Spring 1-1-2013

Evaluation of Thin Bonded Overlays as a Protective System for Highway Bridge Decks

Benjamin Lee Gallaher
University of Colorado at Boulder, gallaher@colorado.edu

Recommended Citation

Gallaher, Benjamin Lee, "Evaluation of Thin Bonded Overlays as a Protective System for Highway Bridge Decks" (2013). *Civil Engineering Graduate Theses & Dissertations*. 449.
https://scholar.colorado.edu/cven_gradetds/449

University of Colorado at Boulder

Evaluation of Thin Bonded Overlays as a Protective System for Highway Bridge Decks

By
Benjamin L. Gallaher
B.S., University of Colorado, 2011
M.S., University of Colorado, 2013

A master's thesis submitted to the Faculty of the
Graduate School of the Civil Engineering Department of
the University of Colorado in partial fulfillment of the
requirement for the degree of Master of Science.

Fall 2013

This thesis is entitled:

Evaluation of Thin Bonded Overlays as a Protective System for Highway Bridge Decks

written by Benjamin L. Gallaher

has been approved for the Department of Civil, Environmental, and Architectural Engineering

X

Dr. Yunping Xi
Committee Chair

X

Dr. Abbie Liel
Committee Member

X

Dr. Petros Sideris
Committee Member

*Date*______________

The final copy of this thesis has been examined by the signatories, and we find that both the content and the form meet acceptable presentation standards of scholarly work in the above mentioned discipline.

ABSTRACT

Gallaher, Benjamin (M.S, Civil, Environmental and Architectural Engineering)
Evaluation of Thin Bonded Overlays as a Protective System for Highway Bridge Decks
Thesis directed by Professor Yunping Xi

Chemical attack from chlorides, exposure to severe environmental conditions, and wearing from direct traffic loading causes highway bridge decks to deteriorate the fastest among all the structural components of a highway bridge. In an effort to better protect the bridge deck and reduce maintenance costs, State Departments of Transportation (D.O.T.) apply protective topical overlays to the bridge decks. The use of Thin-Bonded Overlays (T.B.O.) was investigated by the Colorado Department of Transportation (C.D.O.T) to gage three TBO's performance as an effective protection system. A polyester, an epoxy, and a methyl methacrylate were selected to be evaluated. Each overlay was installed on E-17-QM and monitored for approximately one year. The performance of each overlay was evaluated on: skid resistance, bond strength, resistance to chloride ingress, freeze-thaw resistance, and cost. Skid resistance testing showed that at early ages, each overlay increased the skid resistance of the deck, however after 14 months, each section had skid numbers lower than the bare deck. Chloride tests included testing the profiles of specimens extracted from the deck and from ponded specimens, and from testing the electrical indication of chloride ion penetrability. Physical performance tests included skid resistance, bond strength, and freeze/thaw durability. The MMA proved to be best at preventing the intrusion of chlorides, while Epoxy proved to be the most durable. The short-term results indicate that all three thin bonded overlays can be used as an effective topical protection system to reduce chloride ion ingress and increase the service life of highway bridge decks.

ACKNOWLEDGMENT

The author gratefully acknowledges the Colorado Department of Transportation for their financial support in conducting this research. The author also wishes to thank Mr. Skip Outcast, Mr. David Weld, Dr. Aziz Khan, and their colleagues at the Colorado Department of Transportation Development Applied Research and Innovation Branch for their assistance during the installation, collection of on-site data for this project, and allowing us to use the new Mobile Barrier. Lastly, thank you to Mr. Gregg Freeman, Mr. Edward Nagel, and Mr. Robert Brodsky and their associates for donating the materials, their time, and their effort for completing the installation of each respective test section.

Table of Contents

List of Figures:

List of Tables:

Chapter 1 Overview

1.1 Background

Chemical attack from chlorides, exposure to severe environmental conditions, and wearing from direct traffic loading cause highway bridges decks to deteriorate the fastest among all the structural components of a highway bridge. The American Society of Civil Engineers reported that 24.9% of the 607,380 bridges in national highway system are either structurally deficient or functionally obsolete as of 2011 (Young 2011). In Colorado alone there are 8,591 bridges of which 6.6% (566) are considered structurally deficient and 10.6% (907) are considered functionally obsolete (ASCE 2013). Intrusion of chlorides into the bridge deck is the most detrimental threat to the life-span of the bridge deck. Chlorides cause concrete deterioration and are the catalyst to the corrosion process of the reinforcing steel.

About 70% of U.S. roadways and population are in areas that will receive at least 5 inches of snowfall annually. Roadways must be cleared of snow and ice in order to reduce the direct costs associated with bridge repair and the indirect economic costs caused by loss of business productivity and traffic accidents. To keep roadways clear, the U.S. uses roughly 15-20 million tons of deicing salts each year. Since the 1960's transportation agencies across the world have used a variety of deicing salts including but not limited to: Sodium Chloride (NaCl), Magnesium Chloride (MgCl2), Calcium Chloride ($CaCl_2$), Potassium Acetate (CH_3COOK), Potassium Chloride (KCl), and Calcium Magnesium Acetate (CMA). The most utilized deicing agent is Sodium Chloride, is effective down to temperatures of -6° F. The two other most common deicing agents are Magnesium Chloride and Calcium Chloride; solutions of these deicers are blended or used individually when temperatures are expected to drop below -6° F (Houska).

In an effort to better protect the bridge deck and reduce maintenance costs, State Departments of Transportation (D.O.T.) apply wearing surfaces to the top of the bridge decks. There are four types of overlay systems are commonly used as preventative maintenance systems: asphalt, reinforced Portland cement, non-reinforced polymer modified concrete, and polymer concrete or Thin Bonded Overlays (T.B.O.). Overlay selection depends on existing deck condition, current material and labor costs, job size, and the amount of time the bridge can remain closed to traffic.

A 2001 FHWA corrosion study broke the U.S. economy into 5 major sectors which include infrastructure, utilities, transportation, production/manufacturing, and government. At the time, the U.S. annual direct cost of corrosion was estimated at $137.9 billion (3.1% of 1998 U.S. GDP) of which $29.7 billion (0.67% of 1998 U.S. GDP) made up the cost for the transportation industry. The annual direct cost of highway bridges was approximately $8.3 billion which accounts for 6.02% the annual cost of corrosion (FHWA 2001). This can be further broken down into:

- $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 bridges

According to the Bureau of Economic Analysis, the estimated 2013 US GDP is approximated $16.66 trillion dollars (Bureau of Economic Analysis, 2013). Assuming that the direct annual cost of corrosion stayed at 3.1% of GDP and that the annual direct cost of highway bridges remained at 6.02%, the direct annual cost of highway bridges should be at approximately $31 billion. This can again be broken down into:

- $14.1 billion (2.76%) to replace deficient bridges over the next ten years.
- $7.5 billion (1.45%) maintenance and capital costs for concrete bridge decks
- $7.5 billion (1.45%) for maintenance and capital costs for concrete substructures
- And $1.8 billion (0.36%) for maintenance and capital costs for steel bridges

1.2 Objectives of the Study

In order to improve long term performance in concrete bridge decks, thin bonded overlays were applied to the top concrete surface in an effort to protect the concrete bridge deck. Thus far there has been little systematic research conducted in Colorado for the performance evaluation of Thin Bonded Overlays (TBOs). The aim of this project is to analyze the behavior and cost effectiveness of 3 different thin bonded overlays applied on reinforced concrete decks in comparison with the bare deck under service loads which include traffic, freeze-thaw, and wet/dry exposure.

Objective 1 - To evaluate the ability of various thin bonded overlays to stop the intrusion of chloride from deicers into concrete bridge decks.
Objective 2 - To access the cost effectiveness of the thin bonded overlays.

This document contains a review of the types of protection options available for use on bridges and a review of the performance of the past thin bonded overlay projects. This is followed by the experimental setup, short-term analysis, and performance evaluation of three different thin bonded overlays installed in Denver, Colorado.

1.3 Test Bridge Description

The bridge selected for conduct this experiment was E-17-QM. The bridge is located in the Metro-Denver area over Interstate 25 connecting Interstate 270 and U.S. 36 which is located in *CDOT Region 6*. Constructed in 1998, E-17-QM is an 841 foot long, five-span steel box girder bridge with a concrete bridge deck. From east to west the bridge spans measure: 118 feet, 188 feet, 189 feet, 189 feet, and 151 feet with 3 foot abutments on either side. The bridge deck width is 58.1 ft. from edge to edge. The cast-in-place concrete deck is specified as CDOT Class D Concrete with 400 MPa reinforcing steel.

A 2010 inspection reported the deck condition was good (7 out of 9) and superstructure and substructure condition was very good (8 out of 9). The 2008 Average Daily Traffic (A.D.T.) is approximately 56,900 vehicles with 4% being truck traffic (Braughn 2013). Figure 1-1 shows the deck surface prior to the installation of the thin bonded overlays. In the figure it can be observed where the deck surface has had general repairs including placement of a tar based crack retarder. The number “5” is seen on the lower right-hand side in the figure below shows the end of the previous experimental project and where this new project would begin.

Figure* 1-1 *Deck Surface Prior to Installation

Chapter 2 Literature Review

2.1 Introduction

In 2013, the American Society of Civil Engineers (ASCE) graded the condition of the infrastructure in United States, and gave it a C+. One in nine bridges can be classified as structurally deficient, and that the average age of the 607,380 bridges, is 42 years old (ASCE 2013). In the second half of the last century, it was recognized that chlorides induce corrosion in reinforced concrete structures (Angst 2009). The corrosion of the reinforcing steel leads to the ensuing reduction in strength, serviceability, and aesthetics of the bridge (Stanish 1997). Given the poor condition of the U.S. infrastructure, particularly its reinforced concrete bridges, and the fact that chlorides accelerate deterioration rates, significant research efforts have been made to extend the life-span of our reinforced concrete bridges while mitigating the intrusion of chlorides.

2.2 Chloride Transport

The most crucial factor in the degradation of concrete bridge decks is the intrusion of chlorides into the deck. Next a review of the mechanisms of chloride Ion transport, the theory of chloride diffusion, and the properties of concrete that effect the rate of chloride penetration will be covered.

2.2.1 Chloride Mechanisms

There are three mechanisms for chloride ion transport into concrete: diffusion, hydrostatic pressure, and capillary absorption. Diffusion is the movement of a substance under a concentration gradient. Hydrostatic pressure is the force applied by a fluid at a point within the fluid. This force increases as a function of depth due to gravitation forces acting on the liquid. Capillary absorption is the drawing in of fluids into unsaturated pores through suction and surface tension forces.

For diffusion to occur there must be a species concentration gradient, i.e. the chloride ion gradient and the concrete must be assumed to be a continuous liquid phase. Hydrostatic pressure induces chloride ingress through permeation by an applied hydraulic head that contains chlorides on one side of the concrete. Absorption is driven by moisture gradients formed from the wetting and drying cycles. If water containing chlorides comes in contact with a dry surface, it will be pulled into the pore structure through capillary suction. Of the three mechanisms, adsorption is the main mechanism of how chlorides enter the concrete substrate of a bridge deck (Stanish 1997). However, after initially penetrating the concrete, the ions must diffuse in order to reach the depth of the rebar.

2.2.2 Diffusion Theory

Under steady state conditions, **Error! Reference source not found.**, controls the diffusion process into ny substance, including concrete. The first law relates the diffusive flux to the concentration gradient. For chloride diffusion, J is the diffusion flux of chloride ions ($\frac{\mathrm{mol}}{\mathrm{m}^2 * \mathrm{s}}$), D is the diffusivity or diffusion coefficient ($\frac{\mathrm{m}^2}{\mathrm{s}}$), C is the concentration of chloride ions ($\frac{\mathrm{mol}}{\mathrm{m}^2}$), and X is the position or depth (m). The first law states that the flux moves from areas with high concentrations to areas with low concentrations is proportional to the concentration gradient. The negative sign in the equation below indicates that J is positive when the movement is down the concentration gradient shown in Figure 2-1.

$$\textbf{(2-1)} \qquad J = -D * \left(\frac{dC}{dx}\right)$$

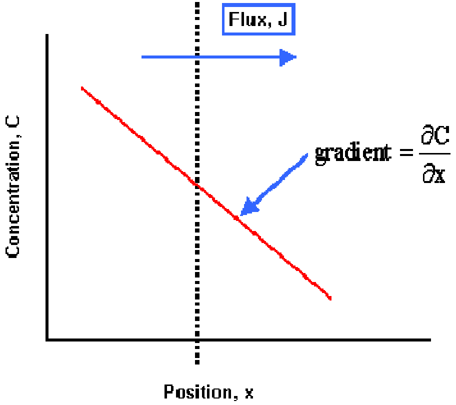

Figure 2-1 Fick's 1st Law 1

The first law can be used to derive Fick’s Second Law:

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

The second law accounts for changing concentrations or non-steady state conditions as well as the effect of changing concentrations with t, time (years).

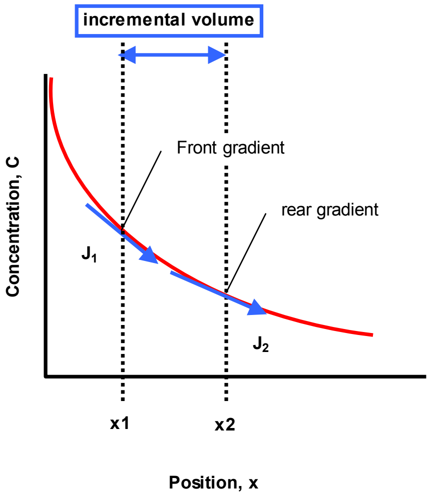

Figure 2-2 Fick’s 2nd Law 2

Fick’s second law has been solved to given the initial boundary condition that the concentration at the surface is constant, C(x=0,t>0) = C0, at an infinite distance from the surface the concentration is zero, C(x=∞,t>0) = 0 and “erf(x)” is the error function.

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

In order to directly apply Fick's Laws to the diffusion of chloride in concrete, the concrete matrix has to be assumed to be a homogenous solution. Concrete is not a homogenous solution and the porous matrix that makes up concrete has both liquid and solid components and the diffusion through the pore structure is significantly higher than diffusion through the solid components. Therefore, the rate of diffusion in concrete depends on not only the diffusion coefficient through the pore structure but also the physical characteristics of the pore structure itself. To account for this effect, the diffusivity, D, is changed to D_{eff} in all the above equations.

2.2.3 Properties of Concrete that Effect Chloride Ingress

As mentioned earlier, the rate that chloride can penetrate into a concrete substrate depends on the pore structure of the concrete itself. The pore structure of concrete is affected by the type of cement utilized, aggregate type/size, mixing techniques, and physical age. The permeability of concrete is dependent on the physical characteristics of the cement paste. The characteristics of the cement paste is affected by the water-to-cement ratio, mixing speed, and if cementing or chemical additives are utilized (Stanish 1997). Another condition that affects the pore structure is the curing temperature. Concretes that are cured at room temperature have a longer time to fully hydrate which ensures the diffusion coefficient remains low however the extended cure time leaves the concrete in a low quality condition for a longer period. Curing time is accelerated with higher temperatures which produces a higher quality, more resistant concrete at a younger age. Conversely, curing at a higher temperature does not give the cement adequate time to fully hydrate which increases the diffusion coefficient (Detwiler et al 1991).

2.2.4 Critical Chloride Concentration

The critical chloride concentration (C_{crit}) is defined in two ways; the content required for the depassivation of steel, or the content once visible deterioration has begun. The large gap between the two definitions leaves no general agreement of what Ccrit is. Research covering the last fifty years has presented values of Ccrit ranging from 0.04% to 8.34% total chloride by weight of cement (Angst 2009). The United States and Europe has arbitrarily defined the critical chloride content to be approximately 0.4% chloride by weight of cement (Angst 2009). For this study, Ccrit will be conservatively defined as 0.2% by weight of cement.

Previous studies have accounted for several different factors that affect the critical chloride concentration including but not limited to: Concrete/steel interface, type of binder/cement used, water/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 cement are the 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 of these three types of deicers, calcium chloride has a more detrimental corrosive effect than other deicers.

2.3 Types of Protection Systems

Several methods and products currently exist to prevent the penetration of chlorides and protect the reinforcing steel in a concrete bridge deck including: topical protection systems, corrosion inhibitors, cathodic protection/prevention, and alternative reinforcement steel bars. Topical prevention systems act as a barrier between the body of the deck and the surface by preventing the infiltration of water, oxygen, and chloride ions into the deck. Corrosion inhibitors are additives to the cement mix that decrease the diffusivity coefficient of the concrete. Cathodic protection uses impressed current and/or an external anode to repel the chloride ions away from the steel. Lastly, alternative reinforcement bars are made with materials that isolate the steel from the concrete that have higher corrosion thresholds. (Liang 2010).

This section of the report will focus on the topical protection systems. The earliest use of topical systems on bridge decks was in the late 1950's (Sohanghpurwala et al 1996). The purpose of topical systems is to form a protective layer between the bridge deck and the hazardous external conditions. Topical protection systems can be broken down into four main categories: Asphalt and Water Proofing Membranes (AWPM), concrete sealers, Concrete overlays, and Thin Bonded overlays.

2.3.1 Asphalt and Water Proofing Membranes

Asphalts can be placed directly on the deck, or on top of a water proof membrane. Asphalts commonly contain 5% air voids which allows the penetration of water and harmful contaminates, making the system susceptible to freeze/thaw damage (Dintz 2010). For the purposes of topical overlay systems, membranes are a barrier that is placed on top of the roadway surface and then another material is added on top of the membrane to act as the protection. Membranes can be split into three categories: built-up membranes, preformed sheet membranes, and liquid membranes. Water proofing membranes have be in use in the US, Canada and Europe since the 1960's. The average life span is 15-20 years when applied to a new deck and 5-10 years when applied to a rehabilitated deck (Russell 2011). Two new categories of membranes developed in the mid 1990's, torch-applied sheet membranes and spray applied liquid membranes, were installed in 1997 and are expected to have a service life of up to 50 years (Liang 2010).

2.3.2 Concrete Sealers

Sealers protect concrete by either forming a film-forming coating, by pore-blocking the capillary pores, or by forming a hydrophobic pore liner. Common concrete sealing systems include: linseed oil, epoxies, silanes and siloxanes, and methacrylates. Linseed oil was the first type of sealer product used in the United States however the oil is known to have short service life of two to five years. Epoxy sealers have been in use since the 1960's, although pinholes over the entire sealer surface are common indicating issue with sealing. Silane and Siloxane sealers form a hydrophobic layer on the concrete surface, but are known to be sensitive to the surface conditions during installation.

2.3.3 Concrete Overlays

2.3.3.i Reinforced Portland Cement Concrete Overlays (PCC)

A PPC overlay is made up of the same material as the concrete bridge deck. The PCC overlay consists of a single layer of concrete and depending on the thickness, an additional layer of reinforcing steel in both directions. On average PCC overlay are a minimum 2.0 inches thick. PCC systems protect the deck by increasing the amount of low permeable material that the chloride ions must pass through. These systems can also provide additional structural resistance due to the composite behavior once the overlay has cured to the deck surface (Sprinkle 1993, Liang 2010). In order to place a PCC overlay, the top 5 mm± of the existing deck must be removed to ensure an adequate bond. The structure needs to be checked for additional dead load capacity, and existing barriers may need to be modified or replaced to maintain required heights. Depending on the thickness of the overlay and environmental conditions, traffic would need to remain closed for up to 7 days before the deck could be reopened to traffic. The main advantage of a PCC overlay is the low cost of materials (Caltrans 1996).

2.3.3.ii High Performance Concrete Overlays (HPC)

High Performance concrete overlays are modified PPC overlays with the addition of either latex, silica fume, micro silica, slag, or fly ash. The addition of these additives increase the strength, decrease permeability, and can reduce the thickness to approximately 2.0 inches. High performance concrete overlays can be as thick PPC overlays although with the addition of additive the thickness can drop to as little as one inch (Sprinkle 1993). Although the use of HPC overlays can reduce the additional dead load in comparison to PCC overlays, the capacity should still be checked. Early cracking can occur in HPC's due to plastic and drying shrinkage which can propagate through the surface. This cracking allows chlorides and moisture to penetrate into the deck. More specific types of HPC overlays include Low slump dense concrete, Latex modified concrete, and fiber reinforced concrete will be discussed further next.

2.3.3.iii Low Slump Dense Concrete (LSDC)

Low Slump Dense Concrete (LSDC) overlays have a high cement content of over 800 lbs/yd^3 and a water-to-cement ratio below 0.4. While LSDC overlays have shown to prevent moisture and chloride ingress at early ages, the LSDC's have also been shown to have a lower skid resistance, surface cracking, high cost, and difficult installations. A reduction in surface cracking and easier installation has been reported by using high-range water reducing admixtures and allowing for proper curing. LSDC's have shown to have service lives of up to 25 year if done properly (Kepler et al. 2000).

2.3.3.iv Latex Modified Concrete Overlays (LMC)

The American Concrete Institute (ACI) defines a LMC as a mixture of hydraulic cement and aggregates combined at the time of mixing with organic polymers that are (re)dispersed in water. This type of concrete was first used in 1957 on US-23 in Michigan and maintained its bond for 11 years (Greenman 1970). Compared to PCC concrete, modern LMC's are more resistant to corrosion and have better mechanical properties such as compressive, tensile, and flexural strengths, and greater freeze-thaw resistance. LMC have been further modified into high early strength LMC's, and very high early strength LMC's to reduce closure times. Recently, LMC overlays have begun to use Type K cement over Type I/II cement due to the reduction in damage observed from shrinkage effects (Liang 2010).

2.3.3.v Fiber Reinforced Concrete Overlays (FRC)

Different fibers have been introduced to overlay mixes to reduce early age cracking and minimize crack widths, however, FRC overlays have had mixed results. In Oregon and South Dakota, the FRC overlays performed roughly the same as the overlay without any fibers. The types of fibers that can be added to the overlays include: asbestos, glass fiber, polypropylene, and carbon fibers. Ultra-high performance fiber reinforced concrete has been developed and tested in Europe with promising results as far as permeability and tensile strength. However, the ultra-high performance overlays are expensive due to their high fiber content and the additional cost for the fiber dispersion agents (Manning 1995, Liang 2010). The Minnesota Department investigated of a polyvinyl alcohol FRC as an overlay but experienced reflective cracking into the deck from the drying shrinkage of the new FRC overlay (Akkari 2011).

2.3.4 Polymer Concrete Overlays or Thin Bonded Overlays (TBO)

2.3.4.i Background

A polymer concrete overlay is an overlay where a polymer completely replaces the Portland cement as the main binder. The lack of Portland cement significantly reduces the thickness of the overlays, which are commonly less than 0.5 inches thick, but no thicker than 1 inch. The reduced thickness and chemical nature of polymer overlays have many benefits including reduced dead loads, faster cure times, semi-impermeability, additional skid resistance, and often no additional deck modification is required (Knight 2004).

The first TBO's installed in the 1950's were a single layer of coal tar epoxy, spread onto the deck with a broadcast of fine aggregate on the top. In the 1960's and 1970's the TBO's began using oils, extended epoxies, polyester resins, and methyl methacrylates. The first case where a modern polyester polymer overlay was used was in 1976 on Route 44 in Grand Rapids, Michigan. This overlay was reported to still be in service after 16 years (Pfeifer 1999). The majority of overlays from that time period were installed using the broom and seed method which will be defined later.

Early stage TBO's had mixed success and failure rates. Many of the overlays suffered from early age delamination due to thermal incompatibility, exhibited reflective cracking, hardening due to UV exposure, and pitting due to air bubbles in the binder. Interest in TBO's increased in the 1980's, and material suppliers began to develop new resins and installation processes in an effort to mitigate the above performance issues. New materials have been developed and need to be investigated to test their ability to prevent chloride intrusion and to check the durability of the overlays (Russell 2004).

2.3.4.ii Definitions

In order to better understand what polymer overlays are, a few key definitions have been taken from the glossary of ACI 548.5R-94 *Guide to Polymer Concrete Overlays*.

- Broom and Seed – The method of PC application in which alternate layer of resin and aggregate are built up to form an overlay. In the simplest form of application, the resin is distributed onto the deck by broom and immediately followed by the broadcasting or seeding of aggregate.
- Epoxy Resin – A condensation product of bisphenol A and epichlorohydrin, terminated by at least two highly reactive epoxy groups.
- HMWM (high-molecular weight methacrylate) – A low viscosity substituted methacrylate monomer that is characterized by low volatility.
- Methacrylate – One of a group of resin formed by polymerizing the esters of amides of acrylic acids.
- Methyl Methacrylate – A colorless, volatile liquid derived from acetone cyanohydrin, methanol, and dilute sulfuric acid.
- Polyester – One of group of resins, mainly produced by the reaction of unsaturated dibasic acid with dihydroxy alcohols.
- Polymer – The product of polymerization; more commonly a rubber or resin consisting of large molecules formed by polymerization.
- Polymer Concrete – A composite material in which the fine and coarse aggregate are bound together in a dense matrix with a polymer binder
- Premix Overlay – Aggregates and binder are combined or mixed together before place of the system
- Resin – Certain liquid prepolymer products, such as unsaturated polyester and epoxy prepolymers, which are subsequently cross-linked to form hardened polymer.

2.3.4.iii Resin Types and Materials

There are four main resin types used in thin bonded overlays: epoxy, methacrylate, polyester, and polyurethane. All four act as a binder replacement for Portland cement.

Epoxy TBO’s are a two-component system made of an epoxy resin in combination with a catalyst or hardener. Epoxies are a versatile structural adhesive that bonds well to Portland cement concrete due to the epoxies specific molecular structure.

Methacrylate resins are derived from a mixture of a methyl methacrylate monomer and an organic peroxide initiator. The methacrylate TBOs requires a primer to be applied to the point of application prior to installation in order to achieve an adequate bond.

Polyester TBO’s are normally a two-component system made of a polyester resin in combination with a catalyst or hardener. The properties and performance of the overlay primarily depend on the chemical makeup of the polyester resin used. The purpose of the catalyst portion of the system is to control/reduce cure time. The majority of polyester overlays systems use a primer prior to the overlay application to ensure good bonding to substrate surface.

Polyurethane TBOs can be a single or two-part system that has similar characteristics of a dense rubber. The overlays are used to form multiple-layers and then add aggregates to the final layer to increase the skid resistance of the system. The liquid form of the polyurethane system can be used as part of a waterproofing membrane as well. (Aboutaha 2005)

The only other component of thin-bonded overlays is the aggregate. Aggregate types can vary from quartz, silica sand, basalt, or aluminum oxide or a blend of any of the previously mentioned aggregate types. The most important factor of the aggregates that are broadcast is to contain less than 0.2% moisture (Fowler, 2011) and must be free of any contaminates such as dirt, oils, and other organic compounds.

2.3.4.iv Installation methods

Surface preparation is the most vital step to achieve the best performance for any overlay. The deck surface should be dry for at least 24 hours prior to overlay installation, shot blasted and then cleared of any contaminates during the entire installation process. Careful preparation, maintaining a clean work environment, using quality materials, following manufactures specifications for installation/cure times, and first class workmanship ensure a proper bond to the deck surface (Semen 2005).

The application of a TBO can be done in one of three ways depending on the overlay type. Multi-layer overlays are mixed on site and then applied to the deck utilizing the broom and seed method described the definitions section 2.3.4.ii above. Slurry overlays have the resin binder and fine aggregate mixed together prior to spreading the slurry onto the deck surface. Immediately after the slurry mixture of binder and fine aggregate is spread on the deck, a larger aggregate is then broadcast onto the surface. Premixed overlays can be mechanically spread and vibrated to consolidate the overlay to achieve the design depth or they can be spread with hand tools. The depth of the overlay can be controlled depending on the installation technique but typically thin bonded overlays are less than 0.5 inches thick (Fowler 2011).

Previous work with TBO's has shown that this method of application is vulnerable to contamination from dust, debris, moisture. The overlay is at high risk of premature failure if the roadway needs to be reopened to traffic between layers (Dintz 2010).

2.4 Performance of Thin Bonded Overlays

Over the past 35 years, various thin bonded overlays have been installed and monitored by state Departments of Transportation, Universities, and independent researchers. In this section, several of these studies on TBOs will be highlighted and reviewed. The studies compare the performance of different type of polymer overlays in both field and/or lab experiments. Many state DOTs have experimented with TBO's several times. In this section only 1-2 tests will be discussed from each selected state.

2.4.1 Twenty-Five Year Experience

Sprinkle (2004) evaluated the 25 year performance of 5 different thin bonded polymer overlays. The overlays were installed in California, Michigan, Ohio, Virginia, and Washington. The overlays were constructed with epoxies, epoxy urethanes, premixed polyesters, methacrylate slurries, and polyesters. The skid resistances of the new overlays were tested following ASTM E 524. The resulting skid numbers ranged from 50 to 60 immediately after installation. After 20+ years of service the majority of the overlays maintained a skid number between 30 and 40, except for the methacrylate which began to steadily lose skid resistance after approximately 4 years. The tensile bond strengths of the epoxy, epoxy urethane, and premixed polyester did not change significantly over time; however, the polyester overlay began losing strength over time and was estimated to fail 10 years after the 1995 evaluation. The permeability to chloride ion intrusion for all overlay types remained at a negligible to very low level after 10 years. The methacrylate, epoxy, epoxy urethane, and premixed polyester overlays provided adequate protection from the penetration of chloride ions over the full service life of the overlay. The author concluded that if the overlays can be installed in accordance to AASHTO specifications, then thin bonded overlays could be used to provide bridge decks protection from chloride intrusion and provide additional skid resistance for up to 25 years (Sprinkle 2004).

2.4.2 Montana, 1995

In 1995, the Montana DOT received a contract to monitor and evaluate the performance of 3 different polymer overlay systems on 13 different bridges for 2 years. The three overlays were Thorotop - a polymer concrete, Flexolith - an epoxy, and an MMA system were selected to be evaluated. The most notable observation from this project was the poor performance of the Thorotop polymer concrete. All of the Thorotop overlays were reported to have the lowest skid resistance, and some sections of this overlay exhibited complete wear-through down to the original deck surface. The epoxy and MMA products displayed minimal cracking but no delamination or loss of skid resistance after two years of service. MDOT concluded that although early observations indicated that 2 of systems were performing adequately, the evaluation period needed to be longer in order to make a thorough evaluation (Johnson 1997).

2.4.3 New York, 1999

The New York DOT installed forty-four thin bonded overlays covering a total of 202,632 ft^2 of bridge decks from 1999 – 2007. Thirty-eight of the forty-four overlays were epoxy based, and one each of MMA, polyurea, polyester, polyurethane, vinyle ester, and one not identified as a resin. Over the 8 year period only 25% of the epoxy TBOs was performing adequately. Seven of the epoxy overlays were rated to be in very good to excellent condition, while the other 5 exhibited defects including, short cracking, thickness reduction due to wearing, and small delamination. The polyester and urethane overlays remained in very good condition; however the polyester overlay did display some polishing. The only overlay determined to be completely failed was the MMA. The 8 year evaluation noted approximately 10% of the overlay had been removed due to spalling, and 10-20% of the surface aggregate had fallen out (NYSDOT 2007).

2.4.4 Illinois, 1999

Two multiple-layer thin bonded overlays were installed on adjacent bridge decks on I-57 by Illinois DOT. Prior to the placement of the overlays the half-cell potentials and chloride contents of the passing lane on both sides were analyzed. The half-cell potentials for the deck indicated “very low” chloride permeability which the authors deemed unreasonable because the decks were 29 years old at the time the cores were extracted. The initial average chloride content at the level the reinforcement was 2.6lbs Cl^-/yd^3 of concrete (0.41% by weight of cement) which is above the US accepted critical chloride level of 0.4%. After the initial preparation and before the full scale installation, a small test area was constructed and tested for bond strength to ensure preparation and installation methods were satisfactory. Skid tests conducted 4 weeks, 10 months, and 20 months after installation were still comparable to typical values for a bare Portland cement deck and superior new asphalt concrete overlays.

Due to the fact that the chloride content at the rebar depth was already exceeding the critical chloride level, chloride contents were not checked again, and the overlays performance was based on the skid resistance and visual performance. Both overlays were installed correctly and after twenty months both overlays showed little to reasonable signs of wearing, therefore it was assumed that the overlays were providing a semi-impermeable layer for protection against chloride ion penetration (Pfeifer 1999).

2.4.5 Michigan, 2003

A field survey of 7 bridges in the Upper Peninsula was conducted in the winter of 2001 to document the anti-icing effects and durability of epoxy TBO’s in comparison to 14 non-coated bridge decks (Alger, 2003). The authors noted that there was no observable difference between the amounts of snow covering the TBO decks versus the bare decks. The following summer, a survey of the 37 TBO bridge decks found that the majority of decks exhibited some level of damage varying from light pitting to large delaminations. The authors concluded that the majority of damage incurred was due to poor surface preparation. Overlays with multiple coats appeared to ensure a good bond, seal, and surface for the bridge decks. No decks were tested for chloride content; however, the results from the field survey indicate that they overlays were providing a protective layer between the environment and the concrete deck surface.

2.4.6 Missouri, 2007

As of 2007, Missouri has installed over 300 epoxy polymer thin bonded overlays, with the first one being installed in 1989. Several of the overlays have exceeded their 10-15 year life expectancy while others have failed in 2 years. Pitting due to the use improper mixing tools, was observed in sixty-two of the ninety-eight overlays monitored. The author suggested that decks that require more than 5% patching and repair, are not good candidates for the placement of an overlay due to the probability of early failure. The author also concluded that overlays on bridges with longer spans were more likely to fail early due to the flexibility of the bridge and thermal incompatibility of the overlay (Harper 2007).

2.4.7 Kansas, 2009

Kansas DOT has installed and monitored several TBO projects for the last 20 years. From 1999 to 2009, KDOT has installed 90 thin bonded polymer overlays, 14 of them being multi-layered systems (Meggers 2009). Kansas has chosen to install polymer overlays over other protection systems due to TBO's reduced lane closure times which reduce user costs and traffic control costs. The table below shows a cost comparison of a polymer concrete overlay vs. a silica fume overlay. The cost per day included traffic safety costs, milling and patching of the original deck surface, and installation on a 350 ± foot long bridge deck.

Table 2-1 - Average cost comparison of two overlay types

	Silica Fume Overlay	**TBO**
Two Lane Highway	*$700/day* *(closed for 20 days)*	*$1200/day* *(closed for 5 days)*
Four Lane Highway	*$800/day* *(closed for 20 days)*	*$335/day* *(closed for 5 days)*

Meggers (2009) reported that overall KDOT has had positive experiences with TBOs hence the increased use with time, although they have also had some poor experiences. To reduce the number of failures, KDOT developed a standard for selecting the type of protection system to be utilized. For decks with 3-10% distress a polymer overlays is selected, for 10-50% distress a silica fume overlay is selected, and if greater than 50% distress, further inspection is required (Krass 2008). Given the guide lines provided by the KDOT, it is advantageous to install a TBO overlay early in the structures life.

2.4.8 Oregon, 2010

Oregon conducted a comparative study of eight different overlay systems to identify and then recommend for future use (Soltesz 2010). The overlays were placed on two different bridge decks and subjected to traffic loading from trucks and passenger vehicles included vehicles with studded snow tires. Each product manufacture was responsible for deck preparation, aggregate selection, and TBO installation in each respective test section. Overlay types included in the study were: epoxy, MMA, polyester, and Urethane thin bonded overlays.

The overlays were compared based on locked wheel skid resistance, aggregate characteristics, abrasion, water absorption of the resin, tensile strength of the resin, flexural strength, and visual inspection. After exposer to approximately 1.3 million vehicles, three overlays, Tyregrip – a single-layer epoxy, Safetrack HW – a single-layer MMA, and Urefast PF60 – a multi-layer urethane, began to wear through down to the deck surface. Although the other 5 products did not wear through, they performed poorly in terms of skid resistance. Each overlay was predicted to have a lower skid resistance than the bare deck after only 5 months.

2.4.9 Colorado, 2011

Colorado DOT installed two thin bonded epoxy overlays in 2011 to evaluate the performance of two commercially produced products (Young 2011). The products were installed on an existing curved deck in the southern Denver area. Prior to installation the deck had all roadway stripping removed and was then cleaned using an abrasive blaster and compressed air. The products were compared based on their physical properties such as anti-icing, prevention of chloride intrusion, bond strength, substrate depth, and skid resistance and traffic safety. Each overlay produced an adequate bond to the deck and provided a suitable protective layer to prevent chloride intrusion which was seen by the reduced chloride content in the bridge. Early results indicated a reduction of traffic accidents in the area, however further investigation is required to confirm the results.

Chapter 3 Products & Experimental Testing Methods

This study investigated 3 different commercially produced products to test their performance as an effective structural protection system. Each companies overlay test specimens shall herein be referred to as follows: “Control” – bare deck, “Polyester” by Kwik Bond, “Epoxy” by Euclid Chemical, and “MMA” by Plexicoat America. Once the overlays were installed, sample specimens were collected and tested for their respective durability and mechanical properties. Specific tests will be described later in this section.

3.1 Product Descriptions

The Polyester TBO was provided from Kwik Bond Polymers. PPC MLS is a multi-layer polyester based binder. PPC MLS is designed to be applied to concrete bridge decks to reduce damage due to de-icing salts and improve the coefficient of friction. The main features are ultra-low permeability, high early bond strength, rapid cure time at low temperatures and increased skid resistance. The KBP 204 primer is used so the product can penetrate into the deck ensuring a good bond and re-bonded existing cracks. The polyester lab specimens can be seen in Figure 3-1 Kwik Bond Lab SpecimensFigure 3-1.

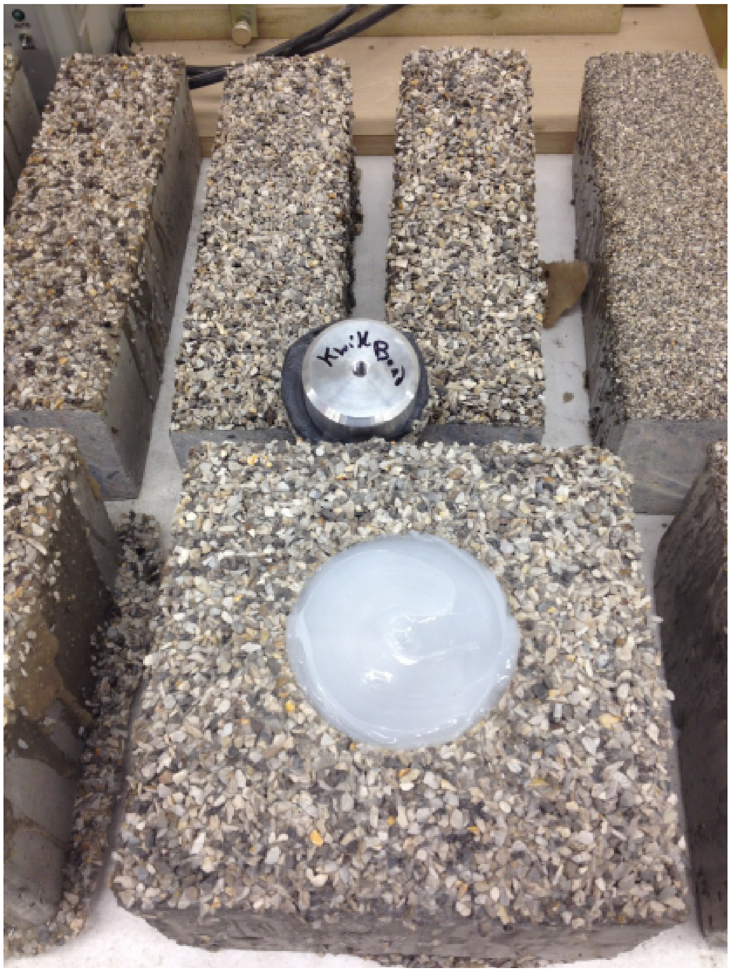

Figure 3-1 Kwik Bond Lab Specimens

The Epoxu product was provided by Tamms Industries & Euclid Chemical. Flexolith is a two part, 100% solid, low modulus, semi-impermeable epoxy binder. Flexolith was designed for use in areas where stress relief and resistance to mechanical and thermal movements are required. The main features are rapid cure time, contributes to LEED points, can be used as broadcast system, and ease of application. Section 3's lab specimens can be seen in Figure 3-2.

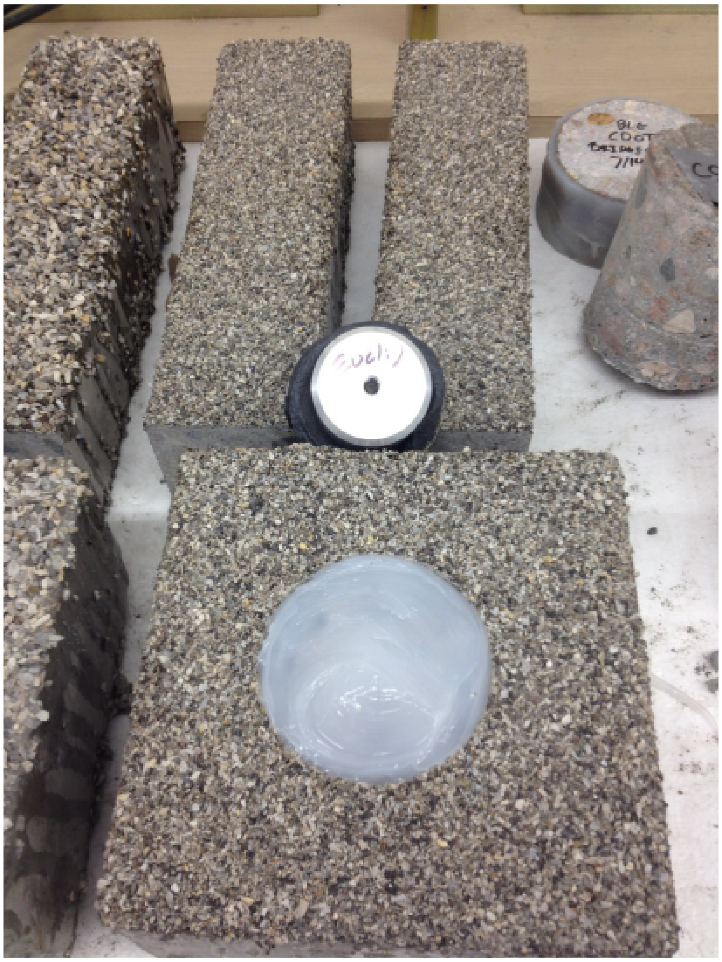

Figure 3-2 Flexolith Lab Specimens

The MMA product was provided by Plexi-Coat America. Plexideck is a single layer Methyl Methacrylate (MMA) resin. Plexideck designed for concrete bridge decks where waterproofing, skid resistance and minimal addition of dead weight are required. The key features of this system include full cure time in 1 hour, impermeable, increased skid resistance, and weighs less than 3lb/sq ft.

Figure 3-3 Plexideck Lab Specimens

3.2 Skid Resistance Test

ASTM E 303- Standard Test Method for Measuring Surface Frictional Properties Using the British Pendulum Tester

Skid resistance is the measure of the traction produced by the wheels of a vehicle under the combined effect of snow, ice, and loose materials on a road surface. The skid resistance of a surface is developed when vehicle tires are partially or fully prevented from rolling under lubricated conditions and begin to slide on top of the surface. The skid resistance is an important measure for determining how safe a roadway surface is. The majority of traffic accidents are due to driver error; however, the condition of the roadway does have a significant role. Skid resistance is one of the most influential factors when considering traffic accident rates at specific locations.

The skid resistance test is to measure of how the application of the thin bonded overlays changes the frictional performance of the bridge deck. The testing system is comprised of a British Pendulum Tester shown in Figure 3-4, which is placed directly on the deck surface.

To conduct the test, the tester is placed directly on the deck surface and then leveled by turning the leveling screws until the sprit level is centered. Zero the tester by raising the pendulum until it can swing freely. Set up the pendulum in the release position and place the pointer against the adjustment screw. Release the pendulum and make sure that the pointer reads zero. Let the pendulum hang freely and place the spacer directly underneath. Move the pendulum to one side of the spacer and lower the pendulum slowly until it contacts the surface and then repeat for the other side. Place the pointer against the adjustment screw and place the pendulum in the release position. Apply sufficient water to cover test area, and release the pendulum but not record the result. The test is repeated four more times, applying water each time and then recording the results. This test is performed immediately after initial curing, and again during the 2nd and 3rd site visits.

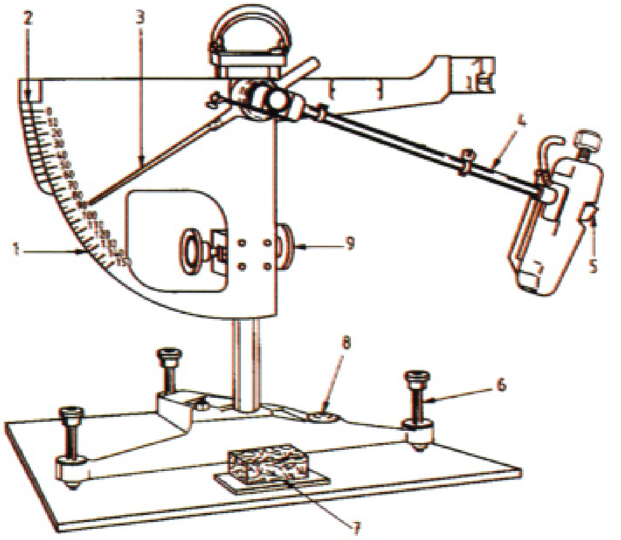

Figure 3-4 British Pendulum Test Apparatus

Photo Credit (http://www.istone.ntua.gr/Training_courses/wp1/slip_resistance.html)

3.3 Pull-off Strength (Bond) Test

ASTM D 7234– Standard Test Method for Pull-Off Strength of Coatings on Concrete Using Portable Adhesion Testers

The pull-off strength of the thin bonded overlay determines the largest perpendicular tensile force that a material system can bear before failure through or at the interface between different sections system.

The system is comprised of the concrete deck, thin bonded overlay, bonding adhesive and testing apparatus which can be seen in Figure 3-5. Failure will occur along the weakest plane within the system.

The test is performed making a circular cut 2 inches in diameter that cuts through the entire thin bonded overlay and penetrates 0.5 inches deep in the bridge deck at two locations in the specified test section. Then secure the steel disk perpendicular to the thin bonded overlay surface with an epoxy adhesive. Once the adhesive is cured, the testing apparatus is attached to the disk to apply a tensile force perpendicular to the test surface. The force is monitored and gradually increased until a plane within the system fails or until a certain value is achieved. The test is performed after the thin bonded overlays have fully cured.

For this study, the in-house specimens used for the bond test will be resealed with silicone and then for the ponding test discussed in section 3.6. To minimize road closure times for the 2nd and 3rd evaluation periods, an additional four inch core removed from each section on the deck. Once the specimens are shipped to the University of Colorado, the bond test will be performed on the 4 inch specimens. This reduces the lane closure times by not waiting for the epoxies to fully cure while on the deck and allowing to bonding agents to cure for a full 24 hours off site.

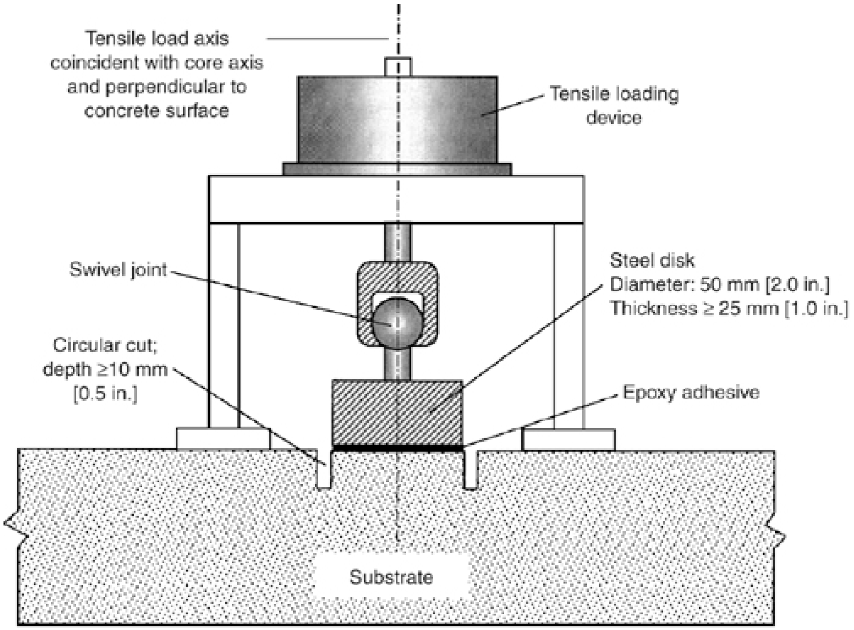

Figure 3-5 Pull-off Method Test Setup

3.4 Chloride Profile Test

ASTM C 1218– Standard Test for Water-Soluble Chloride in Concrete and Mortar

The presence of water-soluble 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 testing conditions.

The test is performed by extracting a core from the bridge deck at least 4 inches deep past the thin bonded overlay and shipping the specimens to CU-Boulder. Drill into the specimens at 0.5 inch intervals and collect the pulverized concrete dust, see Figure 3-6. Collect approximately 10 grams of the powderized concrete and place into add to 50 ml clean glass beaker and add diluted concentration of nitric acid and hydrogen peroxide. Cover and shake the specimens for approximately 5 min. Let the specimen rest for a full 24 hours then using Rapid Chloride Testing apparatus measure the voltage of each sample.

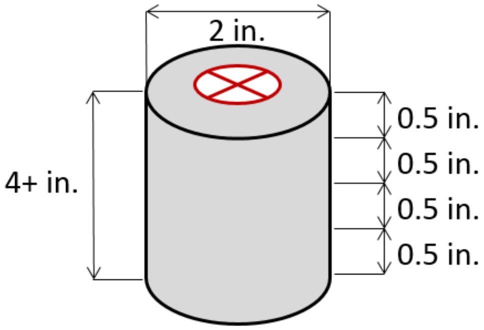

Figure 3-6 Chloride Profile Test Setup

3.5 Chloride Permeability Test

ASTM C 1202 – Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration

The purpose of this test is to determine the electrical indication of concrete’s ability to resist chloride ion penetration. This test is the laboratory evaluation of the electrical conductance of the concrete samples, which is known to show a good correlation with chloride ponding tests, ASTM C 1543.

The test is performed by removing a core from each section to the rebar depth past the thin bonded overlay and shipping the specimens to CU-Boulder. For the preparation, first the specimens will be prepared by using a water-cooled diamond saw to cut the specimens 2 inches from the face of specimen. Because the rebar depth is roughly 4 inches, each specimen will have only one piece used in the permeability test, and the bottom remain portion will be discarded. Second, in order to prevent chemical solutions from leaking through the sidewalls of the disc and to create a linear flow of electrical current, the cylinder walls of specimens will be sealed with a coating of silicone and allowed to dry for 12 hours. Third, after drying, the specimens will be vacuumed for 3 hours. A container filled with de-aerated water will cover the specimens and a vacuum pump run for one additional hour. Finally, the specimens will be submerged in water for 18 hours. Each specimen will then be immediately loaded into Prove-It testing apparatus to record the charged passed in coulombs, which can be seen in (Stanish et al. 1997).

After the preparation, add chemical solutions to the two chambers: one with 3% solution of NaCl and the other with 0.3 NaOH. The capability of chloride ions to pass through faces of concrete specimens is measured and recorded in terms of the impedance in coulombs over the total time of the test from the supplied software. Once the test cycle is started, a 60 Volt of DC voltage will be imposed across the concrete specimens for six hours. For this experiment, the thin bonded overlay will be exposed to the sodium chloride solution and the interior portion core will be exposed to the sodium hydroxide solution. The experimental setup is shown in Figure 3-7. Common experimental values are show in Table 3-1.

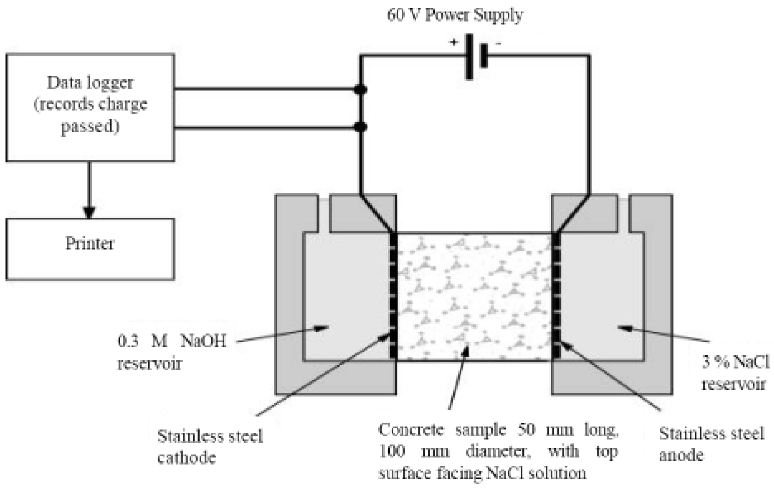

Figure 3-7 Rapid Chloride Permeability Test Setup I

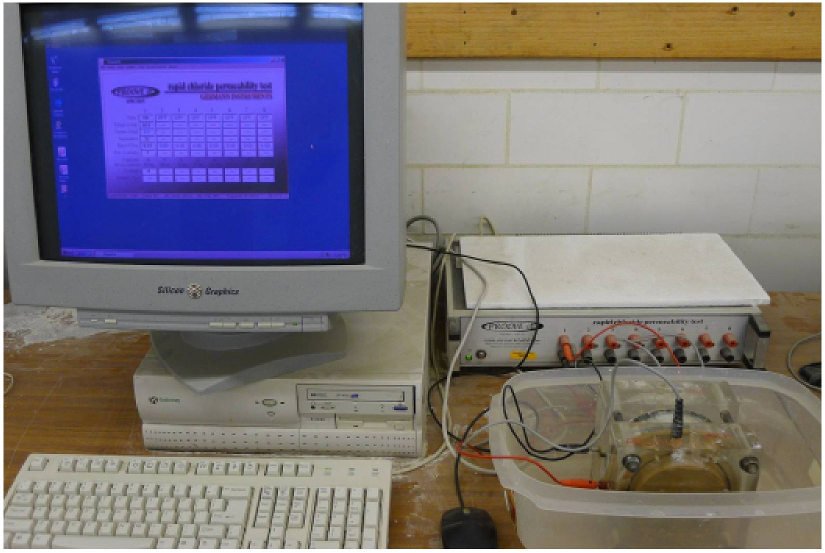

Figure 3-8 Rapid Chloride Permeability Test Setup II

Table 3-1 - Chloride Ion Penetrability based on charge passed

Coulombs Passed	Chloride Ion Penetrability	Typical of
>4000	*High*	*High w/c-ratio*
4000-2000	*Moderate*	*0.4-0.5 w/c-ration*
2000-1000	*Low*	*w/c-ratio<0.4*
1000-100	*Very Low*	*Latex Modified Concrete*
<100	*Negligible*	*Polymer Concrete*

3.6 Chloride Penetration by Ponding Test

ASTM C 1543 – Standard Test Method for Determining the Penetration of Chloride Ion into Concrete by Ponding

The purpose of this test is to establish a correlation between the indirect measures of the chloride-ion penetration of concrete ASTM C 1202 discussed later. This test will be performed in order to determine the penetration of chloride ions into concrete from a sodium chloride pond.

The test will be performed by casting square specimens, 7 inches wide and 4 inches deep for each type of overlay and a control. Then a sodium-chloride solution is ponded on the surface of the specimens, seen in Figure 3-9. Samples will be taken at 0.5 inch interval and chemically analyzed to determine the chloride content at that depth. The chloride content will be measured by using the same technique described in section Chapter 1.

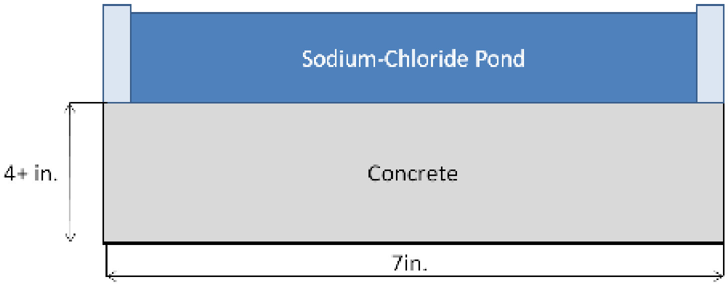

Figure 3-9 Ponding Test Setup

3.7 Rapid Freeze-Thaw Test

ASTM C 666 – Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing

The purpose of the freeze-thawing cycle test is to investigate the resistance of the thin bonded overlay system under 300 repeated cycles of the freeze and thawing process under standardized conditions. This test is conducted with a Logan Rapid Freeze-Thaw Chest, shown in . 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-thawing cycle test is controlled by the raising temperature range from 0 degrees F to 40 degrees F and the decreasing temperature range from 40 degrees F to 0 degrees F. The ASTM standard states that at the end of the cooling period, the temperature at the center of the specimen is 0 ± 3 degrees F (-17.8 ± 1.7 degrees C) and at the end of thawing period, the temperature at the center of the specimen is 40 ± 3 degrees F (4.4 ± 1.7 degrees C). In addition, a full cycle must be completed between 2-5 hours. The new digital controlling panel is installed to control the temperature range and duration of time accurately as shown in Figure 3-11.

Figure 3-10 Logan Rapid Freeze-Thaw Chest

Figure 3-11 Digital Control Panels

To ensure the internal temperature of the concrete specimens reach the required temperatures, two thermal couple sensors will be left in the cabinet to calibrate the temperatures for the environment and inside the concrete. The sensor is installed in the center of the specimen as seen in Figure 3-12 (Hamel 2005). Before the test, water will fill each container no more than 1/8" over the top of the specimen's surface. The test program will operate a total of 300 cycles which will be divided into 10 intervals. The length change, weight loss, and pulse velocity are to be measured at each interval.

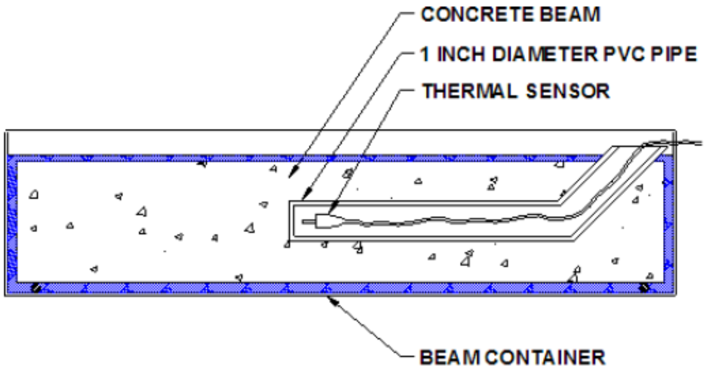

Figure 3-12 Thermal Sensor Installed at Center of Concrete Specimen

Chapter 4 Observations of Installation Process

For this project, three different types of multilayered thin bonded overlays were installed on E-17-QM, a bridge in the greater Denver-Metro Area; see Figure 4-1 for a plan view of the location of each test section on the deck. The University of Colorado at Boulder's research team visited the bridge on the night of July 14th, 2012 to observe and monitor the installation of each TBO by its respective commercial provider. Photos, Figure 4-2 through Figure 4-15, were taken during the visit and show the general installation process for these TBO's.

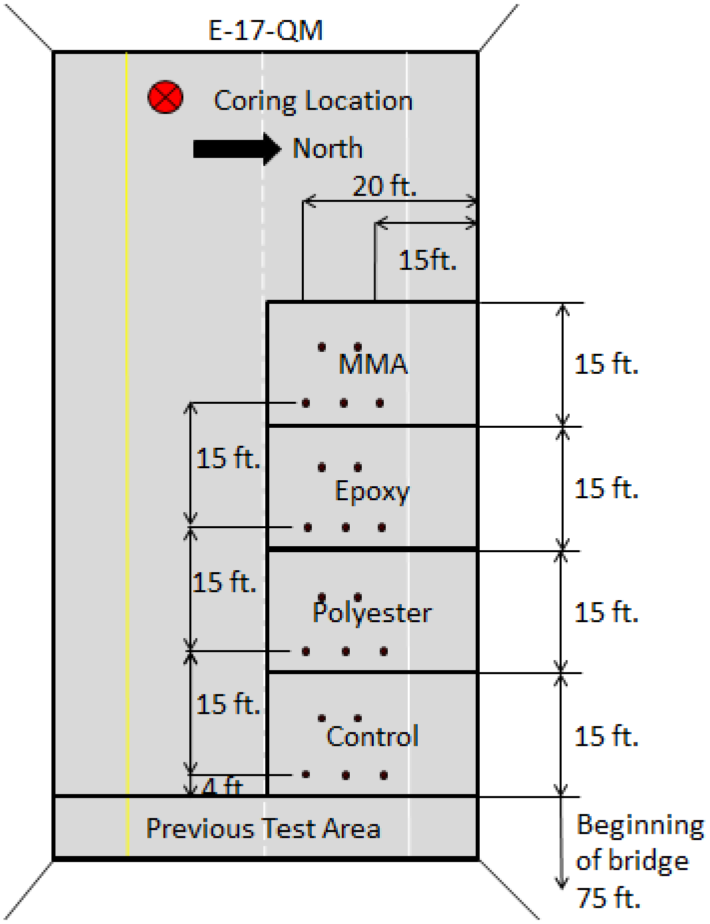

Figure 4-1 Plan View of Test Sections

4.1 General Overview of the Construction Process

Figure 4-2 Traffic Safety Set-up (10:00 PM)

Figure 4-3 Shotblasting (10:30 PM)


Figure 4-4 Prepared Surface (11:00 PM)


Figure 4-5 Residual "Crack-Chaser" Left on Deck

Figure 4-6 Worksite on E-17-QM (11:00 PM)

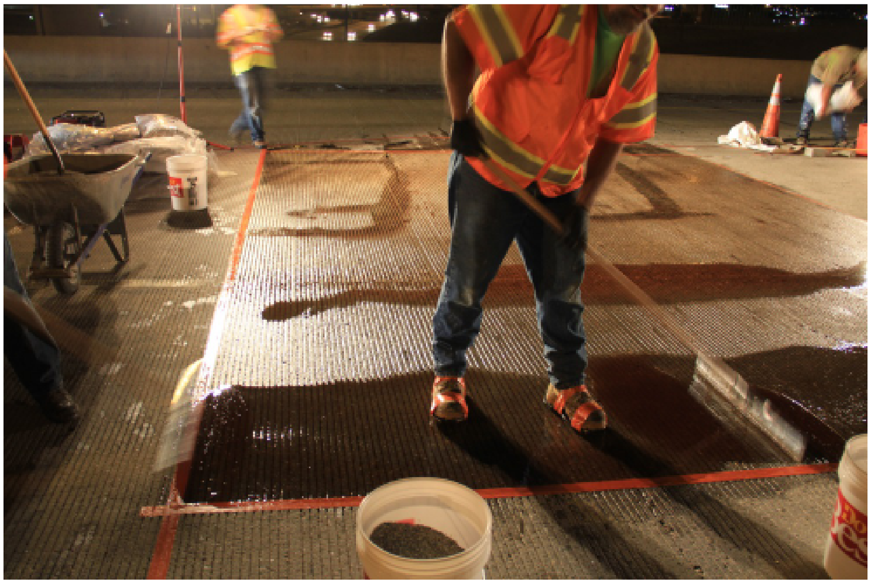

Figure 4-7 Application of First Layer (11:15 PM)

Figure 4-8 Broadcasting Aggregate (11:15 PM)

Figure 4-9 Completion of Broadcasting (11:15 PM)

Figure 4-10 Surface During Curing (11:45 PM)

Figure 4-11 Removal of Loose Aggregate (12:30 AM)

Figure 4-12 Application of 2nd Coat (1:00 AM)

Figure 4-13 Repeat Aggregate Broadcasting/Curing/Removal (2:00 AM)

Figure 4-14 Completion of Skid Test (3:00 AM)

Figure 4-15 Installation Debriefing and Clean-up (3:30 AM)

Chapter 5 Short-Term Performance Evaluations and Analysis

5.1 Skid Resistance Results and Analysis

The American Society of Testing and Materials (ASTM) describe the skid resistance test as a measure of the ability of a traveled surface to prevent the loss of tire traction. Skid resistance tests were performed on the on the day of the installation, 7/15/12, and again on 3/27/13 and 9/4/13. The test was completed with the British Pendulum Tester by a CDOT research professional. A description of the testing conditions is shown below and the test results are shown in Table 5-1, Figure 5-1 & Figure 5-2 . Details for the tests include:

- Test areas were wetted
- Sections were cured enough to open to traffic
- Tests covered the right traffic lane in the right wheel path
- Tests were done with the pendulum traveling in the direction of traffic
- Temperatures during the test were 79.7° F, 43° F, and 67° F, respectively.

Table 5-1 - Average Skid Resistance

Skid test Results				
Test Section	*Product*	*15-Jul-12*	*27-Mar-13*	*4-Aug-13*
S.1	Concrete	70.09	73.53	66.65
S.2	Polyester	86.45	82.07	61.95
S.3	Epoxy	84.40	88.27	58.05
S.4	MMA	78.55	50.07	44.45

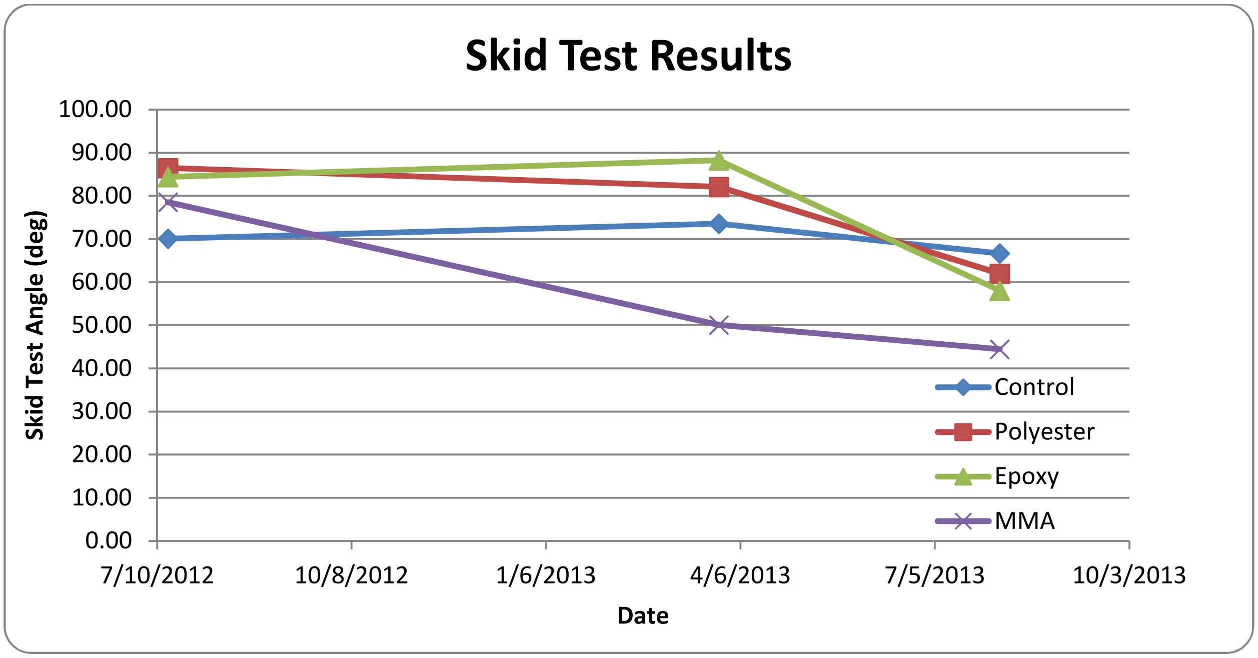

Figure 5-1 Skid Test Final Results

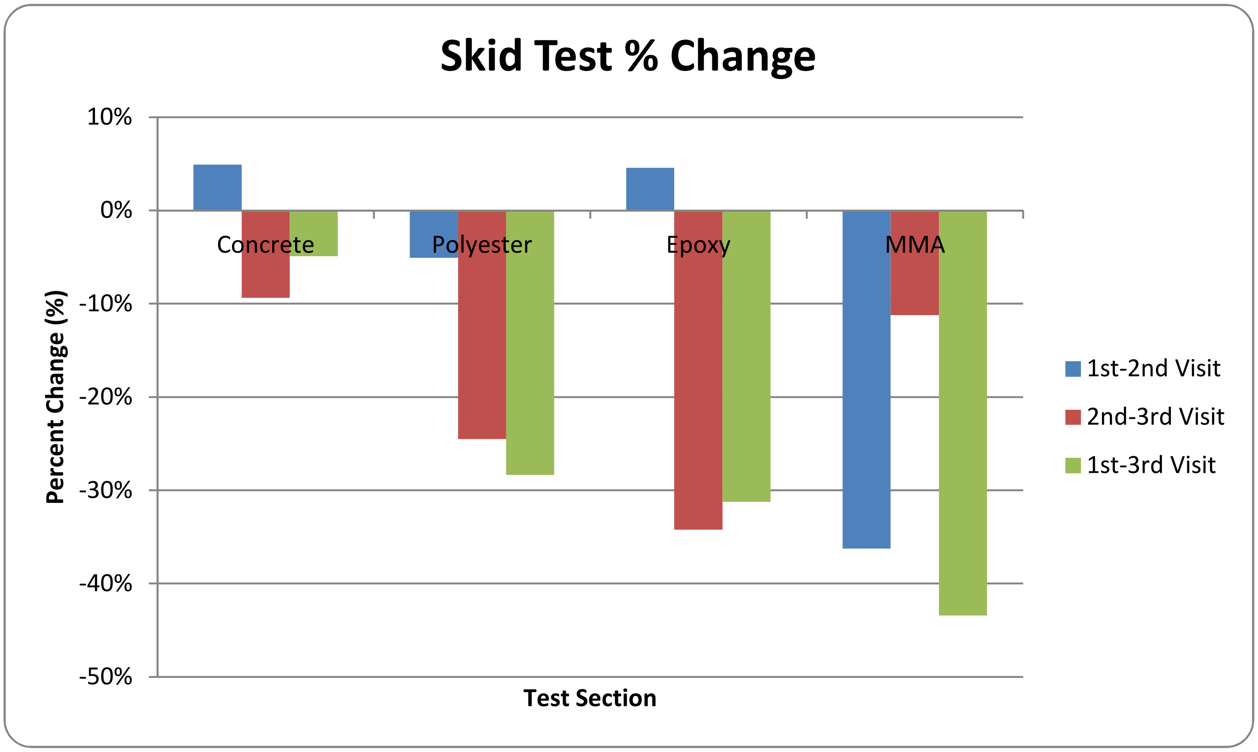

Figure 5-2 Percent Change Between Visits

In Table 5-2 through Table 5-4, the four sections are ranked based on their performance given the time after installation. All tests were in the right wheel path spaced out through each section. In general, the higher the skid resistance number, the higher the skid resistance. For example a skid number of 0 would be nearly frictionless while a skid number of 150 would have an extremely high resistance to sliding.

Table 5-2 - Skid Test Results after Installation

Rank	**1**	**2**	**3**	**4**
TBO	Control	Polyester	Epoxy	MMA
Skid Number	86.45	84.40	78.55	70.09

Table 5-3 - Skid Test Results after 8 months

Rank	**1**	**2**	**3**	**4**
TBO	Control	Polyester	Epoxy	MMA
Skid Number	88.27	82.07	73.53	50.07

Table 5-4 - Skid Test Results after 13 months

Rank	**1**	**2**	**3**	**4**
TBO	Control	Polyester	Epoxy	MMA
Skid Number	66.65	61.95	58.05	44.45

From the above rankings, the following can be concluded:

1) For a short period of time, all thin bonded overlays added to the resistance of the bridge deck.
2) After 8 months the MMA lost approximately 35% of skid resistance potential. All other sections saw less than 5% change.
3) After 13 months, the skid resistance of the polyester, epoxy, and the MMA dropped by approximately 28%, 31%, and 43%, respectively from their initial skid resistance reading.
4) The MMA became more susceptible to sliding than the bare concrete surface between the initial installation time and 8 months.
5) All thin bonded overlay sections became less skid resistant than the bare deck after 1-year.
6) Of the 3 TBO's, the epoxy overlay performed the best, followed closely by the polyester overlay.

5.2 Pull Off Strength (Bond Test) Results and Analysis

The bond strength between the overlay and the bridge deck surface serves as an indicator of current overlay service performance, but can also serve as an estimate for the service life span. The bond test applies a perpendicular force to the over to determine the weakest plane within the system. For this experiment, the failure modes of the bond test are defined as follows:

- B = Failure between bonding Compound and deck surface
- E = Failure between overlay and deck surface
- H = Failure between bonding compound and overlay surface
- O = Failure through the overlay
- C = Substrate failure – This is the preferred type of failure for TBO's

The results from the 24 hour test can be seen in Figure 5-3 through Figure 5-4 and in Table 5-5. The results from the 8 month test can be seen in Table 5-6. The results from the 14 month test can be seen in Table 5-7.

Early on (24 hour<) bond strength is important for thin bonded overlays due to the short period of time before traffic is reopened on the bridge. If a high strength bond does not develop quickly, once the overlay is reopened to traffic, it is at risk of shearing failure from a tractor-trailer locking its wheels up, and aggregate pull out from general traffic wearing. For this experiment, all overlays were installed and allowed to cure for approximately 6 hours before being re-open to traffic. Each overlay was installed on portable test specimens and had the bond test conducted approximately 24 hours after installation.

Figure 5-3 24 hr. Bond Test Results (from top to bottom, left to right) Control, Polyester, Epoxy, MMA

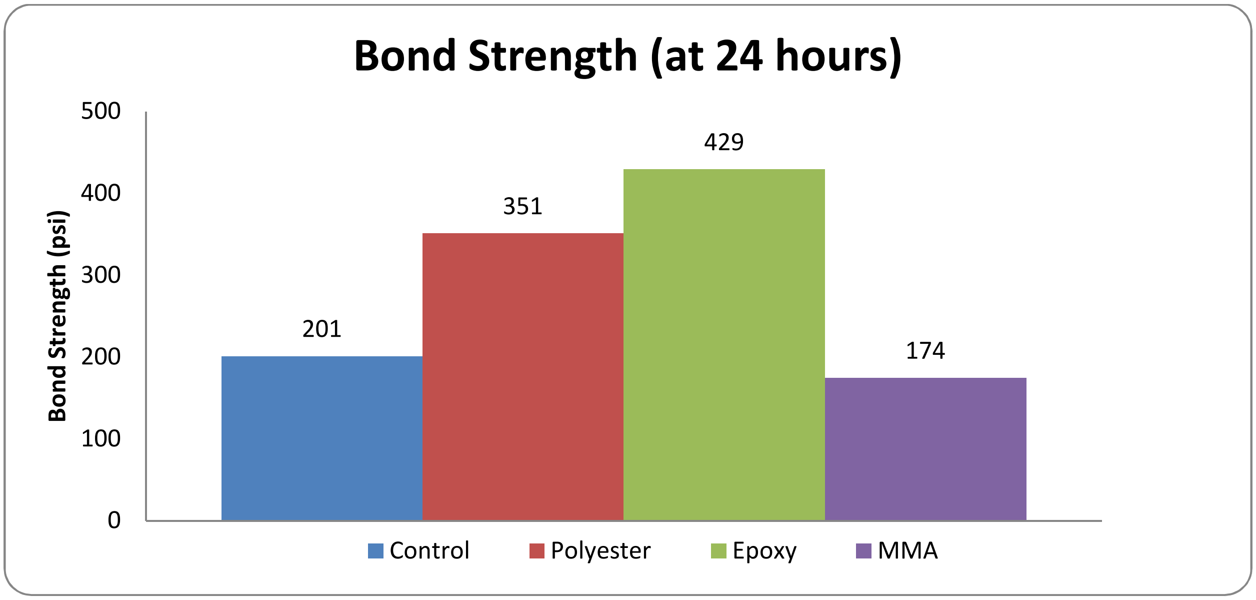

Figure 5-4 Bond Strength at 24 hours

Table 5-5 - Bond Strengths at 24 hours

Section	Pull off Strength (psi)	Failure Mode
Control	201	Bonding & sub
Polyester	351	Overlay&Sub
Epoxy	429	Substrate
MMA	174	Bonding Agent

Figure 5-3 shows the failure pattern for each testing section, which coincidently also shows each type of failure mode except for class O. In order to capture the 24 hour 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. However, the bonding agent used specified a 24 hour time period to obtain a full strength bond and was only given approximately 13 hours to cure to the surface which lead to .

The control section failed at the interface between the bonding epoxy and the top surface of the concrete deck. This is defined as a class B failure. The most probable cause for the class B failure in section 1 was the reduced cure time allotted for the bonding agent. The polyesters failure is defined as a combination of a class E and class C failure. The overlays primer/polyester combo did not penetrate fully into the deck surface making the bond weaker than expected. A closer investigation of the testing specimen showed some concrete failure surrounding the base of the failed test specimen. The epoxy overlay bonded very well to the deck surface causing a class C failure through the existing deck concrete. A class C failure demonstrates that the bond between the overlay and deck surface is stronger than tensile strength of Class D deck concrete. The bonding agent did not bond to the MMA. To improve the bond between the bond between the test disk and the MMA specimen, the manufacture recommended the use of the MMA primer used during installation. Future bonds tests on MMA used the MMA primer, while all other sections used an epoxy binder.

Table 5-6 - Bond Strength at 8 months

Section	Pull off Strength (psi)	Failure Mode
Control	370	Substrate
Polyester	248	Overlay/Deck
Epoxy	406	Subsrate
MMA	169	Overlay

For the 8 month bond strength test, a good bond was formed between all test specimens and the bonding agent; the results can be seen in Table 5-6 above. After 8 months of service on the deck, the polyester and the epoxy saw a 29.3%, 5.66% reduction from the initial bond strength, respectively. The polyester's failure mode changed from a combination of class E/C to purely class E. The failure surface from the specimen clearly shows that the weak interface was between the overlay and the deck surface shown in Figure 5-5. The epoxy failure was again through the concrete, therefore it can be confirmed that the bond between the epoxy overlay and the deck is stronger than the bond strength of the deck concrete. The MMA achieved a good bond using the MMA primer as the bonding agent. The resulting bond test after 8 months of service caused a 169 psi Class O failure through the overlay seen in Figure 5-5. The initial bond test where the bonding agent failed was 2.8% higher, therefore although the initial bond strength of the overlay could not be recorded; it can be assumed that bond strength has been reduced since 24 hour bond strength test. A closer investigation of the testing specimen showed a crack developing between the overlay and deck surface shown in Figure 5-6.

Figure 5-5 Polyester Class E & MMA Class O Failure Modes after 8 months of service

Figure 5-6 MMA Failure plane

Table 5-7 - Bond Strength at 14 months

Section	Pull off Strength (psi)	Failure Mode
Control	355	Substrate
Polyester	224	Overlay/Deck
Epoxy	368	Substrate
MMA	165	Bonding Agent

The bond strength test results after 14 months of service are shown in Table 5-7. The epoxies bond strength still remained higher than the bond strength of the concrete deck. The polyester bond strength was reduced by 36% from the original bond strength after 14 months, and 9.6% from the 8 month test. This is an indication that the effects from the application of deicers, thermal effects, and snow removal may have a more adverse effect on the bond strength of the polyester than the exposure to UV rays and traffic. The MMA bond strength was effectively the same at the 8 month test, however, the weakest plane was between the test disk and the MMA bonding compound.

5.3 Chloride Profile Test Results and Analysis

Out of the seven parameters used to rate the performance of the each test section (skid resistance, bond strength, chloride concentration, chloride permeability, freeze/thaw resistance, and visual inspection), the chloride concentration is the most important. The chloride concentration is the most important parameter because the main function of a thin bonded overlay is to protect the deck and reinforcing steel from chloride intrusion. The chloride profiles obtained from the cores from each test section were analyzed and compared two ways:

i. Profiles of each test section at different time periods.
ii. Profiles at each time period for the different test sections.

The chloride profiles of each section taken prior to installation, at 9 months and at 1 year are shown in Figure 5-7 through Figure 5-10. In each of these plots, the change in chloride concentration as a function of depth over a 14 month period is shown. The first visit occurred on 07/15/12, the second visit occurred 9 months later on 3/27/13, and the third visit on 9/4/13. For this project, the number of cores that had to be kept to a minimum to retain the structural integrity of the deck, therefore only 1 core per section was extracted. For this project, cores were extracted from the deck three times. The first visit, cores were removed from the control section only and it was assumed that the results from those core would serve as a baseline for all other test sections.

There are several trends that can be observed for the plot. First, chloride concentrations in all sections were higher near the surface and gradually decreased as the depth into the deck increased. Beyond 1.5 inches below the surface, the chloride concentrations were all below 0.1% by weight. Chloride levels continued to drop that near the depth of rebar the chloride levels were very low to negligible. Chloride levels only reach the critical level near the surface. The 15 year old bridge deck can be considered to be in good shape given the low concentration distributed through the deck.

For all test sections, there was an increase in chloride concentrations between the first and second site visit which is due to the application of anti-icing and de-icing salts during the winter months. At the surface, all test sections except the MMA were above the Ccrit. This is an indication that chlorides were able to penetrate through the overlays in the winter. There was a significant amount of deicers sprayed on the deck near the time of the second visit because during the winter of 2012/2013, the majority of snowfall in Denver occurred between February and April.

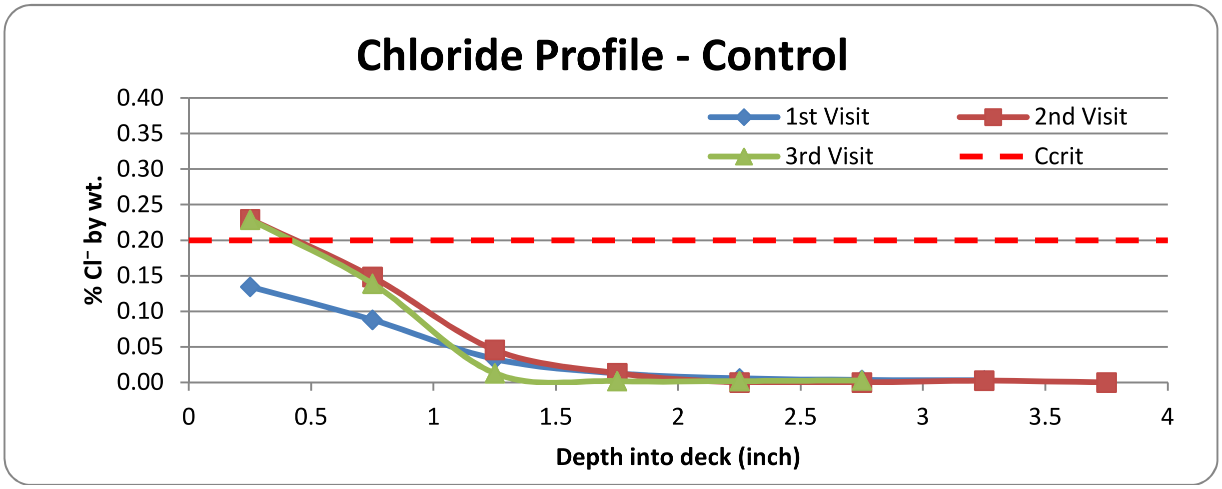

Figure 5-7 Control Section Profiles

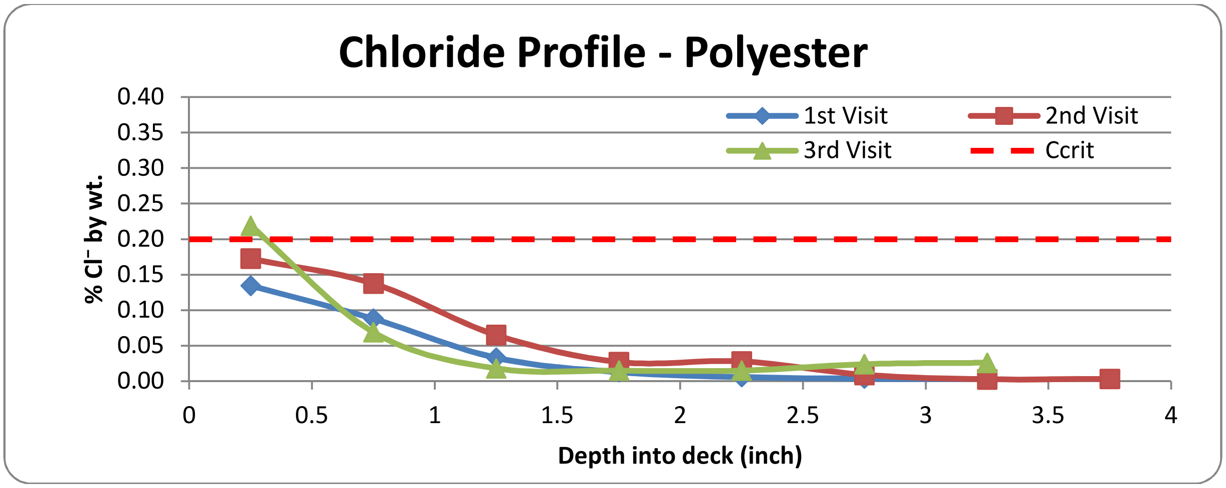

Figure 5-8 Polyester TBO Profiles

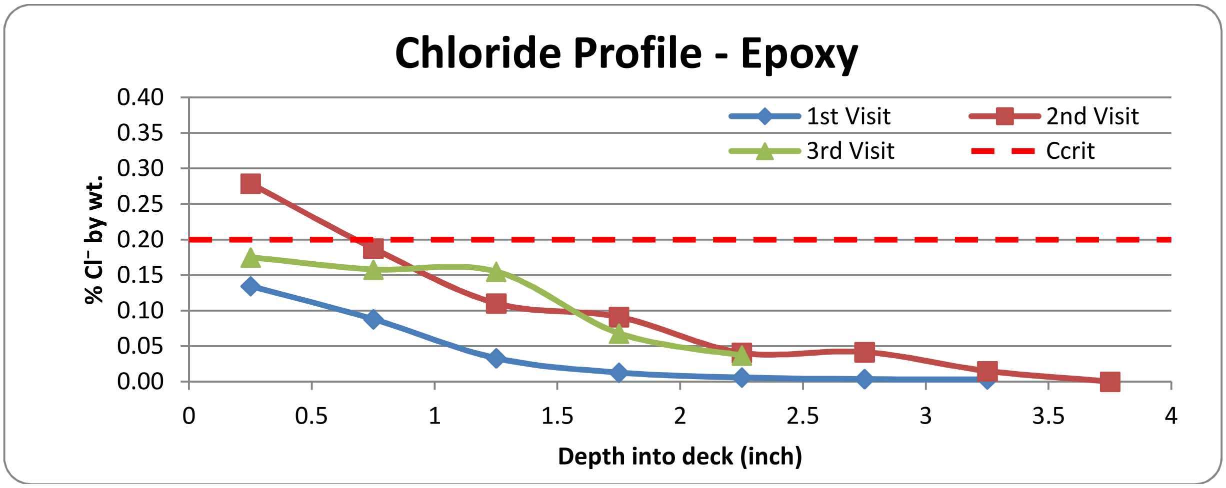

Figure 5-9 Epoxy TBO Profiles

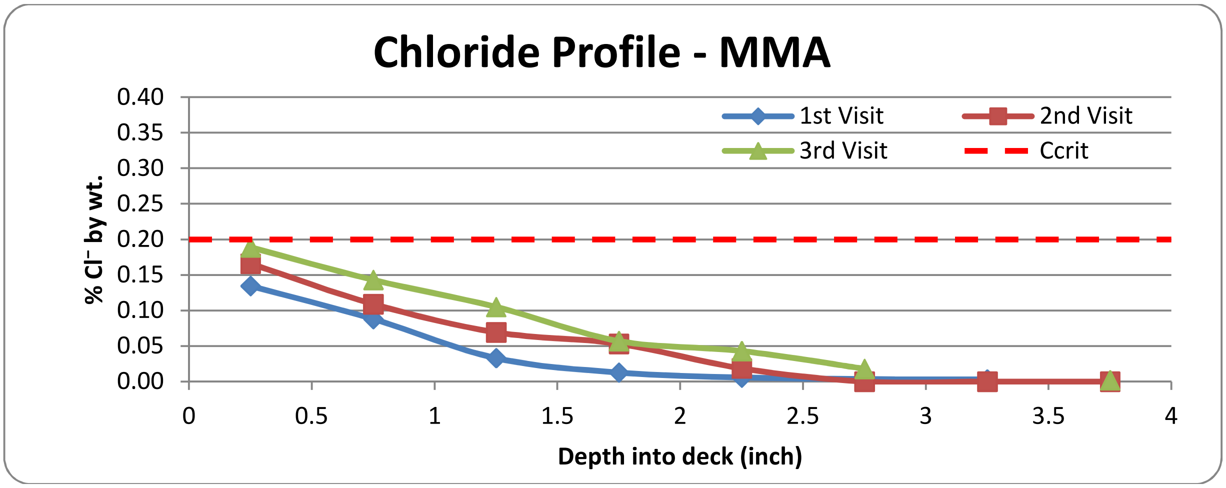

Figure 5-10 MMA TBO Profiles

The comparison of all test sections after 9 months is shown in Figure 5-11 below. The polyester and MMA have slightly lower concentrations at the surface in comparison to the control section. As the depth into the core increased the concentration levels in the polyester and MMA sections became slightly higher than the control section. This is most likely do to the chlorides that had had previously penetrated the surface were diffusing to the less concentrated deeper levels. Similar results have been seen in (Pfeifer 1999). The epoxy chloride profile was an average of 0.05% higher than the control section. The elevated level of chloride indicate that in this test section, chloride were able to pass through the overlay. This could also indicate that the initial chloride levels in this test section were high prior to the installation of the overlay.

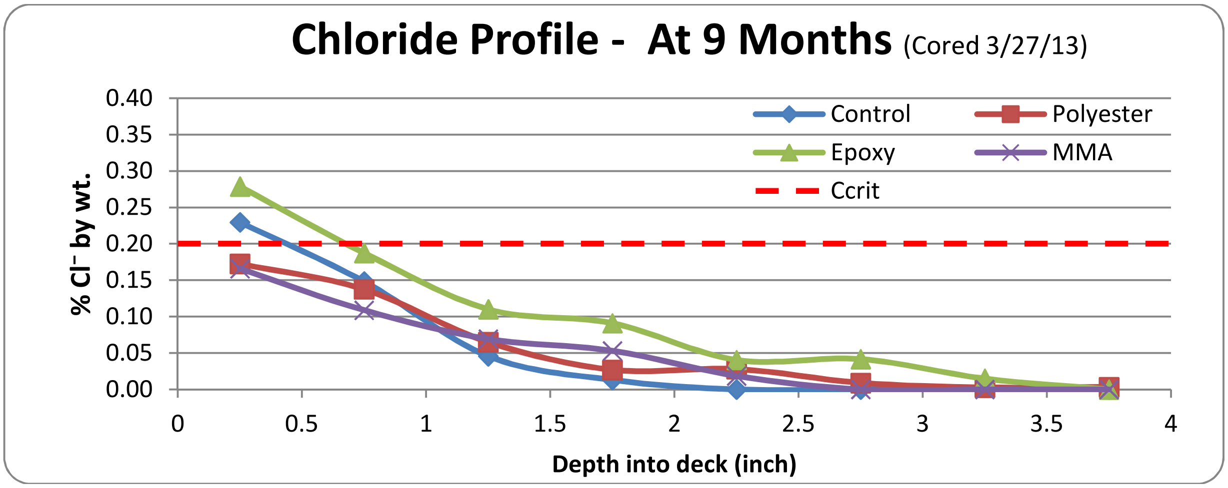

Figure 5-11 Profiles after 9-months on deck

The concentration profiles after fourteen months after installation are show in Figure 5-12. Similarly to the 9 month data, the polyester and MMA chloride concentrations were below that of the bare deck section and as the depth approached the level of the rebar the concentrations became higher than the control section. The epoxy profile also had a lower concentration that the bare deck at the surface, but had a constant concentration down to a depth of approximately 1.25 inches before seeing a noticeable reduction.

Chloride concentrations in concrete normally follow an exponentially decreasing curve, however, the profile of sections the epoxy and the MMA became more linear distribution 14 months after installation. This could be due to trapped chloride diffusing deeper into the deck, deterioration of the overlay due to traffic loading, or environmental effects such as ultra-violet exposure, freeze thaw, or other thermal effects. Results from the profile tests confirm that the MMA is the best at preventing chloride from entering the deck given under service conditions.

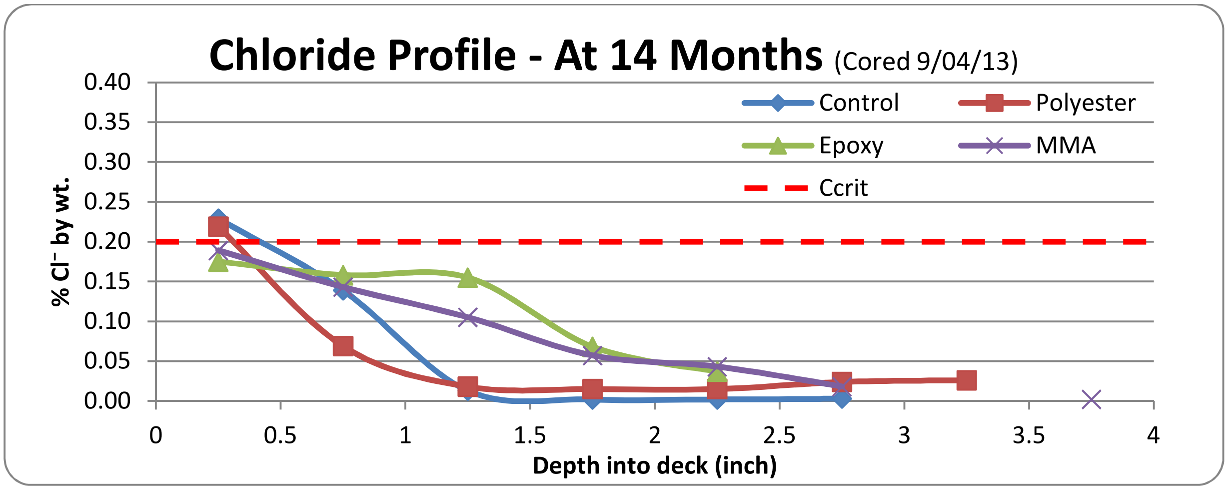

Figure 5-12 Chloride Profiles after 1 year on deck

5.4 Chloride Permeability Test Results and Analysis

The results of the rapid chloride permeability test from each test section over the entire testing period are listed in Table 5-8. Each sample was cored from the left wheel path in the right lane of traffic. Comparing the results from the control test prior to the installation of the overlays to the 8 month specimens subjected to service conditions, it is clear that that the overlays reduce the permeability of the deck. All TBO test sections are report to have a “low” to “negligible” potential for chloride ion penetration, and the control section with the bare concrete deck reportedly has high penetrability.

Table 5-8 - Permeability Results

Installation	Coulombs Passed	Chloride Ion Penetrability
Control	5585	***High***
8 Months	**Coulombs Passed**	**Chloride Ion Penetrability**
Control	5054	***High***
Polyester	35	***Negligible***
Epoxy	14	***Negligible***
MMA	170	***Very Low***
13 Months	**Coulombs Passed**	**Chloride Ion Penetrability**
Control	5767	***High***
Polyester	1363	***Low***
Epoxy	46	***Negligible***
MMA	28	***Negligible***

In , the expected penetrability of a specimen with a water-to-cement ration between 0.4 and 0.5 is expected to pass 4000-5000 coulombs, and polymer concretes are expected to pass less than 100 coulombs. During all time testing periods, the control section passed above 5000 coulombs. This is most likely due to the depth at which the specimen was sampled. The ASTM C 1543 test standard recommends that the specimens tested should start two inches below the surface. To ensure a legitimate comparison to the TBO test sections, all cores were sampled from the surface to a depth of approximately two inches below the surface.

After 8 months of service all TBO test sections reduced the potential chloride ion penetrability from high, to very low to negligible penetrability. After 13 months of service the potential for chloride ion penetrability in the epoxy and MMA section remained very low. The polyester had an increase from 35 coulombs passed at 8 months to 1363 coulombs passed after 13 months of service, which is still considered to have a low potential for chloride ion penetrability. In general, all overlays reduced the potential for chloride ion penetration from the high state seen in all control sections to a low to negligible level.

5.5 Chloride Penetration by Ponding Results and Analysis

The ASTM C 1543 test is a long-term test to measure the penetration of chloride ions into concrete by controlling the concentration of chlorides that the concrete is exposed to while eliminating any other variables. The test requires that the specimens have at least 0.030 m2 (~0.32 ft2) of surface area and a thickness of at least 90 mm (3.54 in). An enclosed frame sealed to the top of the frame holds a 3% NaCl solution that is ponded for the specified testing periods for this project, 6 months and 1 year. At the end of each testing period, the chloride concentration profile at 0.5-inch intervals is determined.

The ponding results of all test section are divided into complete results, 6 month results, and 1 year results show in Figure 5-13 through Figure 5-15, respectively. Six month and 1-year comparisons of individual test sections can be seen in Figure 5-16 through Figure 5-19.

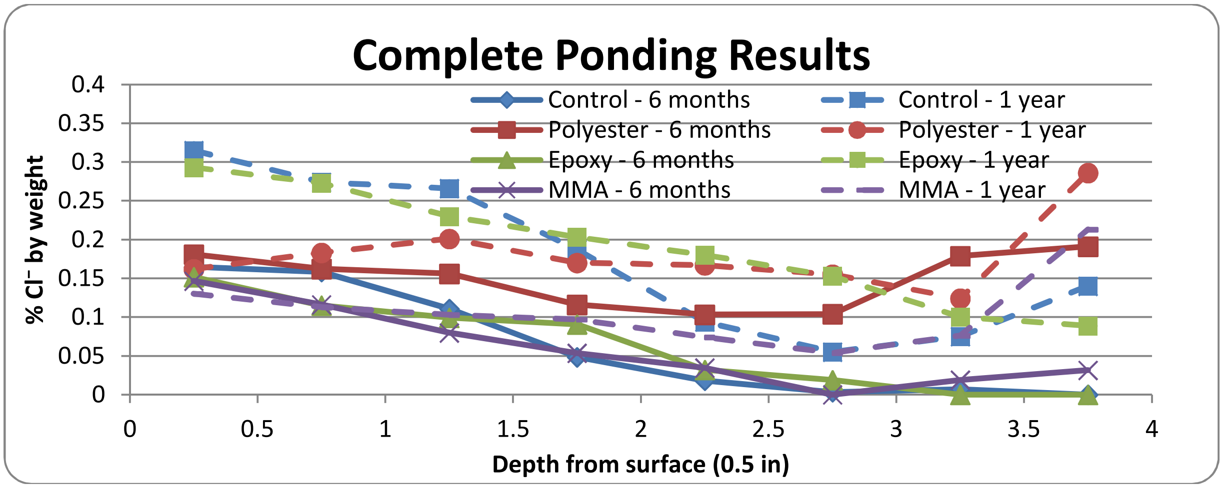

Figure 5-13 Ponding Test Results

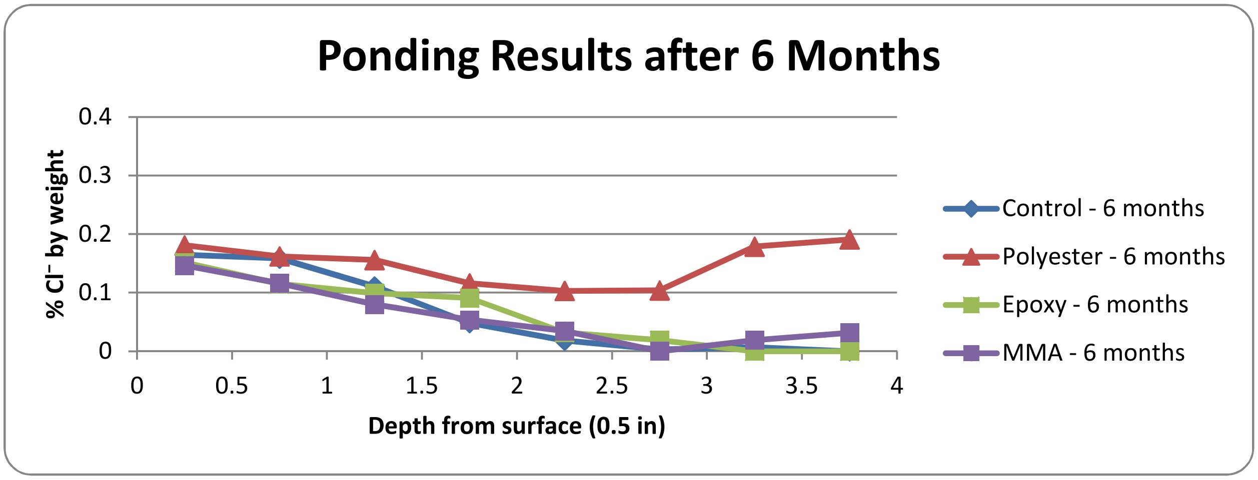

Figure 5-14 Ponding Test Results after 6 Months

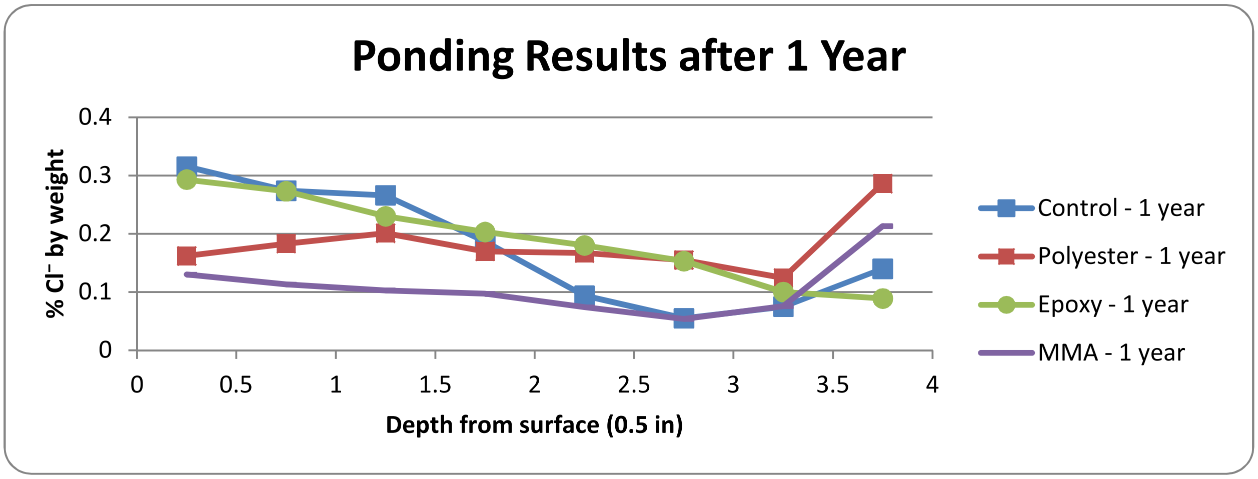

Figure 5-15 Ponding Test after 1 Year

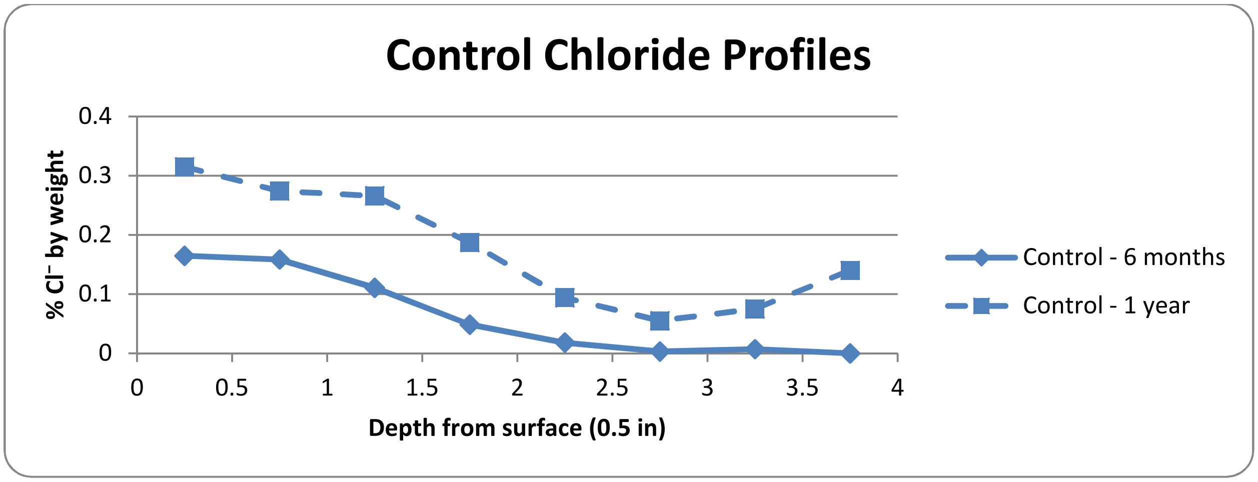

Figure 5-16 Control Section - Ponding after 6 months and 1 year

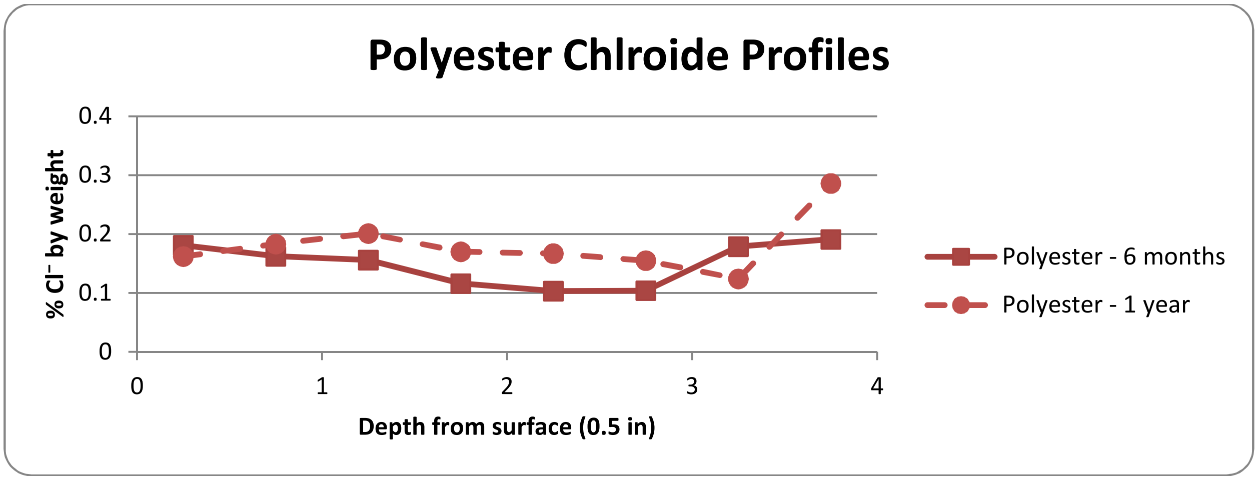

Figure 5-17 Polyester TBO - Ponding after 6 months and 1 year

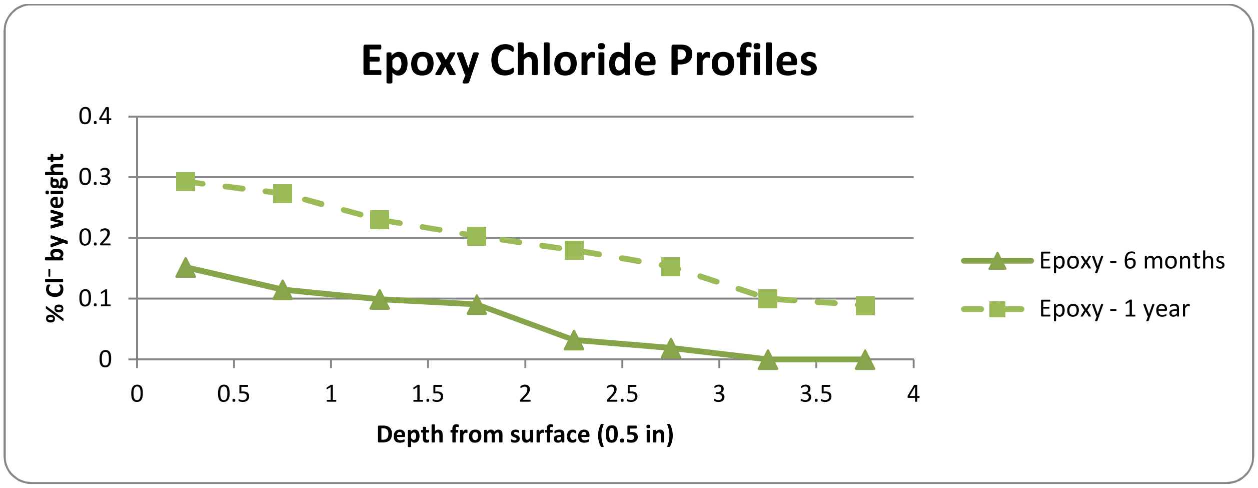

Figure 5-18 Epoxy TBO - Ponding after 6 months and 1 year

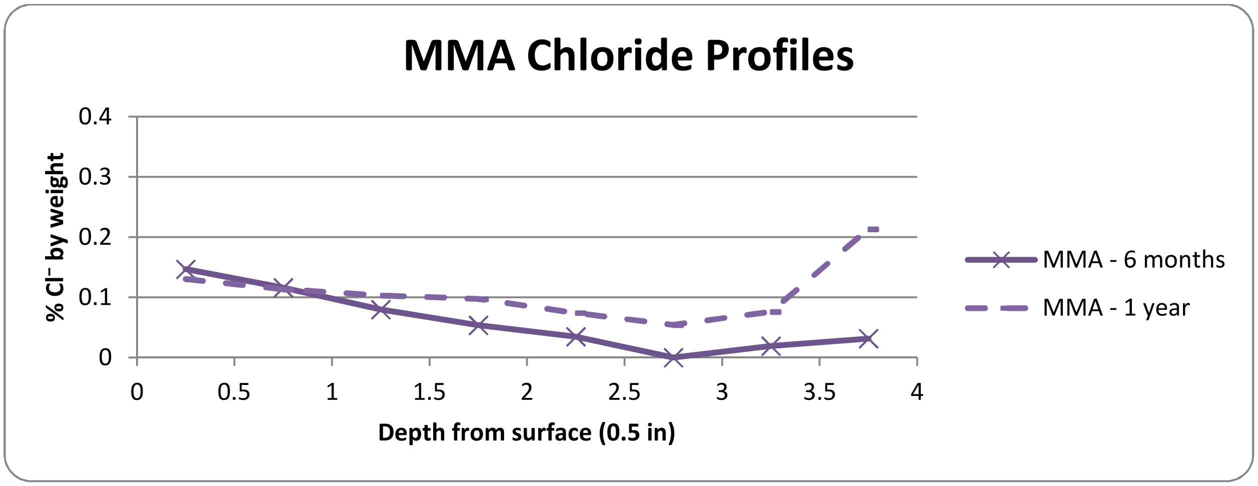

Figure 5-19 MMA TBO - Ponding after 6 months and 1 year

All the ponding test specimens were made in-house at CU-Boulder following the specification for CDOT Class D concrete. The specimens were transported to the bridge site to have the TBOs installed on the specimens and the deck at the same time. Each specimen started with a chloride concentration of 0% at all depths.

After 6 months, the results show that chlorides were able to penetrate through the thin bonded overlays, and after a 1 year the chloride concentration at all levels increased. Chloride concentrations were higher near the surface and decreased further down into the specimen. All test sections chloride levels remain below the critical chloride level of 0.2% Cl- by weight. The average chloride level between 0-0.5-inches for all specimens was approximately between 0.15%- and 0.18%.

After 1 year of ponding, the polyester and MMA profiles remained below the critical chloride concentration at all depths. For both sections, however, the chloride concentrations did not significantly continue to decrease at the depth from the surface increased. This indicates that although chlorides did penetrate through the TBO, the overlay was effective enough to minimize the percent of chlorides penetrated. The control and epoxy chloride concentrations were above 0.2% down to 1.75 inches below the surface. The epoxies chloride levels above the 1.75 inch mark were only slightly lower than the control section indicating that they overlay is only slightly less permeable than the bare concrete surface.

5.6 Rapid Freeze-Thaw Test Results and Analysis

Three inch diameter cores were pulled from each test section and had the base of the specimen cut to ensure a smooth surface. The test was conducted using the Logan Rapid Freeze-Thaw Cabinet described in section Chapter 1 above. Specimens were subjected to 300 freeze thaw cycles, and tested every thirty cycles for change in length, weight and Ultrasonic Pulse Velocity.

i. **Length Change**

Length change of the specimens is measured by a dial caliper with an accuracy of 0.001 inches. The length change from each specimen was measured three times and the average was used to determine the final length change. The length change is calculated by the following equation:

$$\Delta L = \frac{Li - Lo}{Lo} * 100 \quad \textbf{(5-1)}$$

Where:

ΔL = Length change of specimen (%) at x days
L_i = Dial gauge reading at x days
L_0 = Dial gauge reading at 0 days

The relationship between length change and number of freeze-thaw cycles from each test section are given in percent length change versus time in 30 cycle intervals show in Figure 5-20 through Figure 5-22. From these plots it is evident that all specimens that the length changes due to shrinkage and swelling from the freeze-thaw cycles, however, there is nothing conclusive that can be extrapolated from the data.

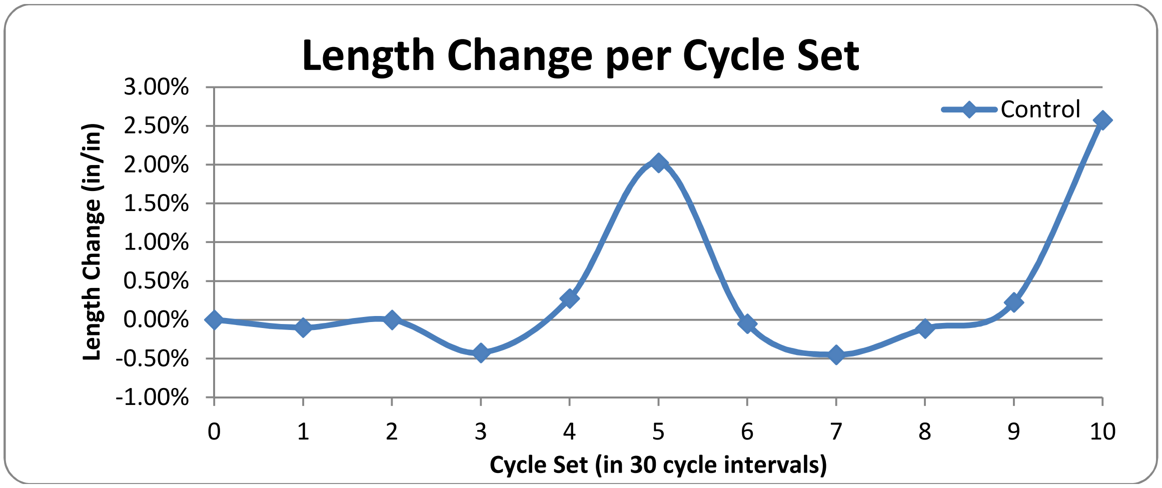

Figure 5-20 Percent length change from control visit

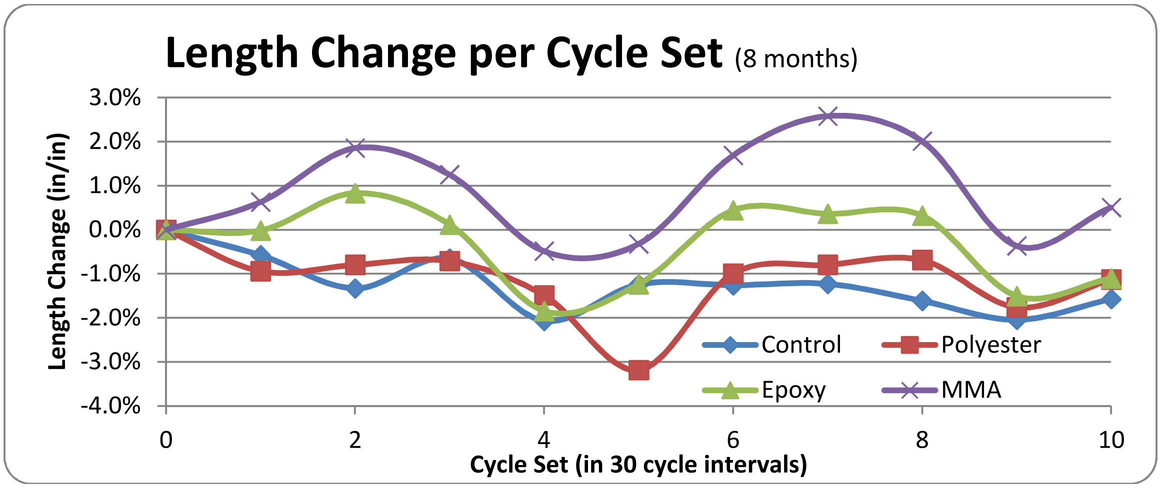

Figure 5-21 Percent length change per cycle set after 8 months

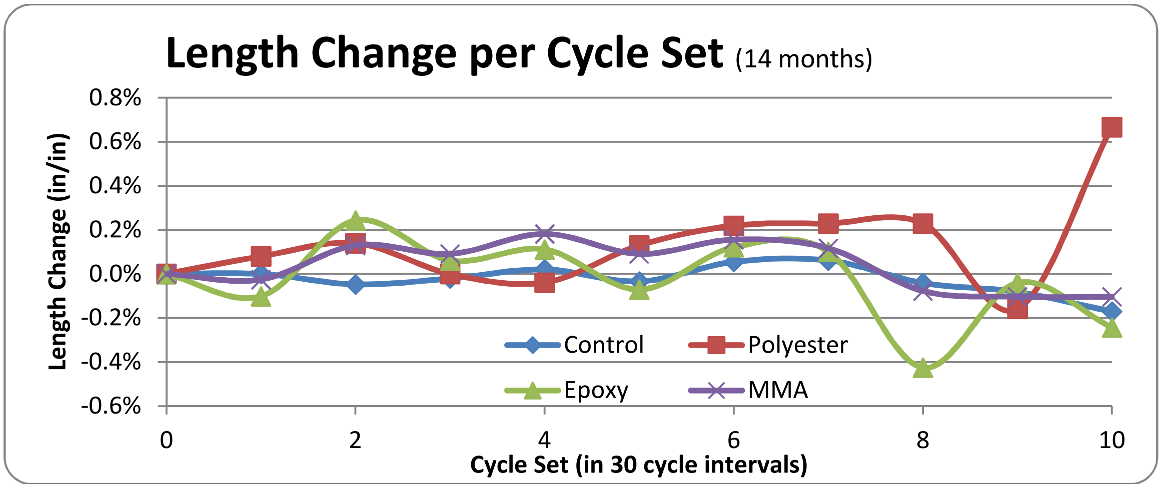

Figure 5-22 Percent length change per cycle set after 14 months

ii. Weight Loss

The weight loss of each specimen was measured using a scale with an accuracy of 0.1 g. The weight change is calculated by the following equation:

$$\Delta W = \frac{Wi - Wo}{Wo} * 100 \qquad (5\text{-}2)$$

Where:

ΔW = Length change of specimen (%) at x days
W_i = Dial gauge reading at x days
W_0 = Dial gauge reading at 0 days

The relationship between the weight change and number of freeze-thaw cycles from each test section are show in Figure 5-23 through Figure 5-25. From the control visit, it can be seen that as the number of freeze-thaw cycles increases, the weight of the specimen increases. This is due to water absorbing into the core which occurred between the first 30 cycles. After 30 cycles the change in weight become stable, which indicates that there was no spalling occurred. The specimens pulled after 8 month had highly random weight changes, and therefore no conclusive results can be extrapolated from this test. The variable results are most likely due a defective scale that had to be replaced, and that the container that was holding the specimen in the Logan freeze thaw chamber had a leak in it, so the water level surrounding the specimen changed between each cycle set. The 14 month test results are more similar to that of the control test. After 60 freeze-thaw cycle, the specimens each gain approximately 3% of their weight in water.

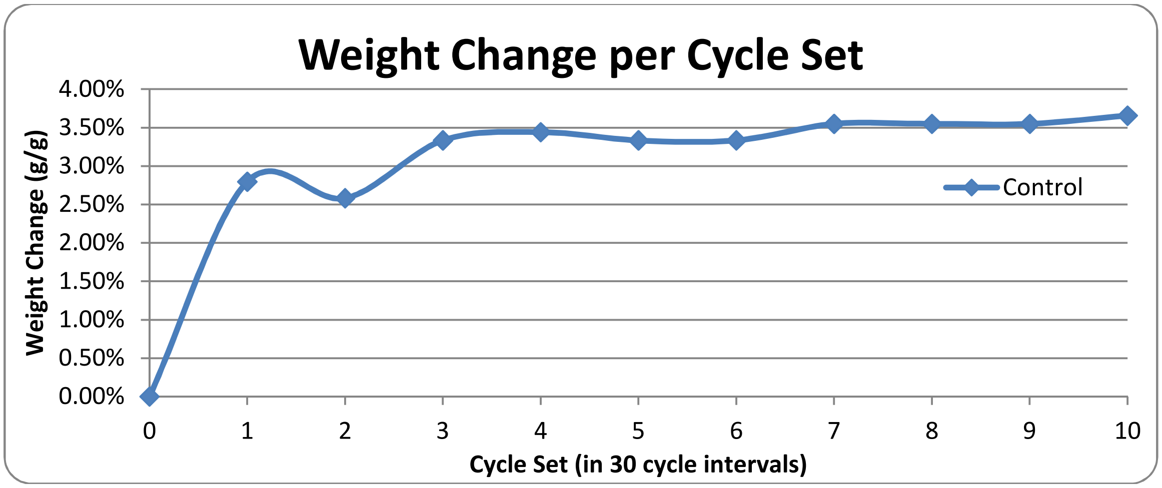

Figure 5-23 Percent weight change per cycle set from control visit

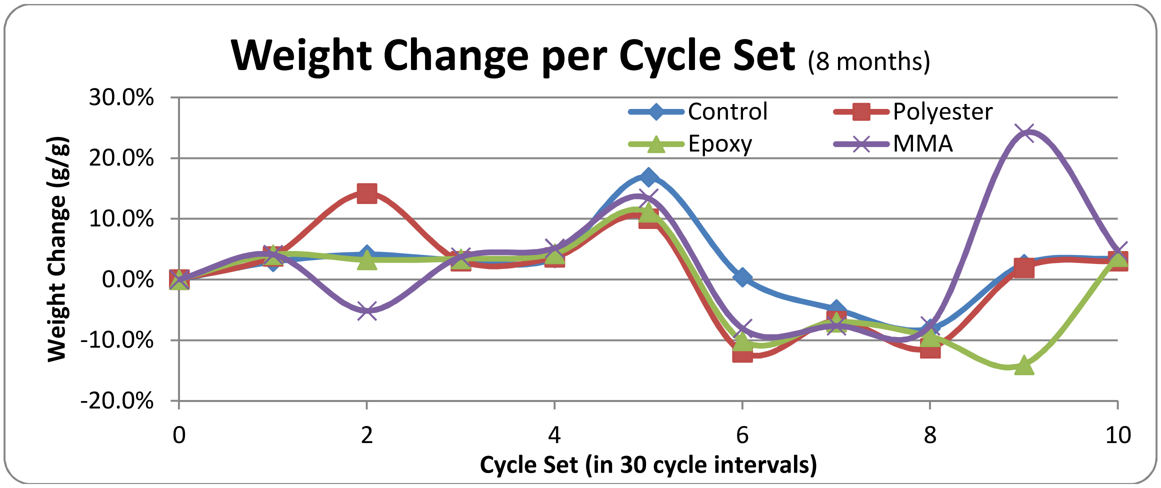

Figure 5-24 Percent weight change per cycle set after 8 months

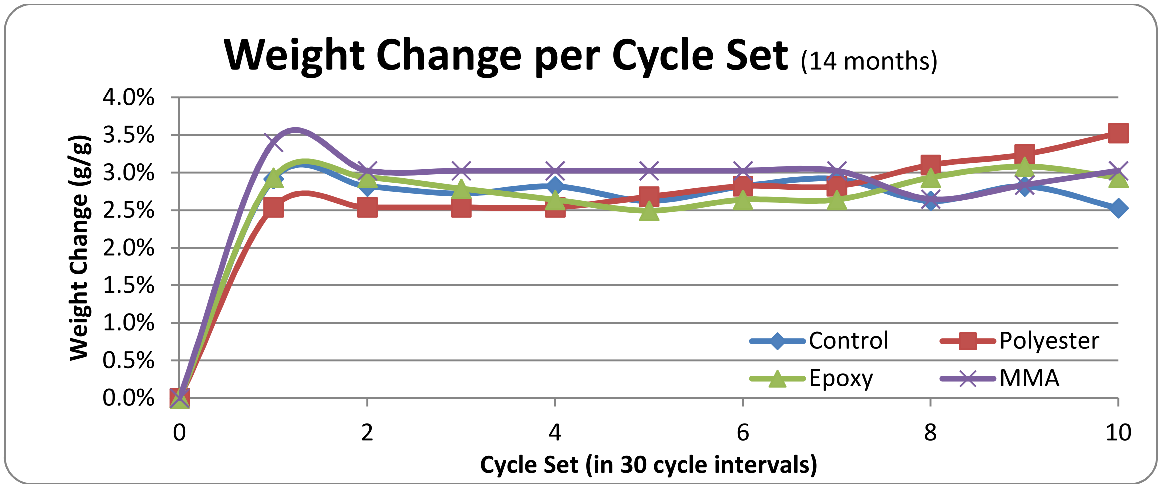

Figure 5-25 Percent weight change per cycle set after 14 months

iii. Ultrasonic Pulse Velocity/ Dynamic Modulus/ Durability Factor

The ultrasonic pulse velocity is a measure of the speed at which an ultrasonic pulse travels through a specimen. The ultrasonic pulse velocity is measured by placing a transmitting and receiving transducer on either side of the specimen measuring the travel time and dividing by the distance between the two transducers which is also the length of the specimen being tested. As the damage and cracking of a specimen increases, the pulse velocity should decrease due to the pulse having to travel around the crack thus increasing the time to through the specimen. For this test, 50 Khz transducers were used. Once the pulse velocity is measured, the dynamic modulus of elasticity can be calculated using **Error! eference source not found.**, where E_d = dynamic elastic modulus (Pa); μ = Poisson's ratio; ρ = Density of specimen (kg/m^3); and V = Pulse velocity (m/s).

$$\textbf{\textit{(5-3)}} \qquad E_d = \rho V^2 \frac{(1+\mu)(1-2\mu)}{(1-\mu)}$$

After the test is complete, and the durability factor can be calculated using **Error! Reference source not ound.**, where DF = durability factor; P = relative dynamic modulus of elasticity at N cycles, %; N = the smaller of the number of cycles at which P reaches the specified minimum value for discontinuing the test or the specified number of cycles at which the exposure is to be terminated; M = specified number of cycles at which the exposure is to be terminated. The durability factor of each specimen from each testing period is shown in Table 5-9.

$$DF = \frac{PN}{M} \qquad (5\text{-}4)$$

Table 5-9 Freeze-Thaw Durability

Installation	Durability Factor
Control	0.974
8 Months	**Durability Factor**
Control	*0.810*
Polyester	*0.629*
Epoxy	*0.784*
MMA	*0.982*
14 Months	**Durability Factor**
Control	*0.674*
Polyester	*0.553*
Epoxy	*0.986*
MMA	*0.978*

Each section had an additional core pulled from the deck to test the bond strength after 8 months under service loads plus an additional 300 freeze/thaw cycles. After three hundred additional cycles, the bond strength from the control, polyester, epoxy and MMA was reduced by 12.9%, 21.3, 21.2% and 75.1%, respectively. The control and epoxies failure planes remained through the concrete, but still had a loss in bond strength indicating that the concrete was damaged due to the thermal effects of freezing and thawing. The most likely cause of the polyesters additional loss in bond strength is the different coefficients of expansion of the polyester overlay and the deck concrete. The failure mode of the MMA is defined as class H. Inspection of the bond test specimen showed that main failure was due to aggregate pullout from the overlay. This is an indication that the weakest plane in MMA is the interface between the aggregate and the MMA resin.

Table 5-10 - Bond Strength at 8 months +300 F/T Cycles

Section	Pull off Strength (psi)	Failure Mode
Control	309	Substate
Polyester	172	Overlay/Deck
Epoxy	290	Substrate
MMA	42	Overlay

Each section had an additional core pulled from the deck to test the bond strength after 14 months under service loads plus an additional 300 freeze/thaw cycles. After three hundred additional cycles, major damage was done to the polyester specimen, and visible damage could be seen on the other specimens. This result was unexpected because none of the other specimens suffered any major damage. The damage can be seen in below. Although the concrete was damaged, all the overlay showed no visible damage. The bond strength from the control, polyester, epoxy and MMA sections were reduced by 27%, 201%, 26%, and 45%, respectively. The results from this test will not be used for the evaluation of the overlays, due the concrete failing beneath the overlays.

Table 5-11 - Bond Strength at 14 months +300 F/T Cycles

Section	Pull off Strength (psi)	Failure Mode
Control	280	Substrate
Polyester	74	Substrate
Epoxy	292	Substrate
MMA	114	Substrate

Figure 5-26 Freeze-thaw damage

5.7 Field Observations

5.7.1 Installation observations

On the night of the installation, the Colorado Department of Transportation's Research Team, University of Colorado's Research Team, representatives from each overlays' manufacture, and contractors travelled to the deck to access the original condition of the deck surface. A visual inspection of the bridge deck, both top and bottom surfaces, were checked for crack patterns, spallings, delaminations, and patches.

It was agreed that the surface of the deck was in good condition, except for the application of crack chaser which was present throughout each section. There were no areas of exposed steel or spalling on the deck surface. Areas where the crack chaser was applied in each section were mapped and can be seen in FIGURE XX through FIGURE XX. An attempt to shot blast the crack chaser out was made, but due to the texture of the deck surface not all of it could be removed, see Figure 5-27. Prior to opening the bridge to traffic, it was noted that the MMA overlay completely covered the aggregate leaving a polished looking surface.

Figure 5-27 Residual crack chaser left on the deck

5.7.2 8 Month Observations

After 8 months of exposure to weathering, traffic, and the application deicers on E-17-QM, the overlays were inspected visually to evaluate their performance. Observations of each overlay section were made to search for areas of debonding, aggregate pull out, pin-holes, and cracking.

Each overlay appeared to be performing well after 8 months of service. There were no signs of delaminations or cracking on any of the test sections. There appeared to be very little aggregate pull-out in the polyester and epoxy sections, but the damage was not extensive enough to document. The only major sign of damage was seen at the joints between sections. To prevent cross contamination between the overlays, each section was separated by a 2 in gap. Damage to the overlays occurred at the edge facing the direction of traffic from the scrapping of snowplow blades. Aggregate pullout on the edges from the snowplow blades between the epoxy and MMA overlays can be seen in Figure 5-28.

Figure 5-28 Joint between Epoxy and MMA sections

5.7.3 14 Month Observations

After 14 months of exposure to weathering, traffic, and the application deicers, the overlays were again inspected visually to evaluate their performance.

After 14 months of service on the bridge deck, there were no major delamination's or cracking observed. However, aggregate pullout was seen in each overlay section. Images of aggregate pull-out from test section can be seen in Figure 5-29. The amount of pullout from each section was evenly distributed over the entire section. The epoxy overlay experienced the most pullout in comparison to the other overlays.

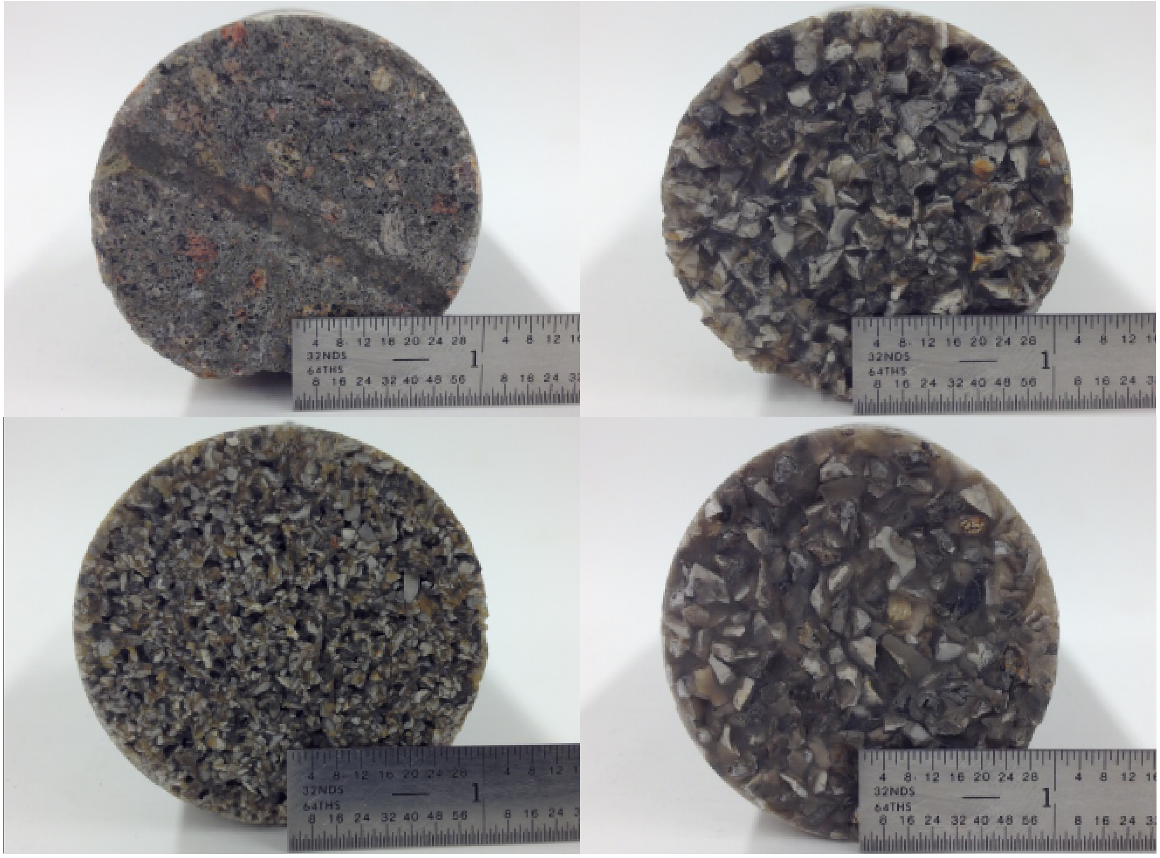

Figure 5-29 Surface after 14 months of service (LRTB-Control, Polyester, Epoxy, MMA)

Chapter 6 Interpretation and Possible Sources of Error

This section includes a discussion of possible sources of experimental error that may have affected the test results and subsequent conclusions.

6.1.1 Skid Resistance

The results obtained from the British Pendulum Tester are designed to correlate with performance of a vehicle traveling at 50 Km/hr (31 mph) with textured tires and then braking with locked wheels on a wet road. The 65 mph travel speed on E-17-QM is over double the intended design speed for this experiment, therefore the skid resistance provided at the higher speeds may differ. The current temperature and environmental conditions on the surface of the roadway vary hourly, and vary considerably between the summer and winter months. The environmental conditions on the testing surface effects the resilience of the rubber boot which can show lower skid measurements in warmer conditions and higher measurements in colder conditions. Ambient air temperature on the bridge varied from 43°F during the 2nd visit in the winter to 67°F during the final visit in the summer. It is important to note that the effect of polishing of the roadway surface has a much larger influence on the results than the environmental conditions.

The manufacturer of the pendulum tester suggests that the skid resistance of a roadway with an ADT greater than 2000 vehicles per day should be 55 or higher. The average skid number from each section except the MMA remained higher than 55 after 14 months of service. Although the final skid numbers from the polyester and epoxy overlays were lower than the bare deck section, the skid numbers are still higher than the suggested values.

6.1.2 Bond Test

Variations between bond tests is common due to: natural variations in the concrete substrate, variations in the drilling procedures, variations in the bonding agent application, and variations in the rate of loading which is regulated by the operator. Due to the limited number of cores that could be extracted from the deck, the repeatability of the test results from each section was not possible, therefore the results from a single test had to be assumed to be the representative value for each respective surface.

Careful consideration was taken during the experiments to limit controllable variations, therefore it can be assumed that the results are a good representation of the bond strength from each section. The bond tests for MMA overlays experienced several problems during testing. The epoxy based bonding agent did not bond to the surface of the MMA overlay for the 24 hour test. The binding agent was then changed following the manufactures recommendations for future tests, however, failure still occurred between the bonded agent and the overlay after 14 months of service. Preferred modes of failure were not seen in any of the bond strength tests from MMA overlay.

6.1.3 Profile Test

To reduce testing time, the Rapid Chloride Tester (RCT) was used instead of following the standard potentiometric titration method used in ASTM C1218 or in AASHTO T260. The accuracy of the RCT was found to be equivalent to AASHTO T260 following a study by the Swedish National Testing Institute. The variation of measurements for this test is 4% according to the manufacturer of the RCT testing unit.

Another factor affecting the results of the profile test is the age of the bridge tested. E-17-QM is a 25 year old bridge and results from the control section indicate that chlorides have already penetrated into the deck. Again, because the number of cores that could be extracted from the deck was limited, the initial condition of the entire deck was extrapolated from the results of a single core. Due to inherent variations in the concrete substrate, the magnitude of chloride diffusion varies from location to location. Pre-existing cracks in the deck prior to the installation allowed the de-icing salts and other contaminates to penetrate deeper into the deck. Major cracking in the deck was recorded in an effort to not pull cores nearby, however, smaller surface cracks could not be accounted for.

6.1.4 Permeability Test

According to ASTM C1202-12, the single-operator coefficient of variation for a single test has been found to be as high as 12.3%. The standard specifies that the specimens should be cut to a two inch width; however, because precision cutting tool were not used the width of each specimen could vary up to ±1/8 inch. Another factor that could have affected the results was the presence of rust in the load cells. Rust acts as a resistor which can reduce the voltage supplied to each load cell, skewing the results. Each testing cell needed to be refurbished after each round of tests. Also, chlorides already present in the deck may also negatively affect the results.

6.1.5 Ponding Test

The same unit that was used to determine the profiles from the bridge deck was used for the ponding test therefore the same sources of error involved with the testing apparatus are applicable. The specimens made in-house at the University of Colorado followed the specifications from CDOT to produce class D concrete, however, natural variations between the two concretes, mixing techniques, and curing conditions, could cause a difference in penetrability between the samples. Other possible sources of error in the ponding include leaks that developed during the test.

6.1.6 Freeze-Thaw Test

This purpose of the freeze-thaw testis to measure the performance the overlay and underlying concrete under accelerated repeated freezing and thawing cycles. Sources of error in the test include variable specimen length, error from measuring equipment, and having multiple operators conducting the test.

Chapter 7 Chloride Diffusion of Concrete under Low Temperatures

The objective of this chapter is to investigate the chloride diffusivity coefficient of saturated concrete as a function of temperature and compare experimental results to a mathematical model. Concrete diffusivity decreases as temperature drops below 0°C due to the formation of ice in the pores of cement paste and aggregate. As the ice forms inside the pore structure, the porosity of the concrete is reduced and thus reduces the chloride diffusivity coefficient. For more background information about chloride ion transport, see section 2.22.2.

7.1. Experimental Study

To investigate the relationship between temperature and the chloride diffusivity, concrete specimens are to be exposed to 25°C, -5°C, and -15°C temperature levels while being ponded with a 25% CaCl2 solution and evaluated at 7, 15, and 30 days. Specimens were produced following the mix design specified in table 7-1 below.

Table 7-1 - Diffusion Mix Design

Material	Proportion (lbs/yd^3)
Cement	575
Coarse Aggregate	1420
Fine Aggregate	1330
Water	320
Air Entraining Admixture (oz/100 lbs)	0.25

7.1.1. Specimen Preparation

Seven samples will be prepared, three for compression test and four for ponding test. All samples will be cast in one batch as 4’’ by 8’’ cylinders. The specimens will be cured in a curing room, de-molded between 24 and 48 hours after casting and cured for 28 days. Three samples will be used to determine the 28-day compression strength according to ASTM C39.

The other four samples will be divided in to three groups, and each sample will be equally cut into three 4’’ by 2.’’ discs after removing 1’’ in from each end of the cylinders. Then each cylindrical specimen will be cut in half. Epoxy resin will be used to seal each side of the discs except the topside. Half of the specimens will be soaked in a water solution for 48 hours to saturate the specimens. The solution contains 1% lime to prevent calcium hydroxide from leaching out of the paste during soaking. The other half will not be saturated. The discs will be put into the moisture room/freeze-thaw chamber for 48 hours to ensure the inside of concrete reaches the design temperature.

7.1.2. Chloride Penetration by Ponding

The ponding test will be done following a procedure similar to ASTM C1543. The solution selected for the ponding test is a 25% $CaCl_2$ solution. (This concentration is relative high, but the surface chloride concentration has little influence on the chloride diffusion coefficient. Therefore, this high salt concentration has no significant influence on the comparison of the diffusion coefficient). After 7/15/30 days of ponding, the chloride concentration profile will be obtained by Rapid Chloride Test (RCT) method. Once the profiles are analyzed from each respective temperature range, the effective chloride diffusion coefficient will be back calculated using Fick's second law. Figure 7-1 shows the setup for the ponding test and Table 7-2 describes the specimen designation.

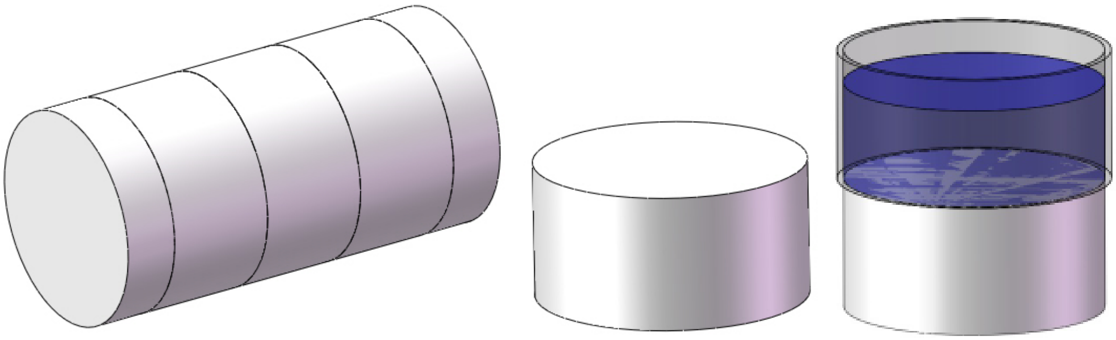

Figure 7-1 Specimen Setup

Table 7-2 - Specimen Details

Designation	**Temperature (℃)**	**Time (days)**	**Pretreatment**
7D+25°C Dry	25	7	non-saturated
15D+25°C Dry	25	15	non-saturated
30D+25°C Dry	25	30	non-saturated
7D+25°C Sat	25	7	saturated
15D+25°C Sat	25	15	saturated
30D+25°C Sat	25	30	saturated
7D-5°C Dry	-5	7	non-saturated
15D-5°C Dry	-5	15	non-saturated
30D-5°C Dry	-5	30	non-saturated
7D-5°C Sat	-5	7	saturated
15D-5°C Sat	-5	15	saturated
30D-5°C Sat	-5	30	saturated
7D-15°C Dry	-15	7	non-saturated
15D-15°C Dry	-15	15	non-saturated
30D-15°C Dry	-15	30	non-saturated
7D-15°C Sat	-15	7	saturated
15D-15°C Sat	-15	15	saturated
30D-15°C Sat	-15	30	saturated

7.2. Results

7.2.1. Comparison of Chloride Profiles

The chloride concentration profile results after exposure to a 25% $CaCl_2$ solution after 7, 15, and 30 days at the three different design temperatures are shown in Figure 7-2 through Figure 7-7. The results are presented two ways:

i. profiles based on number of days ponded
ii. profiles based on design temperature

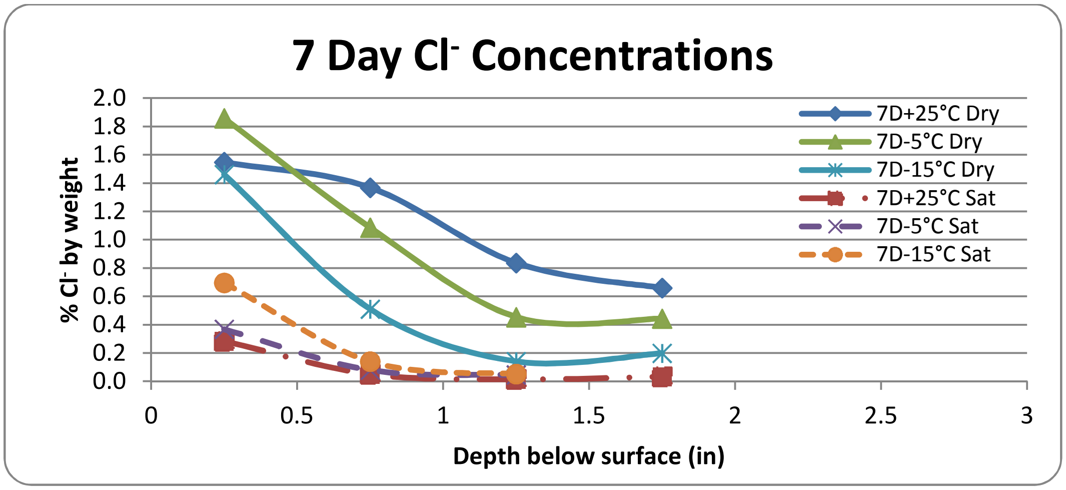

Figure 7-2 7 day concentrations

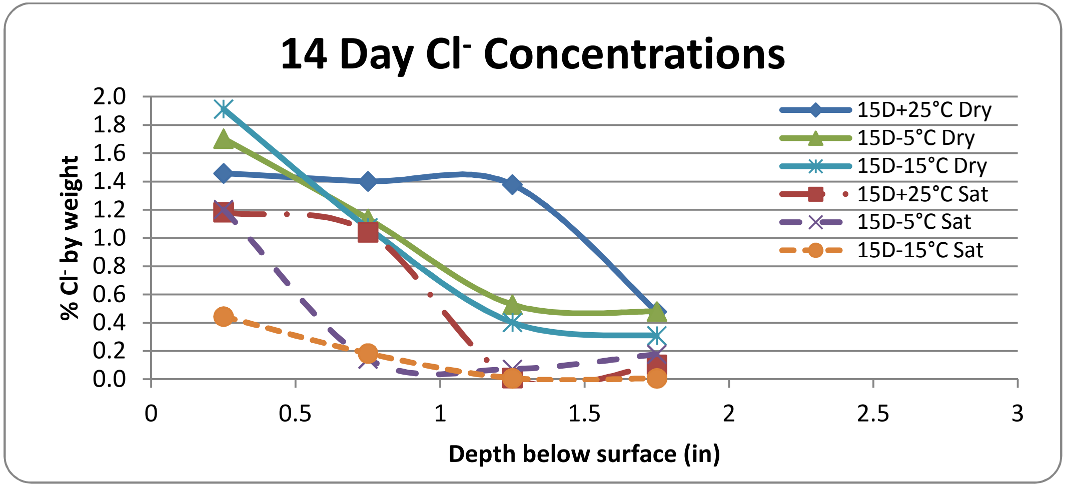

Figure 7-3 14 day concentrations

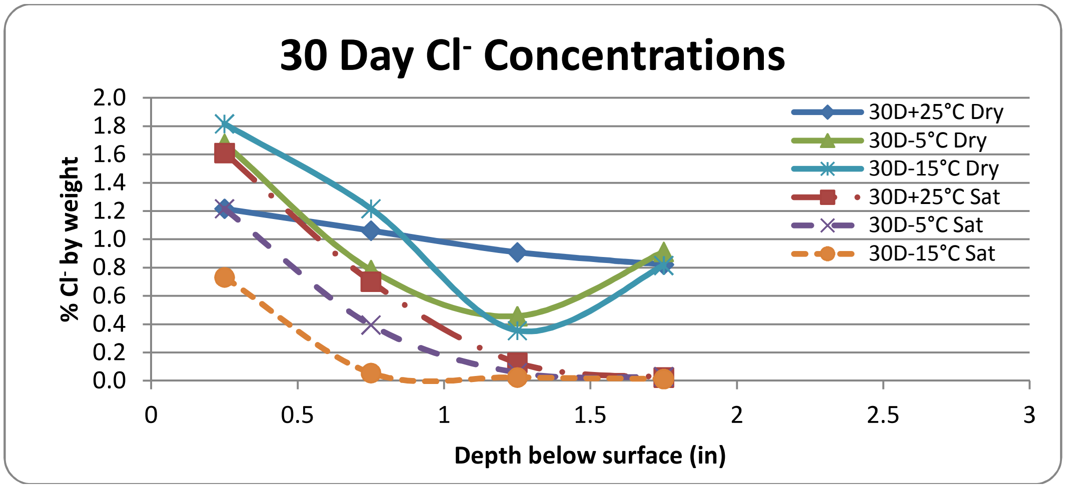

Figure 7-4 30 day concentrations

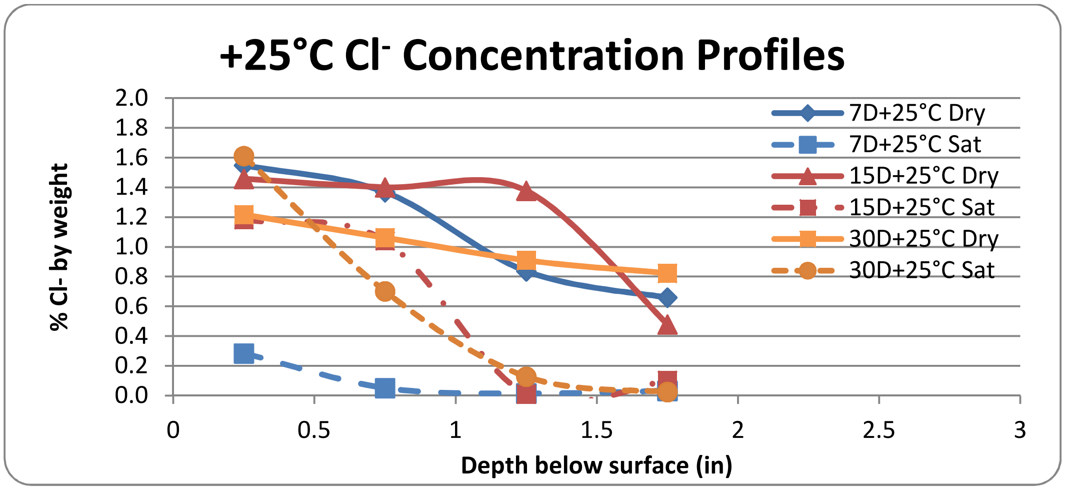

Figure 7-5 25°C profiles

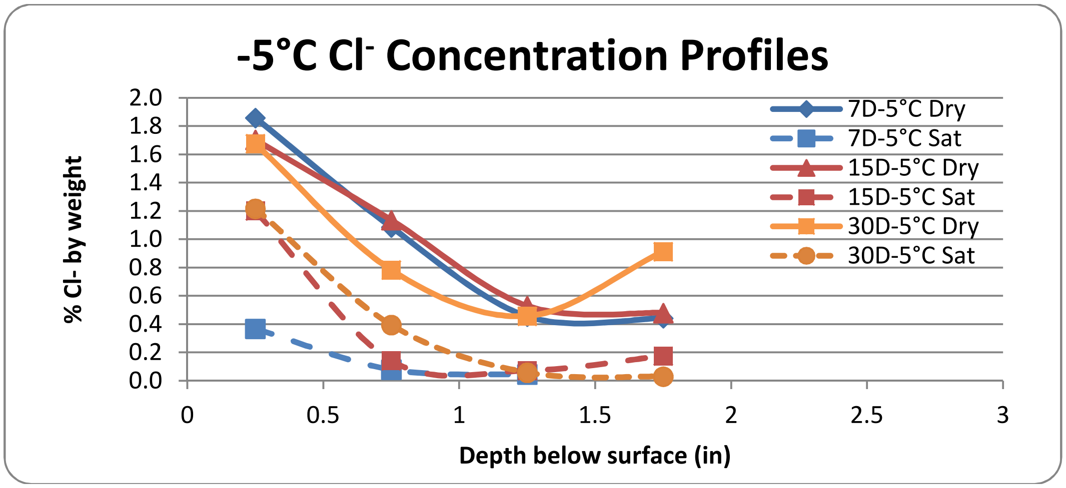

Figure 7-6 -5°C Profiles

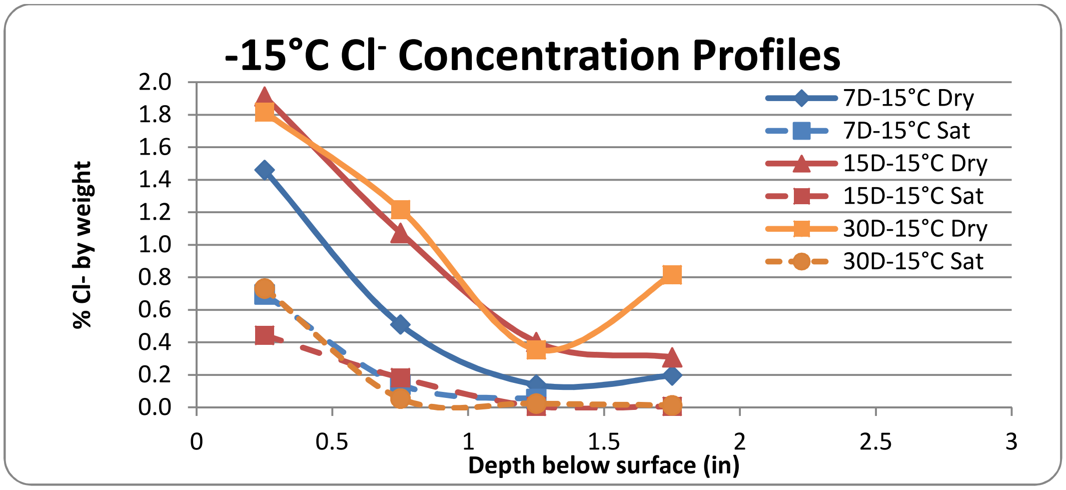

Figure 7-7 -15°C Profiles

There are several trends that can be observed from the above plots. Specimens that were saturated with in the 1% Lime solution had much lower concentration profiles in comparison to the specimens that were unsaturated. For the pre-saturated specimens, chloride ingress was limited to diffusion, while chloride penetrated into the unsaturated specimen by capillary absorption as well as diffusion.

The concentration profile decreased as a function of temperature for both the saturated and unsaturated specimens. The chloride levels decreased due to the formation of ice inside the pore structure of the concrete.

7.2.2. Fitting Fick's Law to Concentration Profiles

Fick's Second Law, **Error! Reference source not found.**, was fit for the concentration profiles after thirty ays of ponding for each temperature treatment. The rearranged Fick's law is show in **Error! Reference source not found.**. The diffusivity for each specimen was calculated at each from each sample depth from each specimen. The average diffusivity after thirty days of ponding at each temperature level is shown Table 7-3.

$$C(x,t) = C_0 * \left[1 - erf\left(\frac{x}{\sqrt{4D_{eff}t}}\right)\right] \tag{7-1}$$

$$D_{eff} = \left[\frac{x}{\left(2 * erf^{-1}\left(1 - \frac{Cx}{Co}\right)\right)}\right]^2 \left(\frac{1}{t}\right) \tag{7-2}$$

Table 7-3 - Effective Diffusivity at different Temperatures

Deff (cm^2/s)	
D (25°C)	7.0E-11
D (-5°C)	4.8E-11
D (-15°C)	2.7E-11

From Table 7-3 we can see that as the diffusivity coefficient drops at the temperature decrease. The formation of ice inside the pore structure decreases the total porosity and thus the moisture diffusivity of concrete.

7.2.3. Diffusivity Model

To model the effect of temperature on the moisture diffusivity, we will utilize the composite theory (Hashin and Shtrikman 1962) for the effective diffusivity of a two phase composite show in **Error! Reference source not found.**.

$$\text{(7-3)} \qquad D_{eff} = D^{(1)}\left[1+\frac{n}{\frac{1-n}{3}+\frac{D^{(1)}}{D^{(2)}-D^{(1)}}}\right]$$

Where:

- D_{eff} = effective diffusivity of a two phase composite
- $D^{(1)}$ = moisture diffusivity of the matrix
- $D^{(2)}$ = moisture diffusivity of the inclusion (Chloride solution)
- n = total porosity of the material

This model is valid for any two-phase isotropic and homogenous composite materials
In order to apply this theory the concrete must be considered a two phase material. One phase is solid (matrix) containing no pores, $D^{(1)}$. The other phase, $D^{(2)}$ is denoted as the porous phase, which includes all the pores. The term *solid* in this context does not mean that $D^{(1)}$ cannot transfer moisture and chloride, but rather is the resistance of concrete solid matrix is higher than the pores. Figure 7-8 shows the plot of Diffusivity vs. Temperature using the data from Table 7-3.

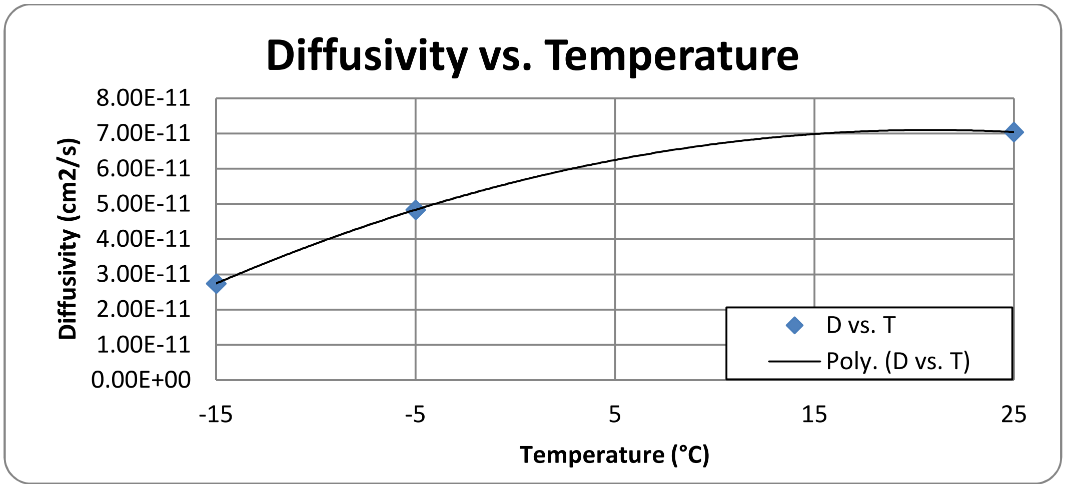

Figure 7-8 Experimental Diffusivity vs. Temperature

Define D_{eff} as the average of the diffusivities calculated at each temperature, while $D^{(1)}$ and $D^{(2)}$ are held constant. The effective diffusivity for a given temperature is found by the equation from the trend line in

Figure 7-8. The relationship between porosity and temperature is found by solving **Error! Reference source not found.** for the total porosity, n. The relationships between Diffusivity vs. Porosity, and Porosity vs. Temperature are shown in Figure 7-9, and Figure 7-10, respectively.

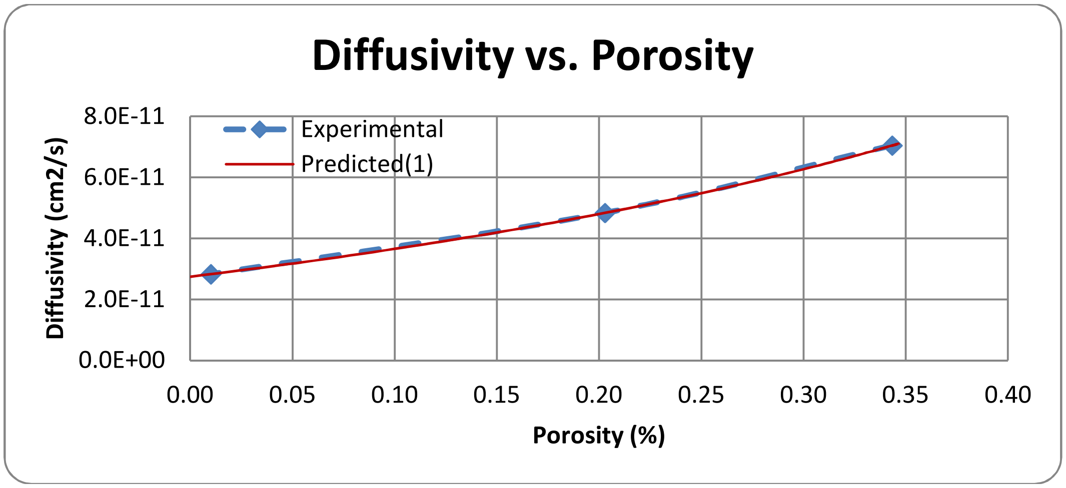

Figure 7-9 Diffusivity vs. Porosity

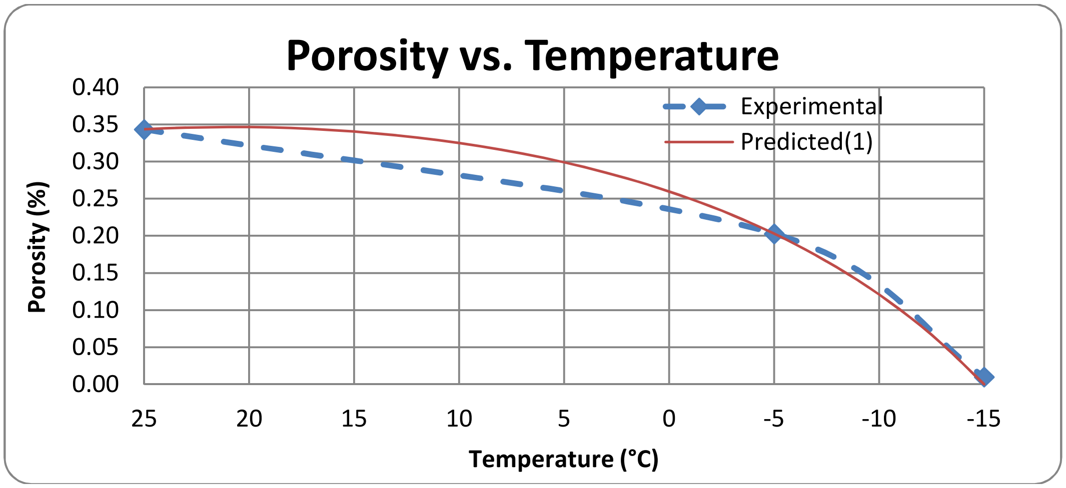

Figure 7-10 Porosity vs. Temperature

Figure 7-9 and Figure 7-10 confirm that the composite theory for a two phase material is effective at modelling the effects of temperature on the moisture diffusivity of concrete. The resulting concentration profiles as a function of temperature from the model prediction are compared to the experimental data in Figure 7-11Figure 7-13. The reduction of porosity with decreasing temperature is an indication of the amount of ice formed in pores. We assumed that the diffusivity of ice is approximately the same as that of solid concrete.

In general the model, underestimates the concentration profile at 25°C, and overestimates the concentration profile at -15°C. The model most likely overestimates the concentrations due to the diffusivity being reduced by not only the reduced pore size, but also the inherently lower diffusivity of ice that is filling the pore space.

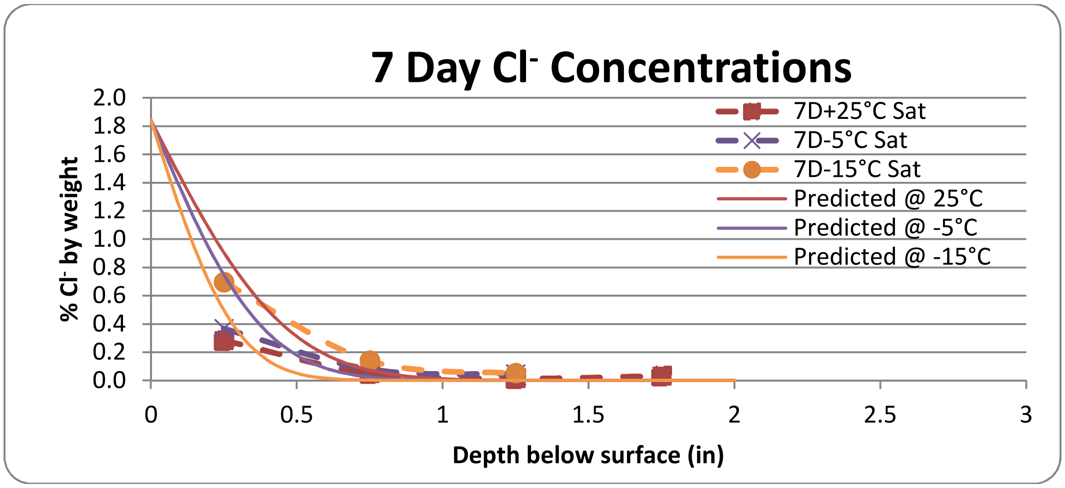

Figure 7-11 7 Day Chloride Profiles

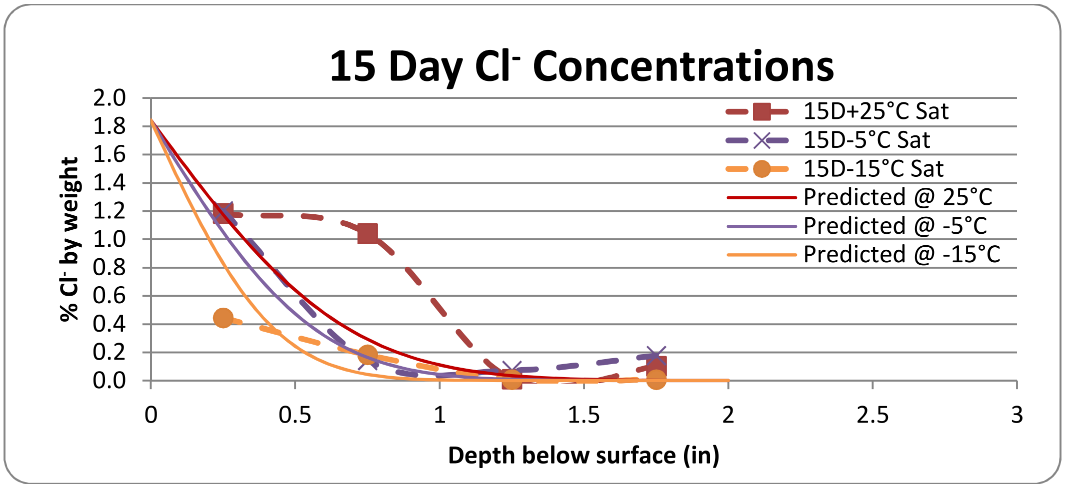

Figure 7-12 14 Day Chloride Profiles

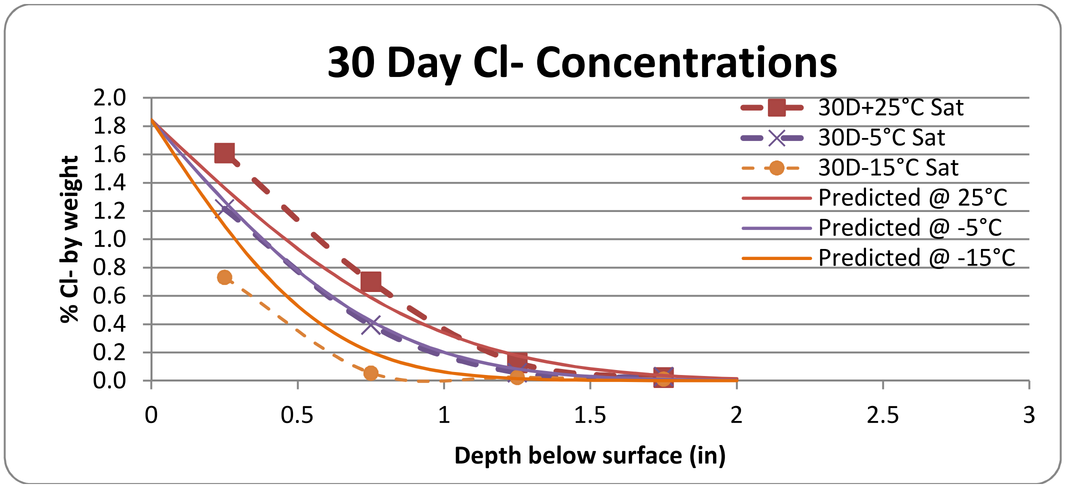

Figure 7-13 30 Day Chloride Profiles

Chapter 8 Conclusions

This section summarizes the important correlations and conclusions established from a fourteen month study testing three different thin bonded overlays in Denver, Colorado. This includes a proposal for future work, cost comparison, rankings from each study, and final product recommendation. The main conclusions are as follows.

iii. The installation of a thin bonded overlay improves the skid resistance of the bridge deck in comparison to the bare deck for a short period of time. After 1 year of service, the overlays provided less skid resistance than the bare deck. It was observed that the Plexideck Methyl Methacrylate product provided by Plexicoat America showed early reduction in skid resistance after eight months and only a slight reduction in skid resistance between eight and fourteen months. The PPC MLS polyester based product from Kwik Bond and the Flexolith Epoxy based products show minimal reduction in skid resistance after 8 months, but both products reported skid number less than the bare deck after 14 months.

iv. The bond strength of the polyester overlay was reduced by 36% after 14 months of service on the deck. The bond strength of the epoxy overlay remained higher than the tensile strength of the concrete substrate for the entire testing period. A preferred type of failure was not achieved by the MMA overlay due to complications with the bonding agents used. When a good bond was achieved the overlay did not peal from the deck, but rather had all the aggregate pulled out.

v. After 25 years of service, the original class D concrete is considered to be in good shape and is preventing the intrusion of chloride very well. One year after the installation the overlays the levels of chloride near the surface (0.75”-1.25” below the surface) were reduced by all products. Beyond the above specified depths, the chloride concentration became higher than the control section. Similar results were seen by Pfeifer, 1999.

vi. The installation of all three thin bonded overlays reduces the potential penetrability of chloride ion into the bridge deck from a high level to a low/negligible level.

vii. The MMA overlay system provided the best protection again the penetration of chlorides after exposure to a 3% NaCl solution for a year followed by PPC MLS system. The Flexolith system appeared to provide the same level of protection as the bare concrete surface.

viii. All overlay sections' durability was reduced after exposure to 300 cycles of freezing a thawing. The MMA is the most durable to freezing and thawing, followed by the epoxy and polyester thin bonded overlays. The bond strength after freezing and thawing did not change for the epoxy overlay. The MMA experienced very poor bond strength to the aggregate broadcasted onto the overlay after 300 freeze-thaw cycles and the PPC MLS system bond strength to the deck was also reduced after exposure to additional freezing and thawing.

ix. The diffusivity model based on composite theory is an effective way to model the effects of temperature on the chloride diffusivity of concrete.

Future work

The examination period needs to be extended in order to confirm results and analysis of this study. To better classify the performance of each overlay, more studies need to be conducted to determine if the expected service life of each overlay can be met. The physical performance of each section needs to be monitored for at least another 3 to 4 years to ensure that the skid resistance and bond strength remain at acceptable values. Because a thin bonded overlay is a two-phase system, a chloride penetration model needs to be developed in order to predict the corrosion initiation time for each section. For future projects the overlays should be installed on a new bridge deck in order to minimize the number of variables.

Cost

The estimated cost of each overlay was based off of a medium sized project that included surface preparation on a 300 foot long, 2 lane bridge deck. The estimated price per square yard for each product is shown in Table 8-1 below. Prices shown are only estimates as surface conditions, repairs, and other variables could influence the final cost.

Table 8-1 - Installation Costs

Manufacturer	**S.2 - Kwik Bond Polymers**	**S.3 - Euclid Chemical/ Tammes**	**S.4 - Plexicoat America**
Product	*PPC MLS*	*Flexolith*	*Plexideck*
\$/yard^2	***\$40.00***	***\$36.00***	***\$42.00***

Short-term Performance Rankings

Each section was ranked in comparison to each other based on seven parameters: six being the tests conducted and the other one being the price per square yard. The overall ranking from each overlay is shown in Table 8-2. A ranking of "1" indicates the best performance in relation to the other overlays, "2" performed the second best, and "3" performed the worst in comparison to the other overlays.

Table 8-2 - Overall Rankings

Overall Performance *Test Type*	**S.2 - Kwik Bond Polymers** *PPC MLS*	**S.3 - Euclid Chemical/ Tammes** *Flexolith*	**S.4 - Plexicoat America** *Plexideck*
Skid Test	*1*	*2*	*3*
Bond Strength	2	1	3
Chloride Penatration	1	3	2
Chloride Permability	3	2	1
Pond Penetration	2	3	1
Freeze Thaw Durability	3	2	1
Price	2	1	3
Point total	**14**	**14**	**14**
Final Rank	1	1	1

Based on the results from each test, each overlay is ranked the same. To further analyze the results, the rankings were split into the performance based on chloride resistance and physical properties, shown in Table 8-3Table 8-4.

Table 8-3 - Ranking based on Chloride Resistance

Chloride Resistance	**S.2 - Kwik Bond Polymers** *PPC MLS*	**S.3 - Euclid Chemical/ Tammes** *Flexolith*	**S.4 - Plexicoat America** *Plexideck*
Chloride Penatration	1	3	2
Chloride Permability	3	2	1
Pond Penetration	2	3	1
Point total	**6**	**8**	**4**
Final Rank	2	3	1

Table 8-4 - Ranking based on Physical Properties

Physical Properties	**S.2 - Kwik Bond Polymers** *PPC MLS*	**S.3 - Euclid Chemical/ Tammes** *Flexolith*	**S.4 - Plexicoat America** *Plexideck*
Skid Test	*1*	*2*	*3*
Bond Strength	2	1	3
Freeze Thaw Durability	3	2	1
Freeze Thaw Bond	2	1	3
Point total	**8**	**6**	**10**
Final Rank	2	1	3

Recommendations

Given the results of the short-term analysis of this project, all of the thin bonded overlays tested provided a semi-protective layer on the bridge deck. Based on the rankings from the seven testing parameters, each overlay is scored the same. However, when broken down into effectiveness on preventing chloride penetration, the MMA product from Plexicoat America performed the best; and when compared based on physical performance, the Epoxy based overlay from Euclid Chemical/Tammes Industries performed the best.

All of the thin bonded overlays tested in this project could be used as a short-term protection system for a highway bridge deck. Without further long term data, if CDOT chooses to use a thin bonded overlay as a topical protective system, we recommend the use of the MMA product Plexicoat by Plexicoat America.

References

Aboutaha, R.S., et al. (2005) "Investigation of Durability of Wearing Surfaces for FRP Bridge Decks," Transportation Infrastructure Research Consortium/New York State Department of Transportation (TIRC/NYSDOT), Project #C-01-50, 397 pp.

Akkari, A. (2011) "Evaluation of polyvinyl alcohol fiber reinforced engineered cementitious composite for a thin-bonded pavement overlay," Minnesota Department of Transportation

Alger,R., Gruenberg,S., & Wegleitner, J. (2003) "Field Performance of Polymer Bridge Deck Overlays in Michigan," Michigan Department of Transportation Construction and Technology Division, RC-1422, 1-33

American Society of Civil Engineers, ASCE (2013) "Bridges Report Card – C+," *2013 Report Card on Americas Infrastructure*. American Society of Civil Engineers, <http://www.infrastructurereportcard.org/bridges/>

Angst, U., et al. (2009) "Critical chloride content in reinforced concrete – A review," Cement and Concrete Research, 39, 1122-1138

ASTM Standard C666, 2003 (2008) "Standard test Method for Resistance of Concrete to Rapid Freezing and Thawing," West Conshohocken, PA, 2008, DOI: 10.1520/C0666_C0666M-03R08, <www.astm.org>

ASTM Standard C1202, (2012) "Standard Test Method for Electrical Indication of Concretes Ability to Resist Chloride Ion Penetration," West Conshohocken, PA, 2012, DOI: 10.1520/C1202-12, <www.astm.org>

ASTM Standard C1218, 1999 (2008) "Standard Test for Water-Soluble Chloride in Mortar and Concrete," West Conshohocken, PA, 2008, DOI: 10.1520/C1218_C1218M-99R08, <www.astm.org>

ASTM Standard C1543, (2010) "Standard Test Method for Determining the Penetration of Chloride Ion into Concrete by Ponding," West Conshohocken, PA, 2010, DOI: 10.1520/C1543-10A, <www.astm.org>

ASTM Standard D7234 (2012) "Standard Test Method for Pull-off Adhesion Strength of Coatings on Concrete Using Portable Pull-Off Adhesion Testers," West Conshohocken, PA, 2012, DOI: 10.1520/D7234-12, <www.astm.org>

ASTM Standard E303, 1993, (2013) "Standard Test Method for Measuring Surface Frictional Properties Using the British Pendulum Tester, West Conshohocken, PA, DOI: 10.1520/E0303, <www.astm.org>

Braughn, James (2013) "I 270 ML over I 25 ML, RAMPS," Uglybridges.com National Bridge Inventory Data, http://uglybridges.com/1066703

Bureau of Economic Analysis (2013) "National Income and Product Accounts Gross Domestic Product, 3rd quarter 2013 (advance estimate)" U.S. Department of Commerce, Bureau of Economic Analysis, http://www.bea.gov/newsreleases/national/gdp/gdpnewsrelease.htm

Caltrans (1996) "Memos to Designers - Overlays on Existing Bridges" California Department of Transportation, 3 pp.

Detwiler, R.J., Kjellsen, K.O., and Gjorv, O.E. (1991) "Resistance to Chloride Intrusion of Concrete Cured at Different Temperatures," *ACI Materials Journal*, Vol. 88, No. 1, pp. 19-24

Dintz, A.M., & Stenko, M.S., (2010) "The successful use of thin polysulfide epoxy polymer concrete overlays on concrete and steel orthotropic bridge decks," American Society of Civil Engineers, 2010 Structures Congress, 530-560

Fowler, D.W., Whitney, D.W. (2011) "NCHRP Synthesis 423: Long-Term Performance of Polymer Concrete for Bridge Decks," Transportation Research Board, Nation Research Council, 75 pp.

Greenman, R.L. (1970) "Performance of Latex-Modified Mortar on Concrete Bridge Decks" Michigan Department of State Highways, Research Project 57 B-38, Research Report No. R-726, 7 pp.

Harper, J. (2007) "Investigations of Failures of Epoxy Polymer Overlays in Missouri," Missouri Department of Transportation

Hashin, Z., and Shtrikman, S. (1962) "Variational approach to the theory of effective magnetic permeability of multiphase material," J. Appl. Phys. 33 (10), 3125-3131

Houska, C. (Unknown) "Deicing Salt – Recognizing the Corrosion Threat" <http://www.imoa.info/files/pdf/DeicingSalt.pdf>

Johnson, D., & Stephens, J. (1997) "Monitoring and Evaluation of Thin Bonded Overlays and Surface Laminates for Bridges Decks," Montana Department of Transportation Research, Development, & Technology Transfer Program. 1-89

Kepler, J.L., D. Darwin, and C.E. Locke, Jr. (2000) "Evaluation of Corrosion Protection Methods for Reinforced Concrete Highway Structures," SM Report No. 58, University of Kansas Center for Research, Inc., Lawrence, pp. 222

Knight, M.L. et al. (2004) "Overlay Types Used as Preventive Maintenance on Tennessee Bridge Decks," Transportation Research Record: Journal of the Transportation Research Board. No 1866 pp. 79-84

Krass, P.D., et al. (2008) "Guidelines for Selection of Bridge Deck Overlays, Sealers, and Treatments," National Cooperative Highway Research Program, Transportation Research Board.

Liange, Y., Zhang, W., Xi, Y (2010) "Strategic Evaluation of Different Topical Protection Systems for Bridge Decks and the Associated Life-cycle Cost Analysis," Colorado Department of Transportation, DTD Applied Research and Innovation Branch, Report No. CDOT-2010-6

Meggers, D. (2009) “The Kansas Experience with Polymer Concrete Bridge Deck Overlays,” Kansas Department of Transportation

New York State Department of Transportation (NYSDOT). (2007) “*Field Trip Report on Thin Polymer Overlays,”* NYSDOT, Unpublished report

Russell, H.G. (2012) “NCHRP Synthesis 425: Waterproofing Membranes for Concrete Bridge Decks,” Transportation Research Board, Nation Research Council, 67 pp.

Semen, P.M., & Rolling, R.S. (2005) “A review and discussion of current developments involving bonded concrete overlays of airfield pavements,” U.S. Army Corps of Engineers, Engineer & Research Development Center, Conference on Concrete Pavements, 900-910

Soltesz, S. (2010) “Evaluation of Thin Overlays for Bridge Decks,” Oregon Department of Transportation, Research Section, SPR 304-431

Sprinkle, M. & Sellars, A.R. (1993) “Rapid Concrete Bridge Deck Protection, Repair and Rehabilitation,” Virginia Transportation Research Council, Virginia Polytechnic Institute and State University, Strategic Highway Research Program, SHRP-S-244, 1-73.

Sprinkle, M. (2004) “Twenty-five year experience with polymer concrete overlays on bridge decks,” International Congress on Polymers in Concrete

Sohanghpurwala, A. et al (1996) “Effectiveness of a Cementitious Overlay in Extending the Service Life of a Corrosion Damaged Bridge Deck,” NACE International, Corrosion 96

Stanish, K., Hooton R., and Thomas, M. (1997) “Testing the chloride penetration resistance of concrete: a literature review,” FHWA contract DTFH61-97-R-00022, Department of Civil Engineering, University of Toronto, Canada.

Virmani, Y.P., et al. (2001) “Corrosion Costs and Preventative Strategies in the United States,” U.S. Department of Transportation, Federal Highway Administration, FHWA-RD-01-156

Young, L.M., Durham, S.A., & Bindel, M.K. (2011) “Thin Bonded Epoxy Overlays on Concrete Bridge Deck Surfaces,” Colorado Department of Transportation, TRB 2012 Annual Meeting, 1-17