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EVALUATION OF DIFFERENT TYPES OF WATERPROOFING MEMBRANES (ASPHALTIC AND NON-ASPHALTIC) AS COST EFFECTIVE BRIDGE DECK BARRIERS IN REDUCING CORROSIVE CHLORIDE EFFECTS

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16. Abstract

In the past several decades, reinforced concrete structures have deteriorated similarly by chemical attack, especially chloride attack. For highway bridges, this phenomenon becomes more severe since bridges are exposed to extreme environmental conditions, such as snow and ice. In an effort to better protect the bridge decks and reduce maintenance costs, State Departments of Transportation (DOT) apply waterproofing membranes (WPMs) to the bridge decks. The use of WPMs was investigated by the Colorado Department of Transportation (CDOT) to analyze the performance of four products as an effective protection system: Polyguard, Protecto Wrap, Bridge Preservation™, and Sikadur. Each WPM was installed on Bridge F-17-YB and monitored for approximately two years. The performance of each WPM was evaluated for bond strength, resistance to chloride intrusion, freeze-thaw resistance, and cost analysis. Pull-off testing showed that all the WPMs have higher bond-strength than the control section, especially the constructed-in-place WPMs. Chloride penetration tests included testing the chloride concentration profiles of specimens extracted from the decks and from ponded specimens. The short-term results indicate that all four WPM systems can effectively control the concentration of moisture, but not the chloride concentration. Among the materials tested, the Bridge Preservation™ product provided the best performance. At last, a simplified model has been developed to predict the long-term performance of WPMs.

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Executive Summary

Chemical attack from chlorides, exposure to severe environmental conditions, and wearing from direct traffic loading cause highway bridge decks to deteriorate the fastest among all the structural components of a highway bridge. To reduce maintenance costs, topical protection systems - such as waterproofing membranes (WPMs) - have been applied to bridge decks since the 1950's. The purpose of the WPMs is to not only prevent the intrusion of moisture, but also block the concentration of chloride ions into the deck. The objective of this study is to monitor and evaluate the ability of four different types of WPM products to prevent chloride ingress while increasing durability as a protection system for highway bridge decks.

The four WPM products selected for evaluation in this project were:

(1) Polyguard

(2) Protecto Wrap

(3) Bridge Preservation™ Products

(4) Sikadur

The four WPMs were installed on Bridge F-17-YB on Arapahoe Road over Cherry Creek in the summer of 2015. Each WPM was installed by its respective manufacturer. There was another section without WPM, which was used as control section for comparison. The performance of each WPM was evaluated based on the results from four experimental tests. These tests included: pull-off test, chloride profile test, ponding test, and freeze-thaw test.

The performance of each WPM was ranked based on the analysis and comparisons of the test data.

Pull-off Test

The pull-off test is to obtain the bond strength between the WPMs and the concrete. The bond strength of the WPMs declined around 14.7% per year. Comparatively, the Polyguard and Protecto Wrap showed similar results with the control section. Bridge Preservation™ was better than those two. Sikadur showed the best bond performance with much higher bond strength than others.

Chloride Profile Test

After the application of the WPMs, the chloride concentration levels in the decks decreased from the bridge deck to the deep part. The Bridge Preservation™ showed the best performance compared with the other WPM products. However, it should be noted that all the other WPMs showed worse results when compared with the control section; which means the Sikadur, Protecto Wrap, and Polyguard are not effective to control the concentration of chloride ions, especially the two preformed WPMs.

Chloride Penetration through Ponding test

The chloride profiles in the concrete after ponding test indicated that the chlorides were able to penetrate through all of the WPMs. In this case, the moisture profile proved that all the WPMs can effectively control the intrusion of moisture; however, testing the chloride penetration resistance showed that all the WPMs are not effective compared with the control section.

Freeze Thaw Resistance

The Bridge Preservation™ proved to be the most resistant to freezing and thawing action; while the Polyguard showed the worst performance.

Given the test results of this project, all of the WPMs provided a protective layer on the bridge deck. When broken down into effectiveness of preventing chloride penetration, the Bridge Preservation™ performed the best among the WPMs evaluated; and when compared based on physical performance (bond strength), the Sikadur and Bridge Preservation™ performed the best. The performance difference among different WPMs are not very significant. Except for Bridge Preservation™, the other WPMs did not show effective improvement on preventing chloride ion penetration into concrete.

Table of Contents

List of Figures

List of Tables

CHAPTER 1 OVERVIEW

1.1 Background

In the past several decades, reinforced concrete structures have deteriorated similarly by chemical attack, especially chloride attack. For highway bridges, this phenomenon becomes more severe since bridges are exposed to extreme environmental conditions, such as snow and ice. In addition, the chloride diffuses faster from the bridge deck to all the structural components when the bridge deck suffers from heavy traffic loading; since the heavy cyclic loading aggressively enlarges the cracks that allow seepage of chlorides into the concrete.

According to the data collected, there are approximately 614,387 bridges in the U.S. (144,610 were specifically on the national highway system). Around 56,007 bridges are either functionally obsolete or structurally deficient. In Colorado, the proportion of structural deficient bridges in the state is very low compared to national conditions (only 5.72%). There are total 8,682 bridges in Colorado, of which 497 of them were structurally deficient (NBI 2016). However, the chloride diffusion problem, which will cause severe detrimental threat to the bridges and finally lead to irreversible damage is still dangerous for the reinforced concrete structures. Therefore, more attention must be paid on how to avoid and prevent the damage of the bridge from chloride diffusion.

Due to environmental conditions all over the country, approximately 70% of the U.S. roadways will receive at least 5 inches of snowfall every year. In order to avoid the unnecessary traffic accidents and predictable business productivity loss, the snow and following ice have to be cleared. This process counts on the use of chemical products, such as deicing salts. According to data starting from 1960, the U.S. uses around 15-20 million tons of deicer every year. Different types of deicing salts have been used in field work, such as Sodium Chloride (NaCl), Calcium Chloride ($CaCl_2$), Potassium Chloride (KCl), Magnesium Chloride ($MgCl_2$), Potassium Acetate (CH_3COOK), and Calcium Magnesium Acetate (CMA). The most common one used all over the world is Sodium Chloride, which can be used down to temperatures of -6° F. For some particular areas with extremely cold weather, the Magnesium Chloride and Calcium Chloride can be used as the deicer with the temperature lower than -6° F (Houska 2007).

In order to protect bridge decks from chloride intrusion and reduce potential maintenance costs in the future, the Colorado Department of Transportation (CDOT) decided to investigate potential protection applications. Three types of protection options were discussed: sealers on bridge decks, thin bonded overlays, and waterproof membranes. Sealers installed on bridge decks were investigated in 2010. The research on thin bonded overlays was done in 2015 (Gallaher and Xi 2015). Three different types of thin bonded overlays were studied and compared with the control panel in order to prove effectiveness. In that report, another type of protection strategy was considered: *waterproof membrane*. The selection of waterproof membrane depends on environmental conditions, labor costs, job size, possible material use, existing deck condition, and the length of time the bridge can be closed for work.

1.2 Objectives of the Study

In order to improve long-term performance of concrete bridge decks, waterproofing membranes (WPMs), chemical sealers, and thin bonded overlays are often applied on the top concrete surface to protect the concrete bridge deck. In general, these topical protection systems are developed to reduce the penetration of moisture and chloride ions from deicing salts and thereby prevent the corrosion of reinforcing steel embedded in the bridge decks. Under different service conditions, the performance of the topical protection systems varies. The use of WPMs has been the most popular method for providing proper protection against chloride intrusion into bridge decks. However, major concerns arise regarding the longevity of this system and its long term effectiveness against chloride intrusion and effectiveness as a corrosion inhibitor. Some of these issues include maintaining the required membrane thickness, the optimal time when this membrane should be applied after deck placement, the effect of construction joints or seems, damage due to milling the existing overlay, the minimum or optimal thickness of asphalt required to protect the membrane, and the freeze thaw damage incurred due to the presence of blisters after some time in service.

Until now, there has been no systematic research conducted in Colorado regarding the performance evaluation of waterproof membranes. The main goal of this project is to evaluate the behavior and cost effectiveness of the waterproof membranes applied on reinforced concrete bridge decks under service loads including traffic, freeze-thaw, and wet/dry exposure. This research project has three specific objectives:

(1) To determine the ability of various waterproof membranes to stop or slow down the intrusion of chloride from deicers into concrete bridge decks. The effectiveness of each WPM will be compared with the control section with no WPM.

(2) To build a chloride penetration prediction model to assist CDOT to establish clear guidelines regarding constructability of such membranes as a means for protecting bridge decks to attain a 75-year service life.

(3) To run the cost analysis which will be useful to compare the cost of each WPM and also compare with thin bonded overlays.

The results of the research project will provide necessary information for CDOT to revise the current standard specification, and to identify the optimal products to be used as an effective membrane system on concrete bridge decks.

1.3 Test Bridge Description

The bridge selected to conduct this experiment is on East Arapahoe Road approaching CO Highway 83. The bridge is located in the north area of Centennial, CO. The latitude and longitude of the bridge are 39°35’41.8” and 104°48’45”. Constructed in 1959, F-17-YB is a bridge with 352-foot-length, and 58-foot-width. The deck area is around 36,661 ft^2. After the renewal in 2013, the bridge became longer and larger with 752-foot-length, and 128-foot-width. The structure type of this bridge is made of concrete, and the surface is bituminous. In vertical direction, totally five piers were constructed between the two abutments. From left to the right, the clear distance between the first three piers is 135’. The clear distance is 120’ between the last two piers. In horizontal direction, there are three lanes on each driving direction. The width for each lane is 12’ . The distance between outer lane and shoulder is 6’. There is a sidewalk on each side of the bridge which is 8’3” wide.

CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

In 2013, the American Society of Civil Engineers (ASCE) gave an evaluation for the nation's infrastructure. The U.S. construction only obtained a C+ rating (ASCE 2013). The average age of all of the bridges in U.S. was 42 years. In addition, more than one in nine bridges was defined as structurally deficient. According to another report from FHWA, there was a huge annual direct cost due to corrosion issues, which can be estimated at $137.9 billion (3.1% of 1998 U.S. GDP), which includes $29.7 billion (0.67% of 1998 U.S. GDP) directly from the transportation industry. More specifically, the annual direct cost of highway bridges was approximately $8.3 billion which accounts for 6.02% the annual cost of corrosion (FHWA 2001). Their analysis can be further broken down into four parts:

- $3.8 billion (2.76%) to replace deficient bridges over the next ten years,
- $2 billion (1.45%) maintenance and capital costs for concrete bridge decks,
- $2 billion (1.45%) for maintenance and capital costs for concrete substructures, and
- $0.5 billion (0.36%) for maintenance and capital costs for steel parts in bridges.

2.2 Chloride Diffusion Influence on Concrete Bridge Decks

After lengthy research, the main cause of deterioration in bridge decks has been found to be chloride induced corrosion (Angst 2009). There are three stages in the deterioration process of bridge decks. The first is chloride penetration into the concrete; the second is rust formation and accumulation in the interface between rebar and concrete; and the third is the crack (damage) development in the concrete. Among the three stages, the first one is the longest and thus the most important to ensure excellent long-term performance of concrete decks. It is therefore very important to characterize the penetration process of chloride into concrete structures. Basically, the chloride intrusion penetrates from the bridge deck to the reinforcing steel underneath. The chloride then generates corrosion on the steel surface and further causes dysfunction of the steel in the structure. The corrosion products also increase the total volume of the steel applying pressure on the concrete. Finally, the concrete structure deteriorates and will be destroyed. After the cracking of the concrete deck, more chlorides will more easily intrude and corrode the rebar.

As previously mentioned, the diffusion period is usually the main phase that needs to be addressed. The chloride ions penetrate through the concrete deck to the surface of the rebar. At first, the chloride ions destroy the passive film on the surface of the rebar, which is the final line of defense of the rebar. Once the concentration of chloride ions exceeds the critical value, the passive film will be totally destroyed and corrosion starts. However, this period is the longest phase of the whole process. According to previous research, this phase usually takes around 7-20 years on the bridges in Colorado (Xi et al. 2004). This huge variation comes from the concrete mix design used on the bridge and the number of deicers used on the bridge deck (Enevoldsen et al. 1994). The penetration of chloride basically comes from the chloride diffusion theory.

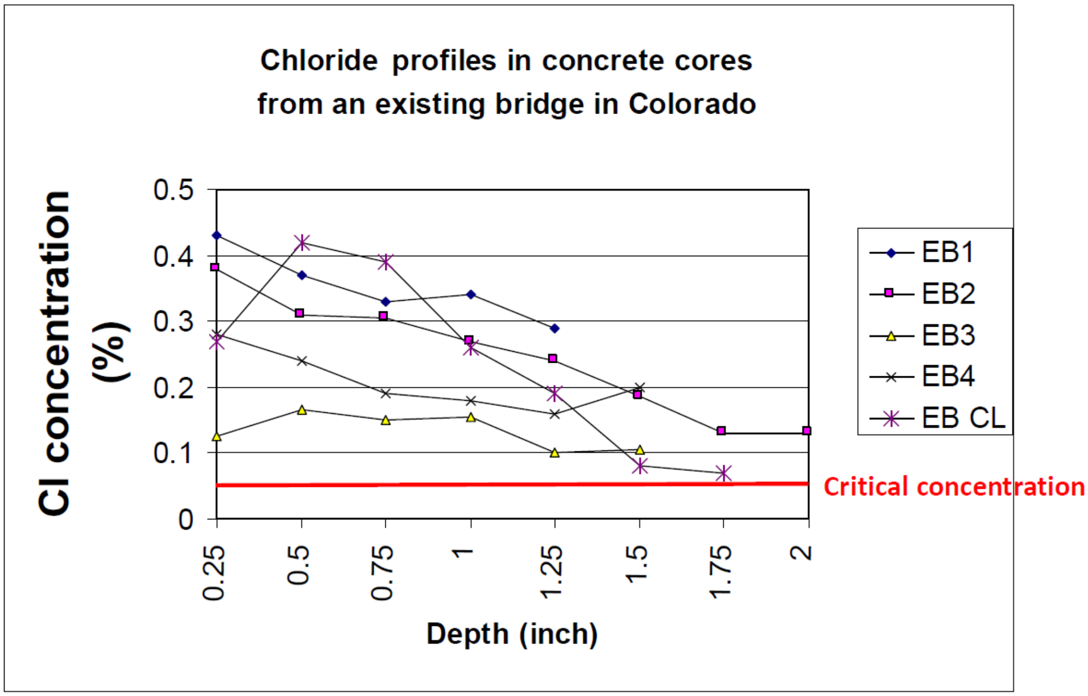


Figure 2-1. Chloride concentration profiles of an existing bridge in Colorado

Figure 2-1 shows the chloride concentration profiles obtained from an existing 20-year-old highway bridge in Colorado. The depth of concrete cover is 2.0 inches which is at the right side of the figure. The critical chloride concentration to trigger corrosion of the rebar occurs at about 0.05%, shown as a red line. One can see that at the depth of concrete cover, the concentrations are just above the critical concentration after 20 years of service loading. With a new WPM installed on the selected bridge deck in this project, we expect that the WPM and the concrete deck will be in very good condition over the project period (two years). The probability of any noticeable corrosion damage occurring in the concrete decks is very small. Therefore, the long-term performance of the WPM-deck systems will not be solely evaluated based on the test data; but will also be partially predicted by some simulation models developed based on the test data. In short, the long-term performance of the WPM-deck system will be predicted based on short-term test data to be collected during the project.

When a WPM is installed on top of a concrete deck, the WPM-deck system becomes a two-layered system (Fig. 2-2). The chloride concentration profile in the WPM and in the concrete deck is shown as a red curve schematically. The chloride profile in a concrete deck without WPM is shown as a green curve, which is much higher than the red curve. This is because the penetration of chloride is slowed down by the WPM. Therefore, the prediction model for the WPM-deck system should be different from those developed for bare concrete decks.

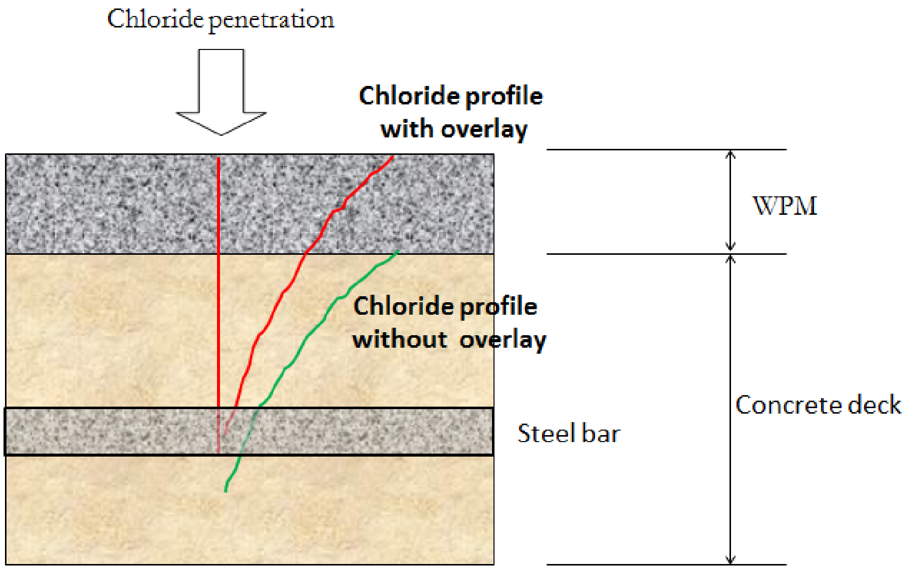


Figure 2-2. WPM-deck is a two-layered system

Chloride diffusion theory is controlled by Fick's first law, shown in Eq. (2-1). Then, considering Fick's second law, Eq. (2-2) can be derived.

$$J = -D \times \left(\frac{dC}{dx}\right) \tag{2-1}$$

$$\frac{dC}{dt} = D \times \frac{d^2C}{dx^2} \qquad (2\text{-}2)$$

where J is the diffusion flux of chloride ions ($\frac{mol}{m^2s}$), D is the diffusivity coefficient ($\frac{m^2}{s}$), C is the concentration of chloride ions ($\frac{mol}{m^2}$), and x is the depth of chloride concentration (m). Fick's second law has been solved with initial boundary conditions at x=0, C=C_0 and x=inf, C=0. The solution of this diffusion equation is shown in Eq. (2-3). Equation (2-3) is the commonly used solution for bare decks (one-layer system).

$$C(x,t) = C_0 \times [1 - \text{erf}\left(\frac{x}{\sqrt{4Dt}}\right)] \qquad (2\text{-}3)$$

where erf is the error function.

However, Eq. (2-3) cannot be used in this project because a two-layered WPM-deck system is not considered in Eq. (2-1). Therefore, another model will be used for the WPM-deck system. Specifically, there will be parameters in the model to consider the effect of WPM on concrete, and the parameters will be determined by the chloride concentration profiles to be obtained in the project.

Recently, some new models have been developed with the coupled diffusion parameters, such as the model presented by Suwito (Suwito and Xi 2006). The model shows the chloride profile is not only affected by the diffusivity of chloride, but also influenced by the moisture diffusion, shown in Eq. (2-4) and (2-5).

$$\frac{\partial C_t}{\partial C_f}\frac{\partial C_f}{\partial t} = \nabla \cdot [D_{Cl}\nabla C_f + D_\varepsilon \nabla H] \qquad (2\text{-}4)$$

$$\frac{\partial w}{\partial H}\frac{\partial H}{\partial t} = \nabla \cdot [D_\delta \nabla C_f + D_H \nabla H] \qquad (2\text{-}5)$$

where t is time, C_f is the free chloride concentration, C_t is the total chloride concentration, H is the pore relative humidity, D_{Cl} is the diffusivity of chloride, $D_\varepsilon = \varepsilon D_H$, ε is the humidity gradient coefficient representing the effect of moisture on chloride diffusion, w is the water content, $D_\delta = \delta D_{Cl}$, and δ is the chloride gradient coefficient representing the effect of chloride concentration on moisture diffusion. From the above model, one can conclude that the concentration of chloride and concentration of moisture are controlled and affected by each other.

2.3 Properties of Concrete Affected by Chloride Concentration

It is widely accepted that the rate of chloride penetration into the concrete mainly depends on the pore structure of the concrete. The pore structure of concrete is influenced by several factors, such as the type of cement used, aggregate properties, mixing procedure, and the physical age of the concrete. In regard to mixing procedure, it also depends on the water-to-cement ratio, mixing time, and additives used (Stanish 1997). After concrete mixing, it is important to cure the concrete in a well-established environment. From previous research, curing concrete at room temperature with full hydration process will provide a longer life and result in a low-level chloride diffusion coefficient. Curing at high temperature will generate an accelerated curing process, which can result in a high quality, more resistant concrete at an early age; however, with the accelerated curing process, the concrete will not have enough time to hydrate properly, which causes an increase of the diffusion coefficient of chloride (Detwiler et al 1991). In addition, the other bad actor with concrete is cracking especially common to CDOT's bridge decks. This bad actor could be caused by several potential factors, such as the corrosion of rebar, and the drying shrinkage of concrete, etc.

2.4 Critical Chloride Concentration

The definition of critical chloride concentration has been discussed and studied in previous research (Breit 1998, Alonso et al. 2000). It can be either the concentration of chloride required for the depassivation of the steel, or the concentration that can generate obvious deterioration of the concrete. From the two descriptions above, it can be concluded that there is a huge gap between the definitions of critical chloride concentration. In the previous research, the total chloride content varied from 0.04% to 8% by weight of cement and 0.04% to 4% by weight for free chloride. In this study, 0.05% by weight will be used as the critical chloride concentration level.

Previous studies have considered several different influence factors that affect the critical chloride concentration, which includes the interface between concrete and steel, type of binder/cement used, water-to-cement ratio, pH of the pore solution, electrochemical potential of the steel, steel type, steel surface condition, moisture content and humidity, available oxygen, internal temperature, chloride ion source type, additives to concrete, and the addition of chloride inhibitors (Angst 2009). Of the above parameters, the interface of the concrete/steel and the pH of the pore solution are the two most important factors in determining a critical chloride concentration. The most common types of deicers used on highway bridge decks are sodium chloride, calcium chloride, magnesium chloride, and potassium chloride. Several studies have shown that among these types of deicers, calcium chloride has a more detrimental corrosive effect than other deicers.

2.5 Types of Protection System

Several different methods and strategies have been used for several decades for preventing the penetration of chlorides and protecting the reinforcing steel from corrosion in the concrete bridge deck. These include corrosion inhibitors, cathodic protection and prevention, alternative reinforcement steel bars, and topical protection systems. Corrosion inhibitors are additives that in low concentration and in an aggressive environment inhibit, prevent, or minimize corrosion (Obot et al. 2009). After the mixing, the corrosion inhibitors would be absorbed on the surface of the reinforcing steel and generate a protective thin film which can block the path of chloride intrusion. The cathodic protection technology is used to control corrosion of the reinforcing steel surface by using it as a cathode of an electrochemical cell. In this example, another less significant metal could be connected to act as the anode (Peabody 2001) and the corrosion potential would transfer from the reinforcing steel surface to the other metal. The alternative reinforcing bars are made from materials that isolate the steel from the concrete and have higher corrosion thresholds compared with normal reinforced concrete (Liang 2010). Finally, topical prevention systems provide a protection layer between the body of the bridge deck and the concrete top surface, which can block the penetration of water, oxygen, and chloride ions from the top to the reinforcing steel.

This project mainly focused on the benefits of using topical prevention systems. The first trial of using topical systems on bridge deck surfaces can be traced back to the late 1950's (Sohanghpurwala et al. 1996). Topical protection systems include 3 different types of protective layers: waterproof membrane (WPM), chemical sealer, and thin bonded overlay. In general, these topical protection systems are developed to reduce the penetration of moisture and chloride ions from deicing salts and thereby inhibit corrosion of the reinforcing steel embedded in bridge decks. Under different service conditions, the performance of the topical protection systems varies. The use of WPMs has been the most popular method for providing protection against chloride intrusion into bridge decks. However, major concerns arise regarding the longevity of this system and its effectiveness against chloride intrusion and effectiveness as a corrosion barrier. Some of these issues include maintaining the required membrane thickness, the optimal time when this membrane should be applied after deck placement, the effect of construction joints or seems, the damage due to milling the existing overlay, the minimum or optimal thickness of asphalt required to protect the membrane, and the freeze thaw damage incurred due to the presence of blisters after some time in service.

The literature review found that the methods reported in 1994 to evaluate waterproofing membrane systems in the field still exist today, but no method has emerged as being universally acceptable. The current membranes outlined in the CDOT Standard Specifications pose a threat of chloride intrusion. This phenomenon is either due to the presence of seams when using the prefabricated sheets or due to the lack of control of the thickness required for the hot applied membranes. The problem with the seams and the deficient thickness is that they are considered as pathways for the chlorides into the concrete decks causing the chloride concentrations to rise above the critical threshold limits thus causing corrosion to initiate. Another concern is the difficulty of repairing the damaged portions of the membranes from the milling operations mainly due to the variation of the asphalt thickness on the bridge deck. Removal of the damaged membranes often requires expensive and abrasive methods such as diamond grinding, and some of the deck concrete cover is lost in the process. The ultimate benefit is a revision to the CDOT Standard Bridge Specification to include performance criteria which will result in improved performance regarding our bridge deck protection systems.

Overall, the performance criteria should be investigated and established for the different membranes based on more stringent criteria; addressing their ability to withstand damage from the typical milling operation, the ease of repairing damaged sections and the optimal application time after deck placement. In addition, further investigation into waterproofing systems is necessary if concerns arise regarding the longevity of the systems and their effectiveness against chloride intrusion, especially as a corrosion barrier at an optimal life cycle cost basis.

2.6 Current Status of Knowledge on WPMs

Waterproofing membrane systems for bridge decks can be divided into constructed-in-place systems or preformed membrane systems. Constructed-in-place systems can be subdivided into bituminous and resinous liquid-sprayed systems. Preformed membrane systems can be subdivided into asphalt-impregnated fabric, polymer, elastomer, and asphalt-laminated board systems. A survey conducted in 2003 indicated that the most frequently used materials have been bituminous for constructed-in-place systems and asphalt-impregnated fabric for preformed systems. At least 23 different proprietary products from 19 companies have been used as waterproofing membrane systems on bridge decks in the United States and Canada since 1994.

2.6.1 Applications of WPMs in the U.S.

Two bridge decks in Kansas were restored using a non-woven polypropylene membrane over an asphalt cement tack coat and topped with a 2-in thick wearing surface of hot mix asphalt in 1985 (Distlehorst 2009). Fourteen years after installation, both decks received ratings of “good” from the Kansas Department of Transportation (KDOT) bridge management inspectors. These results are consistent with an earlier report (Wojakowski and Hossain 1995) that looked at the condition of six bridge decks with asphalt interlayer membrane overlays after 20 to 25 years in service. Three different types of membranes were used: a preformed coal tar and polypropylene sheeting, a coal tar modified polyurethane elastomer membrane covered with an asphalt roofing sheet, and a non-woven polypropylene fabric. All three types of membranes were overlaid with hot-mix asphalt. The system using the nonwoven polypropylene membrane was found to be the most effective.

Four types of overlay procedures used in Tennessee have been identified and shown in Table 2-1. Each of these overlays provides similar benefits for bridge decks: the bridge deck is protected from water, chlorides, and other deleterious materials. General descriptions and applications of each of the methods as well as information about their expected service life, average cost, and frequency of use on Tennessee bridges have been studied. The results of this study indicate that the cost of asphaltic membranes is relatively low; however, their life spans were found to be shorter than other protection systems.

Table 2-1. Expected life and average cost of overlay types

Overlay Type	Expected Life (years)	Average Cost ($/yd2)
Asphalt (both types)	15-20	30-40
Reinforced PCC	30+	70-80
Nonreinforced PMC	25-30	55-65
Thin Bonded (both types	20-30	70-110

Table 2-2. Cost of deck protection systems for post-tensioned segmental bridges, $\$/yd^2$

Strategy	Grinding	Shotblast	Protection	Skid	Initial	Life, yrs.	Life Cycle
Thin Bonded Concrete Overlay	6	6	62	6	80	30	80
Membrane and Asphalt Overlay	6	0	27	18	51	15	96
Thin Bonded Epoxy Overlay (15 yr. Life)	6	6	21	0	33	15	60
Thin Bonded Epoxy Overlay (30 yr. Life)	6	6	21	0	33	30	33
Monolithic Concrete (30 year life)	6	0	24	6	36	30	36
Monolithic Concrete (90 year life)	6	0	24	6	36	90	12
Low Permeability Concrete (90 year life)	6	0	0	6	12	90	4

Table 2-2 shows FHWA cost comparison of various overlay systems. One can see that WPMs have the second highest initial cost and the highest life cycle cost. The information shown in Table 2-1 and Table 2-2 is not consistent, mainly because the life cycle cost of various protection systems depends on many factors including local market for the materials, local traffic and environmental conditions.

Three types of overlay systems were tested on two bridges in Virginia. The objective of this study was to compare Rosphalt overlays to HCC overlays of LMC-VE, LMC, and SFC and epoxy overlays. Rosphalt is an asphalt that is considered to be impermeable and has been used on decks without placement of a membrane. From their results, Rosphalt was found to be more fatigue and rut resistant than the SM-9.5 mixture and should last longer, but based on cost, Rosphalt is too expensive to be considered a competitive overlay system (Table 2-3).

Table 2-3. Comparative costs of different overlays, $\$/yd^2$

Cost Item	Roshpalt	SM-9.5 + Membrane	LMC-VE	LMC	SFC	Epoxy
Overlay	121-218	58	90	83	75	30
Miscellaneous	32	32	32	32	32	16
Traffic	13	19	28	44	44	13
Total	166-263	109	150	159	151	59
Life, yr.	15	10	30	30	30	15
Life cycle costs	332-526	255	150	159	151	118

LMC-VE=LMC with very early hardening cement; LMC=latex-modified concrete; SFC=silica fume concrete.

In 2013, New York DOT applied a bridge preservation program by using the Bridge Deck Membrane (BDM). The installation began by removing all loose dirt and debris, followed by shot blasting. Concrete primer was applied using squeegees and allowed to completely cure for approximately 20 minutes before application of BDM™ spray applied waterproofing. Aggregated top coat was applied immediately following the application of the base spray applied membrane.

Alaska DOT performed field evaluations of select bridges to investigate the effectiveness of the waterproofing membrane bond to the concrete bridge deck and the asphalt overlay (Martinelli et al. 1996). The project was initiated because some of the preformed membranes, generally on high-traffic volume roads, had failed to bond adequately to either the asphalt overlay or the concrete bridge deck. Five proprietary products were included in the evaluation. One recommendation from that research was to require a 4-inch thickness of pavement over the membrane to allow for future pavement surface rehabilitation without damaging the existing membrane.

Many agencies reported that the life of the membrane system is limited by the life of the asphalt. Sohanghpurwala (2006) reported that the service life of hot mix asphalt with a preformed membrane would be less than 10 years if the overlay failed when used to extend the service life of existing bridge decks. Otherwise, the service life would be 25 years. Kepler (Kepler et al. 2000) compared the life cycle costs of 33 different corrosion protection systems and concluded that the use of hot rubberized asphalt membrane was the second-lowest-cost strategy, with assumed discount rates of 2% and 4%. At a 6% discount rate, hot rubberized asphalt membrane was the sixth-lowest-cost strategy. The analysis was based on a service life of 75 years and assumed that the top 40 mm (1.6 in.) of the asphalt overlay was replaced at 20 and 60 years and the membrane and asphalt overlay replaced at 40 years.

In the 1950s, the Shell Petroleum Company developed epoxy asphalt as airport pavement and in 1967 it was first used as surfacing material on the deck of the San Mateo-Hayward Bridge in San Francisco, California. The main advantage of epoxy asphalt is its thermosetting behavior; common asphalt binders are thermoplastic systems. Moreover, epoxy asphalt concrete does not appear to rut, shove, or bleed. Although epoxy asphalt costs more, it possesses high resistance and flexibility, good adhesion to orthotropic steel bridges, perfect waterproofing features, and a fatigue life three times longer than an ordinary asphalt concrete. In addition, the bridge can be opened to traffic as soon as the environmental temperature is reached.

From a technical aspect, recent technological advancements in the production of liquid sprayed polymer/polymer urethane membranes have taken a lead in being an equal or a better membrane system. The seamless operation, the consistency of the material thickness and the ability to detect the presence of any blistering or deficiencies make the use of these type membranes a more attractive option. The field performance has been excellent and a life cycle of 75 years or more is achievable for certain products when proper manufacturer’s recommendations are followed.

In short, the previous statistics are not consistent, and there is a need to establish reliable data on the performance and cost of WPMs based on the specific conditions and environment in the state of Colorado.

2.6.2 Application of WPMs in European countries

In Europe, the application of WPMs on bridge structures is significant (Mertz 1996, Hearn 2005). The prefabricated bitumen sheets are heated with an open flame, partially melting them, to bond them to the epoxy-primed concrete bridge deck and to other overlapping sheets. The system is expected to provide a 30-year service life with appropriate maintenance. In France, most of their bridges were protected by WPMs consisting of mastic asphalt, either epoxy or polyurethane resins. Two types of mastic asphalt were used. One type consisted of an 8-mm (0.3-in.) thick layer of naturally occurring bituminous. Limestone was mixed with refined bitumen applied over a dry surface primed with a tack coat. The system was topped with a 22-mm (0.9-in.) thick layer of asphalt mixed with gravel. The other type consisted of a layer of 4-mm (0.2-in.) thick polymer asphalt mastic followed by a 26-mm (1-in.) thick layer of asphalt and gravel.

In Denmark, polymer-modified bitumen reinforced with nonwoven polyester are used as WPMs. A study in 2004 identified the use of a multiple-level corrosion protection system in Germany (Ralls 2005). The system was reported to have been in use since the mid-1980s. Previously, a system of asphalt overlay on a sheet of mastic had been used, but it did not provide the necessary protection against the ingress of water containing deicing salts. A recent study noted that the use of WPMs on concrete decks for corrosion protection with epoxy underneath to seal cracking in the young concrete is a standard practice throughout Europe (Hida et al. 2010). The use of WPMs on integral and continuous bridges is mandatory in the United Kingdom. The standard deck design in the United Kingdom consists of 8 to 10 inch thick decks with a WPM overlaid with asphalt.

In the European Standard, polymer-modified bitumen (PmB) is the simplest and most widespread waterproofing material, which can be applied rapidly to the deck surface and effectively improve bonding with the steel deck and resist high temperature. A 1- to 2-mm thick PmB bind coating is sprayed on the steel deck surface at a temperature of 180° C to 200° C.

Reinforced asphalt-based membrane consisting of a modified elastomeric and plastomeric bitumen membrane reinforced with nonwoven polyester is a waterproofing sheet for orthotropic steel bridges. It has been used to coat many important bridges, such as the Millau Viaduct Bridge built in 2004. The membrane, packaged in rolls, is laid on the orthotropic bridge after the application of an elastomeric bitumen cold primer containing xylene solvent. This system ensures a good adhesion to the steel deck surface, reducing the risk of pavement sliding or cracking. A 70-mm-thick asphalt concrete layer is applied directly on top of the membrane. Asphalt-based mastic is a pourable waterproofing membrane. The mixture is typically a blend of asphalt binder, elastomeric or plastomeric polymers in a high percentage (>10%), and fine aggregate. Some products include a large proportion of thermosetting polymers, such as epoxy or epoxy-polyurethane resin, which depend on the environmental conditions.

Because of the significant difference in weather and traffic conditions between the U.S. and Europe, some studies recommended that further consideration be given to implementing the use of European WPM systems in the United States (Ralls et al. 2005, Hida et al. 2010).

2.7 Testing Methods

The U.S. Army Cold Regions Research and Engineering Laboratory conducted laboratory studies to develop standardized procedures for the evaluation of bridge deck membranes (Korhonen et al. 1999). They reported that although there are ASTM tests to evaluate various engineering properties of asphalt, rubber, roofing, plastics, and geomembranes, there is no group of standards or specifications to interpret them for the application of WPM on bridge decks. The intent of the work was to recommend tests to compare performance of various membranes. Six sheet products were tested to measure adhesion, tensile strength and elongation, puncture resistance, and water vapor permeability. Liquid-sprayed membranes were not included in the scope of the study. The details of the report will not be listed here.

The New Hampshire Department of Transportation (NHDOT) evaluated various membrane materials, primers, and application methods to determine the effects of materials and installation methods on the adhesion strength of commercially available membranes (Boisvert 2003). Concrete pads simulating dry and wet substrates, as typically encountered on New Hampshire bridge decks, were constructed at two locations. The test program included 11 preformed membranes, 5 liquid-sprayed membranes, and 14 primers in various combinations. The primary method of evaluating the systems was adhesion testing. Manning (1995) described various methods to evaluate waterproofing systems in the field, including visual inspection, electrical methods, embedded devices, physical sampling, ultrasonic methods, and air permeability methods.

The European Organization for Technical Approvals has a report that describes a method for determining the resistance of WPMs to chloride ion penetration following the indentation of the membrane by simulating hot asphalt (EOTA 2007). In this method, three heated concrete blocks with the membrane applied are indented at four locations. The surface of the membrane is then exposed to a saturated sodium chloride solution for 28 days. A sample of the concrete directly below the membrane is then obtained from each block and chloride ion concentration determined. The measured chloride ion concentration is then compared with the reference chloride ion concentration of the concrete block without WPM.

2.8 Colorado Experiences

WPMs have been used in Colorado, but there has been no systematic research conducted specifically for evaluating the performance of WPMs. For example, the PI conducted a study (Xi et al. 2004) to evaluate the performance of various corrosion protection methods used on 16 bridges in Colorado, including six with asphalt membrane overlays. It was found that the data collected in the project was inconclusive at determining which type of method provided the best corrosion protection among epoxy-coated reinforcement, corrosion inhibitors, and WPMs. In 2007, Hearn and Xi (2007) conducted a comparative cost analysis on four different types of bridge decks including WPMs, but no experimental study was done on WPMs. In 2010, Liang (Liang et al. 2010) conducted a study on different topical protection systems for bridge decks including asphalt WPM, but there was no comparative study on different the WPM systems. Therefore, this project will be the first to specifically address performance evaluation and cost analysis of various WPM systems used in Colorado.

2.9 Potential Material and Specified Size

In order to obtain the best waterproof membrane products for Colorado, we considered the references and experiences from successful projects in other states and foreign countries. Therefore, Table 2-4 lists the potential WPM materials.

Table 2-4. Potential WPM materials

Material	Membrane System
Polypropylene	Constructed in place
Reinforced asphalt-based membrane	Constructed in place
Bridge Deck membrane	Constructed in place
Liquid sprayed polymer/polymer urethane	Constructed in place
Asphalt-based mastic	Constructed in place
Epoxy or polyurethane resins	Constructed in place
Two-component polymer	Constructed in place
Methyl methacrylate	Constructed in place
Rubber polymer	Constructed in place
Polymer-modified asphalt	Constructed in place
Rubberized bitumen	Constructed in place
Hot rubberized asphalt	Constructed in place

Reinforced rubberized asphalt	Constructed in place
Non-woven polyester	Preformed
Polymer-modified bitumen (PmB)	Preformed
Styrene-butadiene-styrene (SBS)	Preformed
Bituminous membrane	Preformed
Modified bitumen	Preformed
Polymeric membrane	Preformed
Reinforced tar and resin	Preformed
Coal tar emulsion reinforced with two plies of coated glass fabric	Preformed

In addition, there have been some specifications established by different organizations to control the thickness and other factors of the WPM (Table 2-5).

Table 2-5. Summary of state specification requirements

Property	AASHTO	States
Minimum thickness for rubberized asphalt, mil.	65	50 and 60
Minimum thickness for modified bitumen, mil.	70	50 and 60
Minimum deck or air temperature, °F	35	40, 45, and 50
Puncture resistance, lb.	—	40 and 200
Maximum permeance, perms	—	0.10
Minimum longitudinal overlap, in	2.0	2.0, 2.5, 3.0, 4.0, and 6.0
— = Not specified.		

CHAPTER 3 PRODUCTS AND EXPERIMENTAL METHODS

Based on the previous review and provided commercial products in Colorado, four different types of commercially available products were tested in this study. Their performance would be treated as an effective structural protection system. Each company’s membrane test specimens shall herein be referred to as follows: “Control” – hot mix, “Sikadur 55 SLV” by Sika, “Bridge Preservation™” by Bridge Preservation™, “Protecto Wrap M-400A” by Protecto Wrap, and “Polyguard 665” by

Polyguard. Once the waterproof membranes were installed onto the bridge deck, sample specimens were collected and tested for their respective durability and mechanical properties. The details for all the tests will be discussed later in this chapter.

3.1 Product Descriptions

The Sikadur 55 SLV is a spray waterproof membrane provided by Sika. This product is a 2-component, 100% solids, moisture-tolerant, epoxy crack healer/penetrating sealer, having a fast tack-free time to minimize downtime. It is a super low-viscosity, high-strength adhesive formulated specifically for sealing both dry and damp, existing, non-dynamic cracks. It conforms to the current ASTM C881, Type I and II, Grade 1, Class C, and AASHTO M235 specifications. The Sikadur lab specimen can be seen in Figure 3-1.

Figure 3-1. Sikadur 55SLV lab specimen

Another spray waterproof membrane used is the Bridge Preservation™, developed by Chemline and distributed by Bridge Preservation™, Inc. This membrane is a two component 100% solids auto-catalytic polyuria based spray applied system, which conforms to ASTM C836. It is a cold spray applied waterproofing system, assuring watertight membrane for use on bridge decks, piers and abutments. The Bridge Preservation™ lab specimen is shown in Figure 3-2.

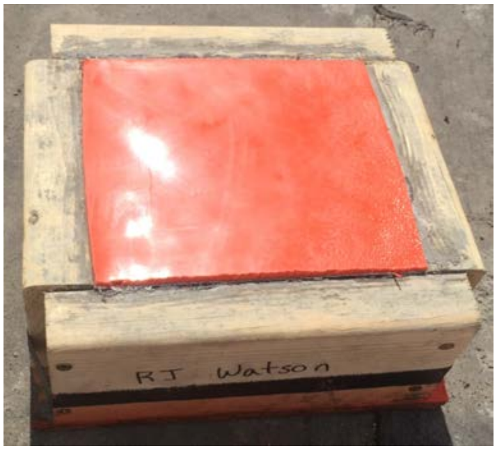


Figure 3-2. Bridge Preservation™ lab specimen

The first preformed waterproofing membrane introduced here is Protecto Wrap M-400A, which was provided by Protecto. The Protecto Wrap is a cold applied, self-adhering sheet membrane for use on bridge decks or parking structures with an asphaltic concrete wearing course. This membrane is designed to prevent penetration of water, salts, acids and alkalis thereby protecting the structure from damage by these elements. It is manufactured from a formulation of premium bituminous resins modified with synthetic resins. This rubberized asphalt is then reinforced with an inert reinforcement to withstand puncture and severe stress. The Protecto Wrap lab specimen can be seen in Figure 3-3.

Figure 3-3. Protecto Wrap lab specimen

The last preformed product, Polyguard 665, was provided by Polyguard Products, Inc. This is a self-adhering membrane consisting of rubberized asphalt laminated to a strong woven polypropylene mesh backing to form a minimum 65 mil membrane. It is completely cold-applied and requires no special adhesives or heating equipment. It is comprised of a rubberized asphalt waterproofing element and a woven pavement reinforcing grade polypropylene fabric laminated to the outer surface. The Polyguard lab specimen can be seen in Figure 3-4.

Figure 3-4. Polyguard lab specimen

3.2 Pull-off Strength (Bond) Test

The bond strength between WPMs and concrete decks was tested in the lab. The bond tests were done in accordance with ASTM D 4541 (the pull-off test) after installation of the WPMs. The system is comprised of the concrete deck, WPMs, bonding adhesive and testing apparatus (Figure 3-5).

The pull-off test involved applying a direct tensile load to a partial core advanced through the WPM material and into the underlying concrete deck till failure occurred. The tensile load was applied to the partial core using a metal disk with a pull pin which was bonded to the overlay with an epoxy. A loading device with a reaction frame applied the load to the pull pin. The load was applied at a constant rate, and the ultimate load recorded at the time of failure. Failure occurs along the weakest plane within the system.

There are three possible failure modes in the tensile bond test.

(1) Failure between bonding compound and WPMs surface

(2) Failure between WPMs and deck surface

(3) Failure in the substrate

The ultimate loads and fractured surfaces from the different waterproofing membranes was compared and analyzed.

For this study, the in-house specimens used for the bond test were resealed with silicone and used for the ponding test discussed in Chapter 3.4. Once the specimens were shipped to the University of Colorado, the bond test was performed on the specimens. After 9 months ponding, the pull-off test was repeated.

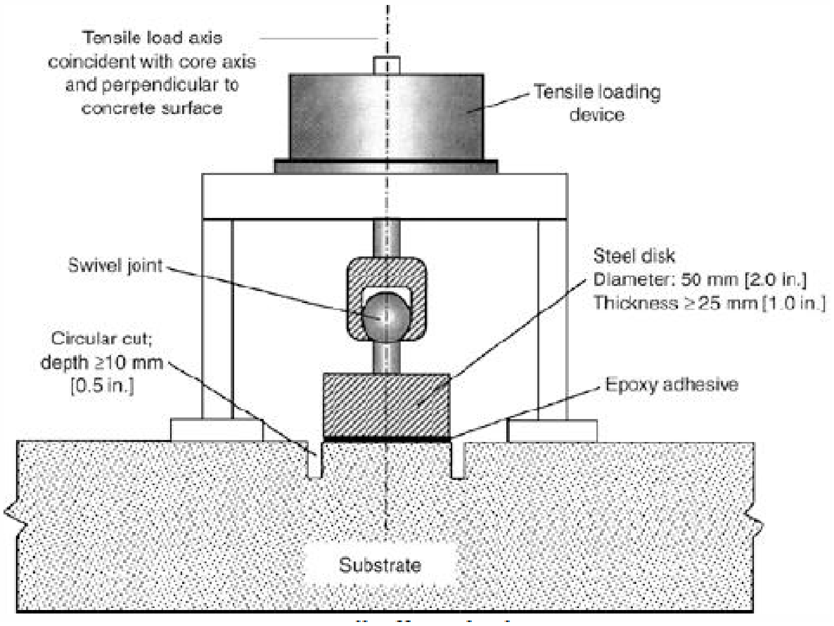


Figure 3-5. Pull-off method test setup

3.3 Chloride Profile Test

The presence of chloride leads to the corrosion of the reinforcement within the bridge deck. This test is performed in order to determine how deep the chloride has penetrated the concrete surface under actual use. The testing procedure follows ASTM C1218.

Concrete cores were taken at different sections, respectively, 24 months after the installation of membranes. The test was performed by extracting a core from the bridge deck at least 3 inches deep past the waterproofing membrane and shipping the specimens to CU-Boulder. The specimens were drilled at 0.5 inch intervals and the pulverized concrete dust was collected (Figure 3-6).

Approximately 10 grams of the powdered concrete was collected and placed into a 50 ml clean glass beaker where extraction liquid was added. The specimens were covered and shaken for approximately 5 minutes. The specimens were allowed to rest for a full 24 hours before using a Rapid Chloride Testing apparatus to measure the voltage of each sample.

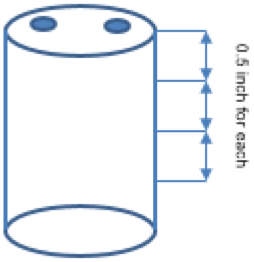


Figure 3-6. Chloride profile test setup

Traffic load and environmental loadings (temperature and humidity) result in deterioration in concrete over time. The chloride resistance tends to decrease over time due to the traffic and environmental loadings. The WPM can block or slow down the penetration of deicing chemicals and protect the concrete underneath. It is intended for the chloride resistance test data to reflect the effectiveness of the protection. For instance, comparing two different membranes A and B installed on concrete with an initial chloride resistance of 3000 C., if the test result of the concrete under membrane A changed from 3000 C to 8000 C (a higher value means a lower resistance), and the test result of the concrete under membrane B changed from 3000 C to 6000 C, then the test data would indicate that membrane B provided better concrete protection than membrane A.

3.4 Chloride Penetration by Ponding Test

Following ASTM C1543, this test was performed in order to determine the penetration of chloride ions into concrete from a sodium chloride pond.

The test was performed by casting square specimens, 7 inches wide and 3.5 inches deep, for each type of membrane and a control. The samples are cast by CDOT on site and delivered to the structural lab in CU Boulder. After delivery, a sodium-chloride solution was ponded on the surface of the specimens (Figure 3-7). Samples were taken at 0.5-inch intervals and chemically analyzed to determine the chloride content at each depth. The chloride content was measured by using the same technique described above.

At the same time, moisture sensors at different depths were installed onto the concrete slab. The moisture profile was obtained during the ponding process (Figures 3-8 and 3-9).

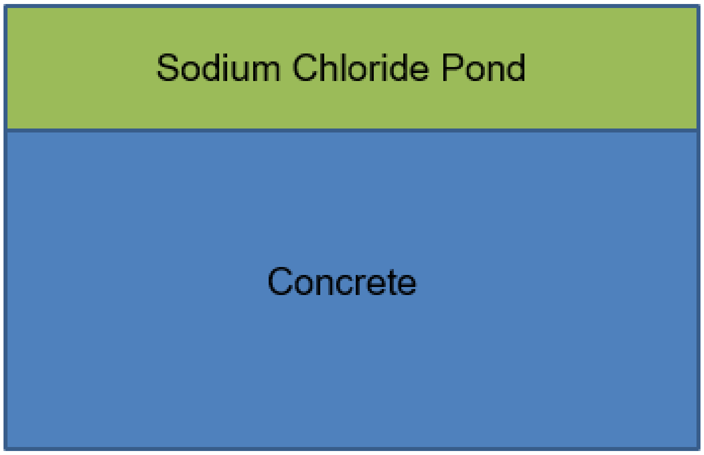


Figure 3-7. Ponding test setup

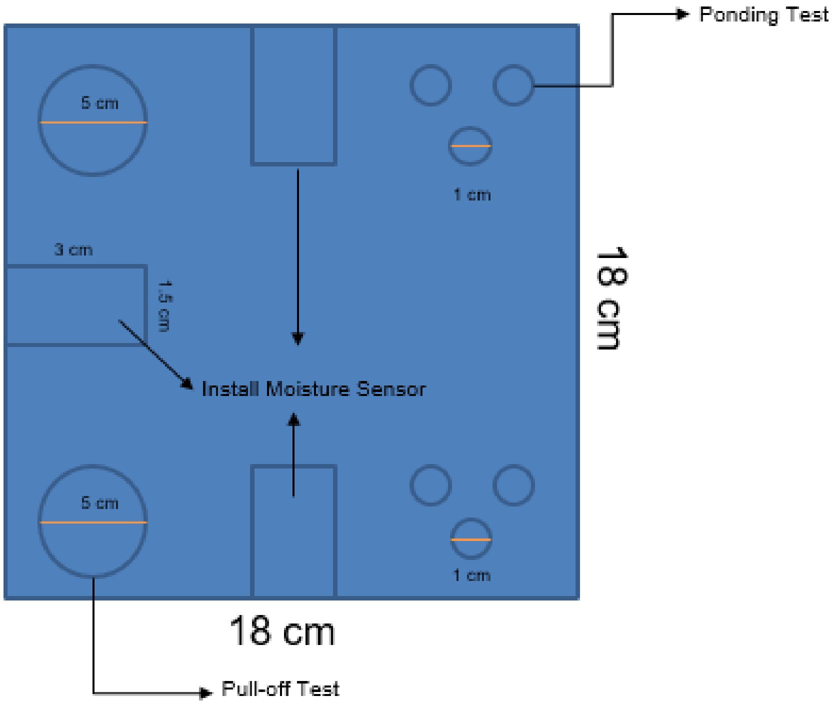


Figure 3-8. Slab layout (top view)

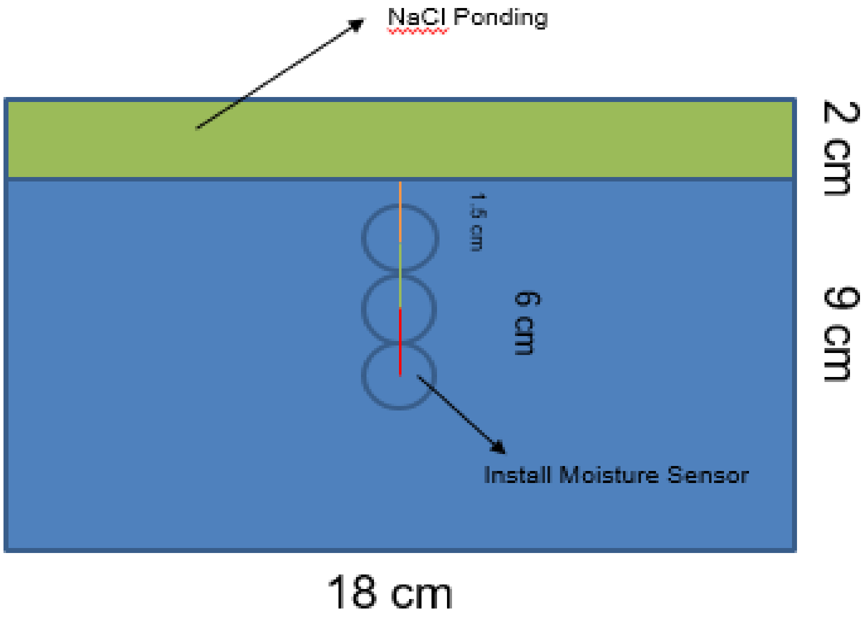


Figure 3-9. Slab layout (side view)

3.5 Rapid Freeze-Thaw Test

Concrete cores were taken at one location in each test section and shipped to CU-Boulder to determine freeze/thaw resistance of the membranes in accordance with ASTM C666 (Figure 3-10). The purpose of the freeze-thawing cycle test is to investigate the resistance of the waterproofing membrane system under 300 repeated cycles of the freezing and thawing process under standardized conditions. This test is conducted with a Logan Rapid Freeze-Thaw Chest (Figure 3-11). This machine uses a 3 inch by 6 inch freezer plate beneath containers to cool the specimens and uses the electric heaters placed between the containers to warm the specimens.

The freeze-thaw cycle test is controlled by raising the temperature range from 0°F to 40°F and decreasing the temperature range from 40°F to 0°F. The ASTM standard states that at the end of the cooling period, the temperature at the center of the specimen should be 0 ± 3°F (-17.8 ± 1.7° C) and at the end of the thawing period, the temperature at the center of the specimen should be 40 ± 3°F (4.4 ± 1.7°C). In addition, a full cycle must be completed between 2-5 hours. The test program was designed to operate a total of 300 cycles. The new digital control panel is installed to control the temperature range and duration of time accurately (Figure 3-12).

Two inch diameter cores were drilled 3 inches into the concrete deck (in addition to the thickness of the WPM). The weight loss and length change of the specimens were monitored vs. number of freeze/thaw cycles. The concrete cores were taken after 12 months of the installation of the waterproofing membrane. Comparison of the freeze/thaw test data will show the protection capability of WPMs under the influence of Colorado weather.

Figure 3-10. Sample prepared for freeze-thaw test

Figure 3-11. Logan rapid freeze-thaw chest

Figure 3-12. Digital control panel

CHAPTER 4 INSTALLATION PROCESSES OF WPMS

For this project, four different types of waterproof membrane were installed on the bridge at East Arapahoe Road approaching CO Highway 83. This bridge is in the north area of Centennial, CO. Figure 4-1 shows the plan view of the location of each test section on the bridge deck. The University of Colorado at Boulder's research team visited the bridge several times to observe and monitor the installation of each waterproof membrane by its respective commercial provider. The photos, shown in Figure 4-2 to Figure 4-13, were taken during the visits and illustrate the general installation process for these waterproof membranes. In addition, all the drilling core locations were located using GPS coordinates in order to prevent drilling into the rebar. Cylinders with 3 inch diameter and 6 inch height were collected at different periods. The GPS coordinates are listed in Table 4-1.

Table 4-1. GPS coordinates for core locations

Point	Northing	Easting	Elevation	Desc.	Section #
801	642831.54	194178.44	5656.37	span2	test section #1
802	642831.64	194188.23	5656.58	span2	
803	642831.58	194198.18	5656.9	span2	test section #2
804	642831.67	194208.15	5657.17	span2	
805	642831.65	194218.14	5657.36	span2	test section #3
806	642831.73	194228.1	5657.53	span2	
807	642831.69	194238.22	5657.66	span2	test section #4
808	642831.82	194248.26	5657.84	span2	
809	642831.98	194258.19	5658.00	span2	test section #5
810	642831.92	194268.13	5658.06	span2	

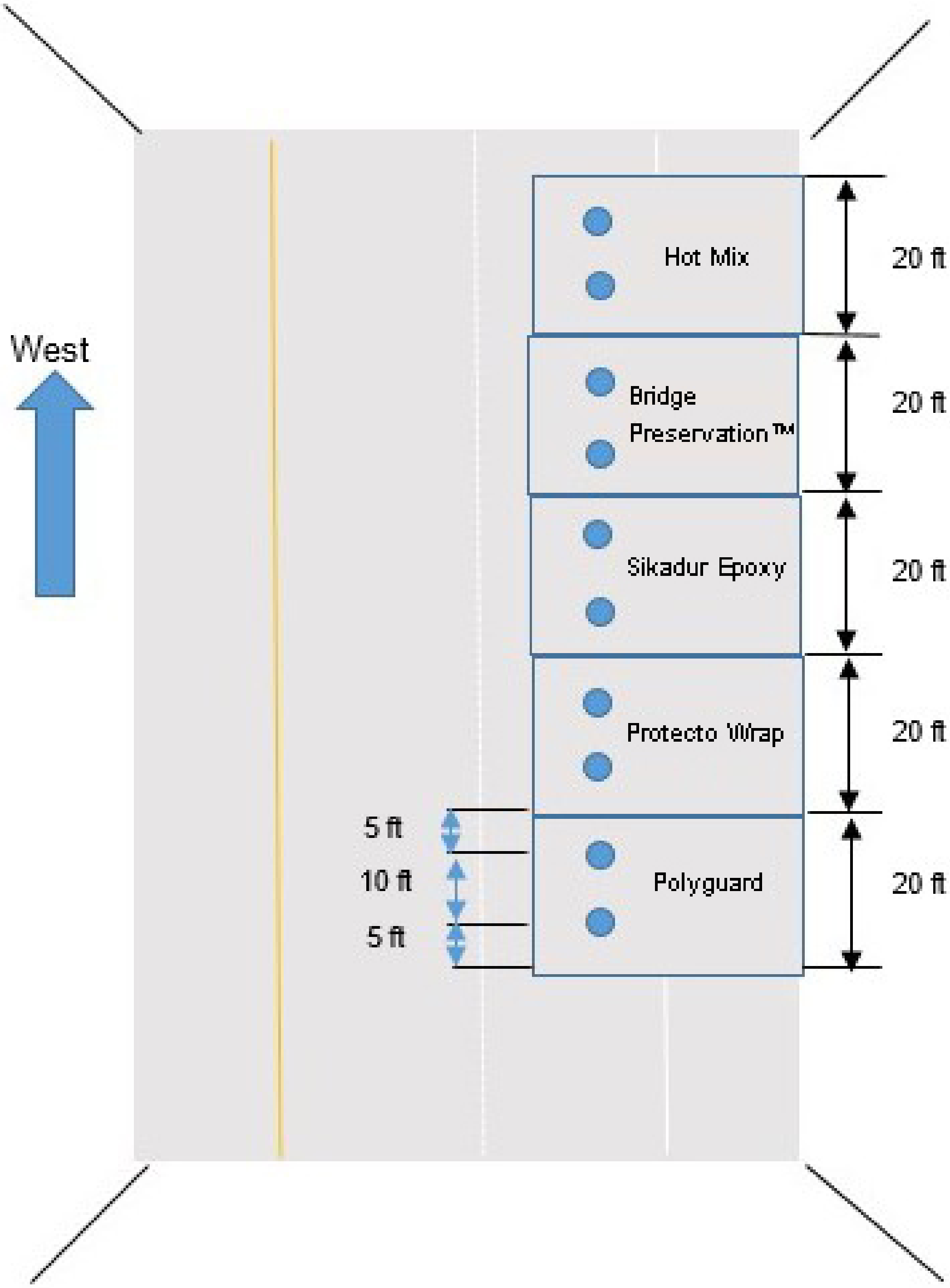


Figure 4-1. Plan view of test sections

Figure 4-2. Rebar installation

Figure 4-3. Slump test before casting the concrete

Figure 4-4. Concrete casting

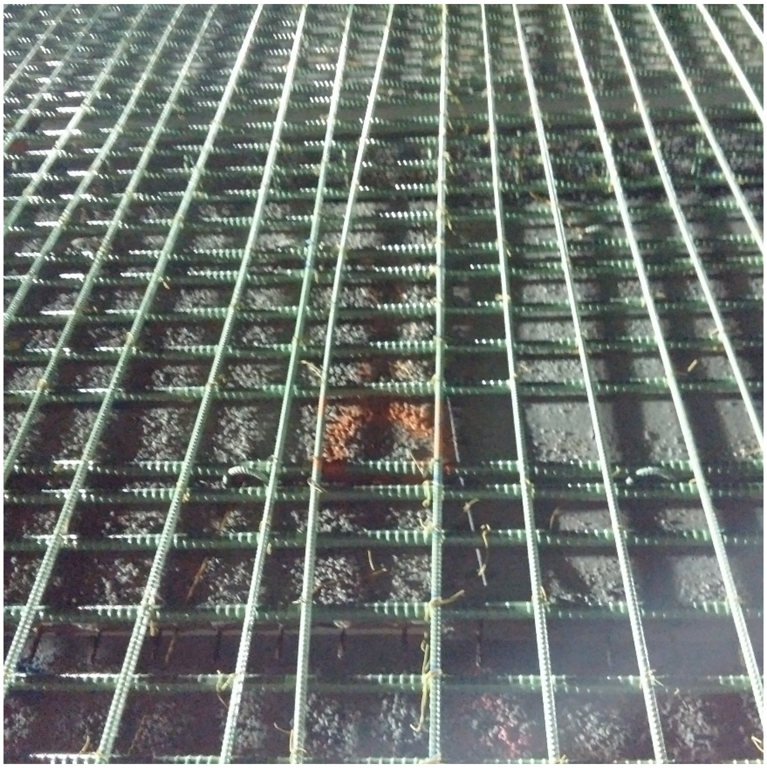


Figure 4-5. GPS location

Figure 4-6. Installation of Protecto Wrap waterproof membrane

Figure 4-7. Installation of Polyguard waterproof membrane

Figure 4-8. Installation of Sikadur waterproof membrane

Figure 4-9. Installation of Bridge Preservation™ waterproof membrane

Figure 4-10. Installation of hot mix control section

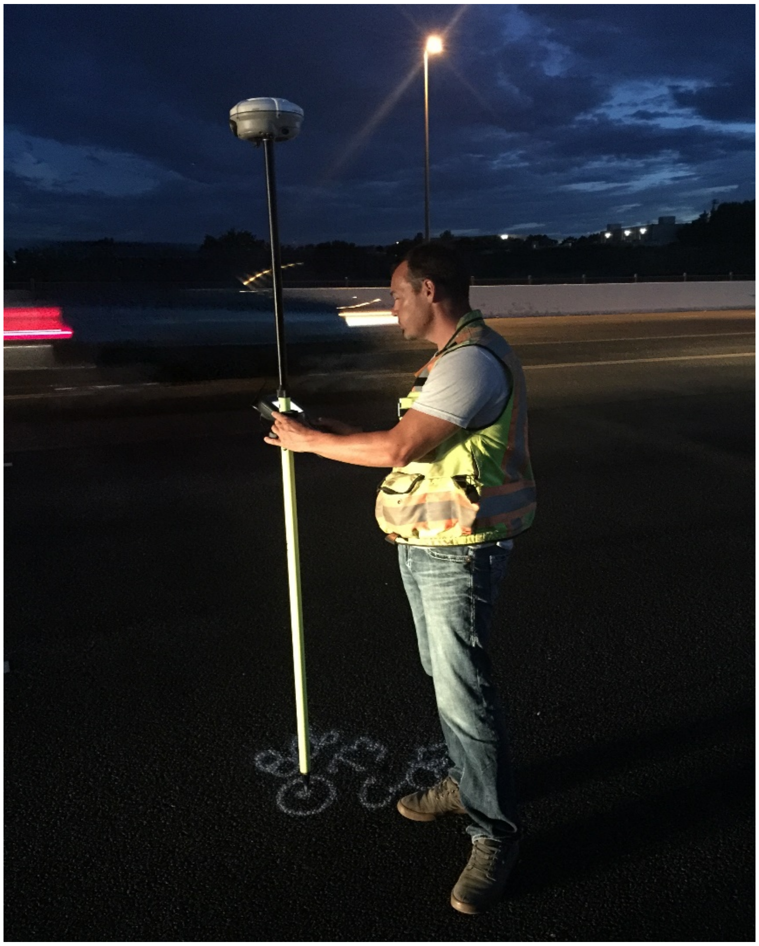


Figure 4-11. Measuring GPS location

Figure 4-12. Drilling concrete cores

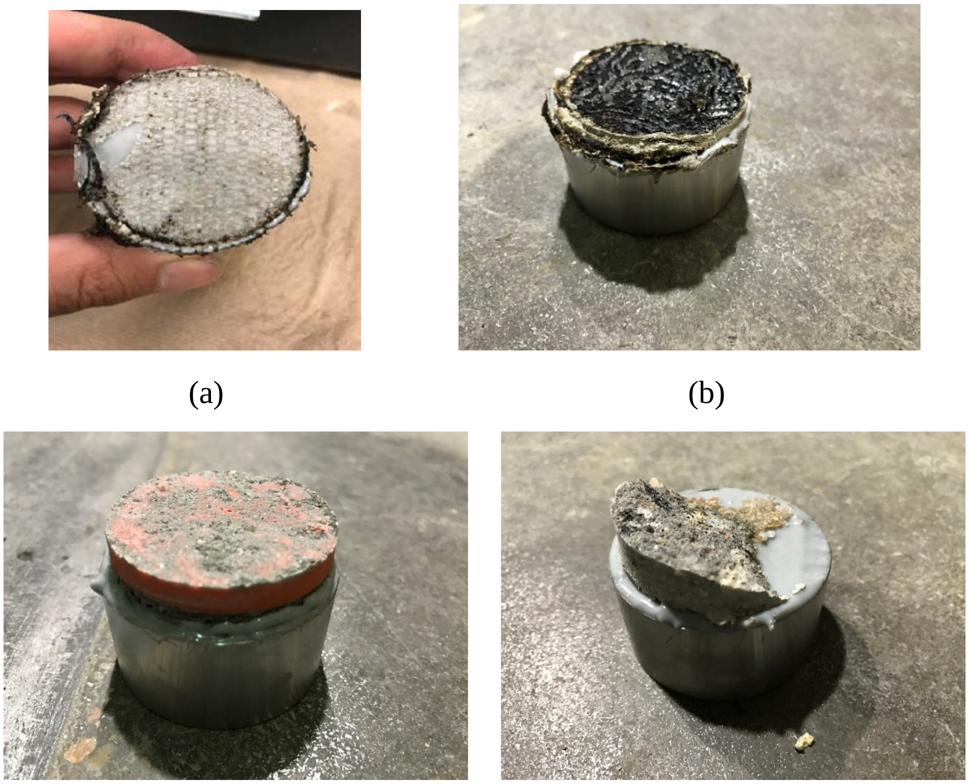
Figure 4-13. Collected concrete core

CHAPTER 5 PERFORMANCE ANALYSIS

5.1 Pull-off Strength (Bond) Test - Results and Analysis

The bond strength between the waterproof membrane and the bridge deck surface serves as an indicator of current WPM service performance, but can also serve as an estimate of the service life span. According to the ASTM standard, the bond test applies a perpendicular force to the core to determine the weakest plane within the system.

The detailed testing procedure was provided in Chapter 3.2. The sample bonding strength was tested 24 hours after casting and after 12 months of ponding on the slab. The results are shown in Figures 5-1, 5-2, 5-3 and Table 5-1.



(a) (b)

(c) (d)

(e)

Figure 5-1. Pull-off test results (a) Protecto Wrap (b) Polyguard (c) Bridge Preservation™ (d) Sikadur (e) hot mix

Table 5-1. Bonding strength and failure mode

WPM	24 hours (Psi)	12 months (Psi)	Failure Mode
Polyguard	11	8	Bonding & WPM Surface
Protecto Wrap	15	12	WPM & Substrate Surface
Bridge Preservation™	29	25	WPM & Substrate Surface
Sikadur	205	198	Substrate
hot mix	11	10	WPM & Substrate Surface

Early bond strength is important for the WPMs before traffic is reopened on the bridge. If the early bond strength does not develop fast, once the WPM is reopened to traffic, the risk of shearing failure could potentially occur from a tractor-trailer locking its wheels up, and aggregate pull out from general traffic wearing. In order to catch-up the early bond strength, the specimens were prepared as soon as they arrived at the University of Colorado Structures Lab and then had the test disks bonded to each section. Different types of WPMs were installed onto the lab-size slab specimens. However, since the bonding agent used specified a 24-hour period to obtain a full-strength bond, the test had to be conducted after 24 hours. The objective of this 24 hours test is mainly considering the potential risk in the early time of the bridge deck. After that, the slab specimens were ponded with 3% Sodium Chloride solution for 9 months. This is to test the influence of chloride penetration on bonding strength. Each winter, there is a significant amount of deicing salt sprayed onto bridge decks throughout Colorado. Since chloride intrusion has the potential to affect the functionality of WPMs, especially the bonding strength, it is necessary to evaluate this issue affected by ponding.

The results clearly show the Sikadur WPM had a much higher bonding strength compared to the others. The two preformed WPMs, Polyguard and Protecto Wrap, showed relatively low bonding strengths, which were pretty close to the hot mix control specimen. The Bridge Preservation™ performed better than these three, except Sikadur. Figure 5.3 illustrates the different types of failure modes of the WPMs. The control section failed at the interface between the WPM and the substrate surface (the asphalt layer is considered the WPM here). The low bonding strength of the hot mix means the bonding epoxy did not fully penetrate into the deck surface. A similar issue was found with the Polyguard. The other preformed WPM, Protecto Wrap, was destroyed at the interface between the bond and WPM; as a result, the tensile strength of the Protecto Wrap was pretty low, even lower than the bonding between the WPMs and substrate. The Bridge Preservation™ showed the same type of failure mode as the control section. However, due to the complex installation, the bonding strength was over two times that of the control panel. Finally, the failure of Sikadur was directly due to the substrate, which indicates the bonding between each layer was very strong.

Considering the results of the 9 month bonding test, a good bond was formed between all test specimens and the bonding agent after 9 months without any other influence factors, such as chloride intrusion. However, the specimens experiencing chloride ponding had relatively low pull-off strength. The chloride-induced strength reduction illustrates how the performance of the different WPMs varies. For the preformed products, the pull-off strength of the Polyguard was reduced by 27%, while the Protecto Wrap experienced a 20% reduction in strength. Of the liquid/spray-applied membranes, the Bridge Preservation™ experienced a 13.8% reduction in bonding strength; while the strongest one, Sikadur, only a 3.4% reduction. The pull-off strength of the hot mix control was reduced by 9%.

In conclusion, the bonding strength is one of the most important factors that needs to be considered in this project. Weak bonding strength would cause the potential risk of WPMs to lose their functionality. From the lab-scale test, the Sikadur provided the best performance, which was about twenty times stronger than the control section. Bridge Preservation™ also showed better performance than the control section. The two preformed WPMs, Protecto Wrap and Polyguard, had similar bonding strength to the hot mix control. The results prove that the construct-in-place WPMs have a better bonding strength than the preformed products. Chloride penetration also showed to have an obvious effect on the pull-off strength of the WPMs; the bonding strength of all the WPMs experienced some level of reduction in those tests. One thing that needs to be clarified is that since the pull-off test was based on the lab-scale, only chloride influence was considered. Other factors, such as UV rays and traffic load, were not considered.

5.2 Chloride Profile Test - Results and Analysis

Among all the parameters used to rate the performance of each WPMs, the chloride profile is the most significant. One of the main objectives of this study was to evaluate the effectiveness of the WPMs as a chloride inhibitor. Increased chloride concentration would cause the corrosion of rebar and further cracking throughout the bridge deck. In this test, the free chloride concentration was analyzed for the concrete specimens collected from the bridge deck at 24 months. Due to restrictions of the bridge structure, only two cores were able to be drilled in each section. After drilling, the cores were sealed by silicone glue in order to prevent moisture and chloride loss. The samples were delivered to the University of Colorado Structures Lab. This testing procedure was provided in Chapter 3.3. The Chloride profile test results are shown in the Figure and Tables below.

Table 5-2. Chloride penetration on Polyguard covered specimen at 24 months

Polyguard	mV readings	% Cl- by concrete weight
0.5	57.60	0.028
1	60.70	0.024
1.5	66.30	0.018
2	74.80	0.012
2.5	78.00	0.01
3	93.60	0.005

Table 5-3. Chloride penetration on Protecto Wrap covered specimen at 24 months

Protecto Wrap	mV readings	% Cl- by concrete weight
0.5	89.15	0.006
1	88.70	0.006
1.5	90.35	0.006
2	93.05	0.005
2.5	92.50	0.005
3	103.50	0.003

Table 5-4. Chloride penetration on Sikadur covered specimen at 24 months

Sikadur	mV readings	% Cl- by concrete weight
0.5	76.55	0.011
1	90.3	0.006
1.5	94.5	0.004
2	94.7	0.004
2.5	95.5	0.005
3	100	0.003

Table 5-5. Chloride penetration on Bridge Preservation™ covered specimen at 24 months

Bridge Preservation™	mV readings	% Cl- by concrete weight
0.5	96.70	0.004
1	98.20	0.004
1.5	98.90	0.004
2	99.40	0.004
2.5	104.20	0.003
3	103.50	0.003

Table 5-6. Chloride penetration on hot mix covered specimen at 24 months

Hot Mix	mV readings	% Cl- by concrete weight
0.5	93.75	0.005
1	93.55	0.005
1.5	97.6	0.004
2	94.7	0.004
2.5	96.3	0.004
3	100.35	0.003

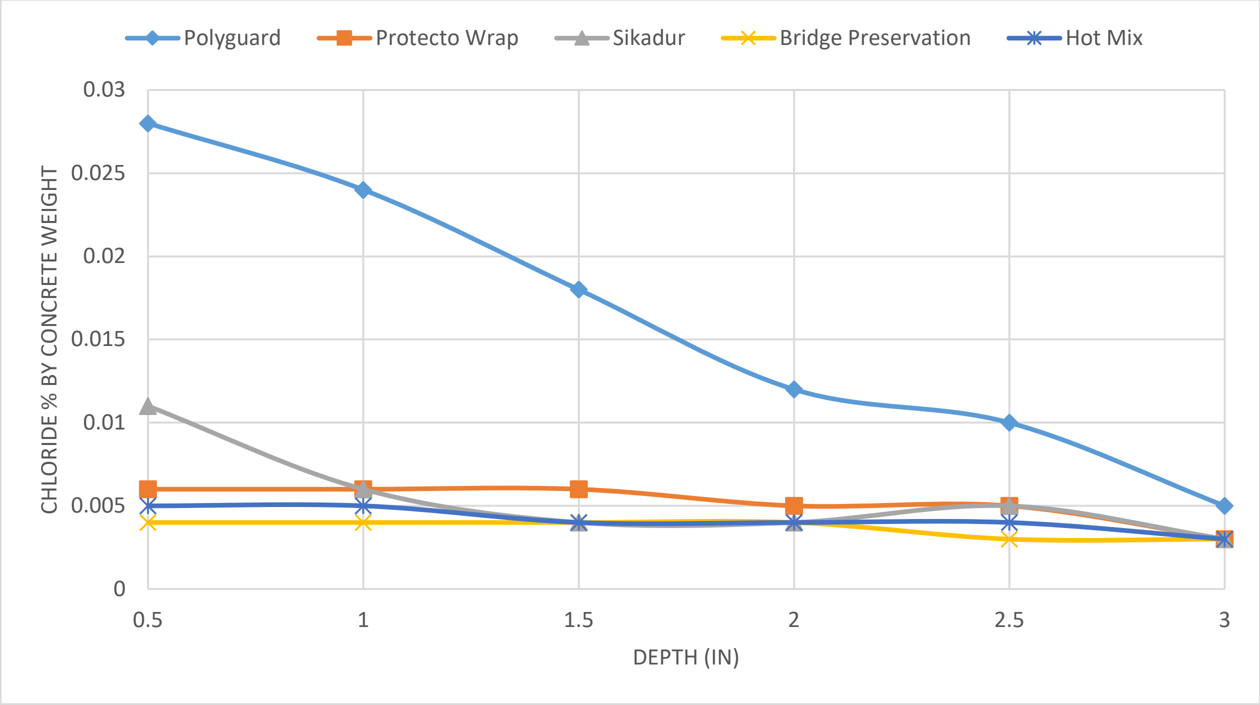


Figure 5-2. Chloride profile of the five different WPMs at 24 months

Chloride intrusion starts at the top of the bridge deck due to the spray of deicers. The traffic load and thermal expansion generate cracks on the deck surface, providing a path to the reinforcing steel that can be destructive by increasing chloride penetration. The results of the Chloride profile test are critical.

Several trends can be deduced from the chloride test results. After two years, it was found that the chloride ions can pass through the WPMs and penetrate into the concrete. All the data showed that the chloride concentrations decreased as the depth increased. Figure 5-2 illustrates the comparison of chloride resistivity among the different types of WPMs. Intrusion of chloride ions into the concrete with the Polyguard cover was much higher than the other four WPMs. The Sikadur WPM had a relatively high chloride concentration in the shallow part of concrete; but the concentration decreased at a similar rate to the other three WPMs in the deeper part of the section. There are minor differences between the remaining three WPMs. The Bridge Preservation™ WPM showed the best performance for preventing the intrusion of chloride ions in the field study. The next best performance was realized by the hot mix covered control section, with no additional WPM included. When installed on bridge decks as a *chloride* barrier, the WPMs in order of performance at 24 months from best to worst are as follows: Bridge Preservation™ > hot mix > Protecto Wrap > Sikadur > Polyguard. The difference between Polyguard and other WPMs are significant. The intrusion of chloride ions through Polyguard is over half of the critical chloride value.

5.3 Chloride Penetration by Ponding Test - Results and Analysis

ASTM C1543 is a long-term test used to measure the penetration of chloride ions into concrete by controlling the concentration of chlorides. This standard test specifically requires the size of the specimens to be at least 0.32 ft^2 of the surface area and at least 3.54-inch thickness. An enclosed wall was built to seal the top of the samples and designed to hold a 3% Sodium Chloride solution for a long time. For the ponding evaluation, specimens were ready to be tested at 9 months and 12 months. The concrete powder was collected at 0.5-inch intervals to measure the chloride profile.

All ponding tests were conducted in the structural lab at CU-Boulder. The slab specimens were casted on site by CDOT. After that, the WPMs were installed on the top surface of the slabs by suppliers. Each specimen started with a chloride concentration of 0% at all depths. The results from the Ponding test at both 9 months and 12 months are shown in the following Tables and Figures.

Table 5-7. Chloride penetration on Polyguard covered specimen at 9 months

Polyguard	mV readings	% Cl- by concrete weight
0.5	8.30	0.262
1	24.40	0.133
1.5	32.40	0.094
2	35.90	0.081
2.5	41.00	0.066
3	47.00	0.051

Table 5-8. Chloride penetration on Protecto Wrap covered specimen at 9 months

Protecto Wrap	mV readings	% Cl- by concrete weight
0.5	26.00	0.124
1	37.30	0.077
1.5	38.80	0.072
2	65.60	0.018
2.5	65.60	0.018
3	75.40	0.011

Table 5-9. Chloride penetration on Sikadur covered specimen at 9 months

Sikadur	mV readings	% Cl- by concrete weight
0.5	45.7	0.054
1	59.6	0.025
1.5	61.9	0.022
2	61.2	0.023
2.5	60	0.025
3	63.1	0.021

Table 5-10. Chloride penetration on Bridge Preservation™ covered specimen at 9 months

Bridge Preservation™	mV readings	% Cl- by concrete weight
0.5	23.30	0.139
1	45.80	0.054
1.5	54.50	0.034
2	60.50	0.024
2.5	78.10	0.01
3	83.80	0.008

Table 5-11. Chloride penetration on control section specimen at 9 months

Hot Mix	mV readings	% Cl- by concrete weight
0.5	46	0.053
1	59.5	0.026
1.5	75.6	0.011
2	79.5	0.009
2.5	85.9	0.007
3	88.9	0.006

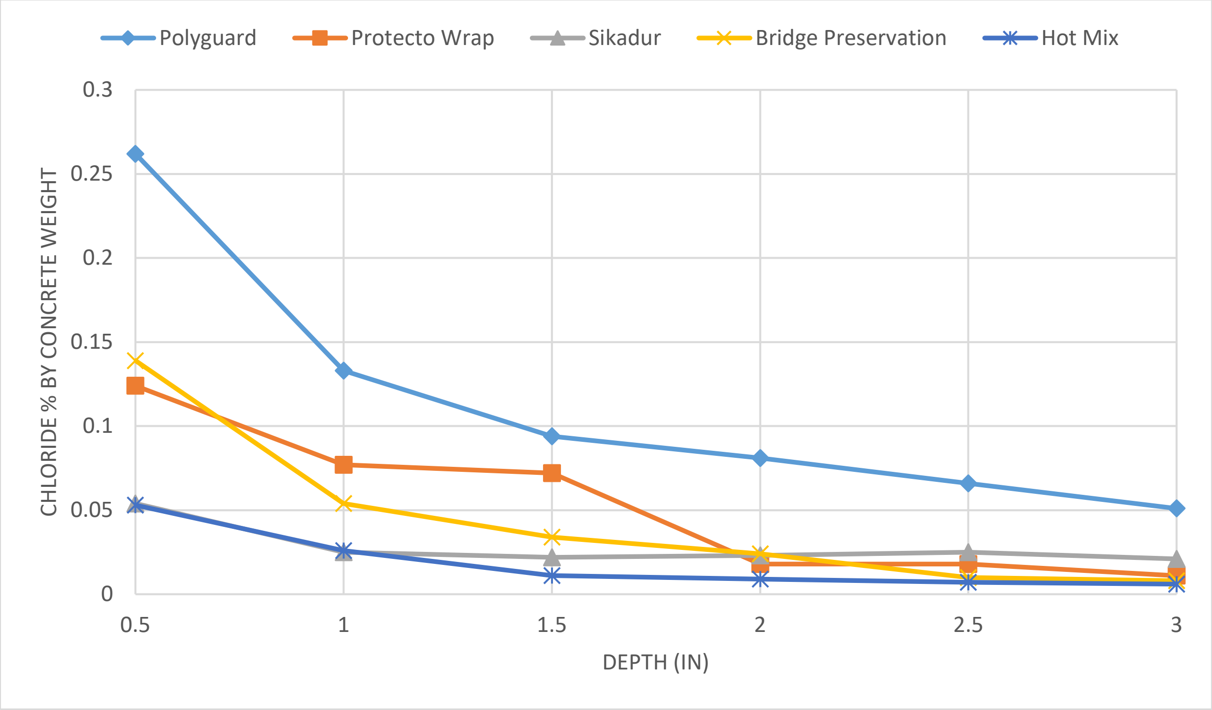


Figure 5-3. Chloride profile of the five different WPMs at 9 months

Figure 5-3 and Tables 5-7 to 5-11 provide the results of the Chloride penetration after 9 months ponding. It was found that the control section specimen (hot mix) provided the best performance on resisting chloride ion penetration after 9 months. Sikadur, which showed a similar trend to the hot mix, performed the second best. When used as a *chloride* barrier with ponding, the WPMs in order of performance at 9 months from best to worst are as follows: hot mix > Sikadur > Bridge Preservation™ > Protecto Wrap > Polyguard. Both preformed WPMs showed deficient performance at 9 months ponding test. These results were relatively comparable to the chloride profile test results obtained from the bridge deck specimens.

Table 5-12. Chloride penetration on Polyguard covered specimen at 12 months

Polyguard	mV readings	% Cl- by concrete weight
0.5	4.00	0.315
1	13.20	0.213

1.5	13.60	0.21
2	16.50	0.185
2.5	26.10	0.123
3	26.80	0.12

Table 5-13. Chloride penetration on Protecto Wrap covered specimen at 12 months

Protecto Wrap	mV readings	% Cl- by concrete weight
0.5	-12.50	0.634
1	9.10	0.254
1.5	20.60	0.156
2	30.80	0.101
2.5	41.20	0.065
3	44.10	0.058

Table 5-14. Chloride penetration on Sikadur covered specimen at 12 months

Sikadur	mV readings	% Cl- by concrete weight
0.5	-12.1	0.623
1	-2.5	0.415
1.5	13.6	0.21
2	13.9	0.207
2.5	25.7	0.125
3	38.9	0.072

Table 5-15. Chloride penetration on Bridge Preservation™ covered specimen at 12 months

Bridge Preservation™	mV readings	% Cl- by concrete weight
0.5	-2.70	0.418
1	9.60	0.248

1.5	24.50	0.132
2	32.40	0.094
2.5	40.90	0.066
3	65.20	0.019

Table 5-16. Chloride penetration on control section specimen at 12 months

Hot Mix	mV readings	% Cl- by concrete weight
0.5	27.7	0.115
1	35.1	0.084
1.5	46.5	0.052
2	57.1	0.029
2.5	59.8	0.025
3	81.3	0.009

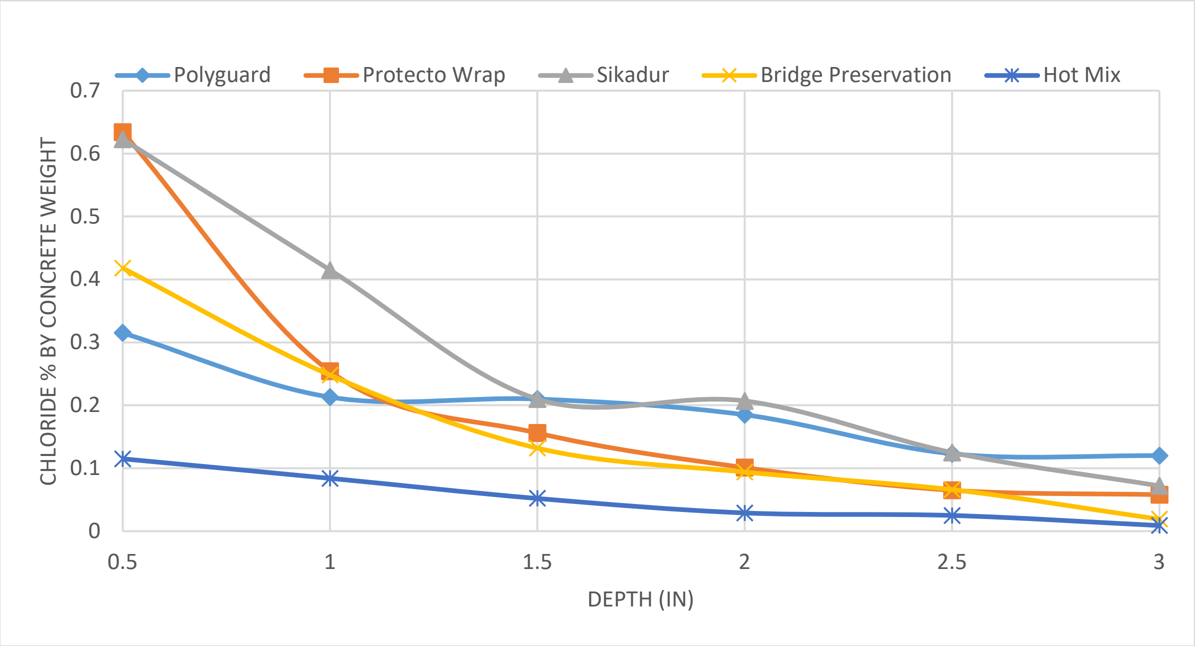


Figure 5-4. Chloride profile in five different WPMs in 12 months

Figure 5-4 and Table 5-12 to 5-16 show the results of the chloride profile after 12 months ponding. After an additional 3 months of ponding, the order of performance among the different WPMs changed. Similar to the 9 month results, the control section specimen was still the best option for preventing chloride penetration. However, the variation amongst the other four WPMs was reduced. Generally, the Bridge Preservation™ was the second-best performer. The other three are more difficult to compare since the one with the highest chloride concentration at shallow depth had the lowest chloride concentration at the deeper depth. At the deepest 3 inch depth after 12 months, the WPMs exhibited the same order of performance as was realized from the 24 month bridge deck specimens.

In addition to the chloride ponding test procedure discussed in Chapter 3.4, the moisture profile in the first 5 days was also monitored during the ponding test. This early stage examination can provide a direct analysis of the material's ability to prevent moisture penetration. The moisture profile results are shown in Figure 5-5. Although at varying levels of performance, all five WPMs were found to provide some measure of moisture protection after 5 days monitoring. When installed on bridge decks as a *moisture* barrier, the WPMs in order of performance from best to worst are as follows: Bridge Preservation™ > Protecto Wrap > Polyguard > Sikadur > hot mix. Bridge Preservation™ and Protecto Wrap showed a huge improvement in blocking moisture penetration. The other two WPMs, Polyguard and Sikadur, showed very little enhancement.

Although it can be concluded that all the WPMs do provide some level of moisture blocking capability; after the 12 month ponding test, it was found that none of the WPMs provide effective control at blocking chloride penetration.

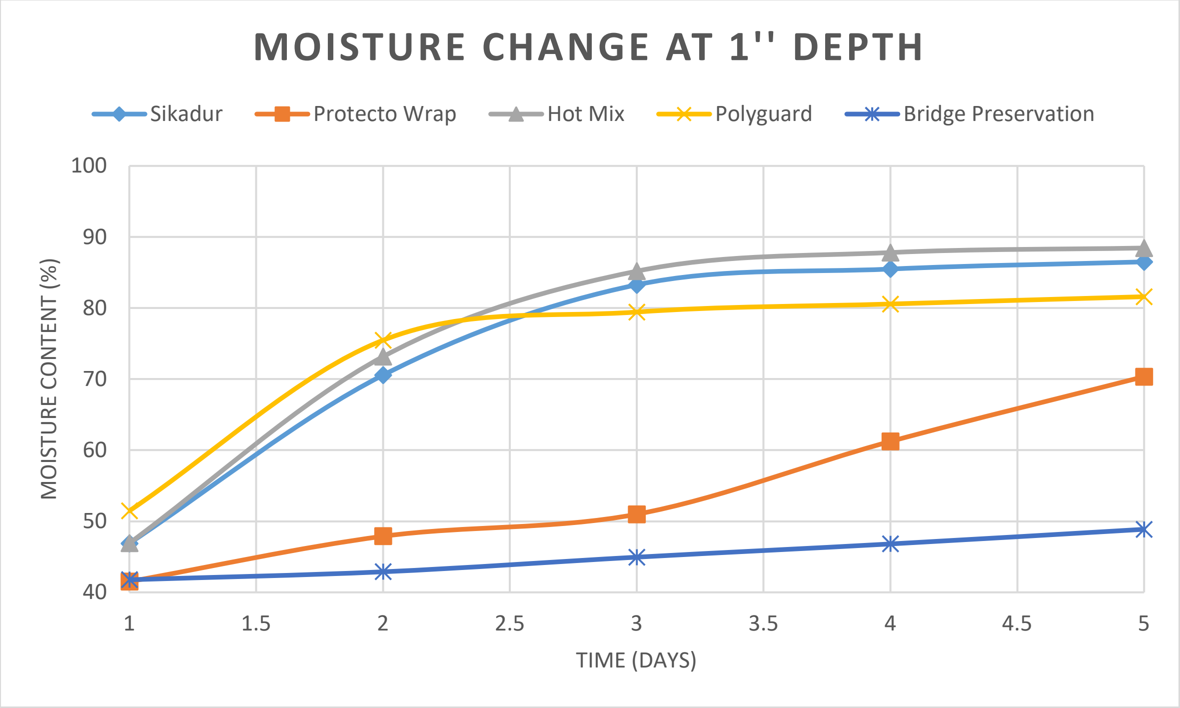


Figure 5-5. Moisture profile of the five different WPMs in the first 5 days

5.4 Rapid Freeze-Thaw Test - Results and Analysis

The 2-inch diameter specimens for this test were taken from different sections of the actual bridge deck at 12 months. The test was conducted by using the Logan Rapid Freeze-Thaw Cabinet described in Chapter 3.5. The samples underwent 300 freeze-thaw cycles in 30 days. The length change and weight loss were measured for each sample in 2 day intervals.

The length change of the specimens was measured by using a dial caliper with an accuracy of 0.001 inches. Two nuts were glued on the surface of the sample for measuring. The length change from each specimen was measured three times and the average value was used to determine the final length change. The following eq. was used to calculate the length change:

$$\Delta L = \frac{L_x - L_i}{L_i} \qquad (5\text{-}1)$$

where ΔL is the length change of specimen (%) at x days, L_x is the dial gauge reading at x days, and L_i is the initial dial gauge reading before the test.

The relationship between length change (%) and cycles is shown in Figure 5-6. Unfortunately, the specimen with the Sikadur WPM installed was broken during the previous test, and the length change could not be measured for this specimen. Therefore, only the remaining four WPMs' change in length were plotted. Length change data was collected at 20 cycle increments, for a total of 300 cycles. All the specimens experienced obvious length changes. Initially, the expansion can be attributed to the water absorption into the core. After 200 cycles, the length changes became more stable, which indicates that no spalling occurred.

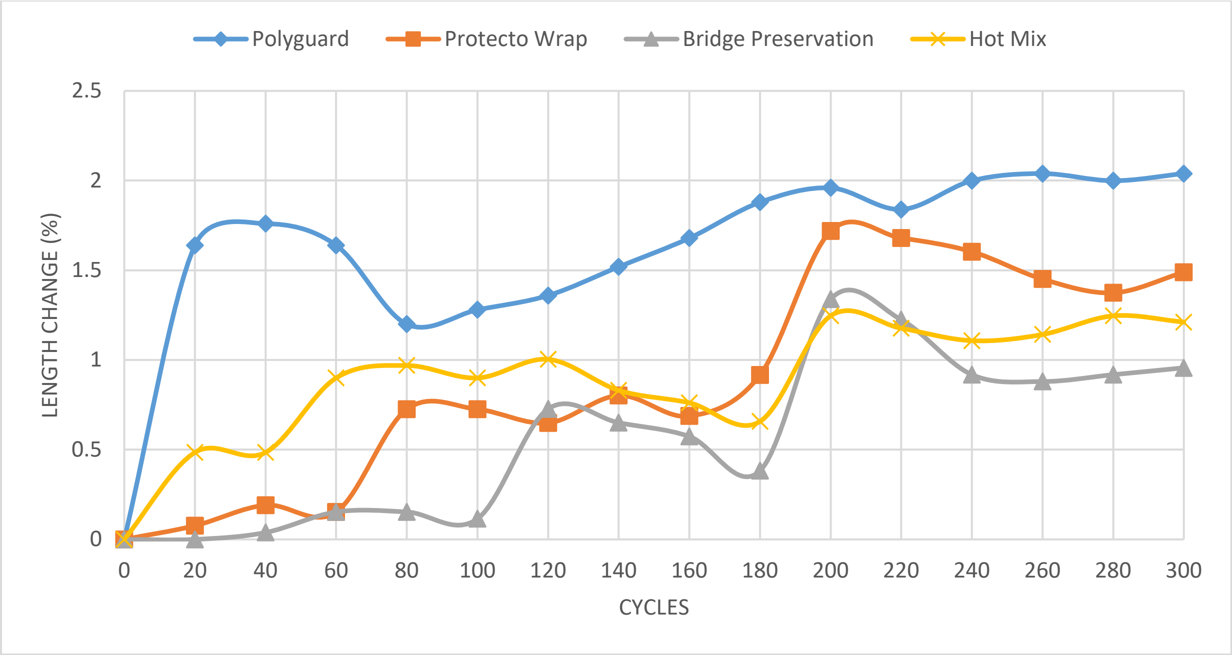


Figure 5-6. Length change after 300 cycles of freeze-thaw

The weight loss of each specimen was measured by using a scale with an accuracy of 1 g. Similar to the length change test, weight loss data was collected at 20 cycle increments, for a total of 300 cycles. The results are shown in Figure 5-7. There was no obvious weight change for any of the specimens during the freeze-thaw cycling. Therefore, no conclusive results can be extrapolated from this test.

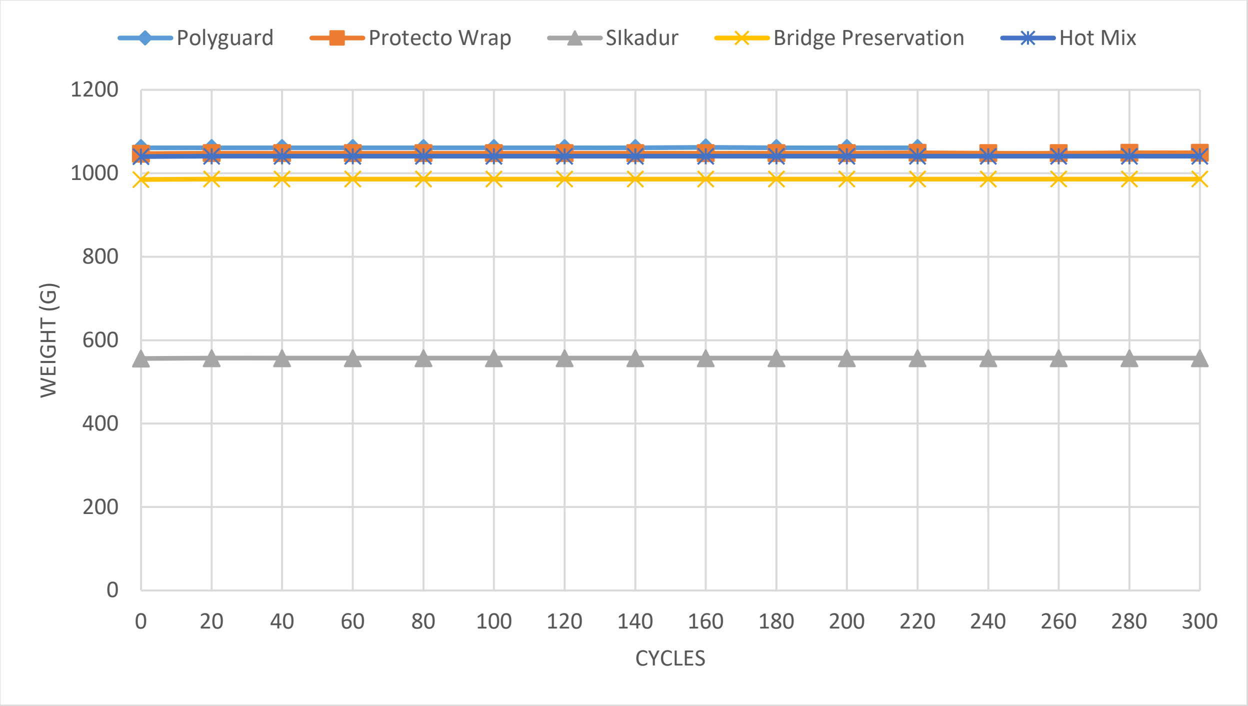


Figure 5-7. Weight change after 300 cycles of freeze-thaw

CHAPTER 6 TWO-LAYERS MODEL TO PREDICT THE CHLORIDE PENETRATION IN THE CONCRETE DECKS

From a previous research, a two-layer model was developed based on a Laplace transform of the diffusion equation (Zemajatis et al. 1999). The solution is presented in Eq. 6-1. This prediction method uses a constant *k* (called sealer characteristic constant) to represent the effect of top layer on the intrusion of chloride into the concrete. In this study, we can use the parameter *k* to take into account the effect of WPMs. Through the adjustment of *k* and D_c by using a curve fitting method to the experimental results obtained in previous chapters, the model can be established.

$$C(x,t) = k\sqrt{t} \times [e^{\frac{-x^2}{4D_c t}} - \frac{x\sqrt{\pi}}{2\sqrt{D_c t}}\left(1 - erf\,\frac{x}{2\sqrt{D_c t}}\right)] \qquad (6\text{-}1)$$

where *C* is the chloride concentration at a depth *x* and time *t*, D_c is the diffusion coefficient, and *k* is the seal characteristic's constant.

In order to show the effectiveness of this prediction model, one case of WPMs is used here as an example: 24-month bridge deck covered by Sikadur WPM. The result is shown in Fig. 6-1. After the curve fitting, the values of *k* and D_c are chosen as 0.02657 and 2.846, respectively. As one can see from the figure, the model can predict the chloride concentration profiles in the concrete deck very well.

After the two parameters of *k* and *Dc* are determined this way, the model can then be used for predicting future chloride concentration profiles at a different *t*. One example is provided here for prediction the service life of Sikadur WPM under chloride ponding condition. The service life in this example means the time for a rebar in the bridge deck to reach the corrosion initiation time. The initiation time is important because when the corrosion of rebar starts, spalling of concrete cover will occur soon. The value of *C* in Eq. 6-1 will be the critical chloride concentration, which equals 0.05%. The depth *x* will be the thickness of WPM and top coating 2.5" plus the thickness of concrete cover 3.0", the total equals 5.5". Taking these values into Eq. 6-1, the time *t* for the critical chloride value to reach the rebar level can be solved, which equals 17.2 years. This can be considered as the corrosion initiation time of the bridge deck covered by Sikadur WPM under a constant ponding condition (this is a condition much severer than actual service condition). It is important to point out that bridge decks are not exposed to a constant ponding condition, and therefore the actual initiation time of the bridge deck is longer than 17.2 years.

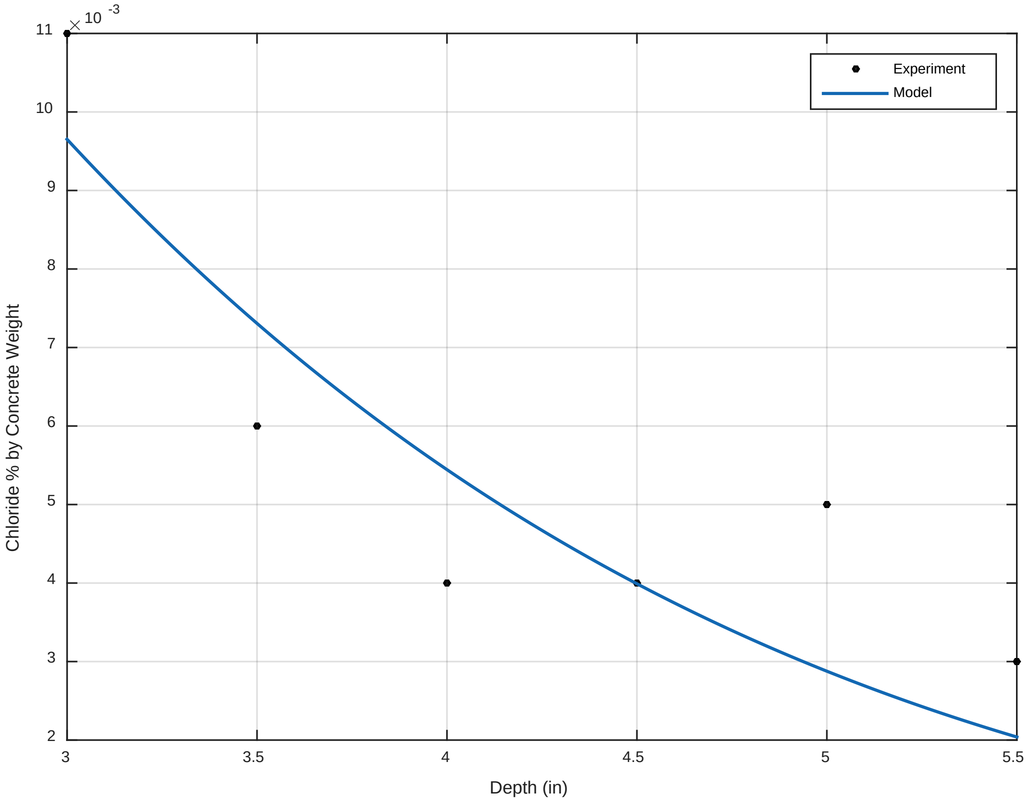


Figure 6-1. Compared results from experimental study and modeling work

For any other WPMs to be used in future projects, a similar method can be used to determine the two parameters of *k* and *Dc*, which may be different from the two values determined based on the present test results of Sikadur WPM. Then, the time for the chloride to reach the critical value at a rebar level can be calculated, which can be considered as the corrosion initiation time of the bridge deck covered by the WPM.

CHAPTER 7 COSTS OF THE WPMS USED IN THE PROJECT

In this project, four different types of WPMs have been installed onto the bridge deck. The manufacturers have provided the cost for spray applied WPMs from a number of agencies that have been using it extensively over the past several years. The data are shown in Table 7-1:

Table 7-1. Cost of WPMs

Agencies	Average of Low Bid Unit Price ($/yd^2)
CT DOT	82
MassDOT	101
NDOT	65
NJ DOT	78
NYS DOT	80
Average	81

Based on the previous research on thin-bonded overlay project, the cost can be compared with WPMs in Table 7-2. As one can see, the cost of thin-bonded overlay is much lower than WPMs. In addition, from the data collected by the manufacturers, it can be found that the price decreases as the size of the project increases. Other factors, such as the number of mobilizations, location of the project, can also impact the price.

Table 7-2. Cost of Thin-Bonded Overlays

Material	Average of Low Bid Unit Price ($/yd^2)
PPC MLS	40
Flexolith	36
Plexideck	42

Therefore, the cost of WPMs is in general higher than that of the thin-bonded overlays. Since the long term performance of WPMs cannot be decided based on the limited test data collected in the present study, the cost effectiveness of WPMs comparing with thin-bonded overlays cannot be determined. Similarly, the test data of the WPMs are not conclusive comparing with the control section used in this study, the cost effectiveness of WPMs comparing with the control section cannot be determined. More test data are needed before cost effectiveness of WPWs can be obtained.

CHAPTER 8 PRELIMINARY GUIDELINES

8.1 Installation Guideline

The installation details of WPMs have been provided by the manufacturers. Generally, the installation process can be separated into nine steps shown below:

(1) Before installing the WPMs, the quality of bridge deck surface has to be inspected and improved based on ASTM C1305. The contamination and rough edges would be removed from the concrete surface. The surface clean process is not allowed to use water. The brooms, vacuum, or compressed air are potentially used for cleaning the surface.

(2) The deck has to be dry before installation of WPMs, generally less than 5% of moisture content has to be achieved. Therefore, the installation must be done in a dry condition.

(3) The primer would be used to enhance the bond strength between concrete deck and the WPMs. The primers used would follow specifications from the manufacturers.

(4) Reinforcing membrane would be installed over cold joints and cracks.

(5) Completely sealing would be necessary with curb up to the depth of the asphaltic concrete overlay.

(6) For preformed membranes, the installation would start from the low point of the deck. The adequate lap between adjacent strips would be provided, usually around 6”. This overlap is in the transverse direction.

(7) Before placing the overlay, the blisters appeared on the top of the membrane have to be repaired.

(8) Traffic pass is not allowed before the asphaltic overlay is installed.

(9) The last step is to use tack coat to enhance the bond between the membrane and the overlay. The asphalt overlay has minimum 2” compacted thickness. The installation temperature is around 290 °F to 340 °F.

8.2 Suggestions

Based on the results obtained from the experimental studies conducted in this project, several suggestions can be made on the selected WPMs as means for prolong the service life of bridge decks.

(1) The chloride concentration into the concrete bridge deck has been widely considered in the U.S. and around the world. The corrosion of embedded steel bars is very harmful to the bridge deck system. Therefore, prevention of the chloride penetration is necessary and installing WPMs may be one of the most effective strategies.

(2) Since the period of this project is short, more field trips should be arranged to revisit the bridge decks and collect more samples for analysis. Further evaluation work can be conducted to confirm the performance of the WPMs installed on the bridge when they are at least five years old.

(3) If one of the WPMs will be used on a bridge, the installation procedure recommended by the manufacturer can be used. Further improvement can be made when more test results are available.

CHAPTER 9 SUMMARY AND CONCLUSIONS

From this two-year project in Colorado, several conclusions can be made about the four different WPMs that were examined through a variety of testing methods. These conclusions are listed below.

(1) The pull-off test was used to obtain the bonding strength between WPMs and concrete deck. After 12 months of ponding, the bonding strength experienced a small decrease.

(2) The chloride profile test was used to analyze the resistivity of chloride penetration. The cylinder specimens were collected from the bridge deck after a 2-year period. During this period, the bridge deck experienced varied weather and traffic loads. From the lab test results, the free chloride concentrations at different depths were measured. The Bridge Preservation™ WPM showed the best performance which was close to the control section. The other three WPMs all showed worse chloride resistivity than the control section, especially the Polyguard.

(3) The chloride concentrations in concrete were measured from the ponding test. Results were collected after 9-month and 12-month periods. The moisture profile was also monitored for the first five-days of ponding in order to prove the effectiveness of moisture resistivity of each WPM. All of the WPMs were found to be effective to prevent the intrusion of moisture. However, all the WPMs showed worse performance than the control section in protecting the concrete from chloride penetration. In general, the constructed-in-place WPMs performed relatively better than the preformed WPMs.

(4) The freeze-thaw test was used to illustrate the effectiveness of the WPMs in protecting the bridge deck from the effect of freeze-thaw temperature cycling. All the specimens (except Sikadur, which was not available for testing) experienced obvious length changes. All the WPMs showed the ability to protect the bridge deck from spalling damage due to freeze-thaw action.

It is suggested that for future work, the examination period needs to be extended in order to confirm the results and conclusions obtained from this study. Such a short period research cannot be used to adjust the long term performance of the WPMs. For short term project, the asphalt layer in the control was effective in controlling salt intrusion. However, the asphalt layer will be ineffective with aging when cracking. At that stage, the performance of WPMs can be obtained more accurate and realistic.

To better understand the performance of each WPM, more studies need to be conducted to determine if the expected service life of each WPM can be met. The physical performance of each section needs to be monitored for at least another 5 years to ensure the bond strength remains at acceptable levels.

A chloride penetration model was adopted in the present study, which can predicted the long-term chloride concentration profiles based on a short-term test data. More work needs to be done when future field trips can be arranged, in order to predict the corrosion initiation time for each section with different WPMs.

The cost effectiveness and construction guideline has been developed based on the information provided by the manufacturers. Long term cost effectiveness can be built based on the long term performance of the WPMs.

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