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Long term bond strength and chloride resistance of epoxy and concrete overlays

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The student author, whose presentation of the scholarship herein was approved by the program of study committee, is solely responsible for the content of this thesis. The Graduate College will ensure this thesis is globally accessible and will not permit alterations after a degree is conferred.

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NOMENCLATURE

CO	Concrete Overlaid
EO	Epoxy Overlaid
FRC	Fiber Reinforced Concrete
F/T	Freezing and Thawing
LMC	Latex Modified Concrete
LSDC	Low Slump Dense Concrete
MMA	Methyl Methacrylate
PC	Polymer Concrete
SFMC	Silica Fume Modified Concrete
TPO	Thin Polymer Overlay

TERMINOLOGY

The focus of this thesis is multiple-layer thin polymer overlay (TPO) that uses epoxy as the binder. TPOs are different from traditional rigid overlays in the following aspects: there are no cementitious materials in TPOs, the binder is polymer materials, and the thickness of TPOs is typically less than one inch – in contrast to several inches of rigid concrete overlays. To better distinguish the TPOs, several definitions are listed below.

Binder—a resin compound which binds aggregate to become polymer concrete.

Epoxy resin—a resin that contains epoxy groups principally responsible for its polymerization.

Monomer—a small molecule from which much larger polymer molecules can be made, usually in liquid form for concrete applications.

Multiple-layer overlay—two or more layers of polymer concrete bonded to concrete; normally each layer consists of an application of resin with aggregate broadcast into the surface.

Overlay system—a composite structure consisting of an overlay material, a substrate concrete and an interface between them.

Polymer—a product of polymerization, more commonly a rubber or resin consisting of large molecules formed through polymerization.

Polymer concrete (PC)—a composite material in which the aggregate is bound in a matrix with a polymer binder.

Premix overlay—a method of initially blending a polymer binder, with fine and coarse aggregate and fillers, if used, and then mixing until all particles are completely dampened. Once the composite has been mixed as required, it is transported and placed. The term applies to polymer concrete.

Resin—a natural or synthetic, solid or semisolid organic material of indefinite and often high molecular weight, with a tendency to flow under stress. It usually has a softening or melting range and usually fractures conchoidally.

Slurry overlay—Overlay applied by placing an application of resin or monomer followed by broadcasting aggregate onto the surface.

Thin polymer overlays (TPOs)—One or more layers of polymer concrete bonded to concrete, normally one inch or less in thickness.

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ABSTRACT

There has been an increasing need to extend the service life of bridges due to deteriorating conditions of infrastructure and associated fiscal limitations. To protect bridge deck against deterioration, as well as to improve bridge performance through better maintenance practices, a better understanding of performance of the recently developed thin epoxy overlay and the well-adopted low slump dense concrete (LSDC) overlay is desired. To evaluate the performance of these two overlays, the following objectives are proposed: to evaluate the initial and long-term bond strength of overlays; to assess the chloride resistance of overlays and to identify factors that affect the initial performance of overlays. To fulfill these objectives, six existing bridges were chosen to install the two overlay types, and field inspections were performed on selected bridges to document substrate surface conditions; substrate cores were extracted and tested by both ASTM C642 and ASTM C666 to evaluate their porosity and durability to cyclic freezing condition; on-site pull-off tests (ASTM C1583) were conducted to assess the initial bond strength of overlays; laboratory pull-off tests (ASTM C1583) were conducted under cyclic freezing conditions to evaluate long-term bond strength and salt-ponding tests (AASHTO T259) were performed to assess chloride resistance.

The results from these testing efforts indicated that the initial bond strength of both overlays are good; the long-term bond strength of thin epoxy overlay decreased sharply after 300th F/T cycles, whereas the bond performance of the LSDC overlay remained unchanged; chloride resistance of the epoxy overlay is much better than LSDC overlay and the percentage of air voids of the substrate concrete was seen to have an effect on the initial performance of the overlays.

CHAPTER 1. INTRODUCTION

Research Background

Increasing the service life of bridges has been of high importance recently due to deteriorating conditions of infrastructure and associated fiscal limitations. The second strategic highway research program (SHRP 2) Project R19A focused upon the development and implementation of a design guide for bridges for service life. The result of this effort, the "Design Guide for Bridges for Service Life", identified nine main categories of research needs and challenges. One of these identified categories included bridge decks, and survey responses from Departments of Transportation have also commonly indicated the serviceability issues related to deck cracking and deck overlay performance as a top concern (Azizinamini et al. 2014). As such, the performance of bridge deck overlays is of importance for extending the service life of bridges, which is the focus of this research.

A wide variety of bridge deck maintenance methods exist, including various types of overlays, deck replacement, deck sealers or crack repairs. Guidelines for the selection of bridge deck overlays, sealers, and treatments for existing bridges have been developed based upon survey results in the past (Krauss et al. 2009). This survey identified methodologies and procedures that are used to guide bridge deck maintenance decisions, which often vary widely by agency. A two-step process for the selection of deck repair options was recommended: the category of repair is first determined, and then the corresponding repair material is selected based upon site conditions, traffic constraints, and other pertinent factors. The category of repair is determined based upon percentage of deck deterioration, estimated time-to-corrosion, deck surface condition, and concrete quality. Based upon these factors, a decision to either do nothing, maintenance, or protective overlay was recommended.

To determine an appropriate repair or preservation plan, the applicability, limitations, and performance of the possible overlay and sealer methods must be well understood. The performance and applicability of concrete overlays has been researched in the past, showing their ability to serve as cost-effective and long-lasting solutions for pavement preservation and rehabilitation (Fick and Harrington 2014). In particular, pervious concrete overlays offer unique advantages and have exhibited good performance in Minnesota, despite the harsh winter climate (Schaefer and Kevern 2011).

Polymer overlays and penetrating sealers, in particular, have risen in popularity, especially when extensive deck deterioration is not present (Alger et al. 2003). Epoxy polymer overlays are intended to prevent further deterioration of the deck, not to fix existing deficiencies. The overall field performance of polymer concrete overlays has been positive for both new bridges and when used in conjunction with more extensive repairs on existing infrastructure (Dahlberg and Phares 2016). Similarly, penetrating sealers act to slow chloride ingress via the creation of a hydrophobic barrier on the concrete surface that acts to repel water. Recommendations for concrete bridge deck sealant placement must take into account the moisture content at the time of application, the water-cement ratio, and other parameters such as surface preparation and finishing (Johnson et al. 2009). Because of their applications for bridge decks in overall good condition, polymer overlays and sealers are ideal candidates for use on new bridges.

The use of polymer overlays and penetrating sealers for preventative maintenance of new infrastructure can diminish chloride penetration and aid in service life extension via the mitigation of reinforcement corrosion. Summers provide the best and optimum seasonal placement of these measures due to required ambient temperatures of over 40 degrees

Fahrenheit (Morse and Schiff 2012). Timing of placement with respect to age must be determined based upon the cost-benefit ratio of the service life.

In general, overlays are applicable for bridge decks in generally good condition as a tool to prolong service life and optimal performance. It is worth noting that when bridge decks or existing overlays are in an actively deteriorating condition, signaled by visible deck cracks, crack repair methods can be applied. Extensive work on both the procedures for epoxy deck injections, as well as an investigation of their performance and extension of service life in Iowa has been an ongoing project for Iowa State University for several years (Wipf et al. 2019).

In order to better understand the applications and ideal scenarios for the utilization of individual overlay types, this research aims to evaluate the performance of two types of overlays: a thin epoxy overlay and a low slump dense concrete overlay. The result of this investigation is an estimated expected service life based upon research findings which include the analysis of bond strength over time, as well as investigating the long-term performance of the overlays through accelerated lab testing.

For a typical Iowa LSDC overlay, 0.25 in. of existing deck surface is removed before the application of a 1.75 in. thick overlay. This procedure leads to a 1.5 in. deck surface raise which has created many connection issues between the approach slab and the overlaid bridge deck. To avoid the elevated deck surface, in the project proposed herein, slight modifications will be made to surface preparation for both overlay procedures. For the thin-bonded epoxy overlay, the top 0.375 in. of the deck was milled before the overlay was applied. For LSDC overlay, the top 1.75 in. was removed by either milling or hydro-demolition.

Research Objectives

The objectives of this study include:

- To evaluate the initial and long-term bond strength of thin epoxy overlay and the LSDC overlay
- To assess the chloride resistance of thin epoxy overlay and the LSDC overlay
- To identify factors that affect the initial performance of thin epoxy overlay and the LSDC overlay

Thesis Organization

The first chapter includes the research background and objectives. The second chapter provides a literature review that explains and discusses the overlays of interest. Previous experiences and understanding of the mechanism of the overlays should provide a strong support and reference for the current research. The third chapter consists of documentation of field inspections and field testing. The field inspection evaluates the substrate prior to overlay closely to check for the location of unsound concrete and corroded rebar. The field testing uses pull-off testing (ASTM C1583) and evaluates the initial bond strength of newly constructed overlays. The fourth chapter presents the procedures and results of lab tests, which include several tests on extracted substrate cores trying to quantitatively define the bridge substrate; and pull-off and freeze-thaw tests on lab samples trying to simulate the accelerated cyclic freezing condition and evaluate the long-term bond strength of the overlays; and the ponding test trying to compare the chloride resistance of the overlays. The fifth chapter discusses and analyzes the results from previous chapters. The sixth chapter concludes the findings of this study and suggests future work that can advance the proposed objectives.

CHAPTER 2. LITERATURE REVIEW

The following literature review consists of two parts, the thin polymer overlays (TPO) and the traditional rigid concrete overlay. In each part, common overlays will first be introduced and common application practices will be explained and illustrated by photos. Then the materials and compositions of the overlays will be discussed in detail. Finally, a few previous practices and survey results will be shown to provide a better understanding of the mechanisms and factors that affect overlay deterioration and performance. Recommendations from experienced overlay agencies across the United States will also be provided for reference.

2.1 Thin Polymer Overlay

2.1.1 History and Development

First introduced in the 1950s, polymer concrete (PC) overlays were neither durable under traffic nor impermeable. These first PC overlays were made of single coal tar layers seeded with fine aggregates and broomed onto the concrete. In the following decade after the first use, oil-extended epoxy was introduced with the aim of improving their performance. According to ACI (1998), the broom-and-seed approach was already under use in the mid-1970s in placing methyl methacrylate monomer and styrene resins systems. It is also during this period that the use of premixed PC which was screeded began. The more brittle and thicker layers often delaminated as a result of thermal incompatibility of the substrate and overlay.

In the 1980s, there was a considerable increase in interest in thin polymer overlays (TPOs). As a result, many material suppliers started the development of resins precisely for these particular applications. It was also this decade that saw a huge improvement in both the construction materials and techniques as a result of better comprehension of the various causes of delamination. The improvement also corresponded with a considerable increase in the performance of TPOs. The thermal incompatibility of concrete and polymers which was among the leading causes of delamination was significantly minimized through the application of lower modulus resins and higher elongation (ACI 2007). Further, there were significant attempts made to improve the resistance of mechanical and chemical attack as well as understanding the requirements in mixing, surface preparations and placement of PC as well as in curing

In the initial stages of development, the TPOs reviews were not considered favorable. According to Furr (Furr 1984), the sand-filled epoxy TPOs were unfavorable solutions to both the waterproofing as well as the surfacing challenge. Furr added that in a total of 12 states, only one was successful in finding an epoxy with good performance. Since then, there has been some substantial improvements regarding the performance, even though certain challenges still persist. According to Furr (Furr 1984), it is now apparent that the flexible resins that are used in thin layers together with wear-resilient aggregates are crucial in producing TPOs which are wear-resistant and thermally attuned with the concrete decks. This survey of provinces and states established that most challenges happen as a result of workmanship errors.

Over the last few years, the application of TPOs has seen a significant upsurge. In his study, Sprinkel (2003) notes that prior to 1990, a total of 139 TPOs had already been placed. The 1990s decade experienced a threefold rise with a further 416 overlays being placed. According to a survey (Fowler and Whitney 2011) conducted in a total of ten provinces and 47 states, about 2,400 TPOs have been developed in Canada and US. This marked a fourfold rise over the total number installed before 1999. In this survey, seven states and three provinces in Canada were among the respondents that reported to have not used TPOs. Almost every state that places TPOs in the US uses epoxy as binder and California is the only state that is reported to mainly use polyester-styrene in premixed overlays.

2.1.2 Thin Polymer Overlay Construction Procedures

Pre-construction Evaluation

With considerable experience and tremendous data now available, more informed decisions can be made for best practices for placing TPOs. Harper (Harper 2007) suggested that the deck is to be sounded (chain-dragging) for delamination; evaluated using copper sulfate electrode method (ASTM C876, test method for corrosion potentials of uncoated rebar) for corrosion in rebar; assessed by examining the cores extracted for chloride content (concrete with chloride content higher than 1.3 lbs./yd^3 is considered contaminated or unsound); and tested for minimum tensile rupture strength by pull-off test (ASTM C1583, test method for tensile strength of concrete repair and overlay materials), deck areas with tensile rupture strength less than 150 psi are considered unsound. All unsound concrete needs to be marked for removal.

Harper (Harper 2007) made some useful comments related to pre-overlay evaluation regarding the investigation of failures of the TPOs installed by Missouri DOT. In the examinations of spalled overlay material, often a layer of concrete was spotted under the polymer concrete (PC) which made it a concrete substrate failure instead of a TPO failure. Missouri DOT also stated that based on their inspection rating system, higher rated substrate leads to better deck and overlay performance. It was thus recommended that for a higher chance of success, TPOs should be placed on decks with less than 5% of unsound concrete area. It was also suggested that more flexible binders be used on bridges with longer spans because the large deflections are more likely to cause cracking in the deck and overlay.

Surface Preparation

Before TPO placement, it is important to ensure that deck surfaces are cleaned in order to eliminate all contaminants such as dirt, paint, weak surface mortar, grease, sand, and curing materials. The surface is supposed to be shot blasted the same day as construction, most preferably, the overlay should be placed immediately after shot blasting. By meeting the ICRI (International Concrete Repair Institute) CSP (Concrete Surface Profiles) 7 profile, it is likely to obtain a satisfying texture. Compressed air is convenient for removing the debris and dust prior to resin application. Figure 2-1 shows the cleaning of the surface using compressed air and sand blasting. Furthermore, in line with ASTM D4263 (test method for identifying moisture in concrete), the surface should be dried to ensure that the plastic sheet remains in place for a minimum of two hours. Some sections of the deck that dry slower, such as gutters and low areas, require testing to verify that the surface is adequately dry for TPO placement.

Figure 2-1.Cleaning the surface using compressed air (left) and sand blasting (right)

Repair of Substrate

According to Fowler and Whitney (2011), the removal of concrete should be done in a way that ensures that the surrounding sound concrete is not weakened or cracked. As such, tools such as chipping hammers that are over 15 lbs. in weight are not advisable.

Further, it is essential to ensure that concrete that has a high content of chloride ion at the rebar level (above 1.3 lbs./yd^3) be replaced prior to the installation of the overlay. According to Sprinkel (1993), the final cleaning can use grit blasting or shot blasting, but shot blasting is not advisable in case of deep patches.

All repair materials should be low shrinkage and applied based on the instructions from the various manufacturers. Such materials are also expected to be adhesive to the resin of the TPOs. In a case where hydraulic cement repairing materials are applied, it should be dried for at least 28 days prior to the TPO placing. Figure 2-2 shows a piece of patching concrete prior to TPO placement. In a case where latex-modified concrete is used as repair material, it should be wet-cured for two or three days before the drying period. Further, the engineer might consider grinding when removing unleveled or rough sections

Figure 2-2. Repair of the substrate by patching

Any crack exceeding 0.04 in. in width should be filled using gravity-filling resins that are compatible with the primer or resin used in the TPOs. Furr (Furr 1984) noted that high-molecular-weight methacrylate is not compatible with epoxy TPOs and could lead to delamination of the overlay when used for crack repair. ACI (ACI 2007) also warns against the placement of a TPO over crack repair materials that could affect the curing or the bonding of the overlay.

Surface Cleaning

Cleaning of the surface should be done through shot blasting or other approved cleaning approaches to remove asphaltic materials, rubber, dirt, oils, paints, weak surface mortar, and laitance, carbonation curing, among other detrimental materials that might affect the overlay curing or bonding process (Sprinkel 1997). Along the deck's edges and other sections that are not reachable for shot blasting, it is advisable to use grit blasting. Figure 2-3 shows shot blasting the substrate for an Iowa overlay project.

Figure 2-3. Shot blasting the substrate

Methods of Application

The need to seal decks from ingress of water and chloride and to provide skid resistance has urged the evolution of application methods, from a simple overlay of polymeric membranes to three well-adopted methods. Each method is closely explained in the following sections.

Multiple-Layer Overlays

Multiple-layered polymer concrete overlays are thinly applied and usually used in bridge deck sealing while creating a uniform, well-bounded, skid-resistant, durable cover. This method is also known as the “broom-and-seed” method as it is applied by spreading the viscous resin (binder) over the deck and is immediately followed by seeding the surface with aggregate. After the initial course has cured, the removal of the unattached aggregates should follow, after which another course is installed and cured. A third course can be installed if necessary or only a single course is installed if sufficient waterproofing and skid resistance can be obtained. According to Sprinkel (Sprinkel 1997), the application rate is approximately 2 lbs./yd^2 of resin and 10 lbs./yd^2 of aggregate for the first course, 4 lbs./yd^2 of resin and 14 lbs./yd^2 of aggregate for the second course. The thickness of the overlay system is typically 0.25 in. depending upon the size of aggregate used. Figure 2-4 shows the spreading (broom) of the epoxy binder followed by broadcasting (seeding) the aggregate over the surface in a multiple-layer polymer overlay construction.

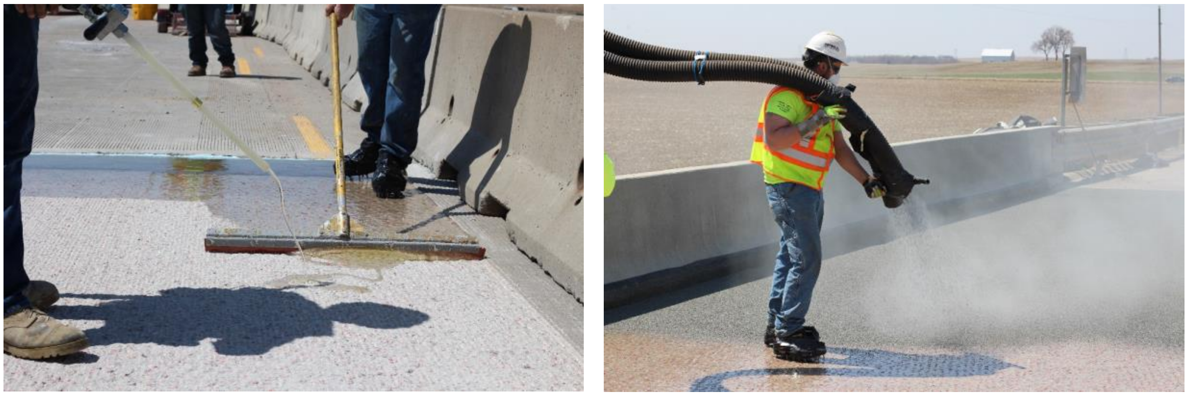

Figure 2-4. Construction of a polymer overlay: spreading epoxy binder (left); broadcasting aggregates (right)

The binder (resin) must have a sufficiently low viscosity to be spread relatively thinly and easily over the deck and still provide adequate bonding to the deck as well as to the aggregate. Furthermore, it is crucial that the binder does not contain solvents or non-polymerizing chemicals so as to avoid pinholes and improve impermeability. The gel time of the binder must allow the workers to evenly spread the binder and broadcast the aggregate excessively over the binder until no wet spots are visible and let the aggregate chips sink in for a good bond. However, the curing of the binder must be relatively quick to allow short traffic control time. Epoxy is the recommended binder for multiple-layer overlay application.

Premixed Overlays

A primer is typically first spread to the deck at a rate of 0.75 lbs./yd^2 to ensure good bonding between the polymer concrete (PC) and the deck. The PC (a mixture of binder and aggregate) is then placed over the primer and a vibratory screed is employed to consolidate the PC. In certain uses, the constant paving and batching equipment have proved useful when placing premixed PC. It is important to attain appropriate skid resistance through the placement of grooves in the freshly placed PC or through a layer of the aggregate on the fresh surface of the PC (Sprinkel 1997). Usually, the premixed TPOs are used specifically in thicker overlay application, often 0.75 in. and up, where uneven riding surfaces need to be covered. It is suggested that epoxy and polyester-styrene be used as resins in premixed overlay applications.

The binder's requirement for the premixed TPOs does not substantially vary from that of the binders applied in the multi-layer systems. But a lower percentage of resin can also provide considerable workability due to the viscosity and the rheology of the resin and the fact that premixed systems mix the aggregate into the PC prior to placement.

These premixed systems typically need a primer to achieve a proper and long-lasting bond between the deck and the PC. In the case of using polyester-styrene resins, high-molecular-weight methacrylate primers are usually employed because they are mechanically bonded to concrete deck and chemically bonded to the PC. Furthermore, the primers also protect the interface of concrete and PC against long-term alkaline attack when wet (Fowler and Whitney 2011).

Slurry Overlays

Slurry overlays are also installed by placing a layer of primer (usually monomer or resin, at a rate of 0.75 lbs./yd^2) prior to the placement of the slurry mixture which consists of silica flour (5.21 lbs./yd^2), binder (5 lbs./yd^2), and silica sand (7 lbs./yd^2). The slurry mixture is usually applied using a gauge rake, which ensures that there is a proper placement depth. Just as applied in the multi-layer overlay, gap-graded aggregate is typically broadcast onto the surfaces at a rate of about 14.0 lbs./yd^2. A resin seal coat (1.25 lbs./yd^2) is then placed after the aggregate. The primer is used to improve the bond between the concrete and the PC, the seal coat is used to keep aggregate from separating from the PC (Fowler and Whitney 2011). The thickness of the slurry overlays (somewhere between 0.25 in. and 0.5 in.) is in the middle between the premix and multiple-layer overlays (Sprinkel 1997). It is suggested that epoxy and methacrylate be used as resins in slurry overlay applications.

Curing of Overlays

The validated minimum curing time under 75°F is three hours for epoxy, polyester and methacrylate TPOs (Sprinkel 1997). The ending criteria of curing is obtaining a compressive strength of 1,000 psi with field-cured cubes (ASTM C579, test methods for compressive strength of chemical-resistant polymer concretes), as specified in AASHTO Guide Specifications (AASHTO 1995).

2.1.3 Materials

This section introduces specifications for typical materials used in TPOs, such as resins and aggregates. Resins act as binder in polymer concrete. Time required in gelling and curing is highly temperature and mix proportion sensitive, thus extra caution must be used when handling and mixing resins. Aggregates provide skid resistance and protection to polymer concrete. Conforming to specified grading is essential to ensure TPO's performance.

Resins

A majority of polymer-based systems have been developed with the purpose of providing protection to the bridge decks. Methyl methacrylates (MMA), polyester-styrenes, and all epoxies (including the modified epoxy urethanes forms) are among the most extensively used.

The time required in curing is largely dependent upon the amount of initiator, as well as the type of curing agent, binder content and curing temperature. For a thin polymer overlay (TPO) to perform well, the cured binder should exhibit certain characteristics, including high tensile elongation, high bonding strength to both concrete and aggregate, as well as relatively low modulus of elasticity. According to Fowler and Whitney (Fowler and

Whitney 2011), the cured binder should also have high resistance to acid rain, tire abrasion, ultraviolet exposures, and concrete alkalinity as well as have an extremely low water permeability. Table 2-1 lists the properties of several binder systems that are used on bridges.

Table 2-1. Polymer binder systems for TPOs

Properties	Epoxy	Polyester	Methacrylate	Test Method
Viscosity, Poise	7-25	1-5	11-13	ASTM D2393
Gel Time, Minutes	15-45	10-25	15-45	AASHTO T237
Tensile Strength (Binder) psi @7 days	2,000-5,000	2,000-5,000	500-1,200	ASTM D638
Tensile Elongation (Binder) % @ 7 days	30-80	30-80	100-200	ASTM D638
PC Compressive Strength, psi @ 3 h	Min. 1,000	Min. 1,000	Min. 1,000	ASTM C579
PC Compressive Strength, psi @ 24 h	Min. 5,000	Min. 5,000	Min. 5,000	ASTM C579
PC Tensile Bond Strength, psi @ 24 h	Min. 250	Min. 250	Min. 250	ASTM C1583
PC Cure Time @ 90°F, h[a]	2	2	2	ASTM C579
PC Cure Time @ 75°F, h[a]	3	3	3	ASTM C579
PC Cure Time @ 60°F, h[a]	6-8	5-6	4	ASTM C579

[a] Time required to obtain compressive strength = 1000 psi.
Source: Sprinkel 1997

Aggregates

Dry, clean and hard aggregates are crucial to TPO performance. Fontana (Fontana et al. 1990) noted that a rise in the moisture of the aggregates by one percent can greatly reduce the PC's strength from which it is made. A majority of contractors in the field make use of pre-bagged aggregates which are provided by the suppliers of overlay materials in an attempt to make sure that the aggregates are free of moisture, dust, oil and to guarantee proper grading for the particular application. Standard bags are also recommended as they ease the effort of keeping track of the rate of application, though larger bags can lead to segregations and the collection of fines lying in the bottom. Aggregate type and grading are important for wear resistance, flexibility, toughness, and crack-bridging ability of the wearing surface, particularly when high-modulus polymers are involved (Carter 1993). Table 2-2 lists common gradings for some of the aggregate systems used for TPOs.

Table 2-2. Typical aggregate grading for TPOs (Percentage Passing Sieve)

Sieve Size	Multiple-Layer Overlays	Slurries: Sand	Slurries: Fine Fillers	Premix Overlays
1/8’’				100
1/10’’				83-100
No. 4	100			62-82
No. 8	30-75			45-64
No. 16	0-5	100		27-50
No. 20		90-100		
No. 30	0-1	60-80		12-35
No. 40		5-15		
No. 50		0-5		6-20
No. 100				0-7
No. 140			100	
No. 200			98-100	0-3
No. 270			96-100	
No.375			93-99	

Source: Sprinkel 1997

Multiple-Layer Aggregates

The specified aggregates for multiple-layer TPOs are usually hard, tough and angular. Calcined bauxite, Basalt (with a minimum of 10 percent aluminum oxide), angular grained silica sand, as well as certain natural granites are some of the aggregates that are often used. The sizes of these aggregates are typically close to a No. 8 sieve which is supposed to keep the overlays both skid resistant and thin.

Premixed Aggregates

For a premixed system, there should be smaller aggregates that support the larger aggregates, which provides long-lasting skid resistance. These aggregates are often properly graded and considerably more regular in shape because they typically pack well and reduce the resin content. Just as the aggregates used in multiple-layer systems, the topping aggregates should be tough and angular to guarantee long-term performance.

Slurry Aggregates

Finer graded fillers such as silica flour are added to provide higher apparent viscosity and offer support to the biggest aggregates within the matrix. There are also small and well-graded aggregates like those used in the premixed TPOs.

The skid resistance and durability of slurry overlay system are some of the factors that are significantly affected by the distribution and relative volumes of the aggregates within the binder systems.

Resin Handling, Mixing, and Placement Temperatures

Handling and Mixing

One precaution that is fundamental to the mixing and handling processes of curing agents and resins is performing the procedures safely in line with the recommendations from the manufacturer. According to Illinois DOT, resins should be kept warm (between 60°F and

90°F) and dry in their original containers. Direct exposure to resins is prohibited, gloves and goggles are required at all times. In line with the Illinois TPO specification, Material Safety Data Sheets must be presented near the resin storage.

According to the Michigan DOT, in case of defective in-place resins, the main cause is likely to be improper mixing and proportioning. Carter (Cater 1993) noted that the best way to minimize errors when proportioning is through the use of different colors when dealing with multicomponent systems. Further, Missouri DOT notes that certain kinds of mixing paddle can also result in air bubbles within the epoxy which would compromise the TPO performance. According to Harper (Harper 2007), the best way to solve or minimize this issue is by using “Sika” or “Jiffy” paddles.

Placement Temperatures

The placement temperature is an important factor and as such should be considered before the process. Some DOTs have different specifications on the minimum temperature of placement, and some do not. Many DOTs specify the minimum temperature for deck and ambient in the range of 50°F to 60°F. According to Harper (Harper 2007), a maximum placement temperature should also be specified for overlaying bridges with large variety in elevations. The resin’s viscosity tends to decrease at high temperatures which would lead to resin ponding at lower elevations.

2.1.4 Applications

According to Sprinkel (1997), TPOs built in line with AASHTO specification (AASHTO 1995) have a service life of about 25 years, not including the multiple-layer polyester and the methacrylate slurry overlays. Carter (Carter 1993) noted that typical TPOs are able to provide service for up to two decades with proper maintenance. He also stated that

TPOs can even provide protection for bridges with non-coated rebar and certain degree of corrosion in high salt environments.

Since resins are expensive, TPOs are more of a preventive method for bridges in relatively good condition than large scale repair or rehabilitation. When the deck surface is good and flat, only a minimum thickness of overlay is required (less than 0.4 in.), TPOs are economically attractive among other repair methods. When the deck is rough and deteriorated, it would take a large amount of overlay material to bring the surface to grade. It was also reported that decks with deteriorated area larger than five percent performed relatively poorly. (Sprinkel 2003 and Harper 2007).

According to Carter's (Carter 1993) observations in Alberta, he noted that TPOs can be placed on other cracked or freeze-thaw damaged overlays and extend their service lives. He also noted that the majority of the TPO failures in Alberta were caused by inexperienced workmanship, therefore experienced workers are required during the construction. Furthermore, he believed that crack repair prior to TPO installation is futile because many unrepaired cracks do not affect TPO performance within five years, but many repaired cracks will eventually reflect upon TPO's surface. He also stated that shot blasting creates a surface texture more uniform than sandblasting. Rougher substrate surfaces provide higher bond strength. Thicker TPOs usually delaminate sooner than thinner TPOs in cold weather due to the thermal incompatibility of the PC and concrete. In multiple-layer overlay applications, attention must be paid to deck patching as not to rise the surface or create a bump, because snowplows tend to damage those spots. Care must be taken to monitor the viscosity of binder when mixing resin components, as temperature can largely affect the required mix time; routine calibration is suggested. Lastly he suggested that an economical application of a thin chip seal coat can provide TPO with shielding against ultraviolet exposure that ages the TPO's wearing surface.

According to Sprinkel (Sprinkel 2003), the bridges that cannot have lane closures for more than a day due to high volume of peak-hour traffic and are very sensitive to dead load or overhead clearance and need a protective wearing surface to provide skid resistance, are most suitable for TPO application. He also stated that for well-conditioned decks with good rideability, multiple-layer overlays are the best fit because this type of overlay is so thin that it follows the surface irregularities. For other decks with relatively good surface, slurry and premixed overlays are advisable.

An overlay test applications in Texas delaminated soon after placement because the bridge deck was sloped, and the primer ponded at the edge of the deck. A large area of overlay delaminated due to the thermal expansion of the accumulated primer (Zalatimo and Fowler 1997).

A bridge in Panama Canal zone was overlaid with epoxy TPO. The primer used was high-molecular-weight methacrylate. Two years after the application, delamination over a large area was observed. Further testing revealed that some epoxies tend to lose bond to high-molecular-weight methacrylate over time.

2.2 Traditional Rigid Overlay

2.2.1 Introduction

The application of rigid overlays on bridges can be tracked back to the 1950s, though numerous modifications have been made to improve the properties of the rigid overlays since then. Popular rigid overlays include low slump dense concrete (LSDC), silica fume modified concrete (SFMC), latex-modified concrete (LMC), fiber reinforced concrete (FRC), and others. The following section offers a short introduction of commonly used rigid overlays.

Low-Slump Dense Concrete (LSDC)

The LSDC was adopted by many states as an overlay material since the 1970s. It has low or even no slump. The high cement content and low water content reduce the permeability if the concrete is well consolidated. A dense overlay mix was used in Kansas earlier in the 1960s (Halvorsen 1993), and Iowa has extensively used LSDC overlay in several projects. Due to the low slump, the placement and consolidation of LSDC can be difficult. In some cases, mechanical tamping is used. In other cases, high-range water reducing admixture (HRWRA) was added in concrete to make placement easier. The application of low-slump or high-density concrete has been incorporated in the specifications of several states, such as: Kentucky, Minnesota, New York, and others.

Silica Fume Modified Concrete (SFMC)

Silica fume has been used to substitute part of the cement in concrete outside the United States since the 1970s. It has been used in bridge decks in the US since 1983 (Luther 1988). It is a byproduct of the silicon or ferrosilicon industry. In cementitious compounds, silica fume works both at the chemical and physical level. Research and practice showed that silica fume modified concrete has better resistance to penetration of chloride ions, higher amount of abrasion-resistance in the surface, higher early and ultimate strength, and lower cost (Luther 1988 and Ozyldirum 1988). In a recent report by FHWA, it was shown that concrete repair mixes for slabs produced with micro silica and fly ash mineral admixtures performed exceptionally well for rebar corrosion. For typical concrete overlays, silica fume is added in the range of 5 percent to 15.5 percent by weight of portland cement. As for curing, the overlay surface shall be completely covered with clean and wet burlap, which shall be well drained and continuously wet for a period of at least 96 curing hours (WVDOH Standard Specifications, 2000) to avoid plastic shrinkage cracking. SFMC has been used in many states in USA, such as West Virginia, New York, Oregon, Ohio, Rhode Island and others.

Latex Modified Concrete (LMC)

LMC has been used for bridge overlays in the USA since 1956. The first LMC overlay was placed in West Virginia in 1961 (Steele and Judy 1977). In general, LMC shows a noticeable increase in the tensile, compressive, and flexural strengths when compared to the normal concrete. As a bridge deck overlay, LMC has higher adhesion or bond strength with any substrate, which significantly increases the interface bond strength. It has good resistance to impact, abrasion, water penetration and freezing-thawing cycling, which is also critical for bridge overlay performance (Ramachandran 1996). The curing for latex concrete is different from that for normal concrete. West Virginia Division of Highways (WVDOH) suggests 48 hours saturated burlap covering immediately after the casting followed by air curing for another 48 hours. ACI developed a standard specification (ACI 548.4-93) for latex modified concrete overlays in 1993. WVDOH also gives general guidelines on LMC application on bridge decks (Section 679 of Supplemental Specifications 2003).

Fiber Reinforced Concrete (FRC)

Since the 1960s, FRC has been developed to construct more durable transportation facilities. Virginia Department of Transportation used steel fibers in 1974 for a bridge deck overlay and recently used steel and plastic fibers in bridge deck and pavement overlays experimentally (Ozyildirim et al. 1997). FRC is known to have high tensile, flexural and fatigue strength as well as high ductility. Furthermore, FRC has less shrinkage cracks and is more durable to thermal and moisture stresses and abrasion than normal concrete.

Currently in the United States, steel, glass, and synthetic fibers are the most widely used fiber types. Blends of steel and synthetic fibers are also available. Usually, certain admixtures are used with fibers to achieve better workability.

2.2.2 Rigid Overlay Construction Procedures

This section introduces the well-adopted methods of constructing traditional rigid overlays. Much like installing thin polymer overlays, surface preparation is one of the most important steps in placing rigid overlays, which ensures the overlay has a sound foundation. The rest of the procedures are quite distinct from those of TPOs.

Surface Preparation

Deck Inspection

Each overlay procedure requires that the existing bridge deck be prepared before overlay application. To prepare the bridge deck, the deck first must be surveyed or inspected. Visual inspection and sounding (ASTM D 4580) identifies deterioration in the concrete. The areas are likely to be small and irregular in shape as identified by the actual cracking, delamination, and spalling. The localized nature of the work limits the alternatives for concrete removal. The deteriorated concrete is, however, relatively easy to remove because of the existing cracks and fracture planes. Half-cell potential measurements (ASTM C 876) and core sampling (ASTM C42) can determine the presence of chloride-contaminated concrete. The results are generally seen as reflective of the overall condition of the structural component. Concrete removal that follows is normally performed in a systematic manner over a large area. Sound but contaminated concrete will be removed.

Deck Repair

To repair the deck, regardless of the overlay type, the deteriorated concrete is removed, and the rebar be cleaned. For full-depth repairs, the concrete in the deteriorated areas is completely removed, whereas for partial-depth repairs, the concrete is typically removed to a depth of 0.75 in. below the rebar. When the concrete deck is repaired, Class D concrete is typically used (Knight et al. 2004).

There are several techniques used for surface preparation depending on the size of the area to be covered. For small areas, the decks are normally scrabbled, sandblasted, or shot-blasted; whilst for large areas, concrete milling machine or hydro-demolition is used. Surface preparations also include the pretreatments of surfaces using different kinds of bonding agents (Wells et al. 1999).

It is frequently necessary to remove surface contaminants such as oil, rubber, and rust from the work area in order to provide a sound, long-lasting bond between the existing structure and the new materials. The objective is to clean rather than to remove material. The following four methods are frequently used:

1. Scrabbling. A scrabbler is a pneumatic or electric tool that removes concrete by impacting the surface with bits or a chisel. There are various sizes of scrabblers, small scrabblers are hand-held and able to work on vertical and rough surfaces, where large scrabblers are capable of working on large areas very efficiently. Vacuum collection systems are frequently used to collect the concrete debris.

2. Planing. Planing refers to removing concrete with a large diamond grinder. The grinder is equipped with a spindle that rotates several parallel concrete diamond-tipped saw blades and is capable of removing half an inch of concrete in one pass. Water is needed to cool the blades while working and the resulting slurry of concrete particles must be properly collected and disposed.

3. Sandblasting. Sandblasters use compressed air to propel sand particles at high velocity. The impact of the particles produces a very abrasive action that cleans and roughens the exposed concrete or steel. The size and capacity of the equipment varies substantially. Small, hand-held tools are used on vertical or irregular surfaces. Vacuum systems are used to recover the sand and resulting debris.

4. Shotblasting. Shotblasters use a rotating paddlewheel to propel steel shot against the concrete surface at high velocities. The impact is capable of removing concrete to depths up to 0.5 in. The roughness of the substrate concrete is controlled by the selection of different shot sizes. Machines vary in size, but their use is limited to horizontal surfaces because a collection chamber must be used to control the rebounding shot. A vacuum system is used to pick up the concrete debris and steel shot, which are then separated so that the shot can be reused.

The surface cleaning methods mentioned above can also be used for concrete removal, but sometimes when it comes to removing the entire deck to a certain depth, specialized machines like the milling machine and hydro-demolition machine should be first considered. A milling machine assembles in a way similar to the planing grinder, but much larger and more powerful. Hydro-demolition can also be used as a high-production, equipment-intensive method for the removal of concrete. More often, hydro-demolition is used to remove cover and matrix concrete simultaneously (Weyers et al. 1993). A milling machine and the surface treated with hydro-demolition are shown in Figure 2-5 and 2-6, respectively.

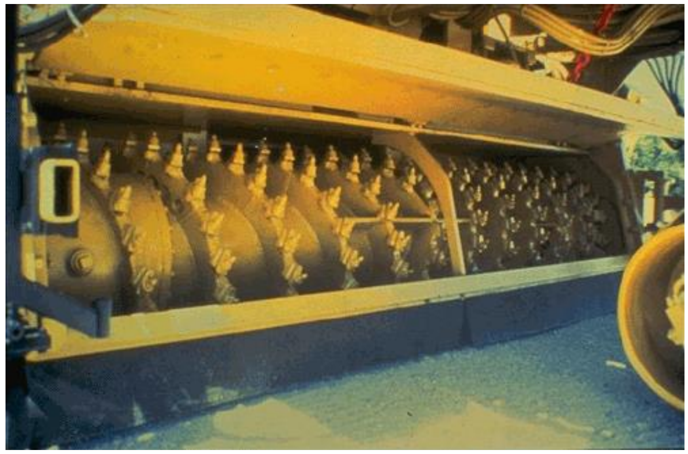

Figure 2-5. Drum of a cold-milling machine

Figure 2-6. Substrate surface after hydro-demolition

After substrate concrete removal and repair, at least 12 hours (preferably 24 hours) before overlay, the deck should be saturated with water and covered with polyethylene sheeting. The deck substrate should be saturated but only the surface should be sufficiently dried at the time of overlay, in other words, all standing water should be removed. Screed rails should be installed so that the finishing machine will provide the minimum overlay thickness as specified in Table 2-3. The supports for the rails should be adjustable; shims should not be used to adjust rail heights. A dry run should be performed to ensure that the finishing machine provides the minimum overlay thickness.

Table 2-3. Minimum overlay thickness

Overlay Type	Minimum Thickness (in.)
LMC	1.5
LSDC	2.0

Source: Weyers et al. 1993

Placement and Consolidation

The overlay concrete should be mixed at the site using a mobile mixer. Before placement, a trial batch should be prepared in the presence of the site engineer to test the calibration of the mixer. Sufficient mobile mixers should be present on the site to allow the continuous placement of the overlay without delay.

A bonding grout should be thoroughly brushed into the substrate immediately in front of the finishing machine. The grout can be obtained by brushing the coarse aggregate out of a portion of the overlay concrete. If sufficient grout cannot be obtained, an acceptable grout can be produced by blending equal parts cement and concrete sand with enough water to produce a stiff grout. The grout applied on the substrate must be kept wet until the placement of overlay.

The overlay concrete should be placed approximately 0.25 in. above final grade. The overlay concrete should be consolidated and finished using a finishing machine. The machine should be capable of spanning the entire placement transversely. Spud vibrators and hand tools should be used as necessary along the screed rails and for any deep pockets. A burlap or carpet drag can be used to texture the surface.

Curing

Within 30 minutes of placement, the fresh concrete should be covered with a single layer of clean, damp burlap. LSDC overlays should be misted for the first 24 hours of curing and then covered with white polyethylene sheeting. Curing shall be maintained for the minimum times shown in Table 2-4. Curing hours should be defined as hours for which the temperature is greater than 45°F. The overlay concrete should be protected with insulated blankets if the temperature is predicted to drop below 45°F.

Table 2-4. Minimum curing times

Overlay Type	Minimum Curing Time (hours)
LMC	48
LSDC	168*

*72 hours is applicable if traffic is light.
Source: Weyers et al. 1993

Cutting Grooves

For skid resistance purposes, by the 14 day of curing, grooves shall be sawed transverse to the center line. The grooves should be approximately 0.2-in. deep and 0.13-in. wide, spaced 0.75 in. on center.

2.2.3 Materials and Proportion

This section introduces all the components required to construct normal concrete (NC), latex modified concrete (LMC), silica fume modified concrete (SFMC) and fiber reinforced concrete (FRC) overlays, and their mix proportions.

Portland Cement

Commercially available Type I Portland cement conforming to ASTM C 150 (Standard specification for Portland cement) is typically used, and has a typical specific gravity of 3.15.

Fine Aggregate

Fine aggregate is essentially sand or any crushed stone or rock particles that are 0.25 in. or smaller. Fine aggregate conforming to ASTM C 33 (Standard specification for concrete aggregates) is typically used. The sieve analysis data of a typical fine aggregate is shown in Table 2-5. The specific gravity (saturated surface dry condition) of sand is 2.61.

Table 2-5. Sieve analysis of fine aggregate

Sieve Size	Percentage Passing
3/8’’	100
#4	97.2
#8	82.3
#16	69
#30	54.6
#50	16.1
#100	2.0
#200	0.7

Source: Luo 2002

Coarse Aggregate

Coarse aggregate conforming to ASTM C 33 (Standard specification for concrete aggregates) is typically used. The specific gravity (saturated surface dry condition) is 2.71. The sieve analysis of a typical coarse aggregate is shown in Table 2-6.

Table 2-6. Sieve analysis of coarse aggregate

Sieve Size	Percentage Passing
1/2’’	100
3/8’’	92
#4	20
#8	5
#16	3

Source: Luo 2002

Silica Fume (Microsilica)

The commonly used commercial silica fume conforms to ASTM C 1240 (Standard specification for use of silica fume as a mineral admixture in hydraulic cement concrete, mortar, and grout). The specific gravity of the silica fume is 2.2. Figure 2-7 shows a sample of silica fume.

Figure 2-7. A sample of silica fume

Fiber

Commercial fibrillated polypropylene fiber is commonly used in fiber reinforced concrete overlays, some of its properties is listed in Table 2-7. An Image of fibrillated polypropylene fiber is shown in Figure 2-8.

Table 2-7. Typical properties of fibrillated polypropylene fiber

Material	100% Virgin Polypropylene
Tensile Strength	97 ksi Avg
Young's Modulus	580 ksi
Melt Point	330°F
Chemical Resistance	Excellent
Alkali Resistance	Excellent
Acid and Salt Resistance	High
Ignition Point	1100°F
Absorption	NIL
Specific Gravity	0.91
Density, Bulk	56 lbs./cu ft. (approx.)
Density, Loose	15-25 lbs./cu ft. (approx.)
Color	White
Fiber Count	8-12 Million/lbs.

Source: Luo 2002

Figure 2-8. Fibrillated polypropylene fiber

Latex

Typical latex is a proprietary styrene/butadiene latex supplied as a white liquid with suspended solids. The specific gravity is 1.04. Typical properties of latex modifier are shown in Table 2-8.

Table 2-8. Typical properties of latex

Test Item and Condition	Limit	Unit
Solids	47.0-49.0	%
pH	9.0-11.0	
Particle Size, red filter	1900-2200	Angstrom
Freeze Thaw Stability, after 2 cycles	0.1 Max	G
Butadiene Content	30-40	%
Weight per Gallon	8.4-8.6	lbs./gal

Source: Luo 2002

Antifoam

Antifoam is a water-dilatable, 10 percent active emulsion that is designed to control foam in aqueous systems. Its typical properties are shown in Table 2-9.

Table 2-9. Typical properties of antifoam

Appearance	White
Active Ingredient, percent	10
Specific Gravity, at 77°F	1
Consistency at 77°F	Medium
Viscosity, cps	2500
pH	7
Suitable Diluent	Cool water

Source: Luo 2002

Other Materials

The high range water-reducing admixture (HRWRA) commonly used in the mixtures is a naphthalene-based superplasticizer conforming to ASTM C 494 (standard specification for chemical admixtures for concrete) Type F.

The air-entraining admixture (AEA) conforming to ASTM C 260 (standard specification for air-entraining admixtures for concrete) can effectively develop air voids within concrete which has been shown to successfully increase durability to cyclic freezing condition.

Mixture Proportion

A total of four mixtures are compared. Normal concrete (NC) is the substrate; latex modified concrete (LMC), silica fume modified concrete (SFMC), and fiber reinforced concrete (FRC) are the overlay mixtures. The mixture proportions are provided in Table 2-10.

Table 2-10. Mixture proportions of rigid concrete overlays

Ingredient	NC	LMC	SFMC	FRC
Cement (lbs.)	568	700	635	635
Sand (lbs.)	1206	1750	1750	1750
Gravel (lbs.)	1750	1206	1206	1206
Water (lbs.)	284	134.4	276	276
HRWRA (oz.)	34		187	200
AEA (oz.)	22		20	16
Silica Fume (lbs.)			55	55
Fly Ash (lbs.)				
Latex (lbs.)		212.6		
Defoamer (oz.)		31		
Fiber (lbs.)				3.06
w/c	0.5	0.35	0.4	0.4

Note: All values are based on one cubic yard of concrete.
Source: Luo 2002

2.2.4 Applications

Krauss (Krauss et al. 2009) prepared the guidelines for selection of bridge deck overlays by surveying and interviewing DOTs of United States and provinces of Canada. The guidelines include useful information and previous experiences from agencies across North America and is presented in this section.

Latex Modified Concrete (LMC) Overlay

Table 2-11 presents the comments on latex modified concrete overlays given by the 17 responding agencies (DE, IL, IN, KS, KY, MA, MI, MO, NC, OK, PA, RI, SD, TN, WA, WV, Ontario).

Table 2-11. Advantages and disadvantages of latex modified concrete overlays

Advantages	Disadvantages
Performs well, protects the underlying deck, or is less permeable than other rehabilitation systems - 11 agencies (65%)	Cost - 9 agencies (53%)
Short cure time or quick installation (two agencies specifically stated use of very high early strength latex-modified concrete) - 6 agencies (35%)	Placement difficulties (need for specialized equipment; lack of contractor experience; sensitivity to weather conditions) - 8 agencies (47%)
Long anticipated life - 4 agencies (24%)	Cracking or debonding - 4 agencies (24%)
Low cracking (some cracks can be self-healing; cracks do not penetrate full depth) - 2 agencies (12%)	Long cure time - 2 agencies (12%) - 1 agency (17%)

Source: Krauss et al. 2009

Use History

All of the responding agencies first used latex-modified concrete overlays more than 10 years ago. Eight (47%) began using latex-modified concrete overlays 10 to 25 years ago, and nine agencies (53%) began using latex-modified concrete overlays more than 25 years ago.

In accordance with the amount of time that latex-modified concrete overlays have been in use, its use is fairly widespread. Nine of the respondents (53%) report that latex-modified concrete overlays have been installed on more than 100 bridges in their state or province.

Selection

Latex-modified concrete overlays were selected by most agencies because of their long service life, good track record, and the fact that use was already approved by their department. Table 2-12 outlines the reasons for selecting latex modified concrete.

Table 2-12. Reasons for selecting latex modified concrete overlays

Reasons for Selection of Low Slump Concrete Overlays	Yes	No
Easy to install	6	11
Long anticipated service life	15	2
Good track record on similar projects	13	4
Already approved by your department	11	6
Research findings were positive	6	11
Inexpensive	1	16
Short lane closures	4	13
Dead load considerations	7	10

Source: Krauss et al. 2009

Table 2-13 shows the averaged anticipated lifespan and cost of latex modified concrete overlay provided by the responding agencies.

Table 2-13. Anticipated lifespan and cost of latex modified concrete overlays

	Anticipated Lifespan (year)	**Cost (dollar per square foot)**
Range	14 – 29	18 - 39

Source: Krauss et al. 2009

Low Slump Dense Concrete (LSDC) Overlay

Table 2-14 summarizes the advantages and disadvantages concluded by the 6 responding agencies (KS, MI, MO, ND, SD, Puerto Rico).

Table 2-14. Advantages and disadvantages of low slump dense concrete overlays

Advantages	**Disadvantages**
Durability and long life - 3 agencies (50%)	Placement issues (long cure times; difficulty in placement; system cannot be produced by the concrete plant) - 4 agencies (67%)
Low cost or cost effectiveness - 2 agencies (33%)	Susceptible to cracking - 2 agencies (33%)
Increased structural capacity - 1 agency (17%)	Dead load - 2 agencies (33%)
Low cure time - 1 agency (17%)	Requires well-prepared deck surface and does not permit monolithic overlay and deck repair placement - 1 agency (17%)
Ease of construction - 1 agency (17%)	Cost - 1 agency (17%)

Source: Krauss et al. 2009

Use History

Five of the agencies using low slump concrete overlays (83%) report that their use began more than 25 years ago, while one agency reports that use began 5 to 10 years ago. For locations where low slump concrete overlays are used, the use is fairly widespread. Four of the responding agencies (67%) indicated that the overlays are used in 100 or more bridges in their jurisdiction. One agency stated that the overlays are used on 50 to 100 bridges, and another agency reports having used the overlays on ten or fewer bridges.

The use of low slump concrete overlays is part of the standard specification in five jurisdictions (83%), and considered experimental in one jurisdiction (16%).

Selection

Low slump concrete is selected by all responding agencies because of the long-anticipated service life and good track record on similar projects. Most agencies use low slump concrete overlays, in part, because they are already approved by the department. The reasons for selecting low slump concrete overlays are provided in Table 2-15.

Table 2-15. Reasons for selecting low slump concrete overlays

Reasons for Selection of Low Slump Concrete Overlays	Yes	No
Easy to install	3	3
Long anticipated service life	6	0
Good track record on similar projects	6	0
Already approved by your department	5	1
Research findings were positive	4	2
Inexpensive	2	4
Short lane closures	1	5
Dead load considerations	0	6

Source: Krauss et al. 2009

Table 2-16 shows the averaged anticipated lifespan and cost of low slump concrete overlay provided by the responding agencies.

Table 2-16. Anticipated lifespan and cost of low slump concrete overlays

	Anticipated Lifespan (year)	**Cost (dollar per square foot)**
Range	16 – 32	13 - 19

Source: Krauss et al. 2009

CHAPTER 3. FIELD INVESTIGATION

This chapter consists of two sections, the first section presents information on the selected bridges and documentation of deck inspections before overlay placement. The second section outlines the field testing that evaluated the initial bond strength of the overlays using pull-off test.

3.1 Field Inspection and Documentation

Soundness and surface preparation of the substrate are crucial for overlay performance (Fowler and Whitney 2011). To have a better understanding of the substrate properties before overlay, six bridges were sampled (three cores from each bridge were extracted for laboratory testing) and inspected. Figure 3-1 shows the locations of the bridges.

Figure 3-1. Locations of the sites inspected

Among the six bridges, three were to be epoxy overlaid (labelled as E1, E2, and E3) and the rest were to be overlaid with low slump dense concrete (LSDC, labelled as C1, C2, and C3). Prior to this project, Siva Corrosion Services, Inc. (SCS) was retained by WHKS to perform corrosion evaluations on the decks of these six bridge in December of 2015. The chloride profile of the bridge substrate was provided and collected as part of this documentation. The following section includes the deck condition (area of damaged concrete) prior to surface preparation, surface condition after the preparation and chloride profile for each bridge. Table 3-1 provides general information of the bridges.

Table 3-1. Basic information of the sites inspected

Site No.	County	Route	Bridge Maint. #	FHWA #	Overlay Type	Age (year)
C1	Kossuth	US18	5521.8S018	32821	LSDC	25
C2	Sioux	US18	8416.6S018	48231	LSDC	16
C3	Sioux	US18	8419.8S018	48281	LSDC	33
E1	Clay	US18	2166.2S018	20291	Epoxy	31
E2	Clay	US18	2181.0S018	20331	Epoxy	12
E3	Sioux	US18	8415.1S018	48211	Epoxy	11

Site C1 – US 18 in Kossuth County, FHWA #32821 (Bridge Maint. # 5521.8S018)

Bridge Description

Bridge C1 carries US 18 over Lott's Creek between Emmetsburg and Algona, IA and was constructed in 1993. The deck is original and does not have an overlay. The Iowa DOT performed a survey of the deck and concrete damage (i.e. delamination and patch repairs) was observed on approximately 1.1% of the deck (a total of 56 square feet).

Chloride Profile

A total of four cores were collected for Chloride profile sampling, with locations randomly distributed throughout the deck. According to SCS, the recommended effective chloride threshold for damage to ECR is approximately 1800 ppm (7.05 lbs./yd^3). The Chloride data from the four cores indicate an average depth with a Chloride content of

1800ppm to be 2.60 in., and the average rebar depth for this bridge is 2.24 in. The average Chloride content at the depth of 1.75 in. (the depth to which the concrete is removed and replaced by concrete overlay) is 3213 ppm (12.58 lbs./yd^3).

Field Inspection Description

Field inspections of site C1 were conducted prior to overlay on May 22, 2018 (south lane) and June 13, 2018 (north lane). Photos and measurements were taken to document the substrate surface condition of the deck. An average removal of 1.75 in. of the original deck was achieved by hydro-demolition, though there were some areas of degraded concrete that were further removed. Figure 3-2 shows signs of extra removal and cracks prior to the overlay placement, and Figure 3-3 illustrates the surface roughness achieved.

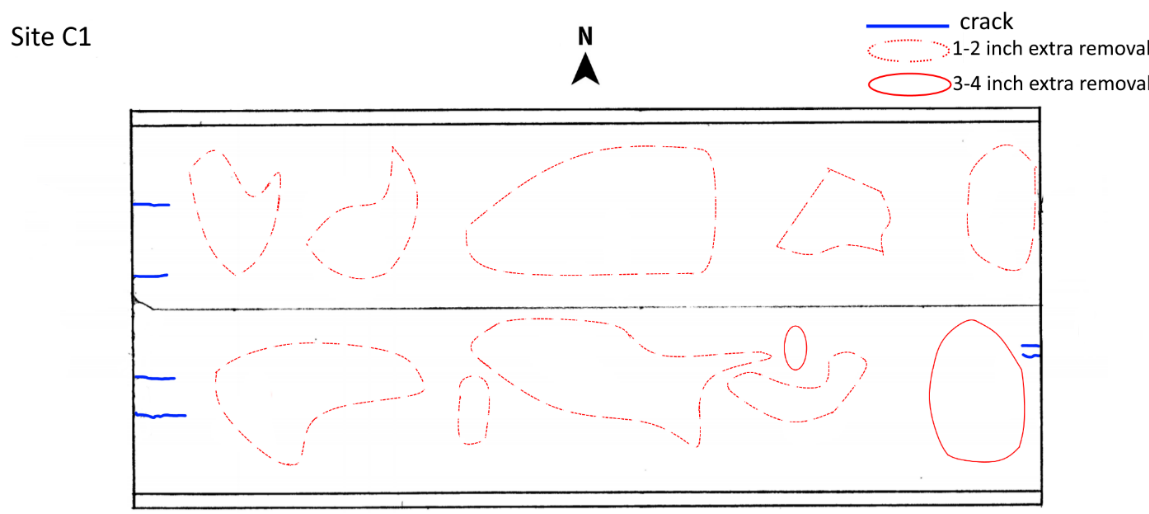

Figure 3-2. Substrate condition of site C1

Figure 3-3. Photo of substrate surface conditions of site C1

Site C2 – US 18 in Sioux County, FHWA # 48231 (Bridge Maint. # 8416.6S018)

Bridge Description

Bridge C2 carries US 18 over Rock River, IA and was constructed in 2002. The deck is original and does not have an overlay. The Iowa DOT performed a survey of the deck and concrete damage (i.e. delamination and patch repairs) was not observed.

Chloride Profile

A total of eight cores were collected for Chloride profile sampling, with locations randomly distributed throughout the deck. According to SCS, the recommended effective chloride threshold for damage to ECR is approximately 1800 ppm. The Chloride data from the eight cores indicate an average depth with a Chloride content of 1800 ppm (7.05 lbs./yd^3) to be 1.54 in., and the average rebar depth for this bridge is 2.40 in. The average Chloride content at the depth of 1.75 in. (the depth to which the concrete is removed and replaced by concrete overlay) is 1453 ppm (5.69 lbs./yd^3).

Field Inspection Description

Field inspections of site C2 were conducted prior to overlay on July 5, 2018 (south lane) and July 20, 2018 (north lane). Photos and measurements were taken to document the substrate surface condition of the deck. An average removal of 1.75 in. of the original deck was achieved by milling, though there were some areas of degraded concrete that were further removed. Figure 3-4 shows signs of extra removal prior to the overlay placement, and Figure 3-5 illustrates the surface roughness achieved.

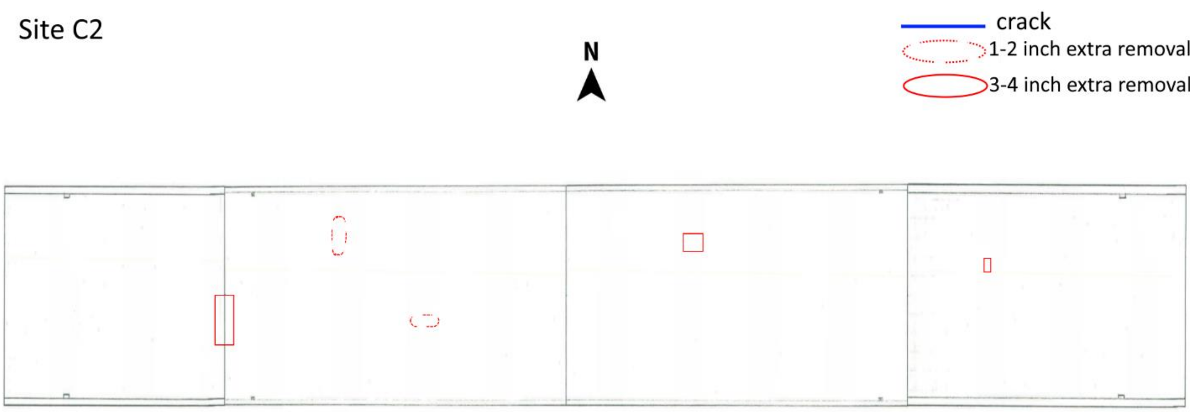

Figure 3-4. Substrate surface condition of site C2

Figure 3-5. Photo of substrate surface condition of site C2

Site C3 – US 18 in Sioux County, FHWA # 48281 (Bridge Maint. # 8419.8S018)

Bridge Description

Bridge C3 carries US 18 over Rogg Creek, IA and was constructed in 1985. The deck is original and does not have an overlay. The Iowa DOT performed a survey of the deck and concrete damage (i.e. delamination and patch repairs) observed on approximately 0.1% of the deck (a total of 6.7 square feet).

Chloride Profile

A total of four cores were collected for Chloride profile sampling, with locations randomly distributed throughout the deck. According to SCS, the recommended effective chloride threshold for damage to ECR is approximately 1800 ppm (7.05 lbs./yd^3). The Chloride data from the four cores indicate an average depth with a Chloride content of 1800ppm to be 1.53 in., and the average rebar depth for this bridge is 2.50 in. The average Chloride content at the depth of 1.75 in. (the depth to which the concrete is removed and replaced by concrete overlay) is 1285 ppm (5.03 lbs./yd^3).

Field Inspection Description

Field inspections of site C3 were conducted prior to overlay on May 11, 2018 (south lane) and May 29, 2018 (north lane). Photos and measurements were taken to document the substrate surface condition of the deck. An average removal of 1.75 in. of the original deck was achieved by hydro-demolition, though there were some areas of degraded concrete that were further removed. Figure 3-6 shows signs of extra removal and cracks prior to the overlay placement, and Figure 3-7 illustrates the surface roughness achieved.

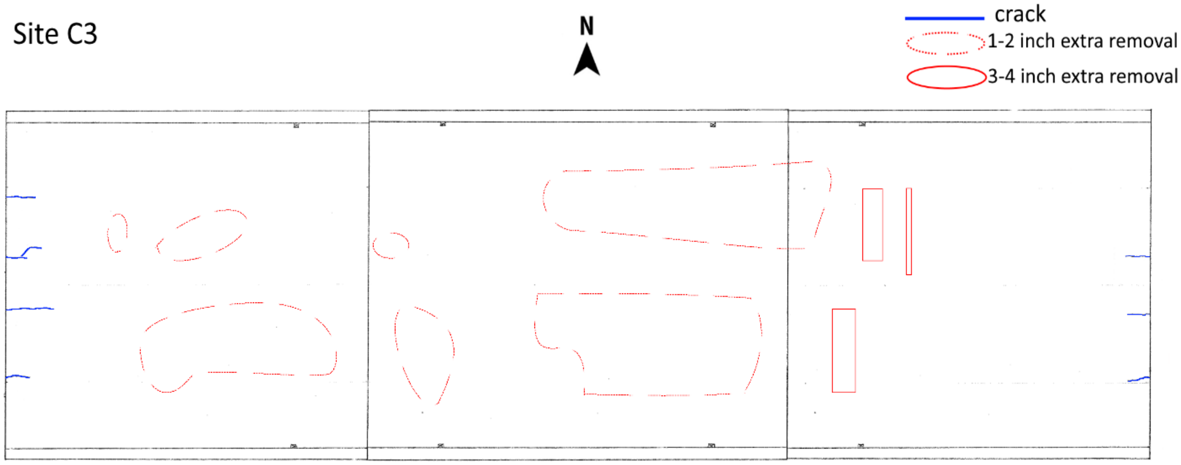

Figure 3-6. Substrate surface condition of site C3

Figure 3-7. Photo of substrate surface condition of site C3

Site E1 – US 18 in Clay County, FHWA # 20291 (Bridge Maint. # 2166.2S018)

Bridge Description

Bridge E1 carries US 18 over the Ocheyedan River between Hartley and Spencer, IA and was constructed in 1987. The deck is original and does not have an overlay. The Iowa DOT performed a survey of the deck and concrete damage (i.e. delamination and patch repairs) was observed on approximately 0.1% of the deck (total of 3.6 square feet).

Chloride Profile

A total of 12 cores were collected for Chloride profile sampling, with locations randomly distributed throughout the deck. According to SCS, the recommended effective chloride threshold for damage to ECR is approximately 1800 ppm (7.05 lbs./yd^3). The Chloride data from the 12 cores indicate an average depth with a Chloride content of 1800 ppm to be 1.78 in., and the average rebar depth for this bridge is 3.30 in.

Field Inspection Description

Field inspections of site E1 were conducted prior to overlay on April 23, 2018. Photos and measurements were taken to document the substrate surface condition of the deck. An average removal of 0.375 in. of the original deck was achieved by milling. Figure 3-8 shows signs of cracks prior to the overlay placement, and Figure 3-9 illustrates the surface roughness achieved.

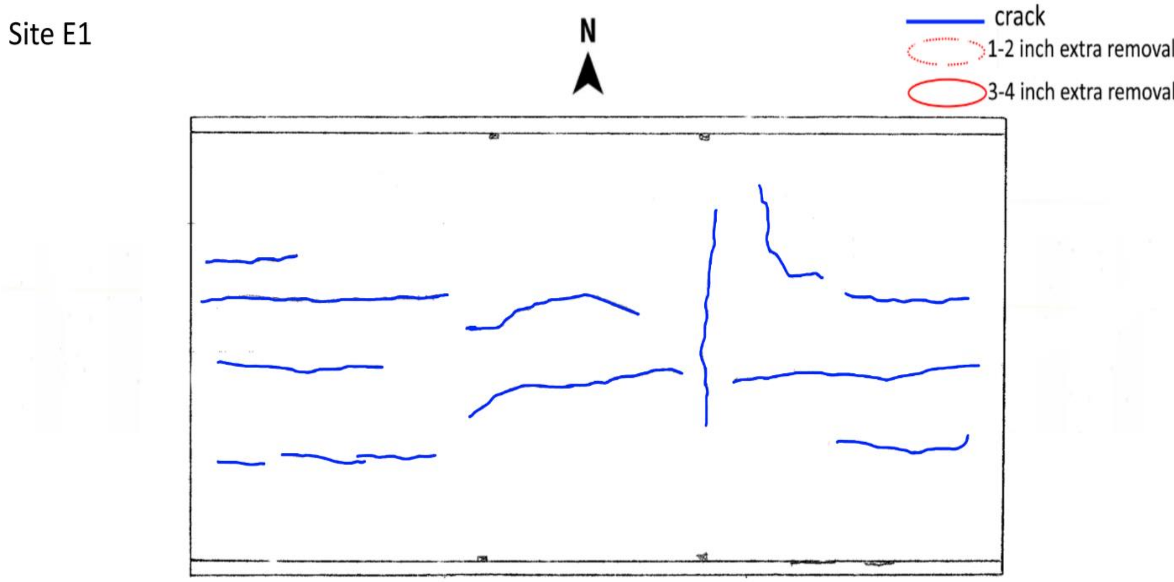

Figure 3-8. Substrate surface condition of site E1

Figure 3-9. Photo of substrate surface condition of site E1

Site E2 – US 18 in Clay County, FHWA # 20331 (Bridge Maint. # 2181.0S018)

Bridge Description

Bridge E2 carries US 18 over Little Sioux, IA and was constructed in 2006. The deck is original and does not have an overlay. The Iowa DOT performed a survey of the deck and concrete damage (i.e. delamination and patch repairs) was not observed.

Chloride Profile

A total of eight cores were collected for Chloride profile sampling, with locations randomly distributed throughout the deck. According to SCS, the recommended effective chloride threshold for damage to ECR is approximately 1800 ppm (7.05 lbs./yd^3). The Chloride data from the eight cores indicate an average depth with a Chloride content of 1800 ppm to be 1.96 in., and the average rebar depth for this bridge is 2.71 in.

Site E3 – US 18 in Sioux County, FHWA # 48211(Bridge Maint. # 8415.1S018)

Bridge Description

Bridge E3 carries US 18 over Dry Run Creek, IA and was constructed in 2007. The deck is original and does not have an overlay. The Iowa DOT performed a survey of the deck and concrete damage (i.e. delamination and patch repairs) was not observed.

Chloride Profile

A total of four cores were collected for Chloride profile sampling, with locations randomly distributed throughout the deck. According to SCS, the recommended effective chloride threshold for damage to ECR is approximately 1800 ppm (7.05 lbs./yd^3). The Chloride data from the four cores indicates an average depth with a Chloride content of 1800 ppm to be 0.98 in., and the average rebar depth for this bridge is 3.54 in.

Field Inspection Description

Field inspections of site E3 were conducted prior to overlay on April 23, 2018. Photos and measurements were taken to document the substrate surface condition of the deck. An average removal of 0.375 in. of the original deck was achieved by milling. Figure 3-10 shows no signs of extra removal prior to the overlay placement, and Figure 3-11 illustrates the surface roughness achieved.

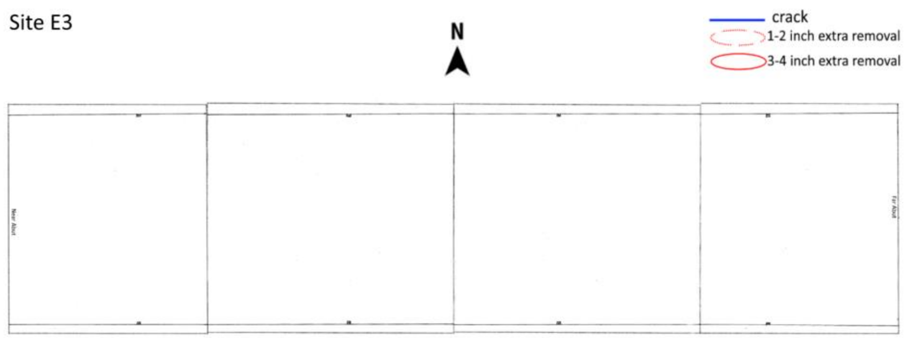

Figure 3-10. Substrate surface condition of site E3

Figure 3-11. Photo of substrate surface conditions of site E3

Summary of Field Inspection

Site C1 and C3 had the largest area of concrete damage (56 square feet and 6.7 square feet, respectively, as determined by Siva Corrosion Services, Inc. (SCS)) and received hydro-demolition as surface preparation for overlay. The rest of the sites were milled. The epoxy overlaid sites did not have surface concrete damage except for site E1, which had a concrete damage of 3.6 square feet. Table 3-2 presents a summary of the data collected by SCS, along with the surface preparation type that was used.

Table 3-2. Field inspection summary

Sites	Area of Unsound Concrete Before Removal (sq. ft.)	Surface Preparation	Chloride Threshold Depth (in.)
C1	56	Hydro-demolition	2.60
C2	0	Milling	1.54
C3	6.7	Hydro-demolition	1.53
E1	3.6	Milling	1.78
E2	0	Milling	1.96
E3	0	Milling	0.98

Source: Siva Corrosion Services, Inc.

3.2 Initial Bond Strength of Overlays

To evaluate the initial bond strength of the overlays, on-site direct pull-off tests (ASTM C1583, test methods for tensile strength of concrete repair and overlay materials) were conducted after the overlays were placed and fully cured (28 days for LSDC overlay, 3 hours for epoxy overlay). Three pull-off attempts were made for each bridge. The procedure for testing involved cutting through the overlay and substrate layers with a circular drill (Figure 3-12), attaching a steel disk to the overlay surface using epoxy, and then pulling on this surface with a tensile force (Figure 3-13) once proper adhesion is achieved. The failure mode was then determined, according to the scenarios outlined in ASTM C1583 and shown in Figure 3-14.

Figure 3-12. One of the circular cuts on site C2

Figure 3-13. The pull-off test mounting device

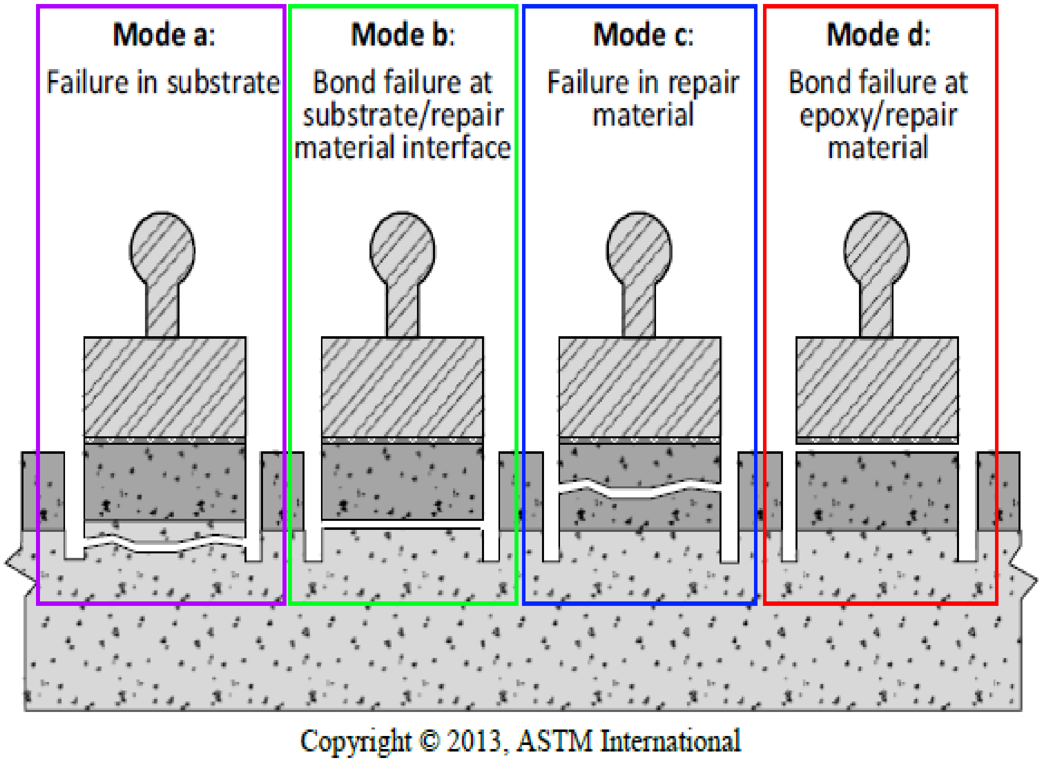

Figure 3-14. Failure modes of pull-off test

Test results

The results of pull-off tests of the CO and EO decks are shown in Table 3-3 and Figure 3-15. Due to the variability involved in field testing, three samples were not always available for each bridge (such as C1 and C2), in which case only two samples provided usable data. It can be observed from the results that the CO decks generally seem to have higher bond strength. However, it is worth noting that the failure mode of the EO decks is in the substrate due to poor substrate quality, which indicates the actual bond strength is higher than the result shown.

Table 3-3. On-site pull-off result of EO and CO decks

Core Number	Strength (psi)	Failure mode
E1-1	154	failure in substrate
E1-2	118	failure in substrate
E1-3	211	failure in substrate
E2-1	102	failure in substrate
E2-2	167	failure in substrate
E2-3	162	failure in substrate
E3-1	303	failure in substrate
E3-2	213	failure in substrate
E3-3	290	failure in substrate
C1-1*	90	failure in epoxy/overlay
C1-2	250	failure in substrate
C1-3	162	failure in substrate
C2-1	284	failure at substrate/overlay interface
C2-2*		
C2-3	211	failure at substrate/overlay interface
C3-1	460	failure at epoxy/overlay
C3-2	412	failure at epoxy/overlay
C3-3	369	failure at substrate/overlay interface

*Invalid results due to testing errors

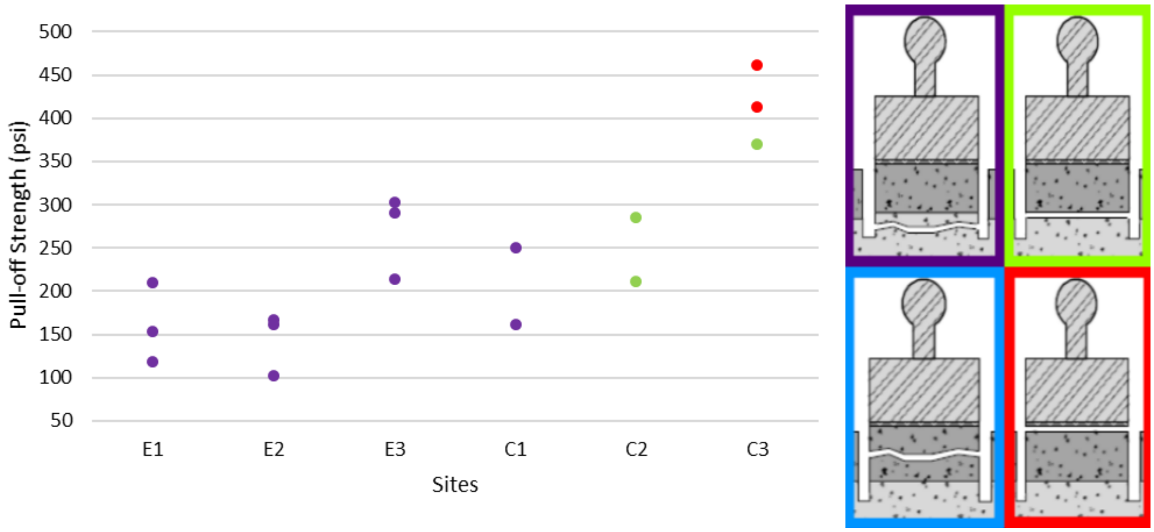

Figure 3-15. On-site pull-off result of EO and CO deck

CHAPTER 4. LABORATORY INVESTIGATION

4.1 Substrate Tests

Introduction

To fully understand the long-term behavior of the bond between the original concrete deck and the overlay, the properties of the substrate is of interest. Therefore, prior to deck removal, three randomly located cores from each of the six bridges were collected as samples to study the porosity and the durability to cyclic freezing and thawing. The porosity (percentage of air void) of the 18 cores was measured according to ASTM C642 (porosity test), and the durability (durability of the concrete to accelerated cyclic freezing condition) was measured using ASTM C666 (freeze-thaw test), Method A.

Porosity of Substrate

The results of ASTM C642 are shown in Figure 4-1. It can be observed that cores from site E3 generally have the least voids, possibly due to its short service age, while cores from site E2 and C1 have the most voids, which might lead to poor freeze-thaw resistance. There is a large scatter in the results of site E2 and E3 which might be due to random sampling.

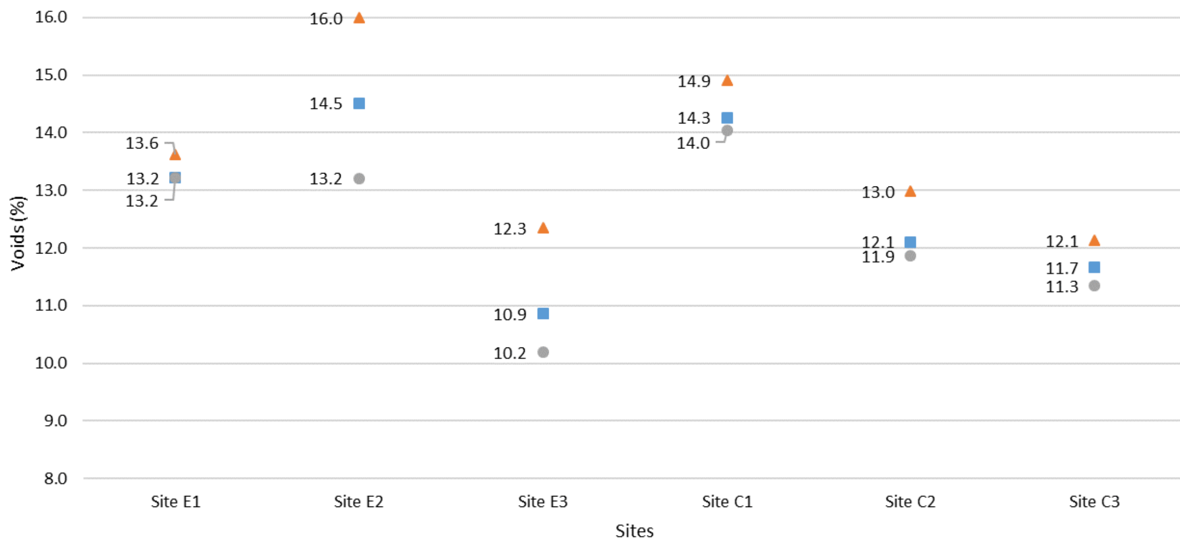

Figure 4-1. Porosity test results on the substrate cores of the six bridges

Cyclic Freeze-thaw Durability of Substrate

The durability factor was measured after the 300th F/T cycle, while the percent mass loss was measured at the 510th cycle in order to achieve distinguishable results. The results of durability factor and percent mass loss are shown in Figure 4-2 and Figure 4-3, respectively. It can be observed that cores from site E3 have the highest durability factor and the second lowest mass loss which agrees with the low porosity of site E3 and indicates that site E3 has generally better deck condition. On the other hand, site C1 has the lowest durability and the most dramatic mass loss which matches with its high porosity result and indicates that site C1 has a relatively poor deck condition.

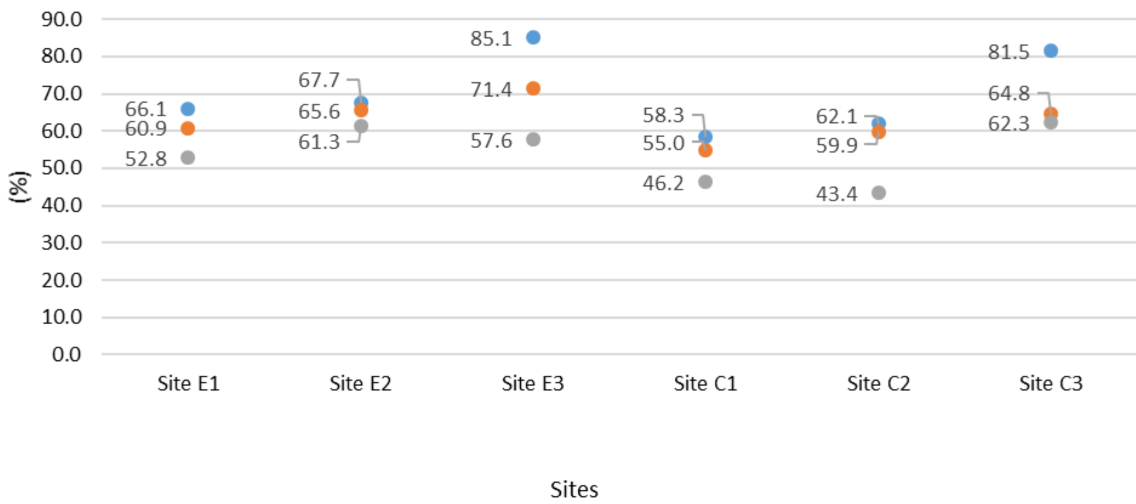

Figure 4-2. Durability factor of the substrate cores of the six sites under cyclic freeze-thaw test

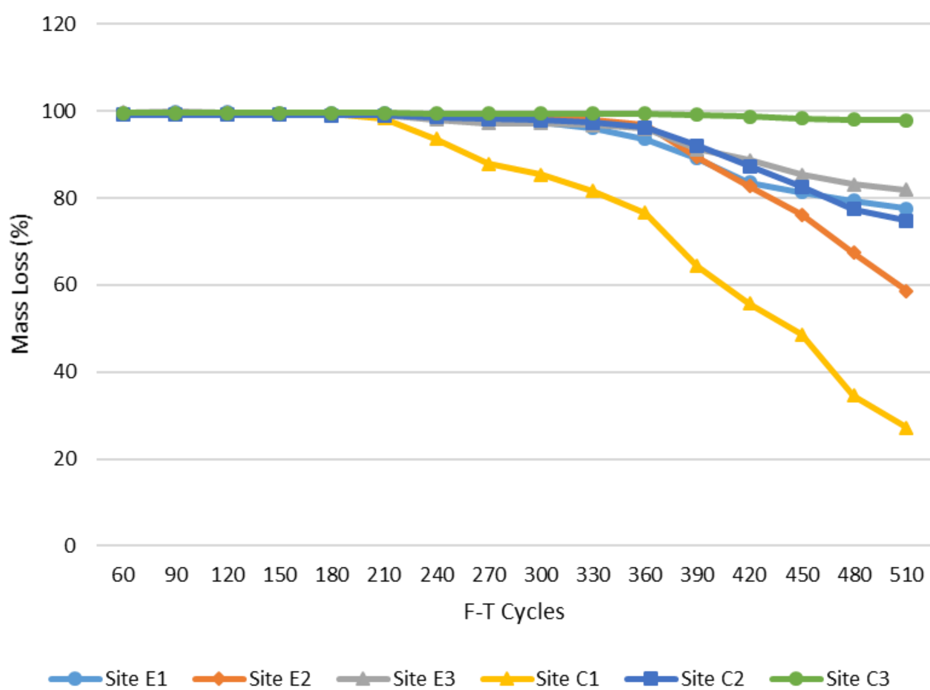

Figure 4-3. Percent mass loss of the substrate cores of the six sites under cyclic freeze-thaw test

The mass loss can be visually assessed as shown in Figure 4-4 and Figure 4-5.

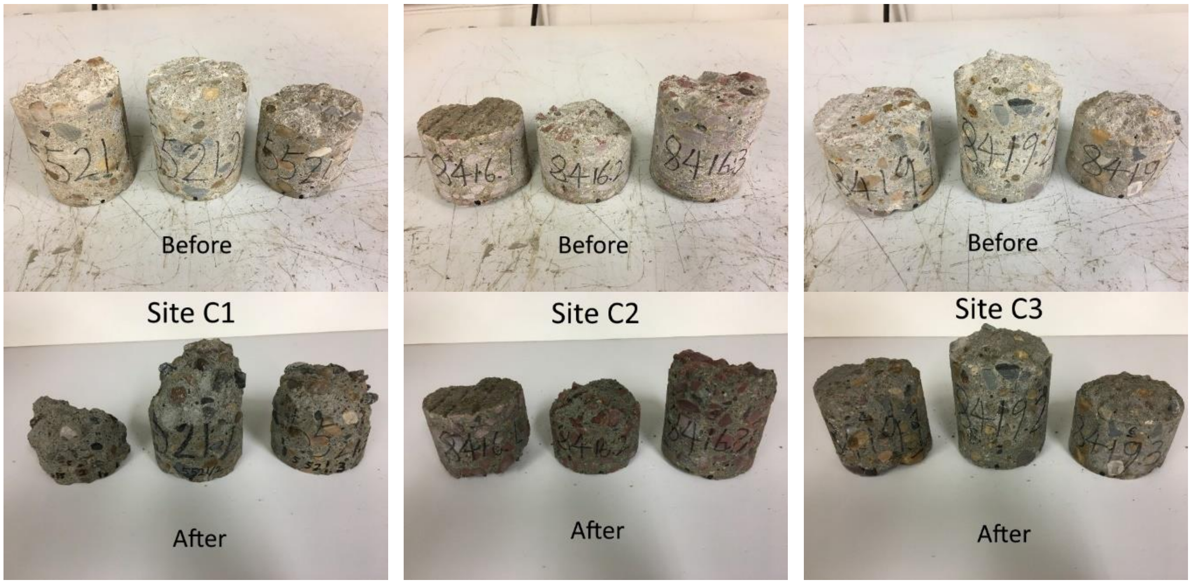

Figure 4-4. Cores from different field sites before and after 300 freeze-thaw cycles: Site C1 (left), Site C2 (middle) and Site C3 (right)

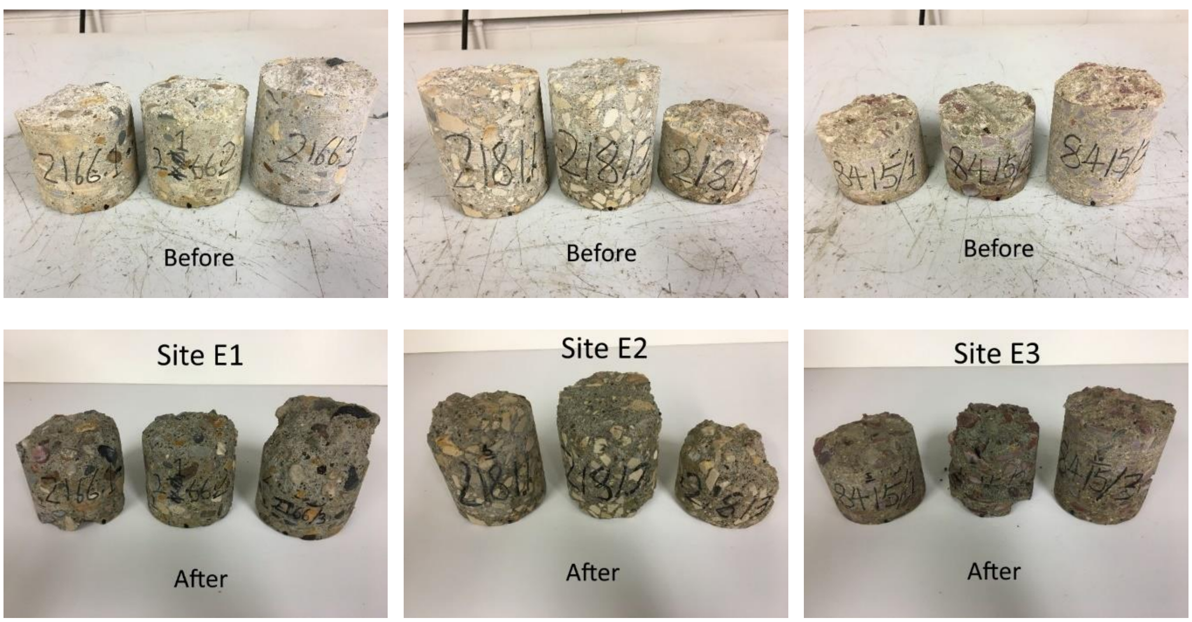

Figure 4-5. Cores from different field sites before and after 300 freeze-thaw cycles: Site E1 (left), Site E2 (middle) and Site E3 (right)

4.2 Overlay Tests

Introduction

In addition to the laboratory tests on the substrate cores, two sets of laboratory tests were carried out to study the permeability and the long-term bond strength of the two types of overlays. The permeability of the overlays was evaluated using AASHTO T 259 (salt-ponding test). The long-term bond strength of the overlays was assessed by ASTM C666 (freezing and thawing test) and ASTM C1583 (direct pull-off test), where the bond strength of the specimens would be tested at different freezing-thawing cyclic stages.

To prepare the epoxy overlaid (EO) slabs and the concrete overlaid (CO) slabs for the tests, eight substrate slabs with the size of 1ft by1 ft. were casted in plywood molds in the lab. To better comply with both the salt-ponding test standard and the freeze-thaw test standard, a constant slab thickness of 3.5 in. is desired. Since four slabs were to be epoxy overlaid (overlay thickness 0.375 in.) and the other four slabs were to be concrete overlaid (overlay thickness 1.75 in.), the substrate slabs for epoxy overlay (EO) should have the thickness of 3.125 in. and the substrate slabs for concrete overlay (CO) should have the thickness of 1.75 in. To mimic the surface roughness of the substrate of the bridge decks after milling, the bottom of the molds was first painted with formwork retarder to prevent the bottom surface of the slabs from hardening. After seven days of moist curing, the slabs were demolded and the uncured mortar on the bottom surfaces of the slabs were washed and brushed away with steel brush to expose part of the aggregates. After another 21 days of curing in the moist room, the surface roughness of the substrate slabs was assessed. The concrete surface profile (CSP) number of the substrate slabs was seven and was similar to the result of milling on the bridge deck substrate. For comparison purposes, the texture of the lab substrate slabs and the bridge deck substrate treated by milling and hydro-demolition are shown in Figure 4-6.

All eight slabs were then taken to the field and overlaid with the same materials as those used for the actual bridge deck overlays. For the CO slabs, the surface was covered with wet cloth and plastic sheeting for seven days before the slabs were retrieved from the field and demolded. The slabs were kept outdoors and cured for another 21 days before testing to again simulate field conditions. For the EO slabs, the slabs were cured for more than 24 hours before test. The surface of CO and EO slabs are shown in Figure 4-7. Four cured slabs (two EO and two CO) were used to determine the chloride permeability, another four slabs (two EO and two CO) were used to evaluate long-term bond strength of the overlays.

Figure 4-6. The texture of the substrate slabs: the lab substrate slab (upper), the deck substrate after milling (bottom left) and the deck substrate after hydro-demolition (bottom right)

Figure 4-7. The surface condition of the CO and EO slabs: the CO slab (left) and the EO slab (right)

Chloride Permeability of Overlays

Salt-ponding test was employed to compare the chloride permeability of the epoxy and concrete overlays. In accordance with AASHTO T 259, two concrete overlaid slabs and two epoxy overlaid slabs prepared earlier were ponded for 90 days. Figure 4-8 shows the slabs during ponding. After ponding, chloride determination was conducted in accordance with AASHTO T 260 (test method for sampling and testing for chloride ion in concrete materials). Samples were extracted from four depths, 1/8 in., 3/8 in., 5/8 in. and 7/8 in., to provide a profile of chloride concentration.

Figure 4-8. Two slabs during ponding: one of the EO slabs (left), and one of the CO slabs (right)

Figure 4-9 briefly illustrates the procedures of chloride determination.

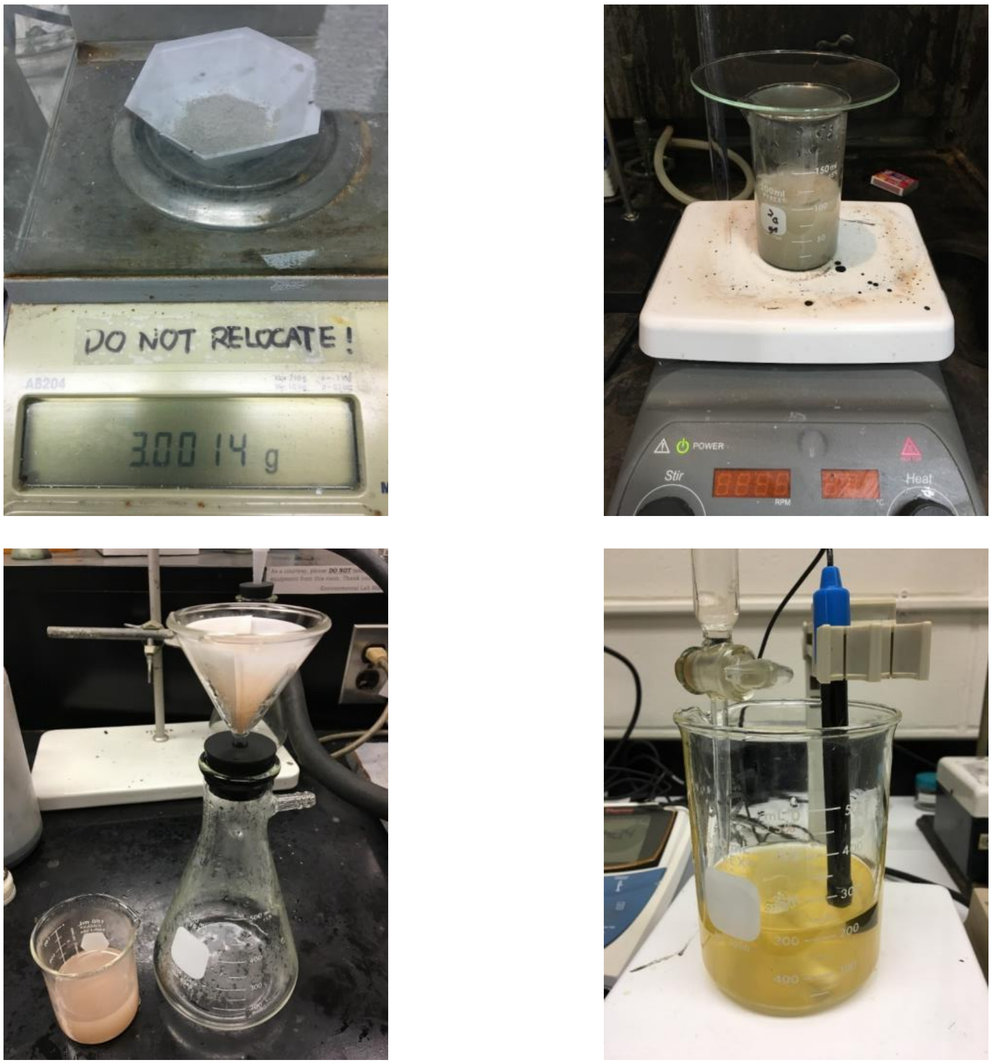

Figure 4-9. Chloride content determination process: weighing (upper left), boiling (upper right), filtration (bottom left), titration (bottom right)

Test results

The result of the salt-ponding test is shown in Figure 4-10. Each curve represents the average result of two slabs of the same type, as little variation in the data points was seen. It can be observed that the epoxy overlay samples have a much lower chloride content at both

1/8 in. and 3/8 in. depths. While both types of overlay samples have similarly low chloride content at 5/8 in. and 7/8 in. depths.

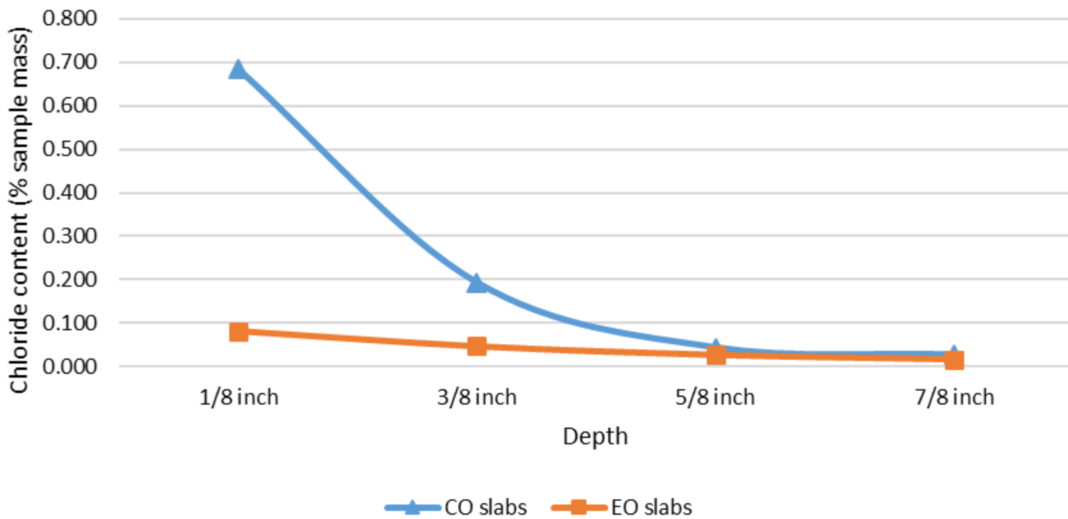

Figure 4-10. Percent chloride content of CO and EO slabs

Long-term Bond Strength of Overlays

To evaluate the long-term bond strength of the overlays, pull-off testing (ASTM C1583) and freeze-thaw testing (ASTM C666) were carried out. Twelve beams (six EO beams and six CO beams) were cut from the four slabs prepared earlier to better comply with the freeze-thaw test standards. The beams were then subjected to accelerated freezing and thawing cycles and tested at different F/T stages to reveal the simulated long-term bond strength. Note that the result of the pull-off test is largely dependent on the substrate tensile capacity. In order to have a more comprehensive interpretation of this pull-off test result as well as identify the factors that affect the initial and long-term performance of overlays, substrate properties were evaluated in previous sections. Four beam specimens are shown in Figure 4-11.

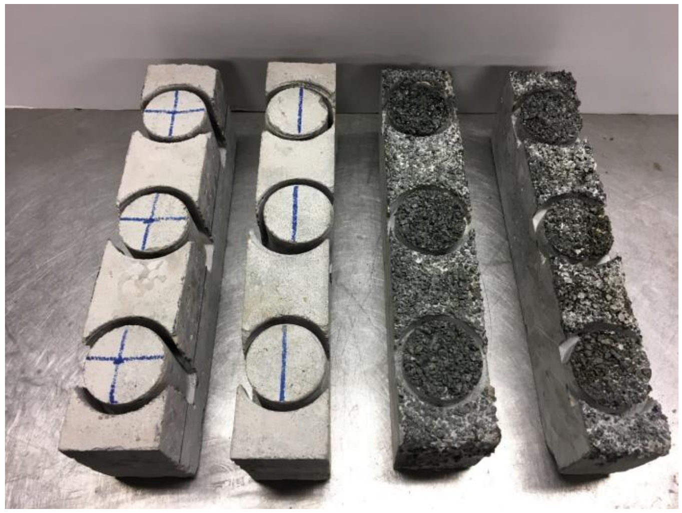

Figure 4-11. The CO and EO beams prepared for pull-off test

The beams shown above were cut with a two-inch core drill bit and the drill bit went through the depth of the overlay and 0.75 in. into the substrate, as shown in Figure 4-12.

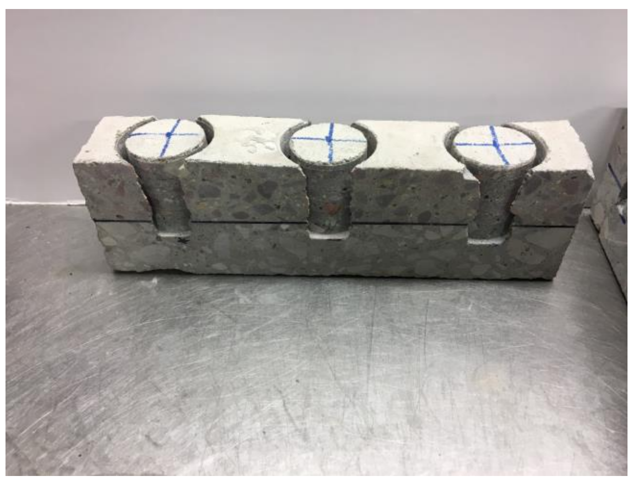

Figure 4-12. The CO beam with two-inch circular cuts

The same pull-off test procedure that was used in the field was followed, as shown in Figure 4-13. Since the beams are too narrow for mounting device to stand on, a steel plate with a hole in the center was placed on the tested beam so that the device was stable.

Figure 4-13. The pull-off test mounting device and the mounting detail: the mounting device (Proceq DY-216 model) (left) and the mounting detail (right)

Since the aggregates attached on the epoxy overlay create a rough surface that is not suitable to apply the two-part adhesive epoxy, the top surface of the EO beams were slightly grinded with a grinder. The surface before and after grinding is shown in Figure 4-14.

Figure 4-14. The top surface of the EO beams for pull-off test: surface before grinding (left) and surface after grinding (right)

Test results

The pull-off test results of the CO beams and the EO beams are shown in Figure 4-15 and Figure 4-16, respectively. Some data points are missing because of unexpected sampling and testing failures. There is a scatter in the results due to the intrinsic heterogeneity of granular materials like concrete. It can be observed that for both 0 and 100 F/T cycles the EO beams generally have higher potential bond strength than the CO beams. But after 300 F/T cycles the bond strength of EO beams has dropped significantly and is generally lower than that of the CO beams.

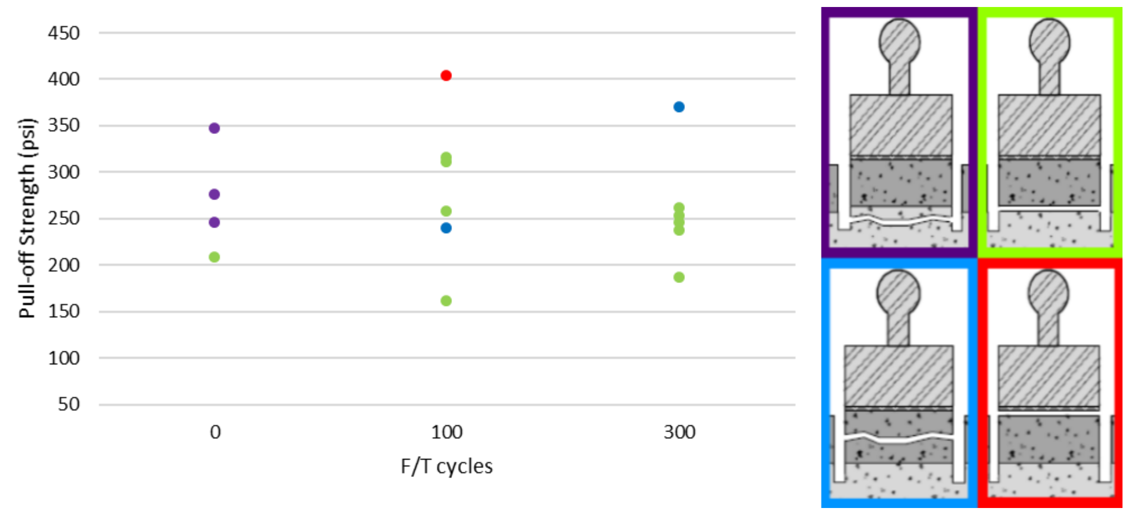

Figure 4-15. Pull-off test results of the CO beams at different freezing-thawing cyclic stages

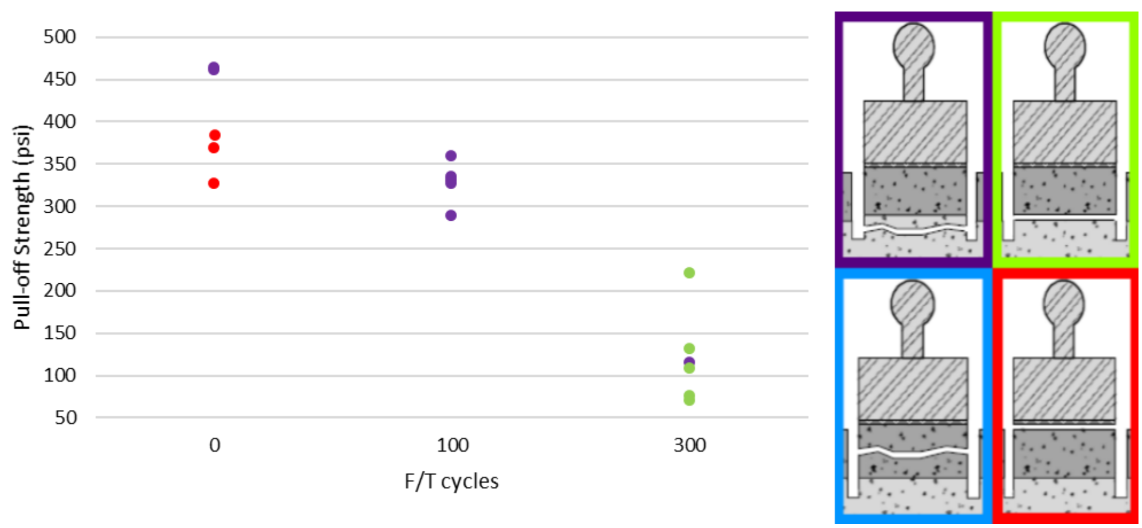

Figure 4-16. Pull-off test results of the EO beams at different freezing-thawing cyclic stages

CHAPTER 5. DATA ANALYSIS AND DISCUSSION

5.1 Properties of Substrate

Table 5-1 shows the results of tests that reflect the condition of the deck substrates. The voids are percentage of air void in the substrate cores given by the porosity test. The durability factor and the remain mass are measures of the durability of the substrate cores to severe freezing and thawing cycles, where the remaining mass was measured after the 510th cycle to obtain performance under prolonged freezing and thawing exposure. The chloride depth is the depth where the chloride concentration in the substrate cores reaches the threshold level to effectively damage rebar. The chloride profile data of the substrate cores was provided by WHKS in 2015. The on-site pull-off results are included because 11 out of 16 test samples delaminated in substrate layer which reflects the tensile strength of the substrate. The other five samples did not delaminate in the substrate layer which indicate that the tensile strengths of those substrates are higher than the result value.

Table 5-1. Composite results of the tests on substrates

Sites	E1	E2	E3	C1	C2	C3
Voids (%)	13.5	14.6	11.1	14.4	12.3	11.7
Durability Factor (%)	59.9	64.9	71.4	53.2	55.1	69.5
Remain Mass (%)	77.6	58.7	81.9	27.2	74.9	97.9
Chloride depth (inch)	1.78	1.96	0.98	2.6	1.54	1.53
On-site pull-off result (psi)	161	144	269	206	248	414
Years of Service	31	12	11	25	16	33

The results in Table 5-1 are averaged across three observations of each site. The green shading indicates relatively good performance among the six sites, whereas yellow and red shading indicates medium and relatively poor performance among the six sites, respectively. It can be observed that sites C3 and E3 generally have the best substrate quality among the six sites, despite the great difference in age. In contrast, site C1 has the poorest substrate conditions as seen by the consistent red shading.

It can be observed from the result of on-site pull-off testing (Figure 5-1) that many of the specimens failed in substrate due to poor substrate condition, thus the data does not reflect the true bond strength, which is higher than the substrate tensile strength. However, the substrate strength revealed by this test corresponds with the other results in Table 5-1, where sites with high pull-off strength generally perform well in other tests. The data also shows that the bond strength of site C3 is generally higher than that of site C2, which is worth noting as the surface preparation for site C3 was hydro-demolition and that of site C2 was milling. Despite the many factors that affect the pull-off test results, this might indicate that hydro-demolition provides higher initial bond strength than milling for rigid overlays.

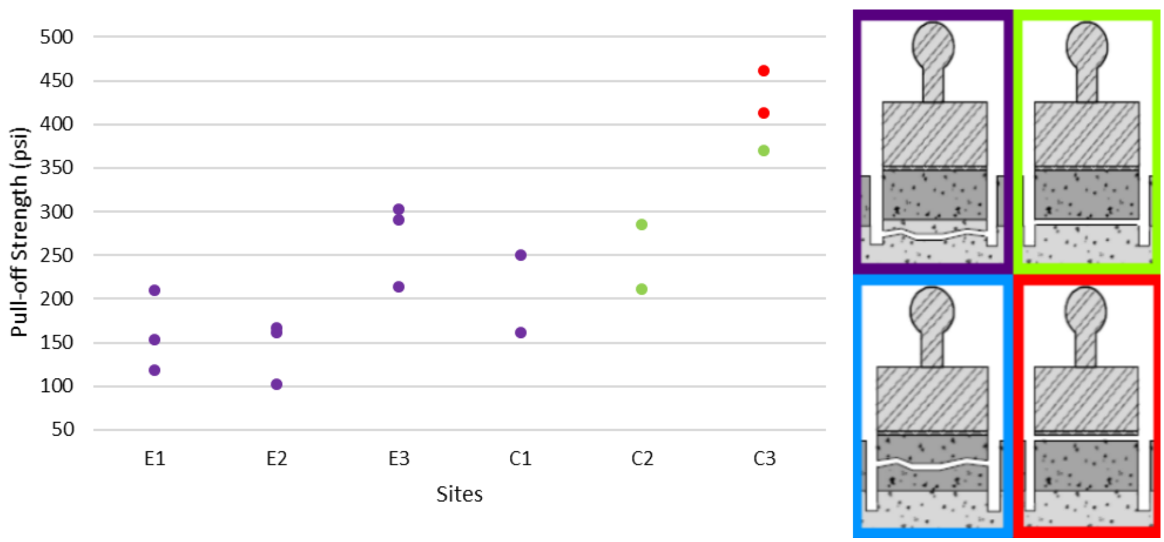

Figure 5-1. Field pull-off test results of EO and CO decks

To identify the factors that affect the initial and long-term bond strength of the overlays, the properties of the substrate (Table 5-1) were studied closely. Four correlations stand out, namely: voids and chloride depth, voids and remain mass, voids and on-site pull-off result, and remaining mass and chloride depth. This indicates that the percentage of air voids of substrate may be the factor that influence the initial performance of the overlays. The four correlations are illustrated below. Figure 5-2 shows the data points of percent air void and the corresponding depth of critical chloride content, as well as a plot of the best-fit line, which has an R-squared value of 0.9487. This indicates there is a strong linear relationship between air voids in concrete and chloride resistance.

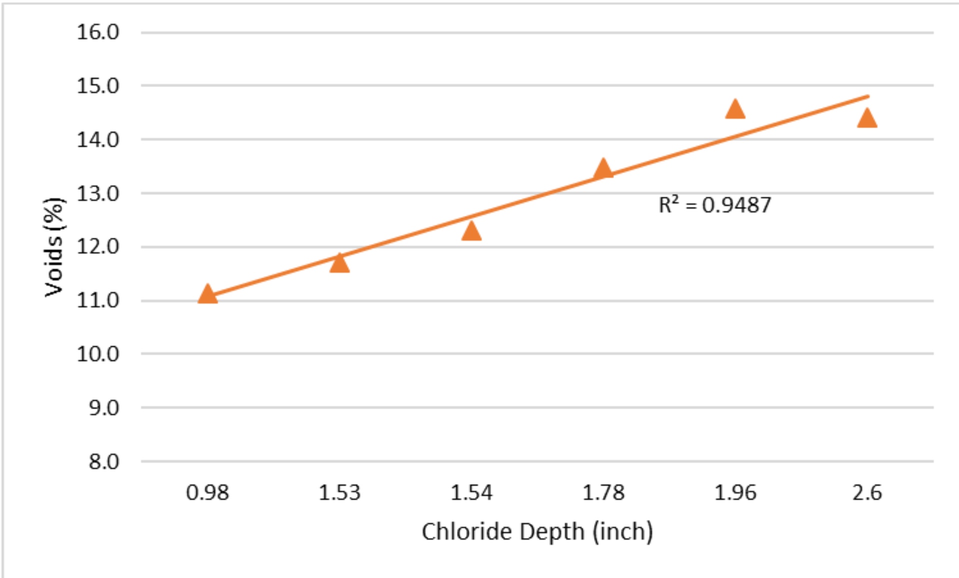

Figure 5-2. Relationship between voids and chloride depth

The remaining mass after 500 freeze-thaw cycles measured in the freeze-thaw test reflects the concrete durability to freezing and thawing condition. Figure 5-3 shows that the R-squared value of the fitted line and the data points of the percent voids and the remaining mass is 0.7136 which indicates that air voids in concrete has a linear relationship with the durability to freezing and thawing cycles.

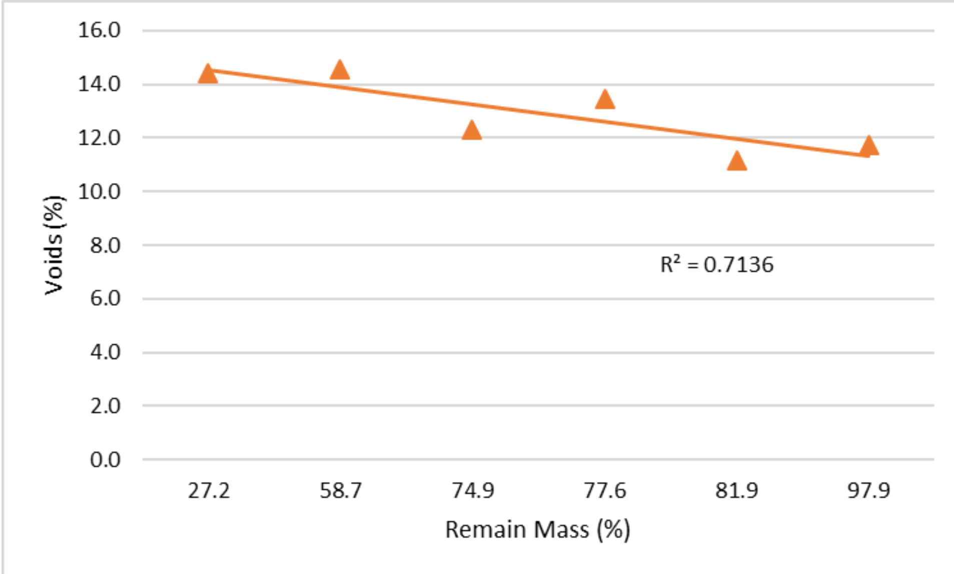

Figure 5-3. Relationship between voids and remain mass

Figure 5-4 shows the plot of the fitted line and the data points of percent air void and the on-site pull-off test results, which has an R-squared value of 0.7625. This indicates there is a linear relationship between air voids in substrate and substrate integrity since the pull-off results reflect the integrity of the substrate.

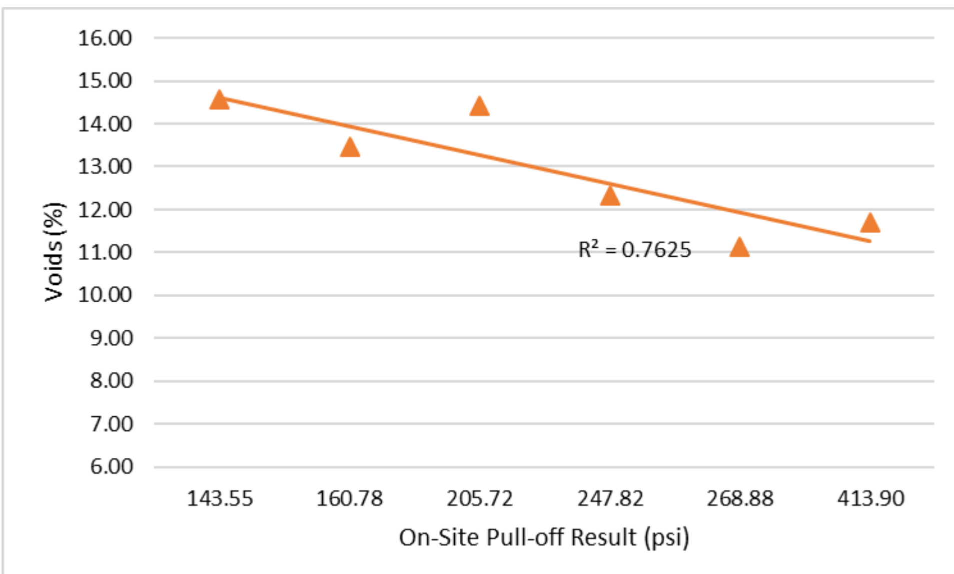

Figure 5-4. Relationship between voids and on-site pull-off result

To better illustrate the relation between the percentage of air voids in substrate and the pull-off strength, Figure 5-5 duplicates both results. It can be observed that the trends of the percentage of air voids and the pull-off strength for both epoxy and concrete overlays show signs of symmetry.

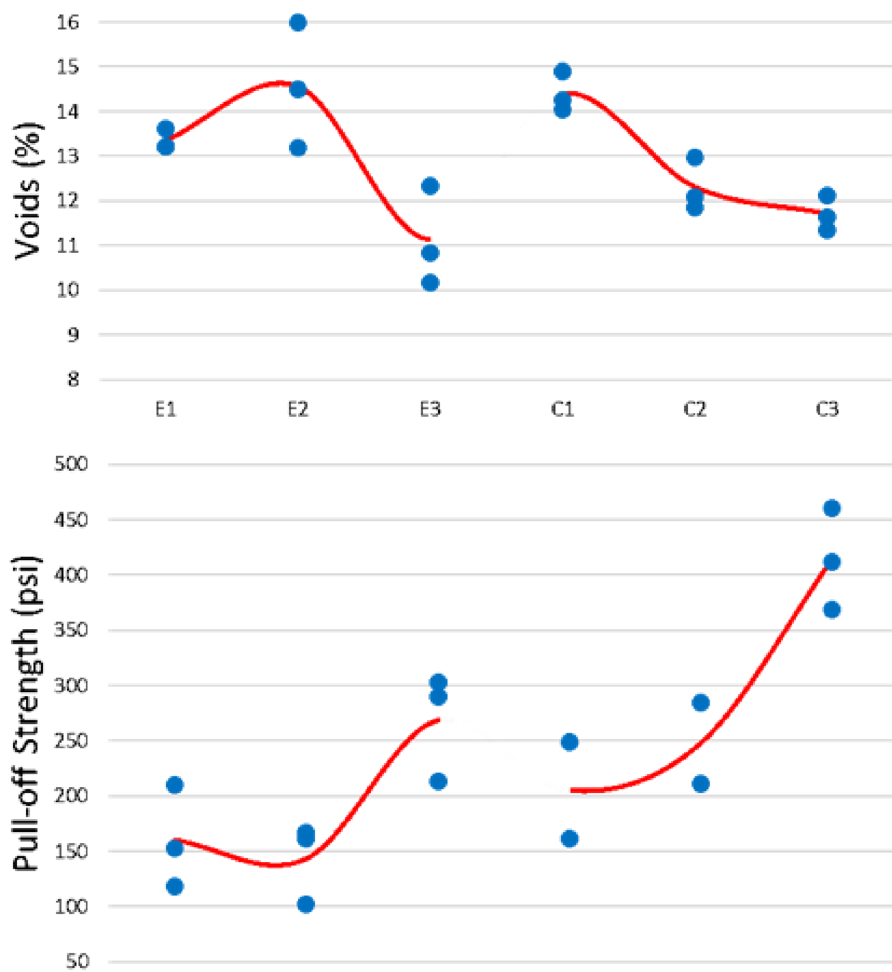

Figure 5-5. Comparison of the porosity test results and the on-site pull-off test results

Finally, Figure 5-6 shows that the R-squared value of the fitted line and the data points of the remaining mass after 500 F/T cycles and the critical chloride content depth is 0.7278. As the remaining mass and chloride depth were explained above, the plot indicates that the remaining mass of substrate has a linear relationship with the critical chloride content depth.

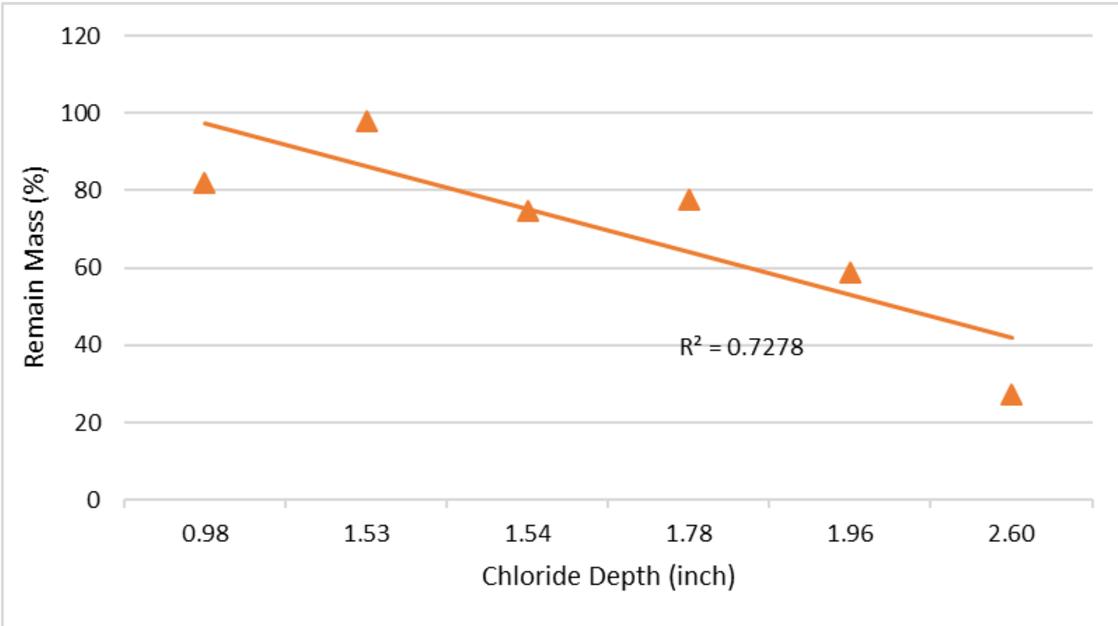

Figure 5-6. Relationship between remain mass and chloride depth

5.2 Long-term Bond Strength of Overlays

A copy of the results of the laboratory pull-off test on CO and EO beams are shown in Figure 5-7 and Figure 5-8, respectively. It can be observed that as the samples went through more F/T cycles, the decrease in bond strength is greater than the decrease in substrate tensile strength because there are more substrate failures than bond failures at the beginning, then bond failure grows at 100 F/T cycles, and dominates at 300 F/T cycles. It can also be observed that the EO beams generally and potentially have higher bond strength than the CO beams at both 0 and 100 F/T cycles, but the bond strength of the EO beams appears to be lower than that of the CO beams at 300 F/T cycles.

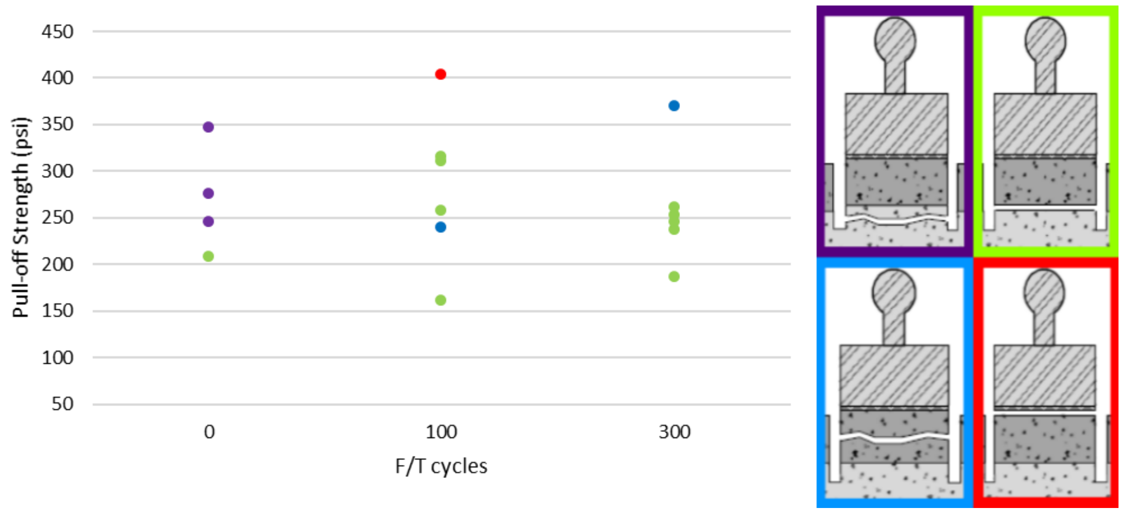

Figure 5-7. Pull-off test results of the CO beams at different freezing-thawing cyclic stages

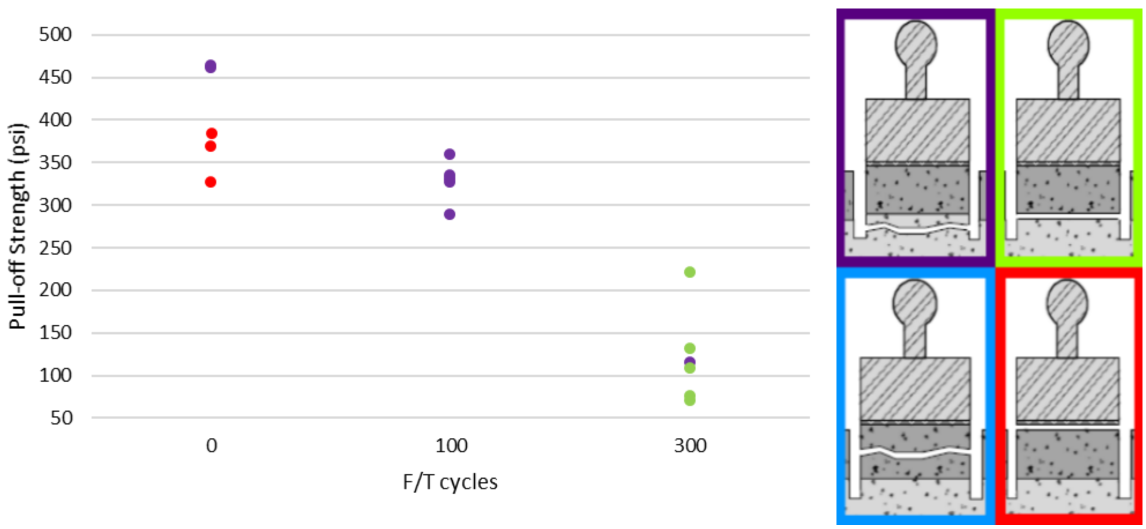

Figure 5-8. Pull-off test results of the EO beams at different freezing-thawing cyclic stages

5.3 Chloride Permeability of Overlays

A copy of the result of the salt-ponding test is shown in Figure 5-9. It can be observed that the concrete overlaid slabs have much higher chloride content at shallow depths (1/8 in. and 3/8 in.) than that of the epoxy overlaid slabs, which indicates that epoxy overlay prevent chloride ingress better than the concrete overlay. But at deeper depths (5/8 in. and 7/8 in.), the chloride contents of both overlays are similarly low, which reflects the extent of chloride ingression.

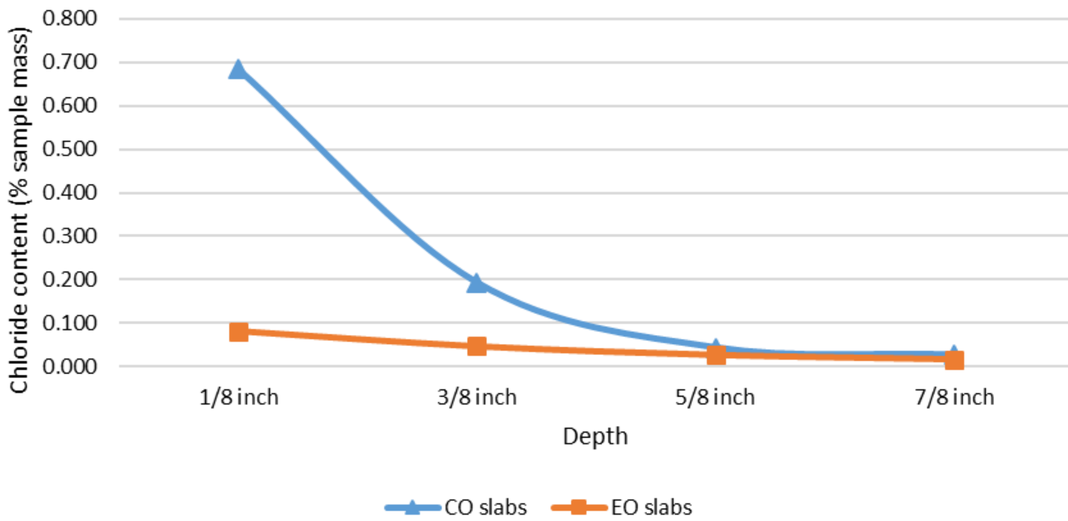

Figure 5-9. Percent chloride content of CO and EO slabs

CHAPTER 6. CONCLUSIONS AND FUTURE WORK

Conclusions

The primary objectives of this study were to evaluate the initial and long-term bond strength of the thin epoxy overlay and the low slump dense concrete (LSDC) overlay, as well as to identify the factors that affect the performance of overlays. The study also sought to assess the chloride resistance of overlays. To fulfill the objectives, field inspections were performed on the selected sites to document bridge deck damage prior to overlay, as well as substrate preparation details; substrate cores of the six bridges were extracted and tested to evaluate their porosity and durability to cyclic freezing and thawing; on-site pull-off tests were conducted to assess the initial bond strength of the two overlays; laboratory pull-off tests were conducted to evaluate the long-term bond strength of the two overlays. The project conclusions are summarized in this chapter.

• **Accelerated freezing and thawing exposure has a greater influence on the bond strength of epoxy overlay than that of concrete overlay.** In the simulated laboratory pull-off tests, the initial (before any F/T cycle) bond strengths of both epoxy overlay and concrete overlay are good, with many concrete and epoxy samples failed in substrate layer. After 300 F/T cycles, both epoxy and concrete overlaid samples failed at bond (between the substrate and the overlay), however, the average bond strength of concrete overlay is almost twice of that of epoxy overlay.

• **The epoxy overlay can resist chloride penetration much better than the LSDC overlay.** The chloride content in the epoxy overlaid slabs is less than 1/8 of the chloride content in the LSDC overlaid slabs at a depth of 1/8 in.

•**Substrate soundness has an influence on the performance of both thin epoxy overlay and LSDC overlay.** The percentage of air voids in the substrate was seen to have the greatest effect on the performance of overlays. In the tests on substrate cores, as the percentage of air voids gets lower, there are linear improvements in the critical chloride content depth (chloride resistance), the remaining mass after 500 F/T cycles (freezing and thawing durability), and the on-site pull-off results.

•**No obvious relationship between the age of the bridge and substrate quality of the bridge has been found in this study.** The two bridge sites that had the best performance overall had underwent 11 and 33 years of service. The 33 year old bridge was the oldest that was investigated and outperformed many much newer bridges.

Future Work

It is suggested that follow-up pull-off tests be performed on-site on a three-year interval basis after the overlay application to evaluate the long-term performance of the overlay. Factors that influence the long-term performance of the overlays can also be identified by again consulting the substrate properties obtained in this study. Concrete cylinders (cores) can also be taken to acquire the chloride profile and deterioration profile of the deck. So that the migration of chloride sealed in the decks and the deck deterioration rate can thus be available for analysis and the relation between them can be further studied. These efforts can help to further identify the factors that affect long-term performance of both overlay types.

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APPENDIX IMAGE LOG OF VISITED SITES

Figure 0-1. Surface condition of bridge deck of site C1 prior to overlay

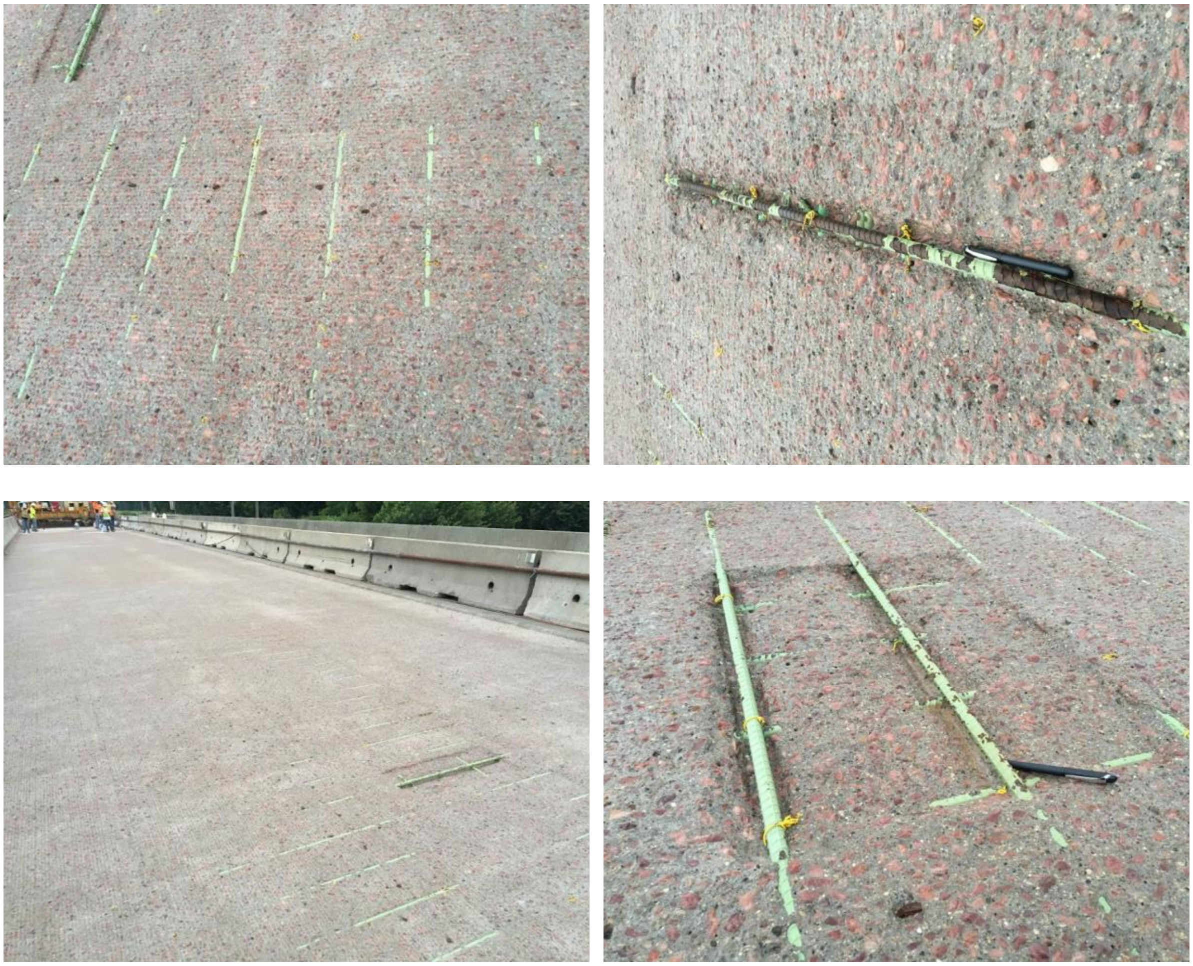

Figure 0-2. Surface condition of bridge deck of site C2 prior to overlay

Figure 0-3. Surface condition of bridge deck of site C3 prior to overlay

Figure 0-4. Surface condition of bridge deck of site E1 prior to overlay

Figure 0-5. Surface condition of bridge deck of site E3 prior to overlay