Long-Term Performance of Overlays: Thin Epoxy Overlay versus Traditional Rigid Overlay

Final Report
February 2020

BRIDGE ENGINEERING CENTER

IOWA STATE UNIVERSITY
Institute for Transportation

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16. Abstract

To improve long-term bridge performance through better design and maintenance practices, as well as to promote service life design (SLD) concepts, the Iowa Department of Transportation (DOT) has sought to implement SLD recommendations from two projects conducted under the Second Strategic Highway Research Program's (SHRP2's) Service Life Design for Bridges (R19A) in future bridge preservation practice.

The aim of the present study was to evaluate the bond strength and chloride resistance of thin epoxy overlays and compare the results with those obtained from low-slump dense concrete (LSDC) overlays. The following specific objectives were proposed: evaluate the initial and long-term bond strength of overlays, assess the chloride resistance of overlays, and identify the factors that affect the initial performance of overlays.

To fulfill these objectives, six existing bridges were chosen for installation of the two overlay types. Field inspections were performed on the selected bridges to document substrate surface conditions, substrate cores were extracted and tested using both ASTM C642 and ASTM C666 to evaluate the overlays' porosity and durability to cyclic freezing conditions, on-site pull-off tests (ASTM C1583) were conducted to assess the initial bond strength of the overlays, laboratory pull-off tests (ASTM C1583) were conducted under cyclic freezing conditions to evaluate long-term bond strength, and salt ponding tests (AASHTO T 259) 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 overlays decreased sharply after 300 freeze-thaw cycles, whereas the bond performance of the LSDC overlay remained unchanged; the chloride resistance of the epoxy overlays is much better than that of the LSDC overlays; and the percentage of air voids in the substrate concrete was found to have an effect on the initial performance of the overlays.

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LONG-TERM PERFORMANCE OF OVERLAYS: THIN EPOXY OVERLAY VERSUS TRADITIONAL RIGID OVERLAY

Final Report
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EXECUTIVE SUMMARY

To improve long-term bridge performance through better design and maintenance practices, as well as to promote service life design (SLD) concepts, the Iowa Department of Transportation (DOT) has sought to implement SLD recommendations from two projects conducted under the Second Strategic Highway Research Program's (SHRP2's) Service Life Design for Bridges (R19A) in future bridge preservation practice.

The aim of the present study was to evaluate the bond strength and chloride resistance of thin epoxy overlays and compare the results with those obtained from low-slump dense concrete (LSDC) overlays. The following specific objectives were proposed:

- Evaluate the initial and long-term bond strength of the overlays
- Assess the chloride resistance of the overlays
- Identify the factors that affect the initial performance of the overlays

To fulfill these objectives, six existing bridges were chosen for installation of the two overlay types. Field inspections were performed on the selected bridges to document substrate surface conditions, substrate cores were extracted and tested using both ASTM C642 and ASTM C666 to evaluate the overlays' porosity and durability to cyclic freezing conditions, on-site pull-off tests (ASTM C1583) were conducted to assess the initial bond strength of the overlays, laboratory pull-off tests (ASTM C1583) were conducted under cyclic freezing conditions to evaluate long-term bond strength, and salt ponding tests (AASHTO T 259) were performed to assess chloride resistance.

The results from these testing efforts indicated the following:

- The initial bond strengths of both overlays are good.
- The long-term bond strength of the thin epoxy overlays decreased sharply after 300 free-thaw cycles, whereas the bond performance of the LSDC overlays remained unchanged.
- The chloride resistance of the epoxy overlays is much better than that of the LSDC overlays.
- The percentage of air voids in the substrate concrete was found to have an effect on the initial performance of the overlays.

CHAPTER 1: INTRODUCTION

1.1 Background

The Federal Highway Administration (FHWA) has reported that more than 25% of the bridges in the US are either structurally deficient or functionally obsolete (Harms et al. 2010). Iowa owns the fifth largest number of bridges among all of the states, while the average condition of these bridges has earned them a letter grade of D+ (ASCE 2015). This means that a large number of bridges in Iowa are undergoing deterioration and require rapid and effective rehabilitation.

The deterioration of bridges often originates via cracking in the top surface of the deck, which is the most exposed part of a bridge to the combined influences of water/chloride ingress, dynamic traffic loading, ultraviolet radiation, and freeze-thaw conditions. Before long, this damage in the bridge deck has the potential to compromise the integrity of the entire bridge. In past research, concrete overlays have shown the ability to prolong the life of bridge decks, and this solution has been widely adopted (Fick and Harrington 2014). However, for bridges that have not shown extensive deck deterioration, polymer overlays have gained popularity (Alger et al. 2003).

In this study, the long-term performance of two types of overlays—a thin epoxy overlay and a low-slump dense concrete (LSDC) overlay—was evaluated to better understand the applications and ideal scenarios for the utilization of each overlay type.

1.2 Objectives

The objectives of this study included the following:

- Evaluate the bond strengths of two types of overlays (i.e., thin epoxy overlays and LSDC overlays) and investigate the change in bond strength over time through on-site testing
- Understand the long-term performance of epoxy overlays and rigid overlays via accelerated laboratory testing
- Investigate how existing chloride that has been sealed in a bridge deck by an epoxy overlay migrates and how that migration might relate or contribute to additional deck deterioration
- Identify factors that affect the initial and long-term performance of the overlays examined in this study

CHAPTER 2: LITERATURE REVIEW

2.1 Bridge Deck Repair Materials and Their Properties

Bridge deck overlays are a necessary and effective method for bridge deck repair, with a wide variety of overlays currently available. A survey (Krauss et al. 2009) indicated that the most popular are asphalt concrete overlays with a waterproofing membrane, high-performance concrete overlays, and polymer concrete (including thin-bonded epoxy) overlays. The survey also pointed out that high-performance concrete, silica fume-modified concrete, fly ash-modified concrete, and polymer concrete (including thin-bonded epoxy) overlays are being tested and more widely used, while the low-slump, low-water-cement ratio concrete overlays are decreasing in popularity.

In order to choose an ideal overlay for specific concrete repair projects, the American Concrete Pavement Association (ACPA) (Harrington and Fick 2014) suggests that the following properties of overlays should be considered: bond strength, freeze-thaw durability, elastic modulus, and shrinkage of the material. For a project in the real world, repair speed and the cost of the repair material also come into play.

2.2 Bonding of Repair Material

When a repair is conducted, the stress distribution and bond specifications of the repair system are mostly influenced by the differences in the properties of the substrate and repair material. Differences in the moduli of elasticity and thermal movements of the two materials cause each layer to show different strains when exposed to the same load, as well as different temperature strains. In addition, shrinkage increases the vulnerability at the interface, especially when a new patch of concrete is applied. Therefore, achieving adequate adhesion at the interface is considered a key factor in the repair process. A repair system can be considered as a composite system with three phases: the substrate, the patching material/overlay, and the interface between them (Bakhsh 2010).

2.3 Definition of Bond Strength

The main objective of bridge deck repair is to restore the load carrying capacity and the stiffness of the deteriorated original concrete deck. Adequate bond between the overlay and the substrate is critical (Silfwerbrand et al. 2011), with the bond strength defined as the adhesion between the overlay material and the substrate. Sufficient bond strength is the main parameter in a sound repair system (Beaupré 1999). The bond or adhesion specifications can be considered from two different points of view (Courard 1999): the quantitative measure of the magnitude of the bond, which is often expressed as the required stress or energy to detach the two materials, and the conditions and kinetics involved in joining two materials with two different bond behaviors. The former perspective has been well adopted because the magnitude of the bond can be quantitatively evaluated by bond strength tests such as the pull-off test.

2.4 Epoxy Overlay

Epoxy is a general term for a class of compounds that are generally formed from a chemical reaction between two components: an epoxy resin and a curing or hardening agent, which are typically combined at ratios ranging from 1:1 to 1:3. Overlays constructed using epoxy binders typically have high bond strength and low initial shrinkage, and their properties are not affected by high alkalinity; therefore, these materials are suitable for application on concrete substrates. Epoxy overlays are typically installed using a multiple-layer method (also known as the broom and seed method). Fowler and Whitney (2011) noted that lower modulus and higher elongation resins were developed to address an important factor in overlay delamination, namely thermal incompatibility between polymers and concrete. With these characteristics, epoxy overlays have the potential to generate a very good initial bond.

Repair speed is sometimes one of the most crucial criteria in situations where extended traffic closure is especially unfavorable. Unlike traditional concrete overlays, epoxy overlays have a very short installation time (less than 24 hours). A one-night closure is enough for an epoxy overlay repair, given proper management. Epoxy overlays also cost less than concrete overlays and have an average service life in the range of 9 to 18 years, according to 46 bridge deck repair agencies surveyed in a National Cooperative Highway Research Program (NCHRP) project (Krauss et al. 2009). Additionally, epoxy overlays are generally thinner than concrete overlays, therefore making them ideal for situations requiring minimal deck surface raise.

A research project (Sprinkel 1993) conducted under the Strategic Highway Research Program (SHRP) projected that, under the exposure of moderate deicing salt applications, the time to reach a chloride content of one lb/yd^3 is 25 years with a maintained epoxy sealer and 77 years with a maintained epoxy overlay. The report suggests that epoxy overlays have very good chloride resistance. Given the attributes of epoxy overlays, a growing number of bridge deck repair agencies have developed and installed epoxy overlays over the last decade (Krauss et al. 2009).

Studies on the mechanical properties of epoxy overlay materials indicate that the bonding between an epoxy overlay and a steel deck is highly dependent on temperature (Mo et al. 2012), which leads to the question of the bond performance between an epoxy overlay and a concrete substrate under varying temperatures, specifically the freeze-thaw conditions that prevail in Iowa's climate. Another study investigated the short-term bond strength of epoxy overlays on asphalt surfaces and concluded that the initial bond strength is satisfactory according to pull-off tests (Young and Durham 2012).

However, few published studies have evaluated the long-term performance of epoxy overlays. Recently, the Iowa Department of Transportation (DOT) initiated an overlay project that involved overlaying three bridges with an epoxy (epoxy resin) overlay and another three bridges with an LSDC overlay to repair the decks. This project offers the opportunity to evaluate the on-site initial bond strength of the epoxy and concrete overlays and provides access to epoxy and concrete overlay materials to conduct accelerated laboratory testing for long-term performance evaluation.

2.5 Testing Methods and Conditions

To evaluate the long-term performance of the overlays in terms of bond strength, pull-off tests were carried out on both on-site and laboratory samples. The laboratory samples were built with substrate portland cement concrete (PCC) overlaid with an epoxy or concrete overlay in the field. The samples were then subjected to accelerated freezing and thawing cycles and tested at different freeze-thaw stages to reveal the long-term bond strength. Note that the results of a pull-off test largely depend on the substrate's tensile capacity. In order to obtain a more comprehensive interpretation of the pull-off test results as well as identify the factors that affect the initial and long-term performance of the overlays, multiple cores were extracted from each bridge deck prior to the application of the overlays and were subjected to porosity and freeze-thaw testing. A salt ponding test was also conducted to assess the chloride resistance of both types of overlays.

For a typical Iowa LSDC overlay, 0.25 in. of the 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 such an elevated deck surface, slight modifications were made in the present project to the surface preparation process for both overlay procedures. For the epoxy overlay, the top 0.375 in. of the deck was milled before the overlay was applied. For the LSDC overlay, the top 1.75 in. was removed by either milling or hydro-demolition.

The epoxy overlay studied in this project is a thin-bonded epoxy overlay. To apply this type of overlay, a layer consisting of a hot, freshly mixed epoxy coat is first spread on the milled concrete surface, immediately followed by a layer of broadcast aggregate chips. A single coat typically results in a thickness of 0.125 in., and a double-coat system was applied for this project, which resulted in a thickness of 0.375 in. Figure 1 shows the first coating.

Figure 1. First coating of epoxy overlay

CHAPTER 3: FIELD INVESTIGATION AND TESTING

3.1 Field Investigation

To study the mechanical and durability properties of thin epoxy overlays and LSDC overlays for bridge deck rehabilitation, six bridges in Iowa were chosen. Figure 2 shows the locations of the bridges investigated, and Table 1 summarizes the general information for these bridges.

Figure 2. Locations of the bridges investigated

Table 1. Basic information on the bridges investigated

Site No.	County	Route	Bridge Maint. #	FHWA #	Overlay Type	Age (years)
C1	Kossuth County	US 18	5521.8S018	32821	LSDC	25
C2	Sioux County	US 18	8416.6S018	48231	LSDC	16
C3	Sioux County	US 18	8419.8S018	48281	LSDC	33
E1	Clay County	US 18	2166.2S018	20291	Epoxy	31
E2	Clay County	US 18	2181.0S018	20331	Epoxy	12
E3	Sioux County	US 18	8415.1S018	48211	Epoxy	11

Three of the six bridges were to be overlaid with epoxy, and the rest were to be overlaid with LSDC. Since the condition of the substrate is critical for overlay performance, the substrate condition for each bridge deck was inspected. In addition, after the overlays were placed, the bond between the overlay and the substrate was evaluated via in situ pull-off tests. These efforts are discussed in the following sections. Images of the bridge deck conditions prior to overlay at Sites C1, C2, C3, E1, and E3 are provided in the appendix.

Prior to the start of this project, Siva Corrosion Services (SCS) was retained by the planning consultants, WHKS & Co., to perform corrosion evaluations of the six bridge decks in December 2015. The chloride profiles of the bridge decks prior to deck surface preparation were collected as part of this effort and are also included in the following sections.

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

Bridge Description

Bridge C1 carries US 18 over Lotts Creek between Emmetsburg and Algona, Iowa, 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., delaminations and patch repairs) was observed on approximately 1.1% of the deck (a total of 56 ft^2).

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 epoxy-coated reinforcing steel (ECR) is approximately 1,800 ppm. The chloride data from the four cores indicated that the average depth with a chloride content of 1,800 ppm was 2.60 in., and the average rebar depth for this bridge is 2.24 in. The average chloride content at a depth of 1.75 in. was 3,213 ppm.

Field Investigation Description

Field investigations of Site C1 were conducted prior to overlay application on May 22, 2018 and June 13, 2018. Photos and measurements were taken to document the substrate surface condition of the deck. An average of 1.75 in. of the original deck was removed by hydro-demolition, though some areas of degraded concrete were further removed. Figure 3 shows the depth of removal achieved prior to the overlay placement, and Figure 4 illustrates the surface roughness achieved.

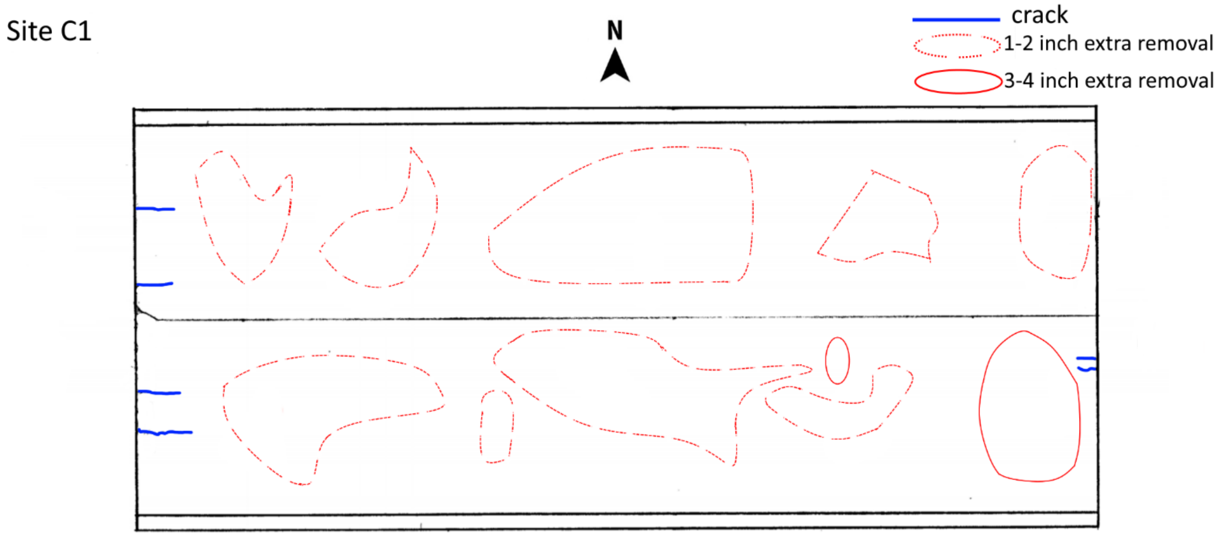

Figure 3. Substrate surface condition of Site C1

Figure 4. Substrate surface conditions for 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 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., delaminations 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 1,800 ppm. The chloride data from the eight cores indicated that the average depth with a chloride content of 1,800 ppm was 1.54 in., and the average rebar depth for this bridge is 2.40 in. The average chloride content at a depth of 1.75 in. was 1,453 ppm.

Field Investigation Description

Field investigations of Site C2 were conducted prior to overlay application on July 5, 2018 and July 20, 2018. Photos and measurements were taken to document the substrate surface condition of the deck. An average of 1.75 in. of the original deck was removed by milling, though some areas of degraded concrete were further removed. Figure 5 shows the depth of removal achieved prior to the overlay placement, and Figure 6 illustrates the surface roughness achieved.

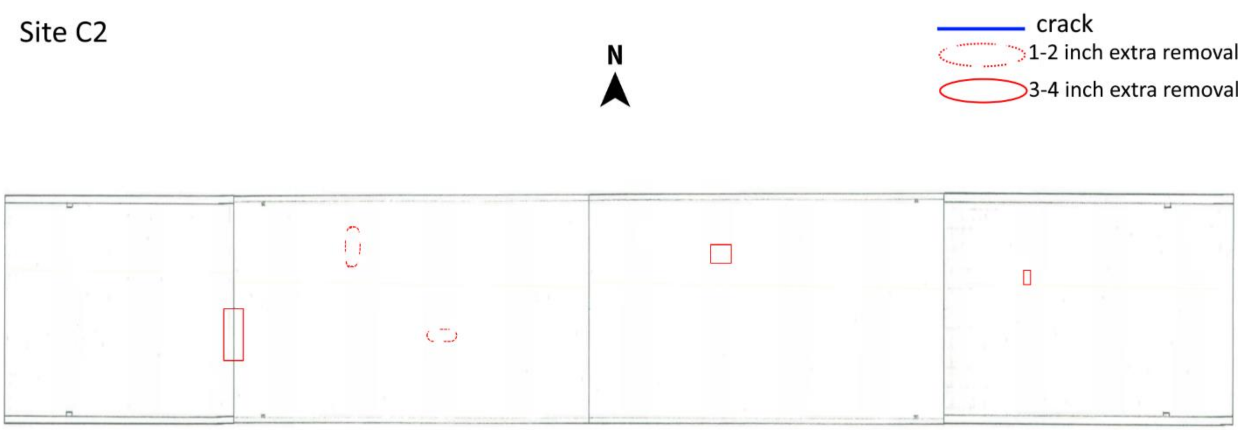

Figure 5. Substrate surface condition of Site C2

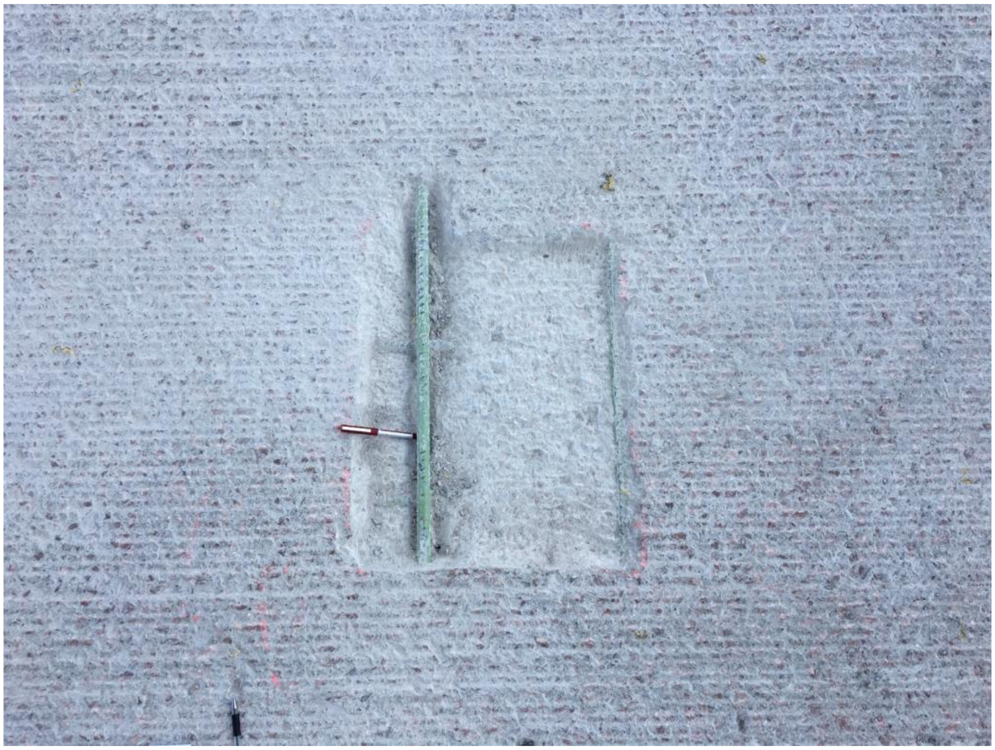

Figure 6. Substrate surface conditions for Site C2

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

Bridge Description

Bridge C3 carries US 18 over Rogg Creek 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., delaminations and patch repairs) was observed on approximately 0.1% of the deck (a total of 6.7 ft^2).

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 1,800 ppm. The chloride data from the four cores indicated that the average depth with a chloride content of 1,800 ppm was 1.53 in., and the average rebar depth for this bridge is 2.50 in. The average chloride content at a depth of 1.75 in. was 1,285 ppm.

Field Investigation Description

Field investigations of Site C3 were conducted prior to overlay application on May 11, 2018 and May 29, 2018. Photos and measurements were taken to document the substrate surface condition of the deck. An average of 1.75 in. of the original deck was removed by hydro-demolition, though some areas of degraded concrete were further removed. Figure 7 shows the depth of removal achieved prior to the overlay placement, and Figure 8 illustrates the surface roughness achieved.

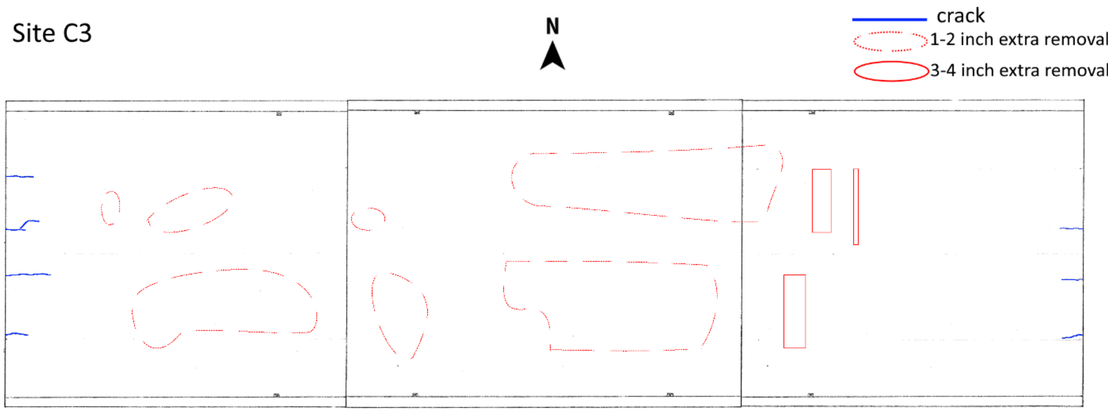

Figure 7. Substrate surface condition of Site C3

Figure 8. Substrate surface conditions for 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, Iowa, 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., delaminations and patch repairs) was observed on approximately 0.1% of the deck (a total of 3.6 ft^2).

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 1,800 ppm. The chloride data from the 12 cores indicated that the average depth with a chloride content of 1,800 ppm was 1.78 in., and the average rebar depth for this bridge is 3.30 in.

Field Investigation Description

Field investigations of Site E1 were conducted prior to overlay application on April 23, 2018. Photos and measurements were taken to document the substrate surface condition of the deck. An average of 0.375 in. of the original deck was removed by milling. Figure 9 shows the depth of removal achieved prior to the overlay placement, and Figure 10 illustrates the surface roughness achieved.

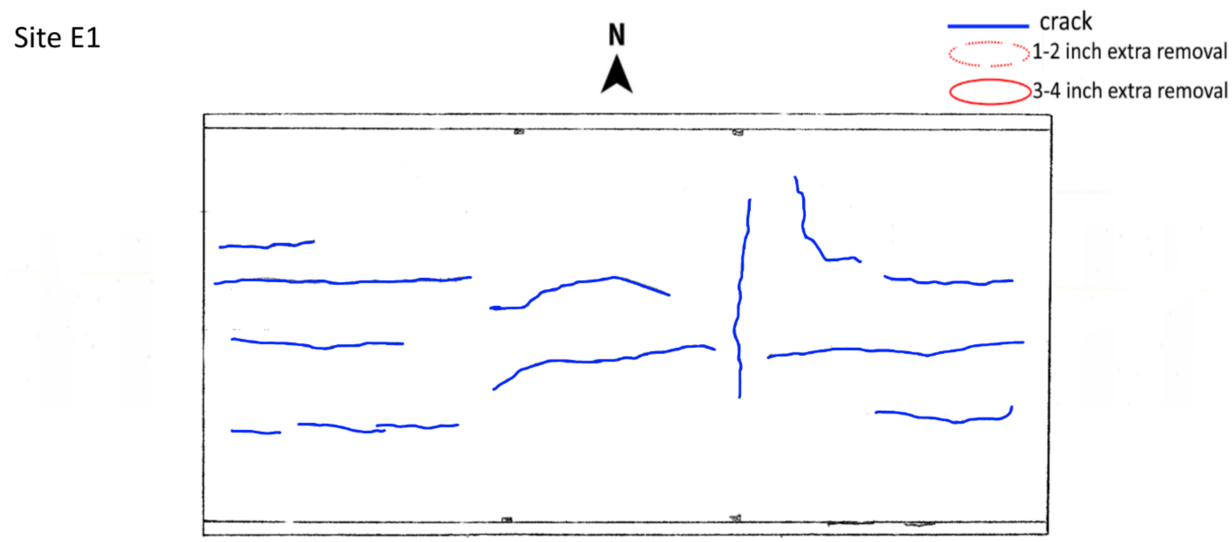

Figure 9. Substrate surface condition of Site E1

Figure 10. Substrate surface conditions for Site E1

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

Bridge Description

Bridge E2 carries US 18 over the Little Sioux River 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., delaminations 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 1,800 ppm. The chloride data from the eight cores indicated that the average depth with a chloride content of 1,800 ppm was 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 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., delaminations 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 1,800 ppm. The chloride data from the four cores indicated that the average depth with a chloride content of 1,800 ppm was 0.98 in., and the average rebar depth for this bridge is 3.54 in.

Field Investigation Description

Field investigations of Site E3 were conducted prior to overlay application on April 23, 2018. Photos and measurements were taken to document the substrate surface condition of the deck. An average of 1.75 in. of the original deck was removed by milling. Figure 11 shows the depth of removal achieved prior to the overlay placement, and Figure 12 illustrates the surface roughness achieved.

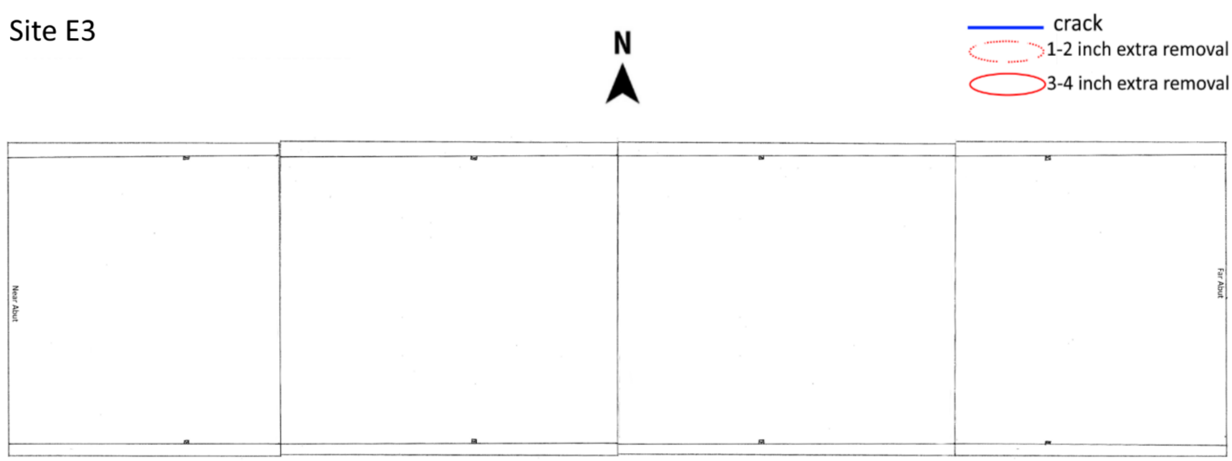

Figure 11. Substrate surface condition of Site E3

Figure 12. Substrate surface conditions for Site E3

Summary of the Field Investigation

Sites C1 and C3 had the largest area of concrete damage (56 and 6.7 ft^2, respectively) and received hydro-demolition as surface preparation for their overlays. The rest of the sites were milled. The epoxy-overlaid sites did not have surface concrete damage except for Site E1, which had an area of concrete damage of 3.6 ft^2. Table 2 summarizes the observations made at the sites.

Table 2. Field investigation summary

Site	Area of concrete damage (ft^2)	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

3.2 Direct Pull-Off Tests

After the overlays were placed, field testing of the new bridge decks was conducted. Following ASTM C1583, the direct pull-off strength test was used to assess the tensile capacity of the bond between the concrete substrate and the surface repair material. Three pull-off attempts were made for each bridge.

The procedure for testing involves cutting through the overlay and substrate layers with a circular drill (Figure 13), attaching a steel disk to the overlay surface using epoxy, and then pulling on this surface with a tensile force (Figure 14) once proper adhesion is achieved.

Figure 13. One of the circular cuts at Site C2

Figure 14. Pull-off test mounting device

The failure mode is then determined according to the scenarios outlined in ASTM C1583 and shown in Figure 15.

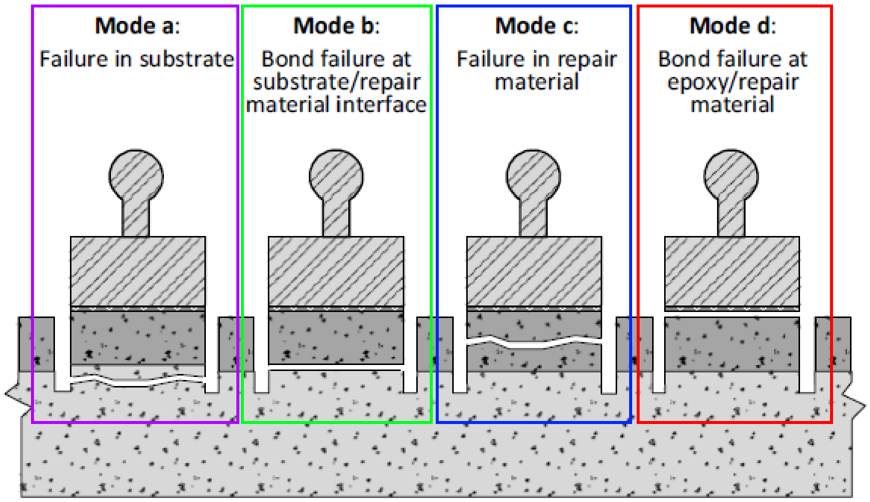

Figure 15. Possible failure modes resulting from the pull-off test

Test Results

The pull-off strengths of the concrete-overlaid and epoxy-overlaid decks are shown in Table 3 and Figure 16.

Table 3. On-site pull-off test results for the epoxy-overlaid and concrete-overlaid 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

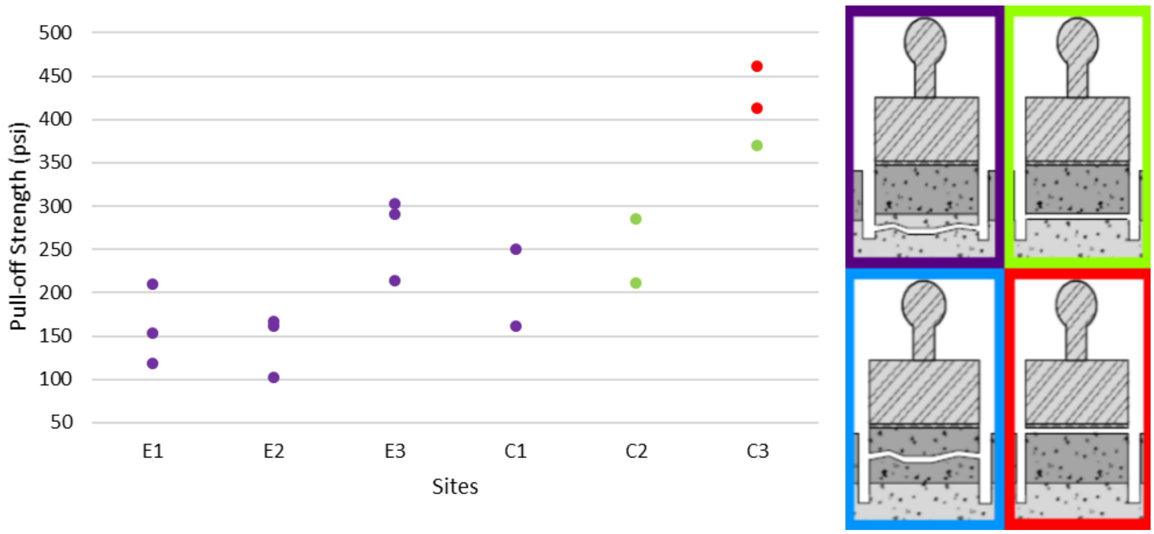

Figure 16. Pull-off strengths of epoxy-overlaid and concrete-overlaid decks

Due to the variability involved in field testing, three samples were not available for every bridge (such as for the bridges at Sites C1 and C2) if testing errors occurred. It can be observed from the results that the concrete-overlaid decks generally seem to have higher bond strengths. It can also be noted that the failure mode of the epoxy-overlaid decks is in the substrate due to the poor substrate quality, which indicates that the actual bond strength is higher than the result shown.

Follow-up field testing was then performed after approximately one year to gauge any changes in performance. The results of the initial and one-year testing are shown in Figure 17.

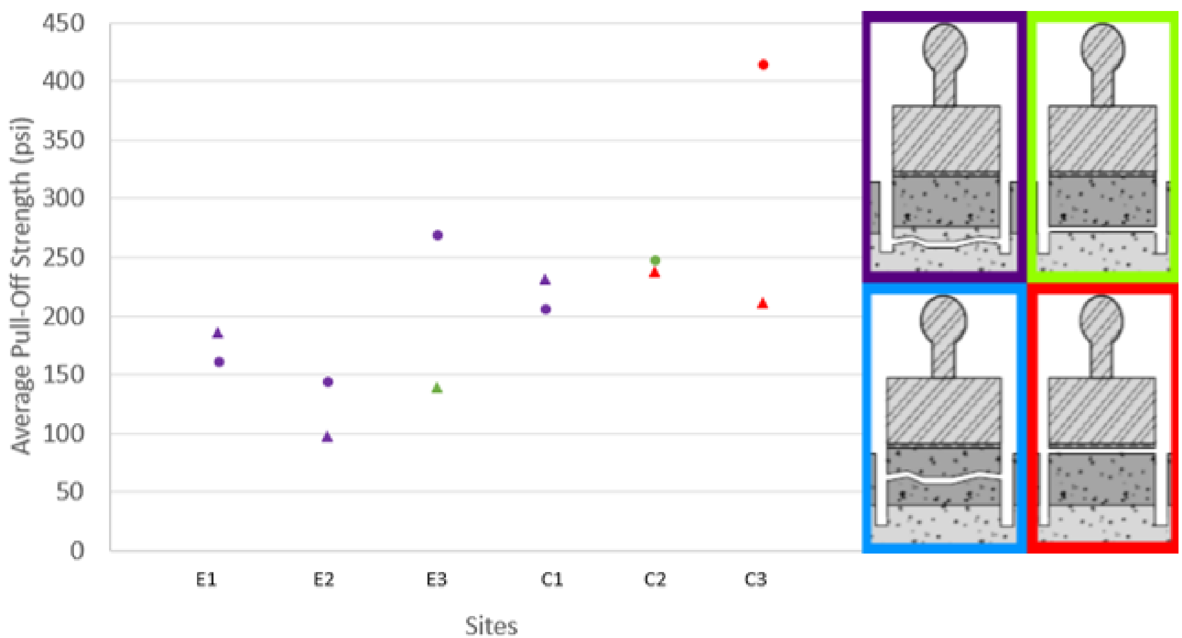

Figure 17. Average initial (circles) and one-year (triangles) pull-off strengths

The values shown are averages of the three pull-off tests performed per bridge. The initial average pull-off strength is shown by circle markers, and the follow-up one-year average pull-off strength is shown by triangular markers. The color represents the failure mode, which was consistent across all locations other than Sites C1 and C3. For Site C1, two cores exhibited substrate failures, and one core had a failure occur between the puck and the overlay surface for both the initial and one-year tests. For Site C3, the initial testing had two failures occur at the interface of the puck and the overlay and one failure occur at the overlay-substrate interface. The color coding for these sites is based upon the majority case.

As can be seen from these results, there does not appear to be an overarching trend in the data. There are not significant deviations in performance after one year, with the exception of Sites E3 and C3. Site E3 experienced a drop in pull-off strength after one year, and, more importantly, the failure mode changed from the substrate to the overlay-substrate interface. This indicates that the bond between the overlay and substrate weakened. As a result, this site should be monitored to watch for signs of declining performance that can be attributed to this weak bond. For Site C3, there was also a significant decrease in pull-off strength after one year. For this site, however, the failures all occurred between the testing puck and the overlay surface. This indicates that the pull-off strength at the site is actually higher than these values indicate and can be attributed to testing errors such as setting time, air temperature, or equipment failures.

CHAPTER 4: LABORATORY TESTING

4.1 Substrate Laboratory Testing

To fully understand the long-term behavior of the bond between the original concrete deck and the overlay, the initial condition 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 bridge decks' porosity and durability to cyclic freezing and thawing. The porosity of the 18 cores was measured according to ASTM C642, and the durability was measured according to ASTM C666, Method A.

4.2 Porosity Tests and Freeze-Thaw Tests on Cores

Introduction

As noted above, 18 cores were collected from the substrates of the six bridges selected for this project to allow for laboratory testing of both porosity and freeze-thaw durability. Porosity tests were conducted to estimate the percentage of air voids in the cores, and the freeze-thaw test was performed to assess the durability of the cores to accelerated freezing and thawing cycles.

Porosity Tests

ASTM C642, Standard Test Method for Density, Absorption, and Voids in Hardened Concrete, was performed on the 18 cores, and the results are shown in Figure 18.

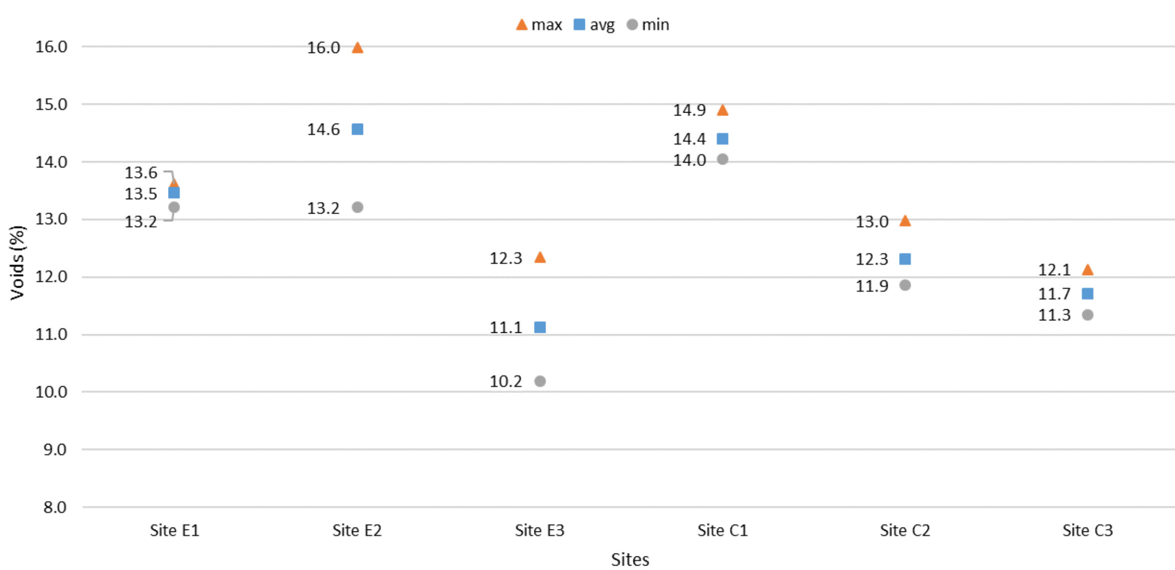

Figure 18. Porosity test results for the substrate cores of the six bridges

It can be observed that the cores from Site E3 generally have the smallest percentage of voids, possibly due to the bridge's short service age, while the cores from Sites E2 and C1 have the largest percentage of voids, which might lead to poor freeze-thaw durability. There is a significant amount of scatter in the results for Sites E2 and E3, which might be due to a random sampling error.

Freeze-Thaw Tests

The freeze-thaw testing followed ASTM C666, Method A. Eighteen cores were prepared for the test. The durability factor was measured at the 300th cycle, whereas the mass loss was measured until the 510th cycle was reached in order to achieve distinguishable results. Both sets of results are shown in Figure 19 and Figure 20, respectively.

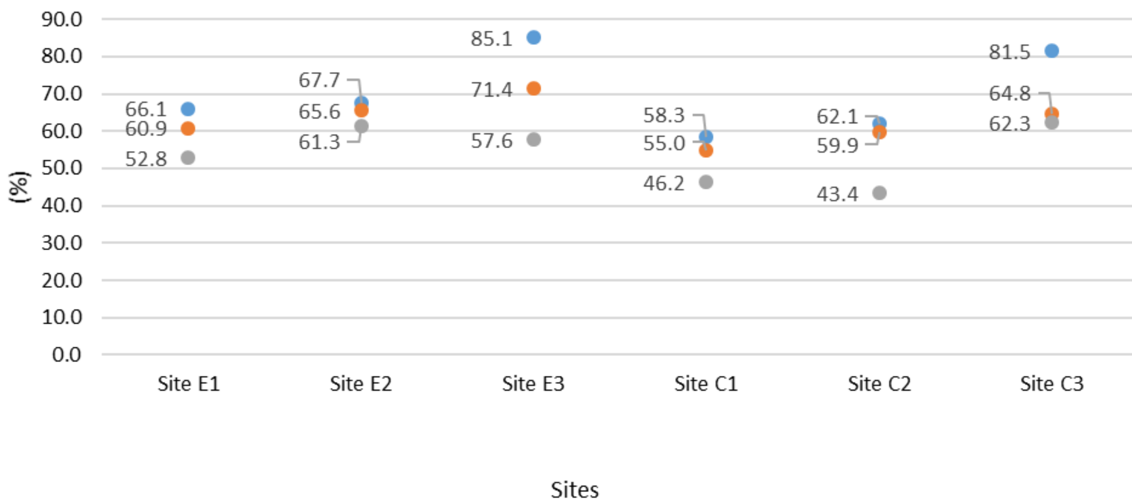

Figure 19. Durability factor for the substrate cores from the six sites under cyclic freeze-thaw testing

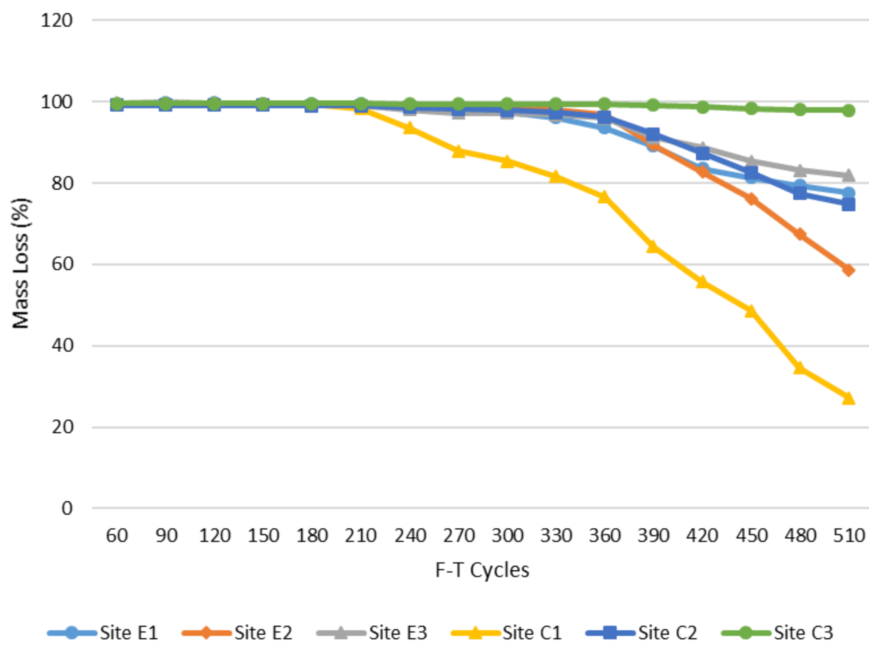

Figure 20. Percent mass loss for the substrate cores from the six sites under cyclic freeze-thaw testing

It can be observed that the cores from Site E3 have the highest durability factors and the second lowest mass loss values. These results agree with the low porosity values observed for Site E3 and indicate that the deck at Site E3 is in relatively good condition. In contrast, the cores from Site C1 have the lowest durability factors and the most dramatic mass loss values. These results match with the high porosity values observed at the site and indicate that the deck at Site C1 is in relatively poor condition.

The mass loss can be visually assessed, as shown in Figure 21 and Figure 22.

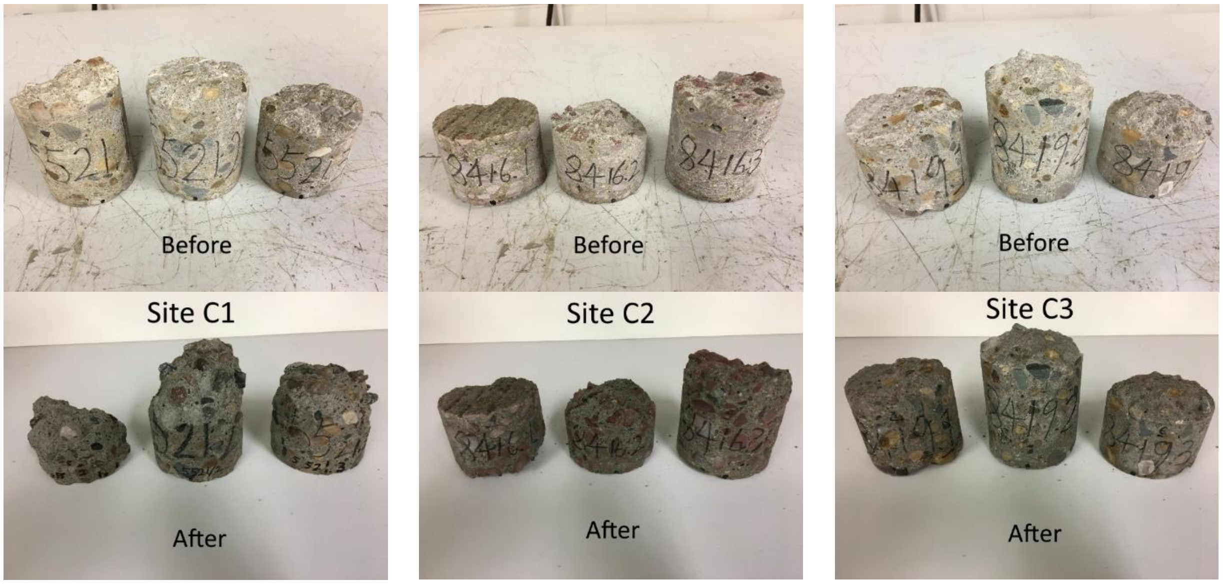

Figure 21. Cores from the different field sites before and after 300 freeze-thaw cycles: Site C1 (left), Site C2 (middle), and Site C3 (right)

Figure 22. Cores from the different field sites before and after 300 freeze-thaw cycles: Site E1 (left), Site E2 (middle), and Site E3 (right)

4.3 Overlay Laboratory Tests

In addition to the laboratory tests on the substrate cores, three laboratory tests were carried out on the two types of overlays to study their permeability, durability to cyclic freezing and thawing, and bond strength. The permeability of the epoxy overlay and concrete overlay was evaluated according to AASHTO T 259 (i.e., salt ponding test). The durability of the overlays was assessed through ASTM C666, Method A and ASTM C1583 (i.e., direct pull-off test), where the bond strength of the specimens was tested at different freezing-thawing cycles.

To prepare the epoxy-overlaid and concrete-overlaid slabs for the tests, eight 1 ft by 1 ft substrate slabs were cast in plywood molds in the laboratory. Four of the slabs were to be overlaid with epoxy, and the other four slabs were to be overlaid with concrete. To comply with the standards for the salt ponding test, a final slab thickness of 3.5 in. was desired. Since the thickness of the epoxy overlay was about 0.375 in. and the thickness of the concrete overlay was 1.75 in., the substrate slabs to be overlaid with epoxy were cast with a thickness of 3.125 in. and the substrate slabs to be overlaid with concrete were cast with a thickness of 1.75 in., resulting in a total thickness of 3.5 in. for both slab types.

The bottoms of the molds were first painted with formwork retarder to prevent the bottom surfaces of the slabs from curing. After seven days of moist curing, the slabs were demolded, and the uncured mortar on the bottom surfaces of the slabs was washed and brushed away with a steel brush to expose part of the aggregates and thereby mimic the surface roughness of the substrates of the bridge decks, which were rough as a result of milling. After moist curing the substrate slabs in the laboratory for another 21 days, the surface roughness of the substrate slabs was assessed. The concrete surface profile (CSP) number of the substrate slabs was seven, which was similar to that resulting from milling the bridge deck substrates. For comparison purposes, the textures of the laboratory substrate slabs and the bridge deck substrates treated by milling and hydro-demolition are shown in Figure 23.

Figure 23. Textures of the laboratory substrate slabs (top) and bridge deck substrates after milling (bottom left) and hydro-demolition (bottom right)

The overlays were then applied to the substrate slabs in the field using the same materials as those used for the actual bridge deck overlays. For the concrete-overlaid 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 again to simulate field conditions. For the epoxy-overlaid slabs, the slabs were cured for more than 24 hours before testing. The surfaces of the concrete-overlaid and epoxy-overlaid slabs are shown in Figure 24.

Figure 24. Surface conditions of the concrete-overlaid (left) and epoxy-overlaid (right) slabs

4.4 Salt Ponding Tests on Slabs

Introduction

The salt ponding test was employed to compare the chloride permeability of the epoxy and concrete overlays. In accordance with AASHTO T 259, two of the concrete-overlaid slabs and two of the epoxy-overlaid slabs prepared earlier were ponded for 90 days. Figure 25 shows the slabs during ponding.

Figure 25. Two slabs during ponding: an epoxy-overlaid slab (left) and a concrete-overlaid slab (right)

After ponding, chloride determination was conducted in accordance with AASHTO T 260. Samples were extracted from four depths, namely, 1/8 in., 3/8 in., 5/8 in., and 7/8 in., to provide a profile of chloride concentration for each slab. Figure 26 shows one of the powdered samples, and Figure 27 briefly illustrates the procedures for chloride determination.

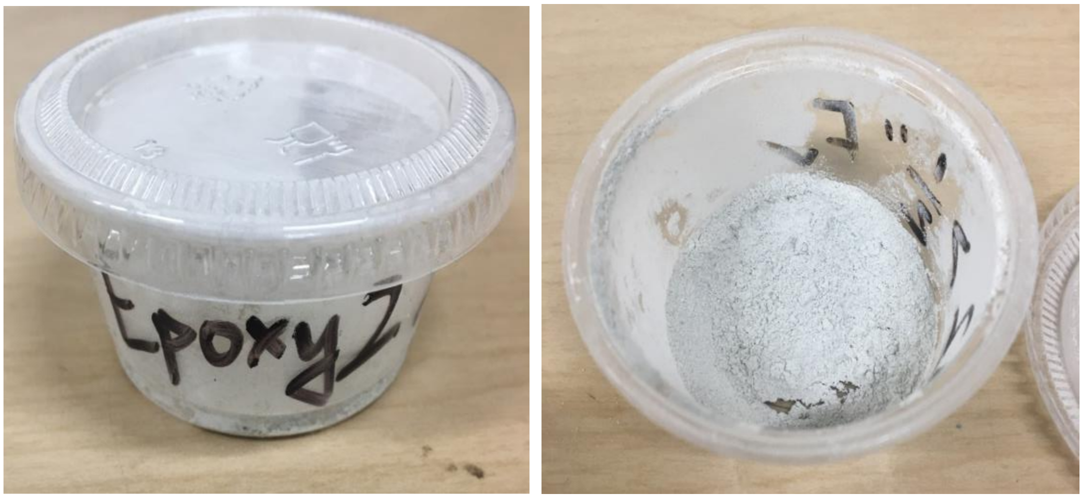

Figure 26. Powdered sample from one of the epoxy-overlaid slabs

Figure 27. Chloride content determination process: weighing (upper left), boiling (upper right), filtration (bottom left), titration (bottom right)

Test Results

The results of the salt ponding test are shown in Figure 28. Each curve represents the average results from two slabs of the same type.

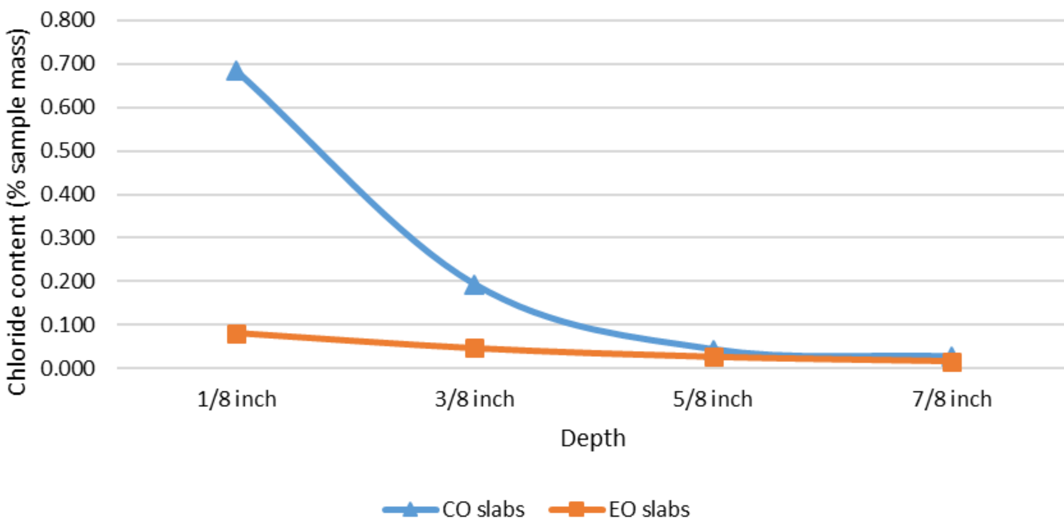

Figure 28. Percent chloride content of concrete-overlaid and epoxy-overlaid slabs

It can be observed that the epoxy-overlaid samples have a much lower chloride content at both the 1/8 in. and 3/8 in. depths, while both types of overlay samples have similarly low chloride contents at the 5/8 in. and 7/8 in. depths.

4.5 Freeze-Thaw Tests and Direct Pull-Off Tests on Beams

Introduction

To determine the effect of freeze-thaw cycles on bond performance, additional laboratory tests were performed on the four remaining overlay slabs. The slabs were cut into a total of 12 beams with dimensions of 12 by 3 by 3.5 in. The beams were divided into three groups, with each group consisting of two epoxy-overlaid beams and two concrete-overlaid beams. The three groups of beams were subjected to cyclic freeze-thaw conditions and were tested using the direct pull-off test when they had been through 0, 100, and 300 freezing-thawing cycles, respectively. The direct pull-off strength test followed ASTM C1583, which evaluates the tensile strength of the bond between the concrete substrate and the surface repair material. Examples of the epoxy-overlaid and concrete-overlaid beams are shown in Figure 29.

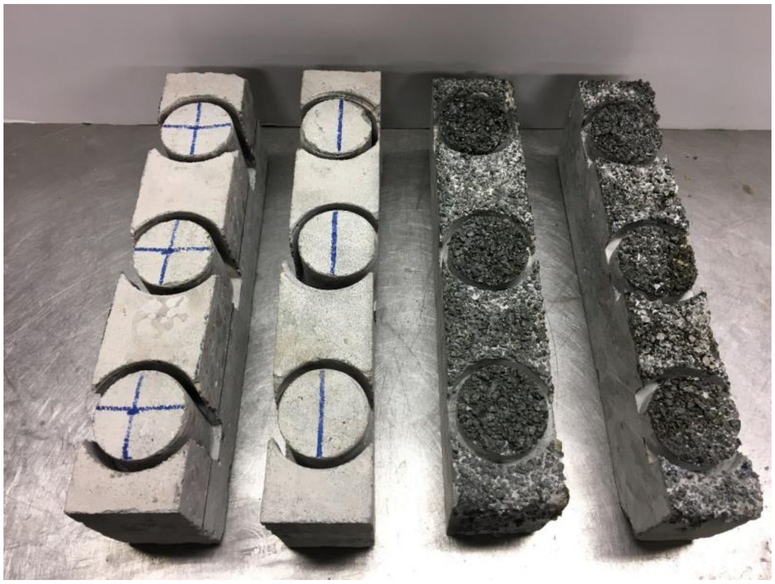

Figure 29. Concrete-overlaid (left) and epoxy-overlaid (right) beams for pull-off test

Each of the beams was cut with a two-inch core drill bit, which penetrated through the entire depth of the overlay and 0.75 in. into the substrate, as shown in Figure 30.

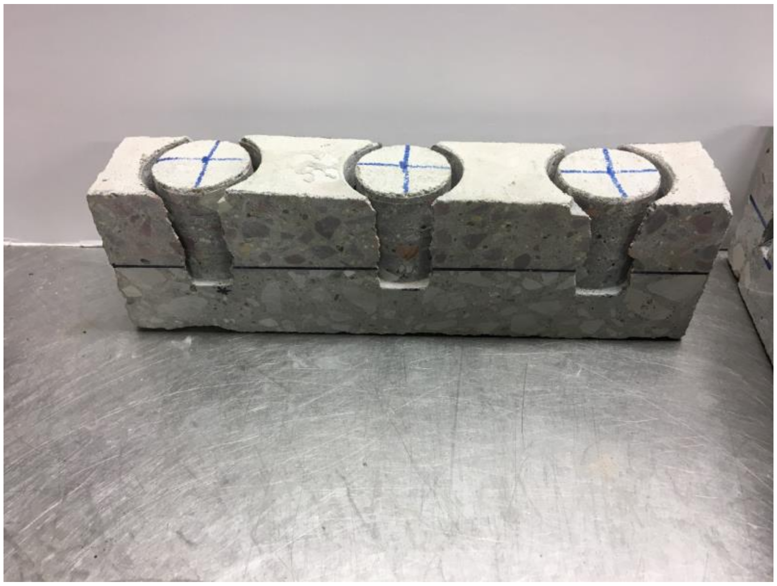

Figure 30. Concrete-overlaid beam with two-inch circular cuts

The same pull-off test procedure that was used in the field was followed, as shown in Figure 31. Since the beams were too narrow for the mounting device to stand on, a steel plate with a hole in the center was placed on the beam being tested so that the device could stand and be mounted steadily.

Figure 31. Pull-off test mounting device (Proceq DY-216, left) and the details of the mounting (right)

Since the aggregates associated with the epoxy overlay created a rough surface that was not suitable for the application of the two-part adhesive epoxy, the top surface of the epoxy-overlaid beams were slightly ground with a grinder. The surface before and after grinding is shown in Figure 32.

Figure 32. Top surface of the epoxy-overlaid beams for the pull-off test before grinding (left) and after grinding (right)

Test Results

The pull-off test results of the concrete-overlaid beams and the epoxy-overlaid beams are shown in Figure 33 and Figure 34, respectively.

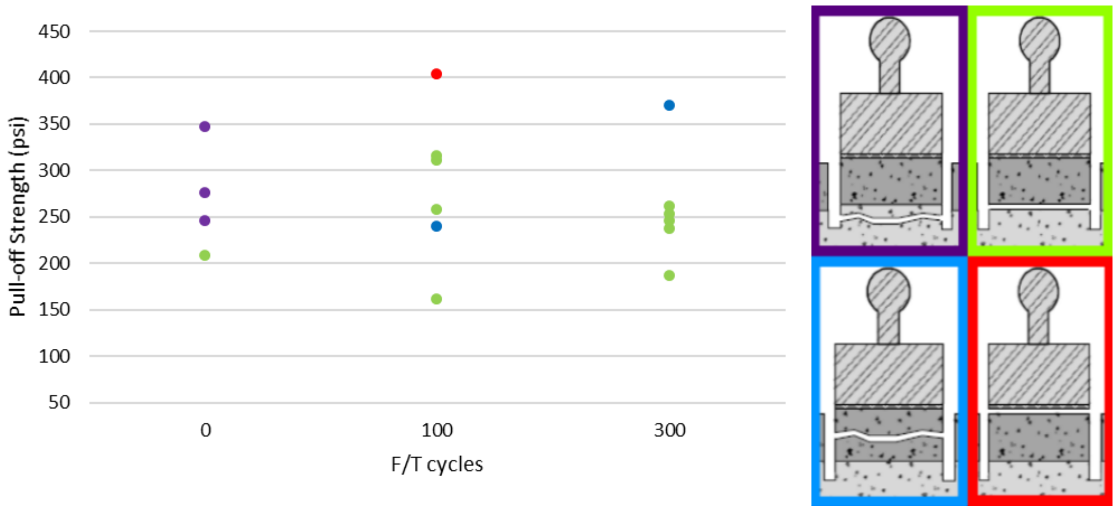

Figure 33. Pull-off test results of the concrete-overlaid beams at different freezing-thawing cyclic stages

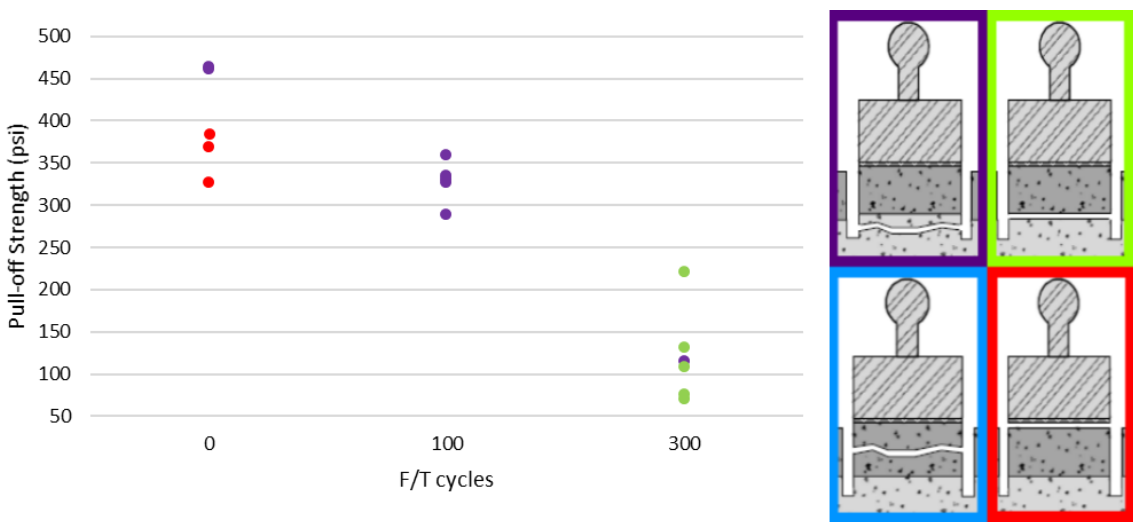

Figure 34. Pull-off test results of the epoxy-overlaid beams at different freezing-thawing cyclic stages

For each overlay type, two specimens were tested at 0, 100, and 300 freeze-thaw cycles, respectively. Some observations are missing because of unexpected sampling and testing failures. There is also scatter in the results due to the intrinsic heterogeneity of granular materials like concrete.

It can be observed that at both 0 and 100 freeze-thaw cycles, the epoxy-overlaid beams generally have a higher potential bond strength than the concrete-overlaid beams. After 300 freeze-thaw cycles, however, the bond strength of the epoxy-overlaid beams drops significantly and is generally lower than that of the concrete-overlaid beams.

CHAPTER 5: DISCUSSION OF TEST RESULTS

5.1 Tests on Substrates

Table 4 shows the results of the tests conducted to determine the condition of the deck substrates and the results of the pull-off tests performed after overlay placement.

Table 4. 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

For each site, the voids represent the percentage of air voids in the substrate cores according to the porosity tests. The durability factor and the remaining mass are measures of the durability of the substrate cores to severe freezing and thawing cycles, where the remaining mass was measured at the 510th cycle to obtain performance under prolonged freezing and thawing conditions. The chloride depth is the depth where the chloride concentration in the substrate cores reached the threshold level at which reinforcement is effectively damaged. The chloride profile data for the substrate cores were provided by WHKS & Co. in 2015. The on-site pull-off test results are included because 11 out of the 16 test samples broke in the substrate layer, which reflects the poor integrity of the substrate.

The results in Table 4 are averaged across three observations for each site. The green shading indicates relatively good performance among the six sites, whereas yellow or red shading indicates medium or relatively poor performance, respectively, among the six sites. 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 indicated by the predominance of red shading.

The results of the on-site pull-off tests averaged across three observations for each site are shown in Figure 35.

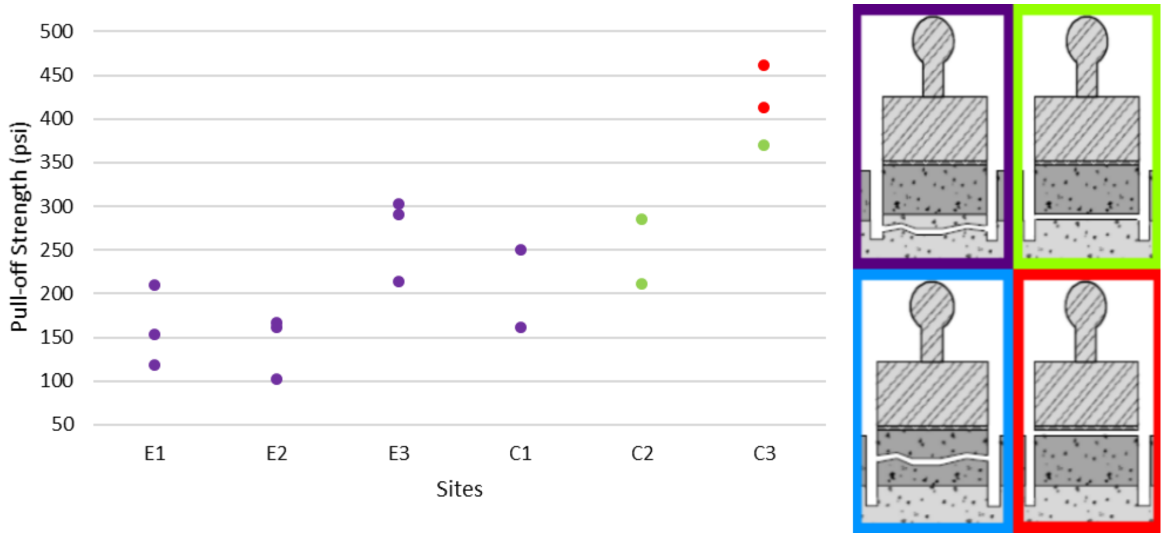

Figure 35. Field pull-off test results for epoxy-overlaid and concrete-overlaid decks

It can be observed from Figure 34 that many of the specimens failed in the substrate due to the poor substrate condition, and therefore the results could not reflect the true bond strength, which is higher than the substrate tensile strength. However, the substrate strength revealed by the pull-off test corresponds with the other results in Table 4, in that sites with a high pull-off strength generally perform well in other tests, and vice versa. As far as can be determined from the results, the bond strength of Site C3 is generally higher than that of Site C2. Meanwhile, the primary difference between those two sites was that hydro-demolition was used to prepare the substrate surface of Site C3 and milling was used for Site C2. Despite the many factors that may have affected the pull-off test results, this might indicate that hydro-demolition provides a higher initial bond strength than milling for rigid overlay placement.

Among the substrate tests listed in Table 4, some correlations stand out, namely those between voids and chloride depth, voids and remaining mass, voids and on-site pull-off test results, and remaining mass and chloride depth.

Figure 36 shows that the R-squared value of the fitted line and the data points for the percentage of air voids and the critical chloride content depth is 0.9487. This indicates that there is a strong linear relationship between the percentage of air voids in concrete and chloride resistance.

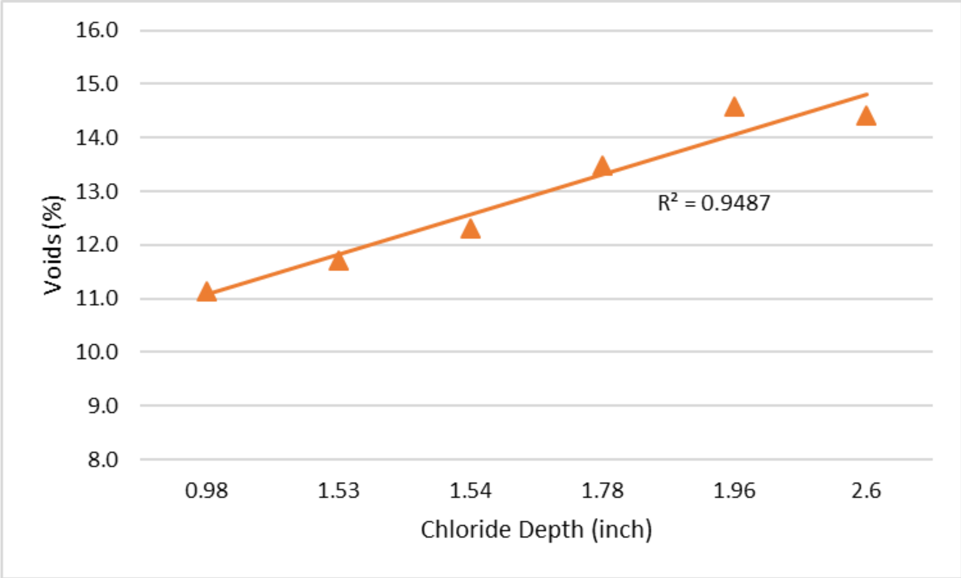

Figure 36. Relationship between percentage of air voids and critical chloride content depth

The remaining mass after 510 freeze-thaw cycles measured by the freeze-thaw test reflects the durability of the concrete to freezing and thawing conditions. Figure 37 shows that the R-squared value of the fitted line and the data points for the percentage of air voids and the remaining mass is 0.7136, which indicates that the percentage of air voids in concrete has a linear relationship with durability to freezing and thawing cycles.

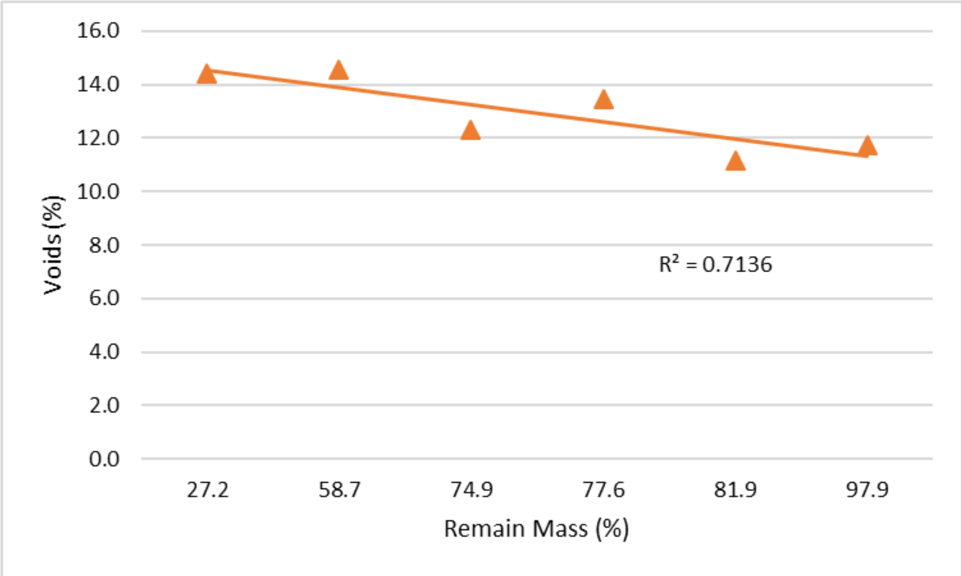

Figure 37. Relationship between percentage of air voids and remaining mass

Figure 38 shows that the R-squared value of the fitted line and the data points for the percentage of air voids and the on-site pull-off test results is 0.7625. This indicates that there is a linear relationship between the percentage of air voids in the substrate and the substrate's integrity, in that the pull-off test results reflect the integrity of the substrate.

Figure 38. Relationship between percentage of air voids and on-site pull-off test results

Figure 39 shows that the R-squared value of the fitted line and the data points for the remaining mass after 510 freeze-thaw cycles and the critical chloride content depth is 0.7278. The plot indicates that the remaining mass of the substrate has a linear relationship with the substrate's critical chloride content depth.

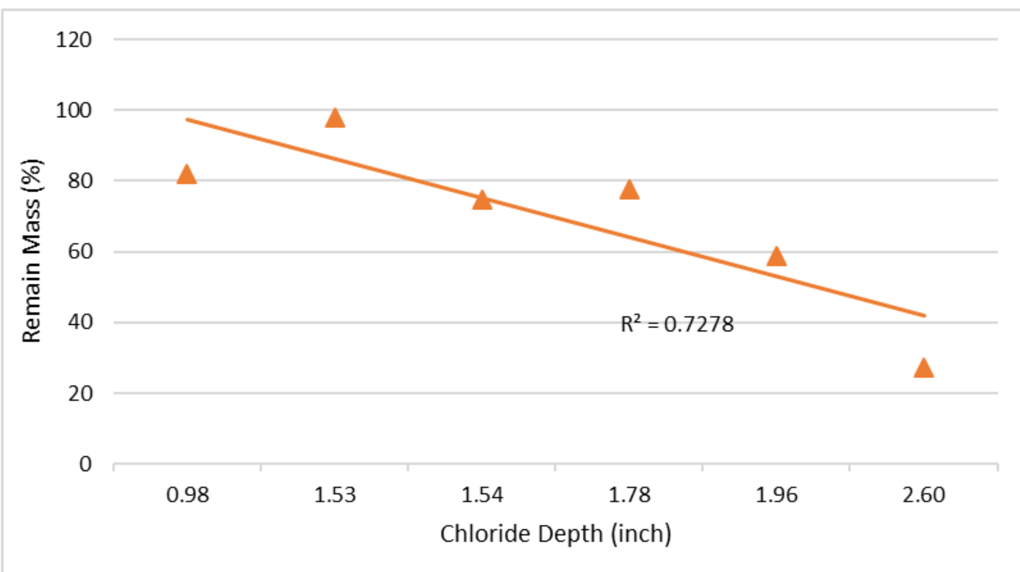

Figure 39. Relationship between remaining mass and critical chloride content depth

5.2 Laboratory Freeze-Thaw Test and Pull-Off Test Results on Beams

The results of the laboratory pull-off tests on the concrete-overlaid and epoxy-overlaid beams are shown in Figures 40 and 41, respectively.

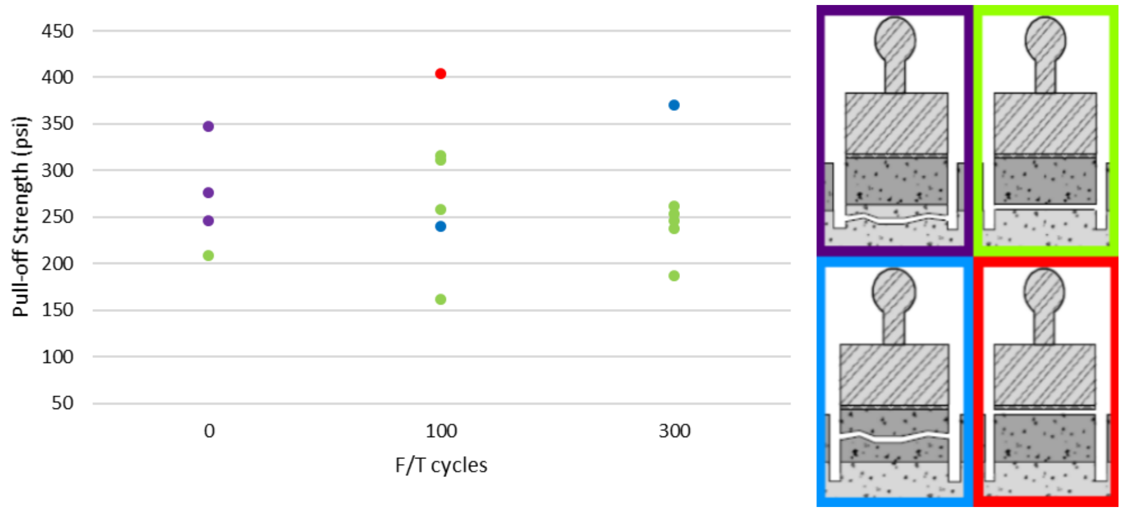

Figure 40. Pull-off test results for the concrete-overlaid beams at different freezing-thawing cycles

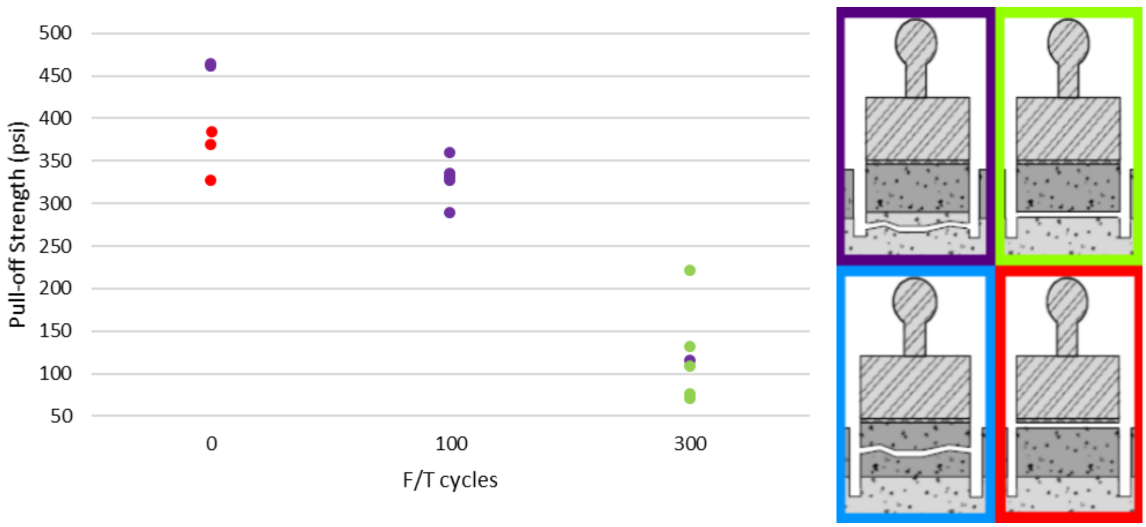

Figure 41. Pull-off test results for the epoxy-overlaid beams at different freezing-thawing cycles

It can be observed that as the samples went through more freeze-thaw cycles, the decrease in bond strength became greater than the decrease in substrate tensile strength. This is evidenced by the fact that substrate failures are more common than bond failures at 0 freeze-thaw cycles, the number of bond failures increases at 100 freeze-thaw cycles, and bond failures dominate at 300 freeze-thaw cycles. It can also be observed that the epoxy-overlaid beams generally have a higher bond strength than the concrete-overlaid beams at both 0 and 100 freeze-thaw cycles, but the bond strength of the epoxy-overlaid beams appears to be lower than that of the concrete-overlaid beams at 300 freeze-thaw cycles. Overall, the epoxy-overlaid samples were much more susceptible to freezing and thawing degradation, as shown by the drastic decrease in pull-off strength with an increase in the number of cycles of exposure.

5.3 Laboratory Salt Ponding Test Results on Slabs

The results of the salt ponding test are shown in Figure 42.

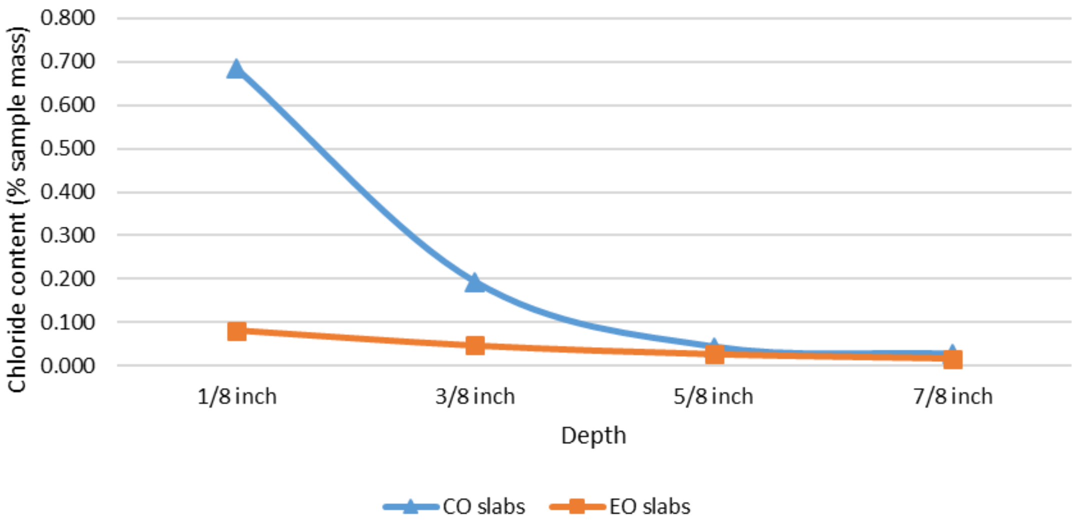

Figure 42. Percent chloride content of concrete-overlaid and epoxy-overlaid slabs

It can be observed that the concrete-overlaid slabs have a 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 overlays prevent chloride ingress better than concrete overlays. However, at deeper depths (5/8 in. and 7/8 in.), the chloride contents of both overlays are similarly low, which reflects the limited extent of chloride ingress in slabs with both types of overlays.

CHAPTER 6: CONCLUSIONS

The primary objectives of this study were to evaluate the performance of epoxy overlays and LSDC overlays and identify the factors that affect their performance. The study also aimed to understand how existing chloride that has been sealed in a bridge deck by an epoxy overlay might relate or contribute to deck deterioration.

To fulfill these objectives, field investigations were performed on six bridges of various ages. The location and the extent of substrate deterioration, the substrate preparation methods, and the bridge deck repair materials were well documented for each bridge. Before overlay application, substrate cores from the six bridges were extracted and tested to evaluate the bridge decks' porosity and durability to cyclic freeze-thaw conditions. After overlay application, on-site pull-off tests were conducted on the six bridges to assess the performance of the overlays both immediately after placement and after one year of service. Laboratory freezing and thawing tests and pull-off tests were also conducted to understand the long-term performance of the overlay types. The project conclusions are summarized as follows:

- **Freezing and thawing exposure has a greater influence on the bond strength of epoxy overlays than on the bond strength of concrete overlays.** In the laboratory pull-off tests, the initial (before any freeze-thaw cycles) bond strengths of both the epoxy overlays and the concrete overlays were found to be good, though many concrete and epoxy overlay samples failed in the substrate layer, making the precise bond strength unavailable. After 300 freeze-thaw cycles, both the epoxy- and concrete-overlaid samples were found to have failed at the bond between the substrate and the overlay, and the average bond strength of the concrete overlays was found to be almost twice of that of the epoxy overlays.

- **The epoxy overlays can resist chloride ingress much better than the LSDC overlays** because the chloride content in the epoxy-overlaid slabs was found to be less than 1/8 of the chloride content in the LSDC-overlaid slabs at a depth of 1/8 in.

- **The percentage of air voids in the substrate has the largest impact on the substrate's properties.** As the percentage of air voids decreased, linear improvements were found in the critical chloride content depth (chloride resistance), the remaining mass after 510 freeze-thaw cycles (freezing and thawing durability), and the on-site pull-off test results.

- **The remaining mass after 510 freeze-thaw cycles has a strong linear relationship with critical chloride content depth.** This confirms that bridges with better freezing and thawing durability usually have better chloride resistance.

- **No relationship was found between a bridge's age and its substrate quality or bond strength.** In fact, the oldest bridge in the study was found to perform the best in both laboratory and on-site tests.

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APPENDIX: IMAGE LOG OF VISITED SITES

Figure 43. Surface condition of bridge deck of Site C1 prior to overlay

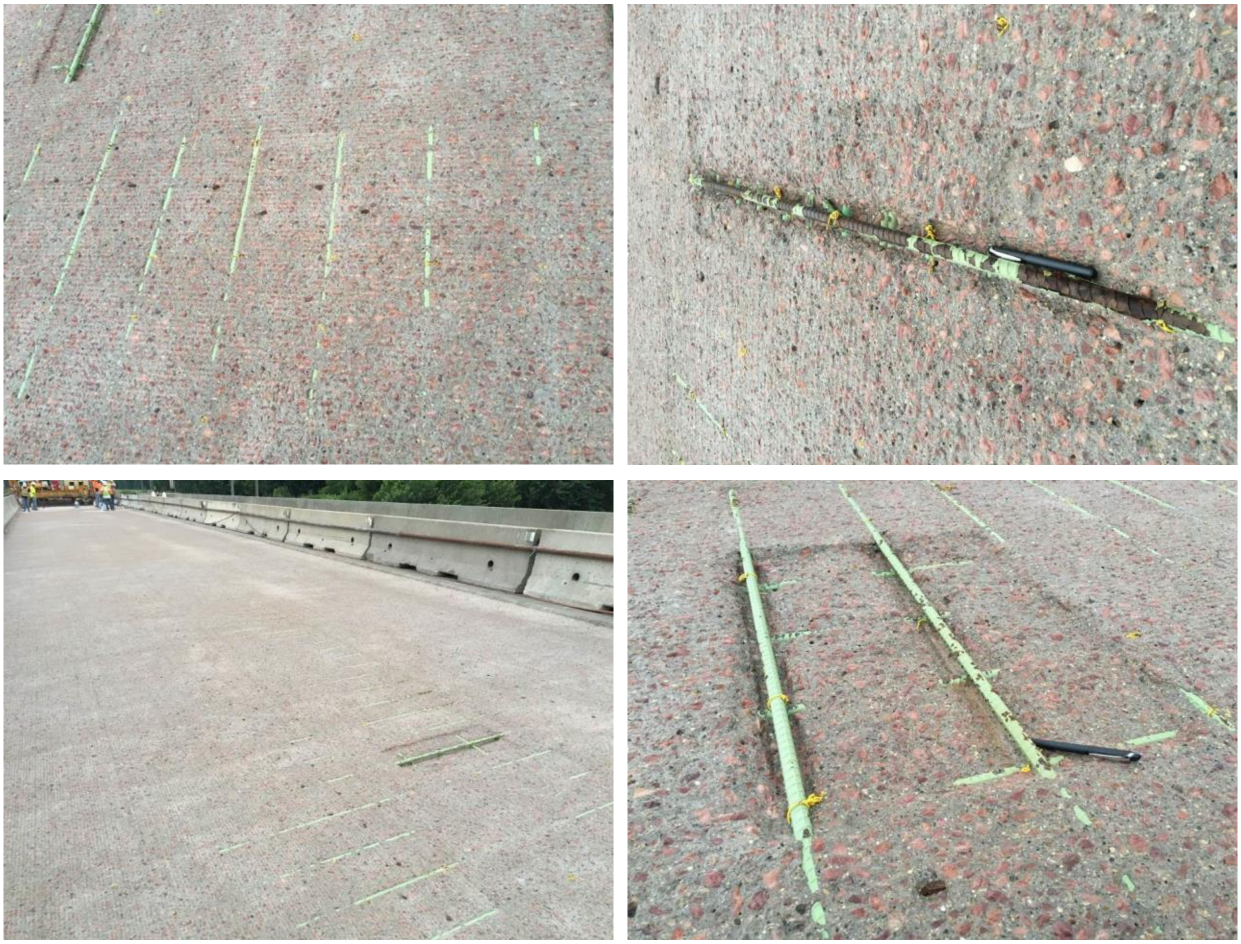

Figure 44. Surface condition of bridge deck of Site C2 prior to overlay

Figure 45. Surface condition of bridge deck of Site C3 prior to overlay

Figure 46. Surface condition of bridge deck of Site E1 prior to overlay

Figure 47. Surface condition of bridge deck of Site E3 prior to overlay

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