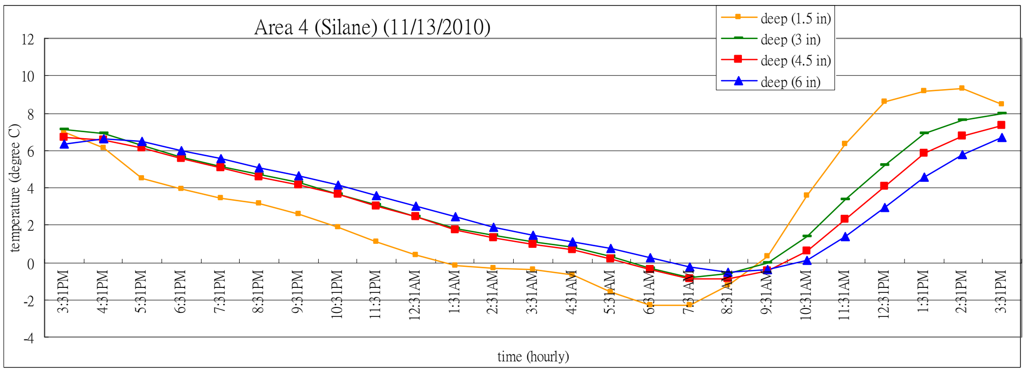

Fig 5.9 Comparison of temperature variations at different depths over 24 hrs. (Silane)

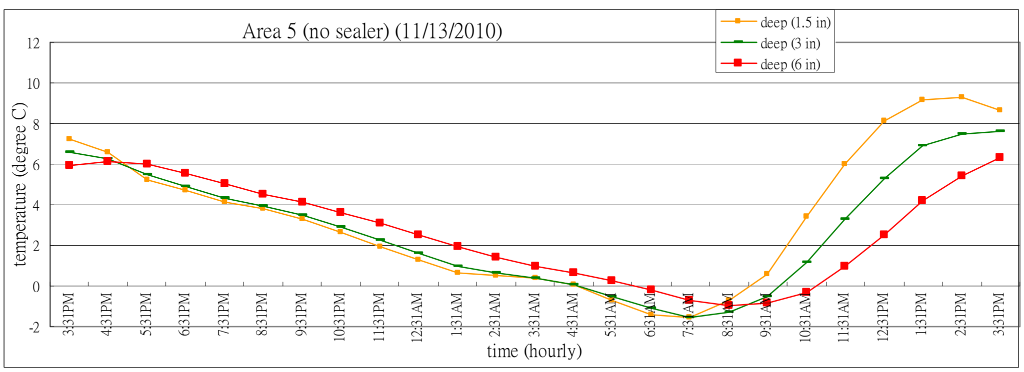

Fig 5.10 Comparison of temperature variations at different depths over 24 hrs. (no sealer)

From these five figures, we can observe that:

(1) During most of daytime, the surface temperature is higher than the inside temperature. Specifically, from 08:30 am to 4:30 pm, the temperature is higher at the surface.
(2) During most of nighttime, the surface temperature is lower than the inside, specifically, from 4:30pm-08:30 am. The reverse of the temperature distribution occurred at about 8:30 am during November, 2010.
(3) The maximum the difference between the surface and deep temperature during the daytime is about 8°C, which is higher than the nighttime difference of 3°C.
(4) As mentioned earlier, the sealers can slow down the thermal conduction process. This can be seen from Fig. 5.6 to Fig. 5.10. For example, during the daytime (on the right side of figures), the temperature difference in Fig. 5.10 (no sealer) is less than 6°C, while the difference is about 7-8°C in Fig. 5.6 (HMWM). The differential temperature over the depth of bridge deck is called temperature gradient. The temperature records indicated that sealers applied on concrete decks can generate a higher temperature gradient in the decks than that of unsealed decks.
(5) From the thermomechanical point of view, the larger the temperature gradient, the higher the thermal stress. High thermal stress may cause cracking in concrete structures. From above test data, the increase of temperature resulted from the sealers is about 2°C (3.6 °F). Taking the average coefficient of thermal expansion of concrete as 5.5 x 10^{-6} inch/inch/°F, the corresponding strain increment is about 20 microstrains, which is very small. Therefore, the increase of temperature gradient due to the sealers is very small, not enough to create any noticeable damage in the concrete.

5.3. Comparisons at Different Depths

Figs 5.11 - 5.14 show hourly readings recorded in the five areas at different depths over a 24-hour period, respectively. The observation is similar to Section 5.2.

(1) Daytime and shallow part (1.5 in. and 3.0 in.) ranking:
1(HMWM)>2(Epoxy1)>3(Epoxy2)>4(Silane)>5(no sealer).
(2) Nighttime: not big difference.

HMWM and Epoxy 1 generated larger temperature differences than the other two sealers. However, the differential temperature is very small, and does not cause any noticeable damage in the concrete. Furthermore, the lowest temperature in the concrete is about -2°C. The applied sealers do not alter the low temperature in the concrete significantly, and therefore, there is no risk for freeze/thaw damage due to the applied sealers.

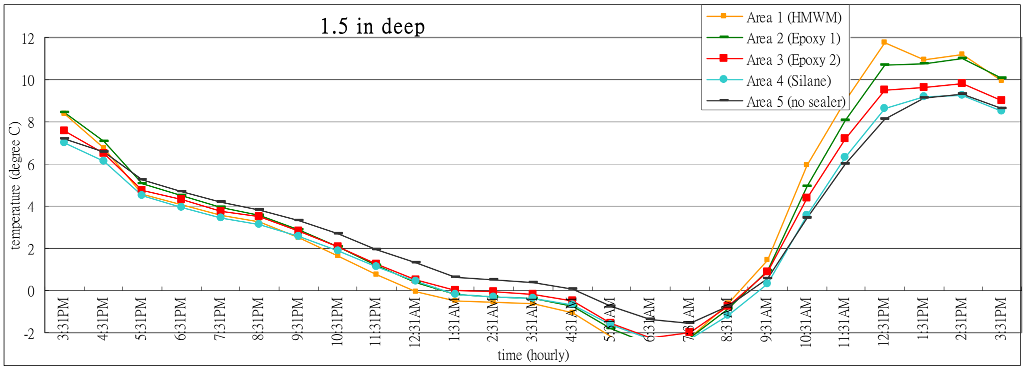

Fig 5.11 Comparison of different sealer areas at the depth of 1.5 inches

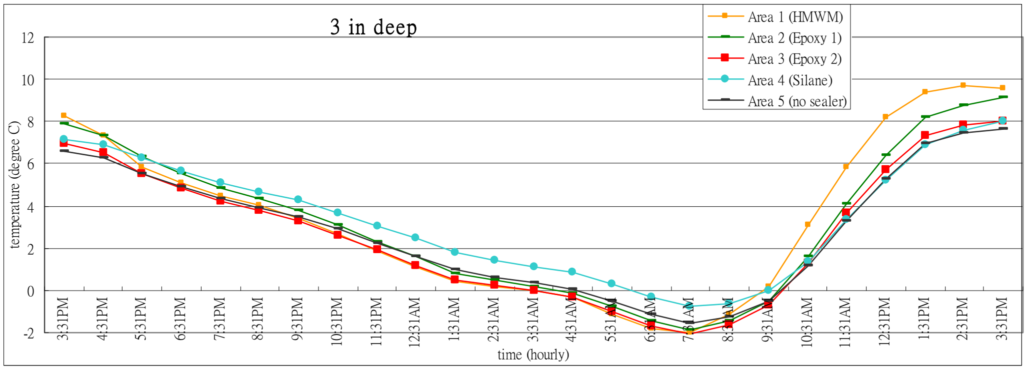

Fig 5.12 Comparison of different sealer areas at the depth of 3.0 inches

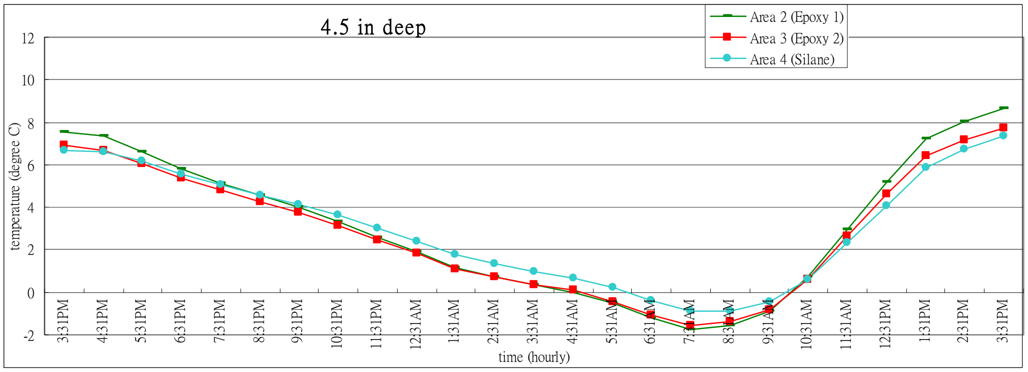

Fig 5.13 Comparison of different sealer areas at the depth of 4.5 inches

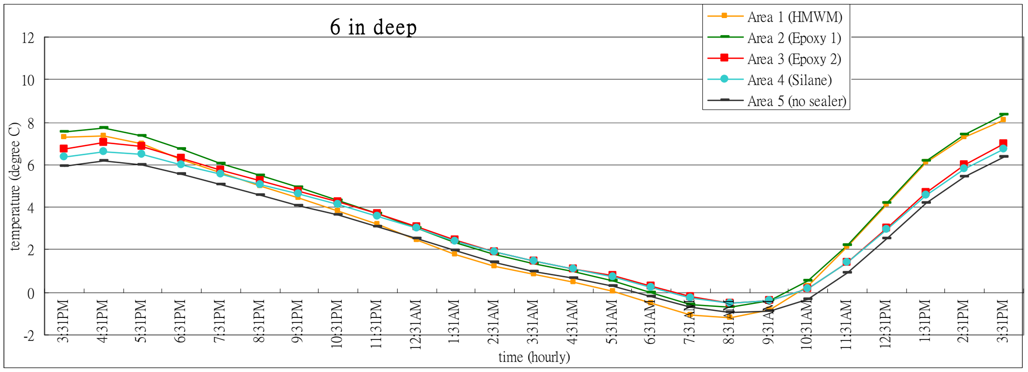

Fig 5.14 Comparison of different sealer areas at the depth of 6.0 inches

5.4. Comparisons of Bimonthly Readings

Figs 5.15 - 5.19 show bimonthly readings recorded from the five testing areas. All readings were taken at the same time of 5:00 pm in June 7, Aug. 7, Oct. 7, Dec. 7, 2010, and Feb. 12 2011. In order to compare the data, we rearranged the readings and summarized them in Fig. 20. One can observe from Fig. 20:

(1) The highest temperatures and lowest temperatures are in July and February.

(2) Near rebar location, the temperature varies between 3-40°C.

(3) The largest temperature variation is in the testing area 2 (Epoxy 1).

(4) In the summer, the order of temperature range is Silane < no sealer < Epoxy2 << HMWM < Epoxy1.

(5) In the winter, the order of temperature range is no sealer < Silane < Epoxy1 < Epoxy2 <<HMWM.

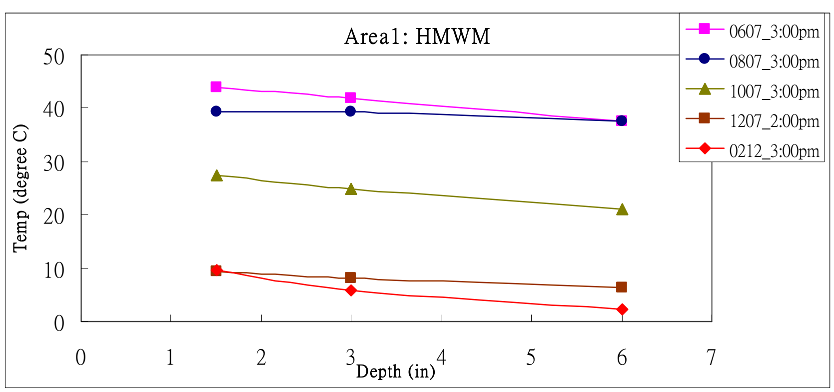

Fig 5.15 Comparison of bimonthly temperature profiles (HMWM)

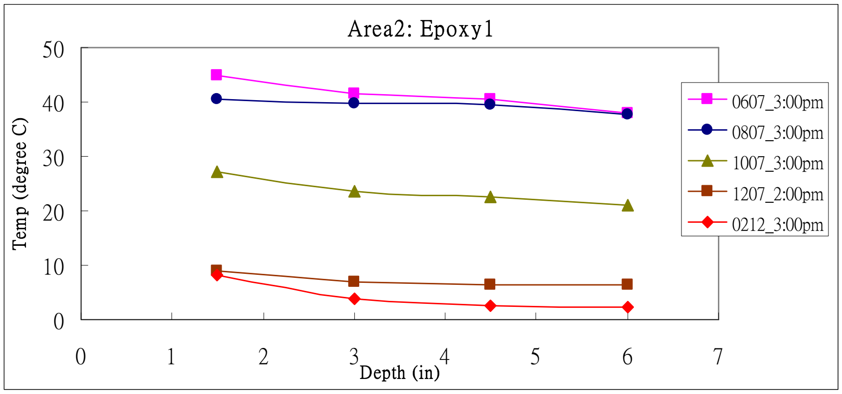

Fig 5.16 Comparison of bimonthly temperature profiles (Epoxy 1)

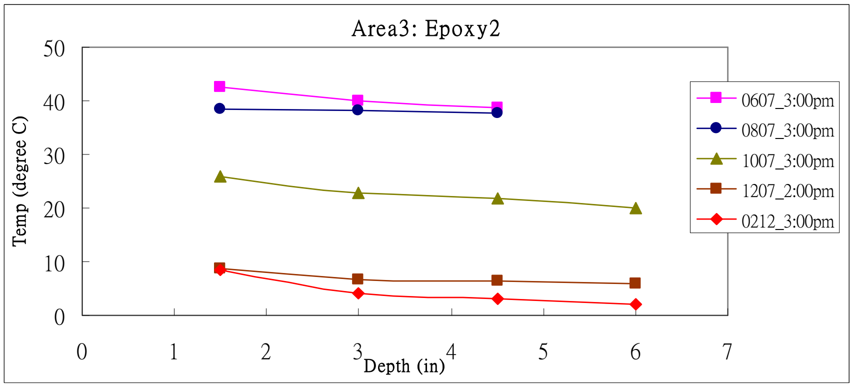

Fig 5.17 Comparison of bimonthly temperature profiles (Epoxy 2)

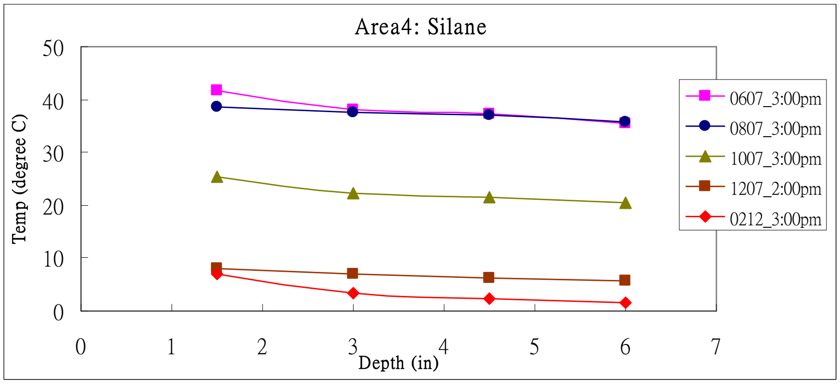

Fig 5.18 Comparison of bimonthly temperature profiles (Silane)

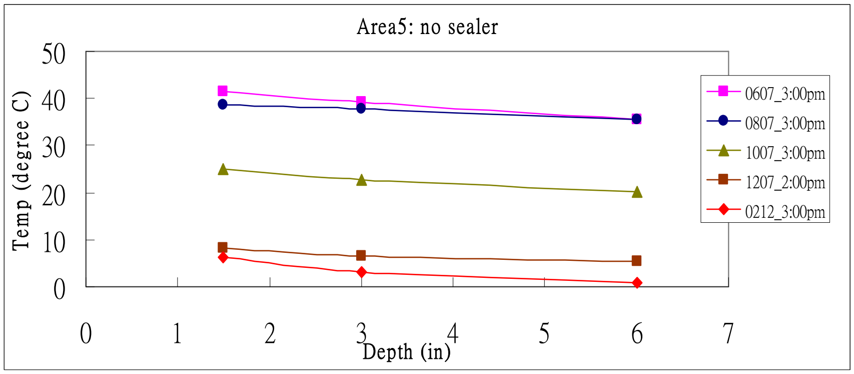

Fig 5.19 Comparison of bimonthly temperature profiles (no sealer)

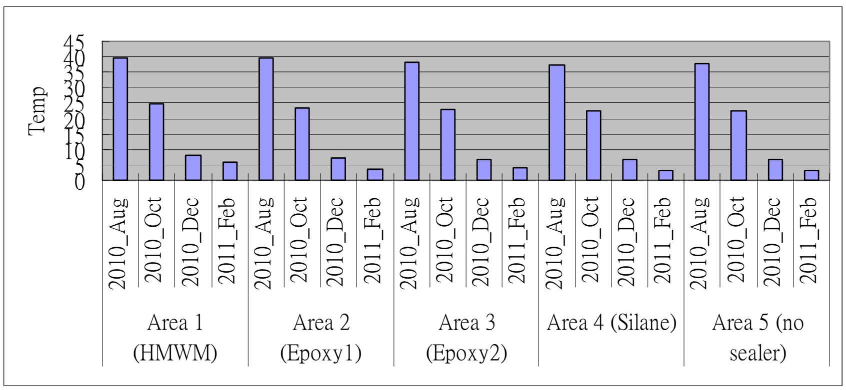

Fig 5.20 Summary of bimonthly temperature profiles

6. TEST RESULTS – MOISTURES

Internal moisture near rebar location plays an important role in the process of rebar corrosion. In this project, the internal moisture in concrete was measured by the pore relative humidity from the embedded integrated sensors described in Section 3.2. The recorded data were analyzed and compared in two different ways.

(1) The wetting and drying process in concrete.
(2) Comparisons of bimonthly readings.

6.1 The Wetting and Drying Process in Concrete

The internal moisture variation in the concrete deck was mainly due to a change in the surface environmental moisture condition, such as rain or snow. Therefore, we planned to observe the wetting and drying process of concrete decks after a rain, and examine the effect of sealers on the two processes. In Fig 6.1 - Fig 6.5, the concrete cores were taken on 05/26/2010. The readings from all five areas were about the same, in the range of 40% to 60%, except in the shallow part of area 5 (no sealer) where 70% of RH was recorded. Then, there was a rain event after 05/26/2010, and the internal relative humidity (RH) values increased sharply during this period in all five testing areas. The results show large increases in moisture level occurred at all depths including 6 inches, from about 50% up to above 80%. The variation of RH over time is very small, not like the large temperature variation shown in Fig. 5.11 to Fig. 5.14. Therefore, the RH variation over time is not plotted.

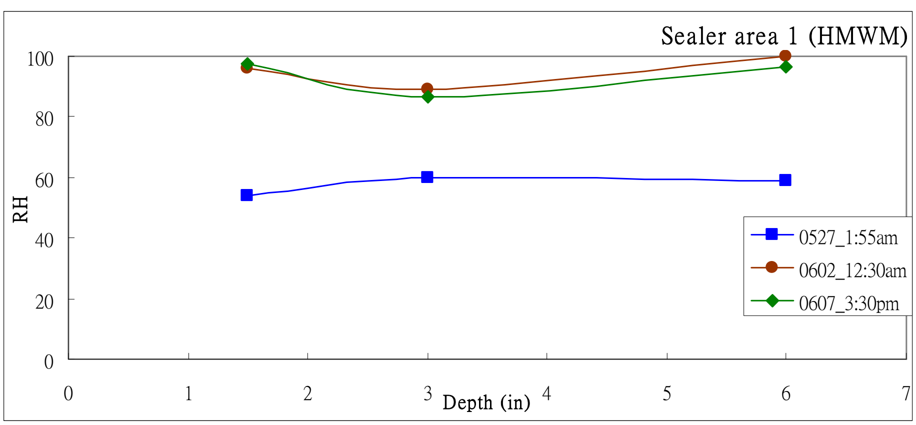

Fig 6.1 Variations of RH in concrete in the two-week period (HMWM)

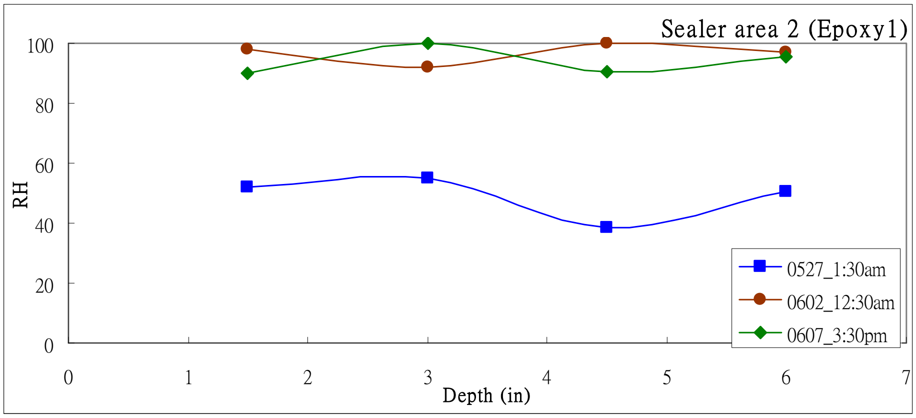

Fig 6.2 Variations of RH in concrete in the two-week period (Epoxy 1)

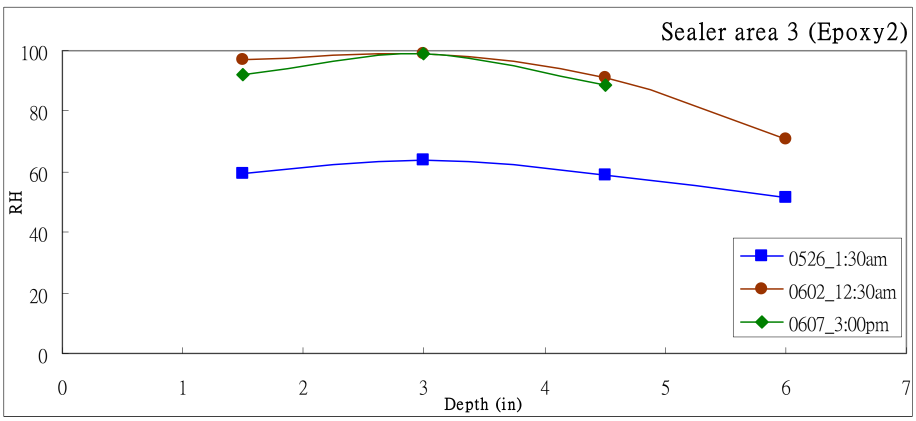

Fig 6.3 Variations of RH in concrete in the two-week period (Epoxy 2)

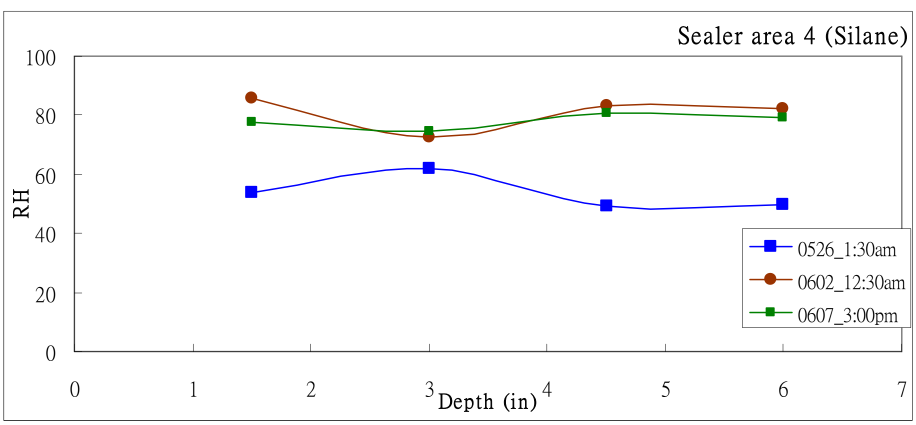

Fig 6.4 Variations of RH in concrete in the two-week period (Silane)

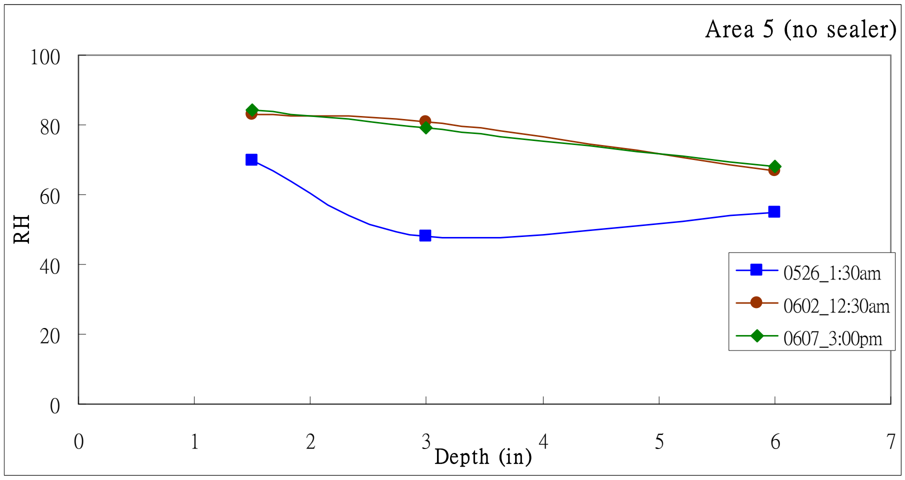

Fig 6.5 Variations of RH in concrete in the two-week period (no sealer)

The sealers were installed on 06/02/2010 after the pavement surface was dried up for several days. There was no rain from 06/02/2010 to 06/07/2010. As shown in the above figures, the variation of RH in all areas in this week is very small, which means that the drying process of the concrete is much slower than the wetting process. One week is not long enough to observe the drying process. The effect of sealers on the moisture diffusion in concrete needs to be observed over a longer monitoring period, therefore, moisture monitoring was continued for the next eight months.

6.2 Comparisons for Bimonthly Readings

This comparison is to see the long-term variation of moisture in concrete decks and the effect of sealers on the variation process. Fig. 6.6 through Fig 6.9 show the moisture variation in concrete decks with the top surface sealed by the four types of sealers, respectively. The moisture data in the unsealed testing section will be analyzed later.

One important observation is that, in each figure, moisture readings at 1.5 in., 3.0 in., and 4.5 in. from June 2010 were reduced by about the same amount during the eight-month period. In another word, the profiles at these three depths kept the same shapes and moved down in a parallel manner. This suggests that after the application of the four sealers, there is no new moisture penetration into the concrete decks from moisture precipitation (rain and snow) during the eight-month period. Thus, the reduction of moisture is not induced by the moisture diffusion, and it may be caused by the hydration reactions of cement. The moisture entrapped in concrete reacts with unhydrated cement particles, and the moisture consumed by the hydration reactions results in the drop of RH in concrete.

Therefore, the sealers are quite effective in blocking the moisture movement into and out of the concrete. The large variation of moisture level at 6.0 in. shown in the four figures is caused by a different mechanism, which is the diffusion (drying) of moisture from the bottom surface of the concrete decks. The bottom surface is exposed to the inside space of steel box girders, which is a confined space all the time and thus the RH value in the box girders can be considered as a constant, which is shown to be about 40% in Fig. 6.1 through 6.5 (the initial reading at 6 in. on 05/27/2010). From these figures, we can conclude that the sealers are effective to block moisture movement, but we cannot determine which sealer is more effective than others.

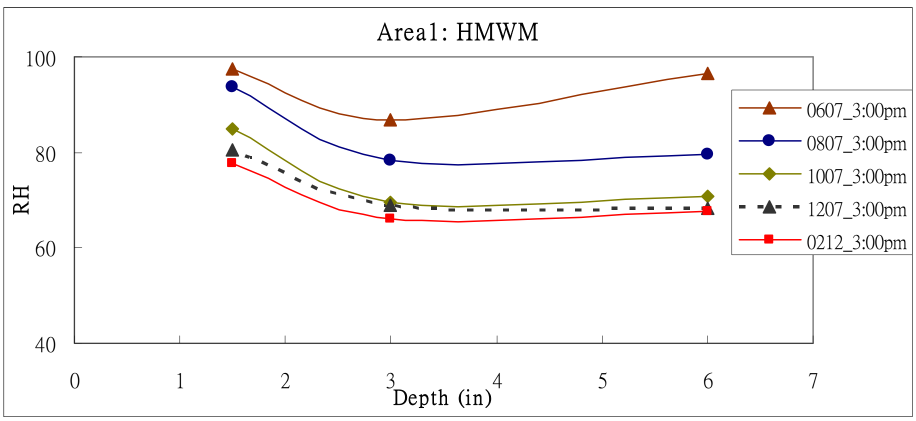

Fig 6.6 Comparisons for bimonthly readings (HMWM)

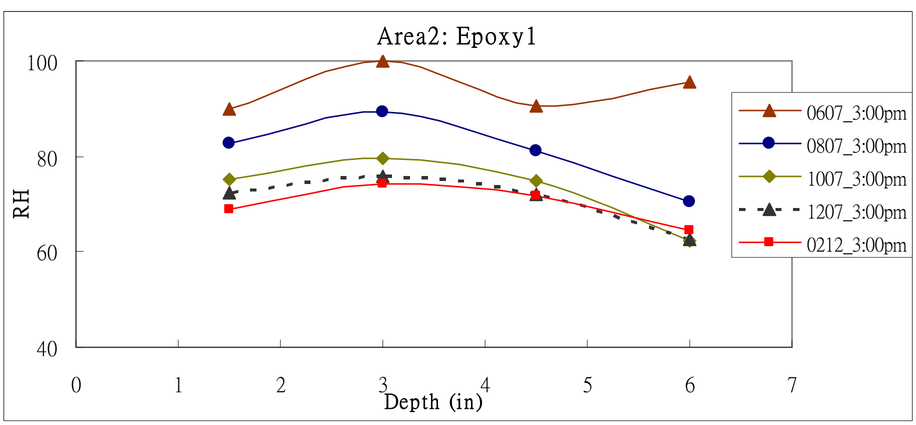

Fig 6.7 Comparisons for bimonthly readings (Epoxy 1)

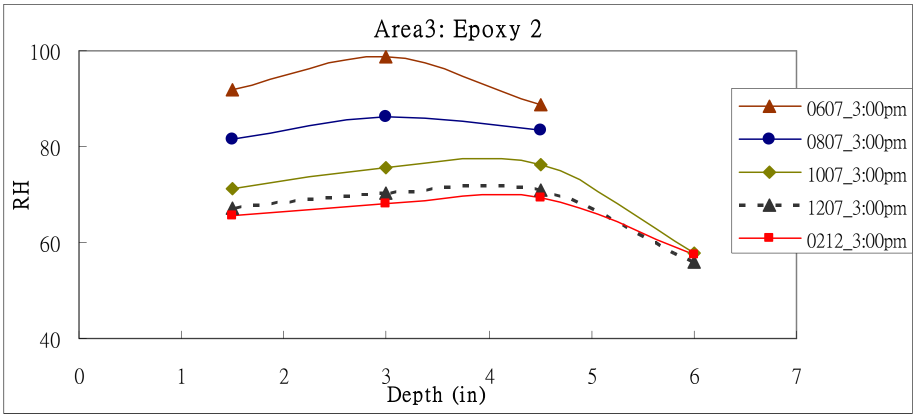

Fig 6.8 Comparisons for bimonthly readings (Epoxy 2)

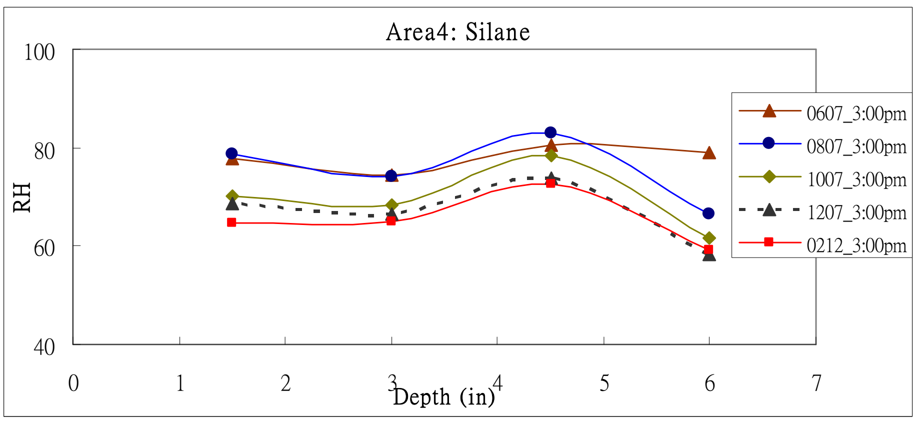

Fig 6.9 Comparisons for bimonthly readings (Silane)

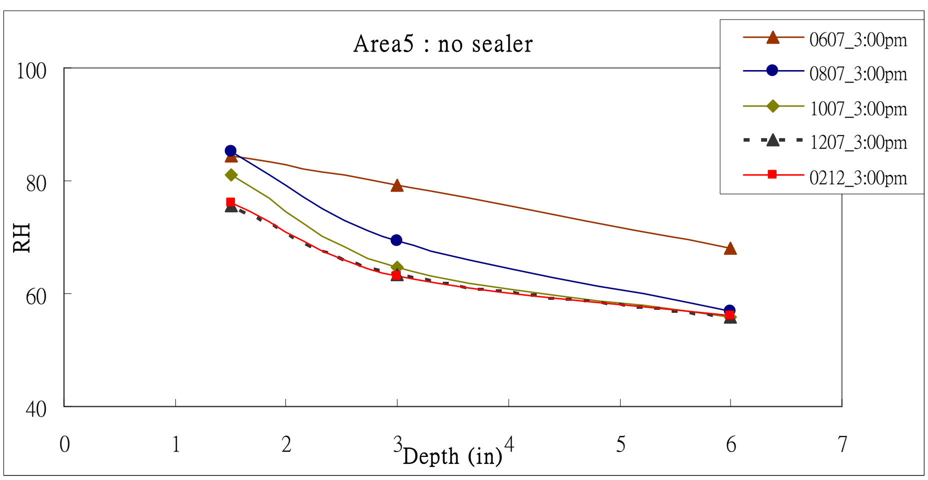

Fig 6.10 Comparisons for bimonthly readings (no sealer)

Fig. 6.10 shows the moisture profile in the unsealed testing section. The curves exhibit typical moisture profiles due to moisture diffusion in concrete. The boundary condition at the top surface is the environmental moisture variation. As explained earlier, the moisture level on the top surface is very high when there is a precipitation. The boundary condition at the bottom surface inside the steel box girder is a constant RH value (about 40%). The moisture distribution in between looks like those curves shown in Fig. 6.10: higher RH on the left (toward the top surface) and lower RH on the right (toward the bottom surface). The variation of profile depends on the amount of precipitation of the year. At the depth of rebar, about 2 in., the steady state moisture levels are about 70% to 85% in the deck, which is high enough to start the steel corrosion process if all other necessary conditions are available, such as high chloride and oxygen concentrations and low pH value in pore solution (Suwito and Xi 2008).

7. TEST RESULTS - CHLORIDE CONCENTRATIONS

Among the four parameters we used to monitor the performance of the sealers (skid resistance, temperature distribution, moisture profile, and chloride concentration), chloride concentration in concrete is the most important one, because the main purpose of the sealers is to block the chloride penetration into concrete decks. In this project, concrete cores were taken from bridge decks four times as shown in Table 3.3. The chloride profiles obtained from the concrete decks were analyzed and compared in two different ways:

(1) Comparisons of each testing area at different time periods.
(2) Comparisons of each time period for different testing areas.

7.1 Comparisons of Each Testing Area at Different Time Periods

Fig 7.1 to Fig. 7.5 show the chloride concentration profiles obtained in each testing area at different time periods in terms of percent chloride by weight of cement. From these figures we can see the variation of chloride concentration over the 18-month period. This period can be divided into two sub-periods. One includes the first two measurements which were obtained before the application of the sealers 11/04/2009 to 05/26/2010; and the other includes the last two measurements after the application of the sealers 11/16/2010 to 05/04/2011.

For the first sub-period before the application of sealers, a general trend can be observed. Basically, the chloride concentrations in all areas increased, which is due to the deicing salts applied on the deck surface and no sealers applied on the decks. There is no curve in Fig. 7.5 for 11/04/2009 for the deck not covered by any sealer (testing section 5). The curve in Fig. 7.4 can be used in Fig. 7.5 because the testing section 4 is adjacent to the section 5. In Fig. 7.4, there is no noticeable increase of chloride concentration from 11/04/2009 to 05/26/2010, but, there is no significant decrease of the chloride concentration. So, this general trend can be considered to be valid for all five sections, which indicated that the chloride from deicers penetrated the deck in the winter and increased the chloride concentration levels in all sections and at all depths.

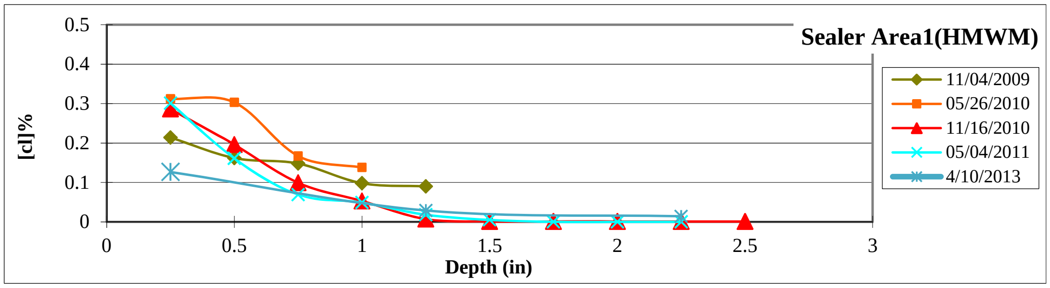

Fig 7.1 Chloride concentrations (HMWM)

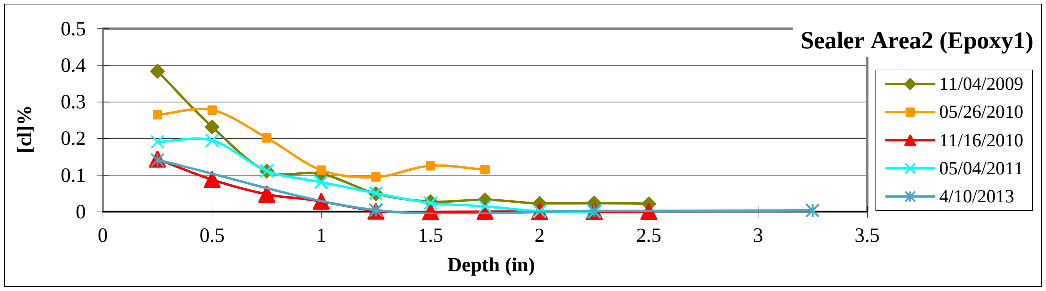

Fig 7.2 Chloride concentration (Epoxy 1)

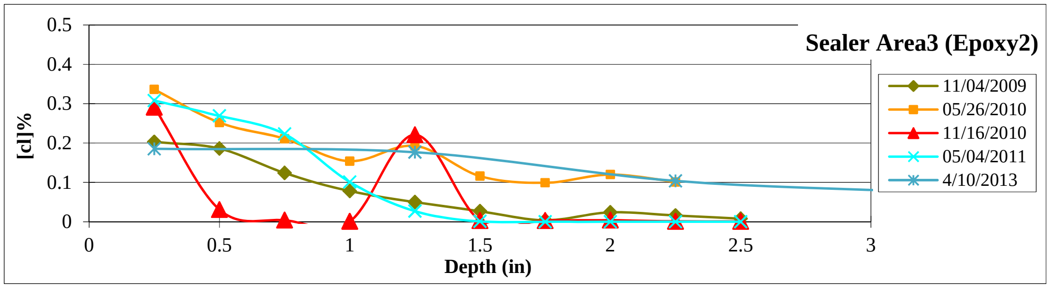

Fig 7.3 Chloride concentration (Epoxy 2)

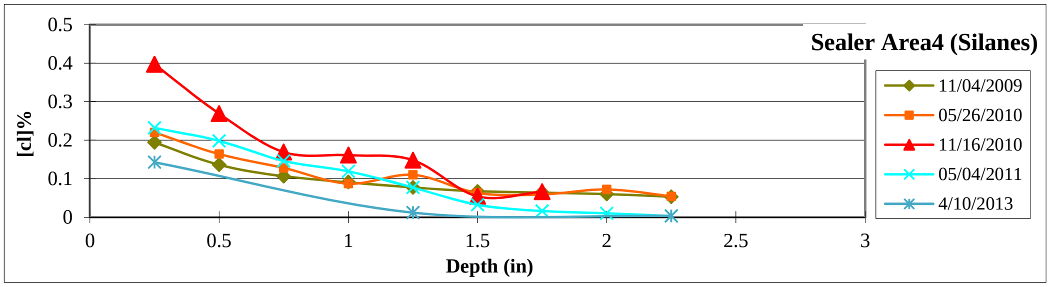

Fig 7.4 Chloride concentration (Silane)

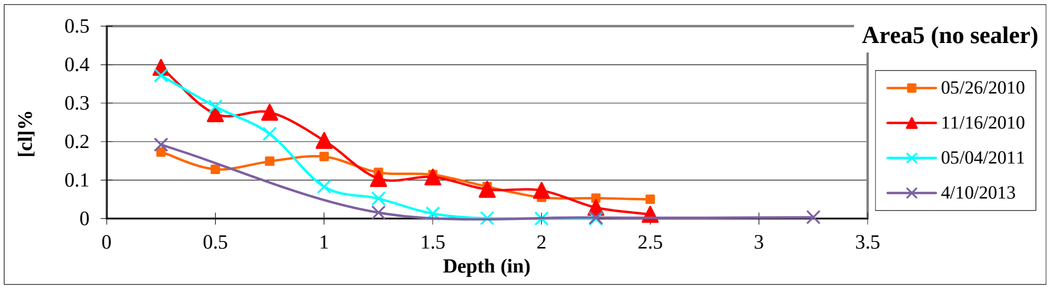

Fig 7.5 Chloride concentration (no sealer)

For the second sub-period, because of the application of the four sealers, the concentration profiles in the five testing sections varied differently. Figs. 7.1, 7.2, and 7.3 show a similar trend: the concentration profiles decreased after the application of the three sealers, namely HMWM, Epoxy 1, and Epoxy 2. This means that the three sealers effectively blocked further penetration of chloride ions from the top surface.

The decrease of the chloride content may be due to the fact that the entrapped chloride (the chloride already in concrete) may react with some components of cement paste and to become chemically combined chloride, resulting in the decrease of the concentration profiles. For instance, Midgley and Illston (1984) found that chloride ions react with some of the hydration products, in particular the tricalcium aluminate and the ferrite phase ($4CaO{\cdot}Al_2\ O_3\ {\cdot}FeO$), and combine to form Friedel's salt ($3CaO{\cdot}Al_2O_3\ {\cdot}CaCl_2 \cdot 10H_2O$), which is insoluble in water (Xi and Bazant 1999). In short, the mechanism responsible to the decrease of chloride content is not clearly understood, and a more detailed study is needed.

It is very clear that the concentration profiles in the testing section 5 without sealer increased significantly in the shallow part of the concrete deck during the second sub-period. Fig. 7.4 shows that the two concentration profiles obtained after the application of the silane did not decease, and they are similar to the first two curves. This means that the silane blocked the further penetration of chloride ions to a certain extent, but not as effective as the other three sealers.

7.2 Comparisons of Each Time Period for Different Testing Areas

In Figs 7.6 and 7.7, the first (11/04/2009) and second (05/26/2010) measurements are represented. One can see that the test results are very consistent for the five testing areas before applying sealers.

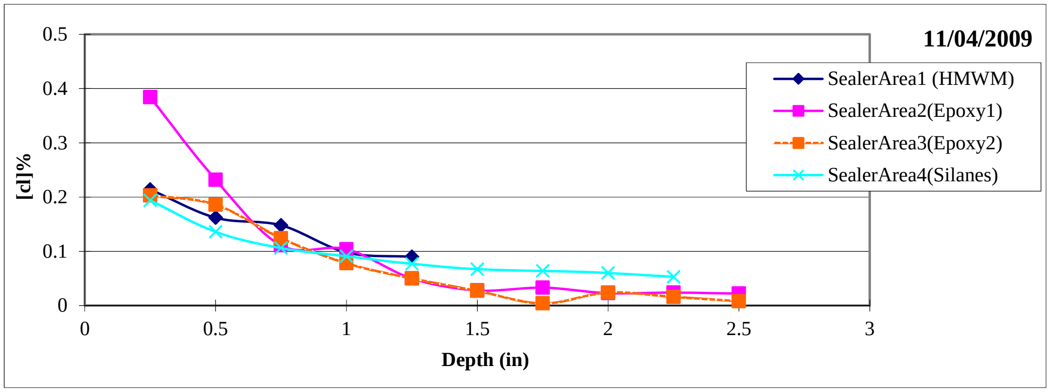

Fig 7.6 Chloride concentrations (11/04/2009)

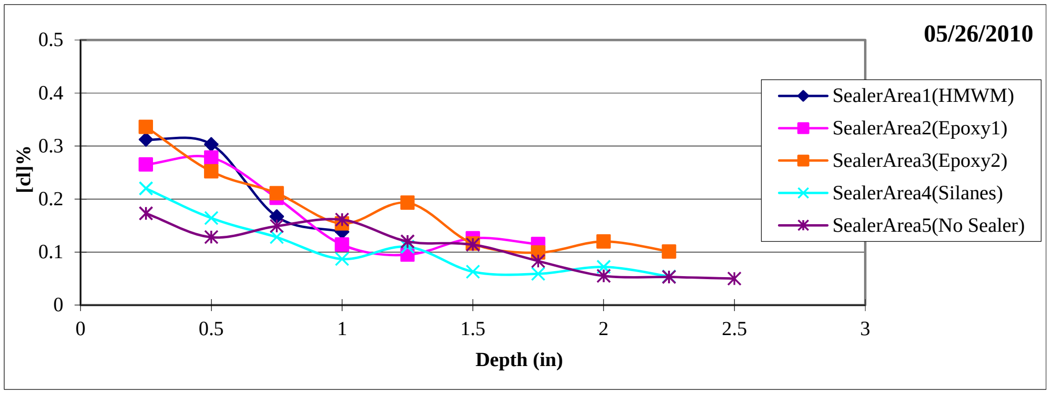

Fig 7.7 Chloride concentrations (05/26/2010)

Comparing the four sealer products during the period 05/26/2010 and 11/16/2010 shown in Fig. 7.8, the concentration profiles in Area 1 through Area 3 are much lower than those of Areas 4 and 5, which indicated that HMWM, Epoxy 1, and Epoxy 2 are better sealers in terms of slowing down the chloride ion penetration than the silane.

During the period between 11/16/2010 and 05/04/2011 (winter season), the curves in Fig. 7.9 show a different trend than that in Fig. 7.8. For example, the curve of Epoxy 2 is almost the same as that of unsealed deck, which means that Epoxy 2 is not effective anymore for blocking the chloride. This could be due to the deterioration of the sealer from traffic loading and from environmental factors such as thermal effect. Similarly, after one year operation on the highway, Epoxy 1 is not as effective as a year ago. Fig. 7.8 shows that HMWM is still quite effective after one year, and thus HMWM is more durable than the other three sealers.

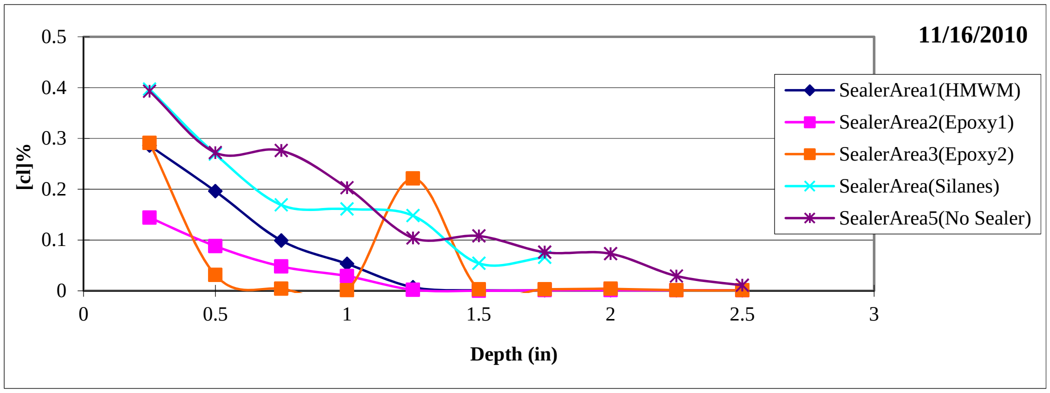

Fig 7.8 Chloride concentrations (11/16/2010)

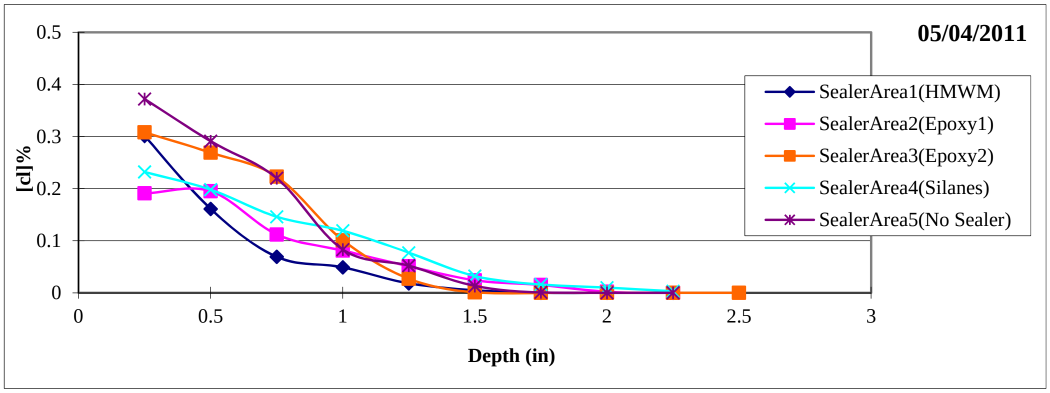

Fig 7.9 Chloride concentrations (05/04/2011)

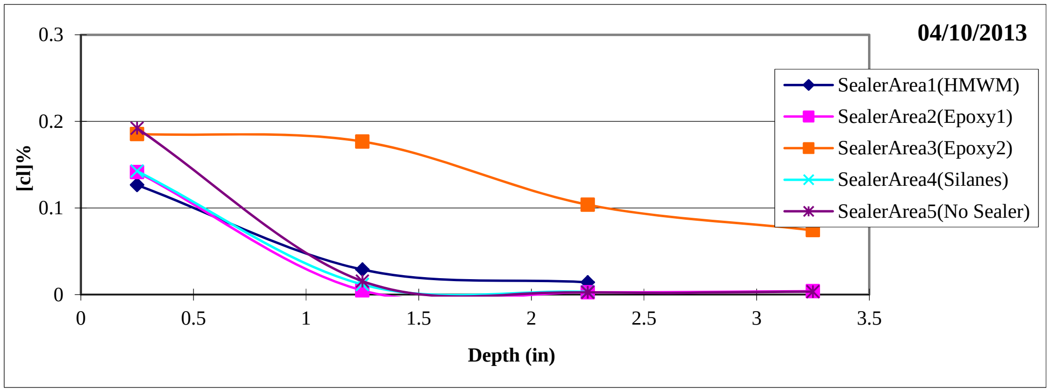

Fig 7.10 Chloride concentrations (4/10/2013)

In April 3013, after 41 months from the installation of the sealers, a field trip was arranged, and concrete cores were taken from the testing areas and chloride concentrations were analyzed. Figure 7.10 shows the results of the five test areas.

The same results were also plotted in Figures 7.1 – 7.5. Comparing the curves in Figures 7.1 – 7.5, it is clear that there is noticeable reduction in all chloride concentration profiles, except area 3. The specimen collected from Sealer Area 3 in 2013 had a crack in the core, which is why the profile has a high chloride concentration throughout the profile. After more than three years and five months, all other sealers exhibit superior protection in comparison to the section with no sealer.

8. CONCLUSIONS

An extensive literature review was conducted on the features and performance of different chemical sealers. Based on the literature review, four sealer products, HMWM, two epoxies, and a silane were selected for evaluation of their skid resistance and their ability to block or slow down the moisture and chloride ion penetration into concrete bridge decks. The four sealers are:

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.

Bridge structure E-17-QM was selected for the field study of the performance of the four sealers. The four sealers were installed on the top deck surface of Bridge E-17-QM by professional contractors on 06/02/2010.

Skid resistance, temperature variation, moisture fluctuation, and chloride concentration profiles in concrete were selected as the four experimental parameters for evaluating the performance of the four sealers. 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 for chloride concentration profiles. The British Pendulum Tester was used to measure the skid resistance of concrete surface with and without sealers.

From the analysis and comparisons of the test data, the performance of four sealers can be ranked in terms of the four testing parameters and the cost.

(1) Skid resistance

Right after the application of sealers, the sealers reduced skid resistance compared to the unsealed deck. After one year, most of sealers have lower skid resistance than the bare deck, except the Silane. The Silane was very close to the bare deck right after the installation and better than the bare deck after one year.

(2) Internal temperature

The sealers can slow down the thermal conduction process in concrete decks. The temperature records indicated that all sealers applied on concrete decks generated higher temperature gradients in the decks than that of unsealed decks. HMWM and Epoxy 1 generated larger temperature differences than the other two sealers. However, the increase of temperature gradient due to all sealers is very small, not enough to create any damage in the concrete.

(3) Internal relative humidity

The recorded relative humidity profiles in all test sections indicated that after the application of the four sealers, there is no new moisture penetration into the concrete decks from moisture precipitation (rain and snow) during the eight-month period. Therefore, the sealers are effective to block moisture movement into and out of the concrete decks. There were reductions of moisture in the concrete after the installation of sealers which was considered not induced by the moisture diffusion, but by the hydration reactions of cement. The moisture entrapped in concrete reacts with unhydrated cement particles, and the moisture consumed by the hydration reactions results in the drop of RH in concrete.

(4) Chloride penetration

HMWM, Epoxy 1, and Epoxy 2 can effectively block the penetration of chloride ions from the sealed surface. There is a decrease in the chloride concentration in the sealed concrete, which deserves a more detailed study. The silane can block the penetration of chloride ions to a certain extent, but not as effective as the other three sealers. After one-year operation on the highway, Epoxy 1 and Epoxy 2 are not as effective as a year ago. HMWM was still effective after one year, and thus HMWM is more durable than the other three sealers. After 3.5 years, all sealers are still providing a protective barrier for the deck; and the HMWM sealer is preforming the best.

(5) Cost

The cost of the HMWM, Epoxy 1, Epoxy 2 and the Silane sealers per square yard installed are approximately \$19.80, \$13.50, \$15.75, and \$13.50, respectively.

These prices are based on a medium to large sized project of covering an area greater than 20,000 square feet. Given the relative performances of the four sealers, Epoxy 1 is the most cost-effective sealer. The HMWM performed the best among the four sealer products, however; is the most expensive one. Based on the 3.5 year chloride data, the HMWM sealer provides a more durable system which may make up for the increased installation price.

9. RECOMMENDATIONS AND IMPLEMENTATION PLAN

Final Recommendations

All sealers tested in the project have no adverse thermal effect and they are effective in blocking moisture penetration. Silane provided a better skid resistance. HMWM, Epoxy 1, and Epoxy 2 can effectively block the penetration of chloride ions, and HMWM is more durable to resist chloride penetration. HMWM achieved the overall best performance among the four sealers. Based on overall price and performance, Epoxy 1 is the most cost-effective product for providing a short-term protective bridge deck sealing system, although its skid resistance is lower than the other sealers.

Without further long-term data, we recommend the use of sealers as a viable short-term protection system. If CDOT chooses to use a long-term bridge deck sealing system, we recommend the use of HMWM over other sealers.

Implementation Plan

Based on the conclusions of this study, it is the belief of the authors that sealer systems are ready for full-scale implementation. Eligible bridges decks should be selected based on the assessment of percent deck deterioration, estimated time to corrosion, deck surface condition, and concrete quality. The need for a sealer system on a bridge deck should be selected based on the above characterization methods.

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