EVALUATION OF BRIDGE DECK SEAL TREATMENT FOR ACCELERATED BRIDGE CONSTRUCTION (ABC) BRIDGE DECKS USING PRECAST PANELS

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**Abstract**

The present research evaluates five different overlay systems for use in precast panels for bridge decks. In this research, field and laboratory tests are performed. The overlay systems are evaluated based on their pull-off strength due to cyclic loading and chloride intrusion.

**Key Words**

Overlays; bridge deck; ABC methods; bond tests; chloride intrusion

**Supplementary Notes**

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EXECUTIVE SUMMARY

The primary focus of this research is to evaluate different bridge deck overlay systems under initial static deflection as well as cyclic loading and recommend acceptable overlay systems and procedures for precast panels used in bridge decks. Two different criteria are used to compare five overlay systems: (i) bond strength between the overlay system and the bridge deck, and (ii) amount of chloride penetration of the bridge deck through the overlays. These comparisons were made through field and laboratory tests.

Three bridges using different deck overlays were examined for bond strength of the overlay to the bridge deck. Ten precast concrete deck panels were built, and tested in the laboratory under cyclic loading for five days to test the bond strength of the overlay near the joint. After cyclic testing, ponding tests were set up over the joints, to test for chloride penetration.

A comparison between the bond strength of different overlay systems resulted in higher bond strength values in the laboratory than in the field. Three of the five overlay systems, S1, S4 and S5 overlay systems had higher average non-epoxy failure bond strengths than the other systems. The majority of pull-off results in the laboratory tests for overlay systems S1, S2, and S4 occurred in the concrete.

All five overlay systems had excellent performance regarding chloride penetration compared to controlled samples without any overlay. This was true for regular ponding samples, as well as samples that had undergone ponding and temperature cycling conditions.
1.0 INTRODUCTION

Steel reinforcement in concrete bridge decks is prone to corrosion caused by chloride ions from de-icing materials. Various overlays are used throughout the country to delay or prevent this corrosion. The Utah Department of Transportation (Utah DOT) has recently changed how it constructs bridges to implement the Accelerated Bridge Construction (ABC) method. This construction process includes half depth precast deck panels, full depth precast deck panels, self propelled modular transport (SPMT) deck and superstructure, and slide-in bridges. ABC bridge decks undergo additional deflection due to installation prior to standard traffic loading. The purpose of this research is to compare five overlay systems for precast panels used in bridge decks.

The two areas of concern for leakage in ABC bridge decks are joints, specifically between precast bridge deck panels, and locations where cracking may already have occurred in the deck due to lifting and placement. Evaluations and research have been performed for precast bridge decks and overlay systems throughout the United States. However, no known research has been found regarding the effects of initial cracking of the bridge deck due to lifting and placement and its effect on the performance of the overlay system.

1.1 Literature Review

In 1995, full depth precast concrete bridge deck panels used in reconstruction were evaluated in several states [1]. Design details and overlay systems were recorded along with the performance of these bridges. It was concluded that precast concrete panels had an excellent performance record. For cases where the performance had not been good, this could be attributed to the type of connection between the slab and supporting system, configuration of joint between adjacent precast panels, construction procedures, lack of longitudinal post-tensioning, and the materials used. It was also reported that longitudinal post-tensioning of precast panels secures the tightness of the joint, keeps the joint in compression, and guards against leakage. All the DOTs included in the study used a waterproofing membrane.

In 2003, the New Hampshire DOT performed field research on two thin overlay bridge deck systems [2]. The two overlay systems were applied on precast full depth bridge decks.
which had replaced the original decks. One overlay system was inspected 34 months after placement and the second 25 months after placement. One system showed some cracks and some snowplow damage at the expansion joints but had not suffered significant deterioration. A second system had significant bond loss between the overlay and the deck, with large areas of overlay missing.

In 1999, the Illinois DOT evaluated two thin-lift polymer bridge deck overlays on two adjacent bridges [3]. Half-cell potential tests were performed prior to overlay placement and pull-off tests were performed on test patches prior to full use of the overlay systems. Performance evaluation of these systems concluded that polymer overlay systems had the potential to provide an impermeable and durable surface with high skid resistance for 15 or more years if the system was applied correctly. In addition, the study concluded that to ensure acceptable overlay performance contractors should be trained in application procedures. It should also be noted that this report did not state whether the deck was precast or cast-in-place.

1.2 Survey

As part of the present research, a survey was sent to several DOTs to determine the performance of overlay systems used in ABC methods. Eight DOTs responded to the survey; of these, six used ABC methods and none reported concerns regarding the performance of the corrosion protection system for ABC bridge decks. The results of the survey are presented in Appendix A.

2.0 RESEARCH METHODS

The primary focus of this research is to evaluate different bridge deck overlay systems under initial static deflection and cyclic loading, and recommend acceptable overlay systems and procedures for precast panels used in bridge decks. Two different criteria are used to compare five overlay systems: (i) bond strength between the overlay system and the bridge deck, and (ii) amount of chloride penetration of the bridge deck through the overlays. These comparisons were made through field and laboratory tests.
2.1 Field Tests

Three bridges using different deck overlays were examined. The overlay systems were all installed approximately one year before the field tests were carried out. Four locations were selected for performing bond tests on each bridge. Bond tests were performed adjacent to a precast deck panel joint at each bridge site. The location of the pull-off tests was near the longitudinal midspan of the bridge and transversely between the first and second girders at approximately the center of the slow lane, as demonstrated in Figure 1.

2.2 Laboratory Tests

Four different laboratory testing procedures were designed for this research: Test Type I, Test Type II, Test Type III and Test Type IV. Test Type I simulates the effects of the application of the overlay after lifting and placement of the bridge deck and evaluates both the bond strength of the overlay to the concrete deck and the penetration of chlorides through the overlay. Test Type II simulates the effects of the application of the overlay prior to lifting and placement of the bridge deck and evaluates both the bond strength of the overlay to the concrete deck and the penetration of chlorides through the overlay. Test Type III or the small sample chemical test is a comparison of the penetration of chlorides through the overlay after a ponding
procedure for a cast-in-place slab. Test Type IV is a freeze/thaw test including a simultaneous ponding test which evaluates penetration of chlorides through the overlay under freeze-thaw cycling.

**Test Type I: Application of deck sealant after movement of bridge deck**

During Test Type I, two 1’-6” x 8’-0” x 8 ¾” concrete deck pieces were turned upside-down and deflected to induce initial cracking on the top face of the deck. This simulates initial cracking during lifting and placement. The two pieces were turned back over and joined through a grouted joint to construct a single 3’-0” x 8’-0” x 8 ¾” specimen. The deck overlay system was then applied per manufacturer’s specifications on the top face of the single specimen where initial cracking had been imposed. Initial bond tests were performed on the combined specimen. The specimens underwent a five day cyclic test loaded on one side of the grouted connection, simulating the gravity transfer through the grout as seen in the field. After each day of cyclic loading, two pull-off tests were performed next to the joint. During cyclic loading the specimen was post-tensioned with a 3/8 inch diameter carbon fiber rod.

The post-tensioning force was removed after the completion of the cyclic test, and then a ponding test was performed on an 11”x11” section over the grouted pocket for 90 days. An acrylic wall was installed around each section and a 3% sodium chloride solution by weight is placed on the designated section to an average depth of ½”. A lid was placed over the ponding section and the depth of ½” was maintained, as shown in Figure 2. At the completion of the ponding period the solution was removed and the overlay was ground down to the top of the concrete. Concrete samples below the ponded section were taken and checked for chloride content per ASTM C1218.
Test Type II: Application of deck sealant before movement of bridge deck

During Test Type II, the deck overlay was first applied on the top of each of two 1’-6” x 8’-0”x 8 3/4 ” concrete deck pieces to simulate the application of the overlay system prior to the precast panel being moved and placed on the bridge. Subsequently, each piece was turned upside-down and subjected to the same initial deflection as the Test Type I specimens to induce initial cracking. The two pieces were then turned back over and joined through a grouted joint to construct a single 3’-0” x 8’-0”x 8 3/4 ” specimen. A second application of the overlay system was then applied as a splice over the grouted pocket and the specimens underwent the same cyclic and ponding tests as Test Type I.

Test Type III: Small sample chemical test

In Test Type III, or the small sample chemical test, 1’-6”x1’-6”x6” specimens were subjected to a ponding test. An 11”x11” section of each specimen was used for the ponding test. An acrylic wall was installed around each section and a 3% sodium chloride solution by weight was placed on the designated section to an average depth of ½” for 90 days. At the completion of the ponding period the solution was removed and the overlay was ground down to the top of the concrete. Concrete samples below the ponded section were taken and checked for chloride content per ASTM C1218.
Test Type IV: Freeze/Thaw chemical test

In Test Type IV, or the small freeze/thaw chemical test, 1’-6”x1’-6”x6” specimens were subjected to a ponding test simultaneously with freeze/thaw cycles for 90 days. An 11”x11” section on the top of each specimen was used for the ponding test. An acrylic wall was installed around each section and a 3% sodium chloride solution by weight was placed on the designated section to a depth of ½”. During the first temperature cycles the specimen was placed on the top of a sealed box with dry ice on the bottom side of the concrete specimen. The dry ice was replaced approximately every three days. For the remaining temperature cycles the specimen was placed inside a large freezer with the temperature on the top and bottom surface of the specimen cycling between 0°F and 40°F. At the completion of the ponding period the solution was removed and the overlay was ground down to the top of the concrete. Concrete samples below the ponded section were taken and checked for chloride content per ASTM C1218.

2.3 Concrete Specimens

Concrete specimens were cast for this research on May 19, 2010 and May 26, 2010 at Hanson Structural Precast, with a 28 day compressive strength of 11,000 psi as shown in Figure 3. Table 1 shows the test matrix. Five specimens underwent each testing protocol. A total of ten large test specimens were provided. The 3’-0”x8’-0” specimens consisted of two 1’-6”x8’-0” halves that were grouted together per Type I and Type II testing protocols. Ten smaller specimens were also built (1’-6”x1’-6”x6”) for Type III and Type IV testing.

The 3’-0”x8’-0” specimens had nine #6 steel rebar at the top and bottom of the panel spaced at 12 in. on center. The panels were post tensioned during the cyclic testing with 3/8” carbon fiber rods. The layout of the panels and the jointed pocket of the panels are shown in Figures 4 and 5. The top surface of the 18”x18” and the 1’-6”x8’-0 specimens were sand blasted to remove the top layer of cement paste, as shown in Figure 6. All grout pockets for the Type II specimens were ground clean from excess overlay with the exception of specimen S2 Type II. Figures 7 and 8 show the prepared Type I and Type II specimens, respectively.

All specimens had two steel hoops placed on them for lifting purposes. The steel hoops were cut off prior to the placement of the overlay system.
Figure 3: Casting of concrete specimens

Table 1: Specimen test matrix

<table>
<thead>
<tr>
<th>Overlay</th>
<th>Test Type I Specimens</th>
<th>Test Type II Specimens</th>
<th>Test Types III and Type IV Specimens</th>
<th>Baseline Chemical Specimens</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No.</td>
<td>Size</td>
<td>No.</td>
<td>Size</td>
</tr>
<tr>
<td>S1</td>
<td>1</td>
<td>3' x 8' x 8 ¾ &quot;</td>
<td>1</td>
<td>3' x 8' x 8 ¾ &quot;</td>
</tr>
<tr>
<td>S2</td>
<td>1</td>
<td>3' x 8' x 8 ¾ &quot;</td>
<td>1</td>
<td>3' x 8' x 8 ¾ &quot;</td>
</tr>
<tr>
<td>S3</td>
<td>1</td>
<td>3' x 8' x 8 ¾ &quot;</td>
<td>1</td>
<td>3' x 8' x 8 ¾ &quot;</td>
</tr>
<tr>
<td>S4</td>
<td>1</td>
<td>3' x 8' x 8 ¾ &quot;</td>
<td>1</td>
<td>3' x 8' x 8 ¾ &quot;</td>
</tr>
<tr>
<td>S5</td>
<td>1</td>
<td>3' x 8' x 8 ¾ &quot;</td>
<td>1</td>
<td>3' x 8' x 8 ¾ &quot;</td>
</tr>
</tbody>
</table>
Figure 4: Panel dimensions

Figure 5: Grouted pocket dimension
Figure 6: Sand blasted top surface

Figure 7: Type I specimens prior to grouting and placement of overlay
2.4 Overlay Application

The application of each of the five different overlays systems took two days for the majority of the specimens. During the first day, the overlay was applied to the 3’-0”x8’-0” Type I specimens, the two 18”x8’-0” Type II specimens, and the two 1’-6”x1’-6” Type III and Type IV specimens. The Type II specimens were precracked and grouted together and the overlay splice over the grouted pocket was then applied at a later date. Each overlay manufacturer was responsible for the application of the overlay for each specimen.

The overlay system S1 is a polyester resin based system and was applied in two lifts. Additional light sandblasting of the top surface was performed by the manufacturer. This blasting focused on the removal of the oxidation of the remaining portion of the steel lifting hoops. A two-part crack sealant was mixed and rolled onto the top surface and saturated into the cracks as best as possible, as shown in Figure 9. The two-part resin overlay was mixed and squeegeed onto the surface. Flint aggregate was then broadcast onto the overlay in a chicken feed manner, and the first layer of the overlay was left to set. Any loose aggregate was brushed off and the second lift of the overlay was mixed and squeegeed on, as shown in Figure 10. Finally, flint aggregate was broadcast on the top layer of the overlay system.
The splice of the S1 system followed the same protocol as the original panels. The grouted section was lightly sandblasted by the manufacturer. An initial two-part sealer was mixed and applied into the cracks and onto the surface. The first layer of the overlay resin was mixed and squeegeed over the grouted pocket and flint aggregate was broadcast. The temperature in the lab was colder than previous applications, so heat guns were used to help the overlay resin to set up. The second coat over the overlay resin was mixed and placed over the surface and flint was broadcast on top and left to set as shown in Figure 11.
The overlay system S2 is a resin based system. The specimens were brushed to remove any debris and a two part resin was mixed at a ratio of 1:1 and squeegeed onto the surface. Subsequently, flint aggregate was broadcast onto the layer of resin. The first layer was left to set for thirty minutes and the second layer was then applied in the same manner. The extra aggregate was brushed away and the resin was mixed to the same proportions. The resin was squeegeed on top of the previous layer and additional flint aggregate was broadcast on top. The splice for the S2 system was a single coat application. The resin was mixed in a 1:1 ratio and squeegeed over the grouted pocket. Flint aggregate was then broadcast onto the layer.

The S3 overlay system consisted of multiple layers. Excessive grout was ground away with a hand grinder by the manufacturer. A primer layer was mixed and applied with a roller. The membrane layer was mixed with the activator and troweled onto the top surface. A second primer was mixed with the activator and rolled onto the membrane. The wear layer was then mixed with the activator and applied, as shown in Figure 12. A layer of aggregate was broadcasted on and a top sealer was mixed with the activator and applied, as shown in Figure 13. The splice was applied in the same fashion. Each layer was applied, the initial primer, the membrane, the second primer, the wear surface, the aggregate and then the sealer. The removal of the forms from the initial application for the Type II specimen resulted in loss of concrete in some locations because the overlay system bonded the wood form to the concrete panels and had to be removed with a chisel.

Figure 11: Application of overlay resin for the splice of S1 Type II specimen
The S4 overlay system consisted of a crack sealer and an epoxy/aggregate overlay, as shown in Figure 14. Any excess grout was ground away by the manufacturer and a shop vacuum was used to remove dust and debris from the top surface. The crack sealer was mixed and brushed on and was allowed to set. A heat gun was used to help set the material, due to the relatively low temperature in the lab. The overlay resin was mixed and squeegeed on. A layer of flint aggregate was broadcast onto the surface. Due to the cold temperature in the lab, the second layer of the epoxy/aggregate was applied the following day. The excess aggregate was
vacuumed from the specimen surface. The resin was mixed and applied using a squeegee and a roller. The last layer of aggregate was then broadcast onto the surface.

The excess grout was ground away and a smooth surface was created for the splice. The dust and debris were vacuumed using a shop vac. The crack sealer was mixed and sponged over the grouted pocket. The first layer of resin was mixed and brushed onto the surface. The first layer of flint aggregate was broadcast on top and the resin was allowed time to set. The second layer was mixed and also applied with a brush. The aggregate was applied in the same manner as before and the whole system was left to set.

The overlay system S5 is considered a polyester overlay. The thickness of this system was larger than that of the other overlays tested in this research. A depth of ¾” was maintained while the other overlay systems maintained a depth of 3/8”. The top surface was ground down by the manufacturer to expose large aggregate using a hand grinder and all the dust was blown away. A primer was mixed and brushed on the surface for bonding and to fill existing cracks. The resin and catalyst for the overlay were mixed with the aggregate and troweled onto the surface. The top of the overlay was vibrated, tined and a light top layer of sand was broadcast onto the surface, as shown in Figure 15.

Figure 14: Application of first layer of resin overlay for the S4 Type II specimens
The application of the splice for the S5 overlay system was similar to the initial application. The grouted pocket was ground down using a hand grinder by the manufacturer. The dust was then vacuumed using a small hand vacuum. The primer was mixed and brushed over the grouted pocket. The resin, catalyst and aggregate were mixed and poured into the splice. A 4” x 4” wood member was used to vibrate the splice to help with consolidation and a light layer of sand was placed over the splice.

3.0 DATA COLLECTION

3.1 Test Setup

A load frame with a hydraulic actuator was used to apply a displacement-controlled load for precracking and cyclic loading for Type I and Type II specimens. An electronic data acquisition system recorded strains during loading protocols.

The 1’-6”x8’-0”x8¾ “ specimens underwent an eight cycle displacement controlled loading protocol to create precracking on the overlay surface, prior to grouting. The specimens were turned upside down for the precracking loading to create cracks on the top surface of the specimen, where the overlay would be applied. The specimens were loaded in the center under a simple span condition. The center of the specimen was loaded at a displacement rate of 0.2 in./min. The displacement ranged from 0.025 in. to 0.3 in. Following the 0.15 in. cycle, the loading was paused after each cycle and the induced cracks on the tension surface were visually
inspected for Type I specimens. Figure 16 shows the test setup and Figure 17 shows the precracking loading protocol used. A single concrete strain gauge was placed at the center of the top surface of the 1’-6”x8’-0”x8¾” sections prior to being turned upside down and placed in the frame for the precracking protocol, to record consistency between specimens.

Figure 16: Test set up for precracking protocol for Type I and Type II specimens
The 3’-0”x8’-0”x8¾” concrete specimens were loaded in a simple span condition for the Type I and II cyclic loading, as shown in Figure 18. A displacement controlled cyclic loading was applied at the center of one of the 1’-6”x8’-0”x8¾” halves, as shown in Figure 19. A loading rate of 0.05in./s was used for all the cycles. Table 2 shows the specified five day cyclic testing protocol. Figures 20 – 22 show samples of the five day protocol.

![Precrack Loading Protocol](image)

**Figure 17:** Precracking Loading Protocol

![Loading setup for precracking of Type II specimen](image)

**Figure 18:** Loading setup for precracking of Type II specimen
Figure 19: Testing set up for five day cyclic test for Type I and Type II specimens

<table>
<thead>
<tr>
<th>Day</th>
<th>Displacement (in.)</th>
<th>Number of Cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.1</td>
<td>7650</td>
</tr>
<tr>
<td>2</td>
<td>0.2</td>
<td>3825</td>
</tr>
<tr>
<td>3</td>
<td>0.2</td>
<td>3825</td>
</tr>
<tr>
<td>4</td>
<td>0.2</td>
<td>3825</td>
</tr>
<tr>
<td>5</td>
<td>0.3</td>
<td>2550</td>
</tr>
</tbody>
</table>
Figure 20: Sample of Day 1 cyclic protocol

Figure 21: Sample of Days 2, 3 and 4 cyclic protocol
The panels were post tensioned with 3/8 in. carbon fiber rods as shown Figure 23, before cyclic loading was applied. This reflects Utah DOT practice of post-tensioning precast deck panels. The induced strain from post tensioning on the rods was roughly 2500 to 3000 micro strains. This corresponds to a force of approximately 6.2 kips for each of the two rods. This led to a stress in the panel of approximately 14.75 psi, which is less than the panel stress currently specified in practice. This post tensioning was applied during cyclic loading and was removed prior to the ponding protocol.
3.2 Instrumentation

A total of eight strain gauges were applied to the reinforcing steel of the 3'-0"x8'-0" specimens. Four were applied to each 1'-6"x8'-0" specimen. The strain gauges are located at the center of the top and bottom reinforcing longitudinal bars adjacent to the grouted pocket and on the adjacent transverse bar as shown in Figure 24. Additional strain gauges were also attached to the carbon fiber post-tensioning rods to measure the initial strain in the rods.

3.3 Pull-off Tests

All bond tests were performed using a digital dynamometer. The testing procedure was as follows:

1) Drill a 2 in. diameter circular ring to a depth of 3/8 in. below the concrete surface.
2) Remove debris at the pull test location with air or shop vacuum.

![Figure 24: Strain gauge location for Type I and II specimens](image-url)
3) Mix concrete/metal quick set epoxy and place on dolly and drilled section of concrete deck.

4) Place dolly on overlay surface and apply pressure. Prior to testing, adhesive was cured per temperature recommendations, for a minimum of one hour.

5) Attach dynamometer to the dolly and apply pull-off force on the dolly.

6) Continue to apply force until the dolly is pulled off the deck.

Test results were determined based on which layer failed in each test (i.e. the concrete failed, the bond between the overlay and the concrete failed, or the overlay failed) and the pull-off pressure. Figure 25 shows the pull-off test on one of the bridge decks.

Figure 25: Pull-off test on bridge deck
3.4 Chloride Test

All chloride tests were performed per ASTM C1218. Four samples were made per each hole at a depth increment of 3mm for a total of 12mm of hole. A titration test was performed on each sample to determine the percent of chloride in the sample per unit weight. The percent chloride for each sample is determined from the following equation.

\[
\text{Cl}, \% = \frac{3.545(V_1-V_2)N-0.10}{\text{w}}
\]  
(1)

where \( V_1 \) is the volume (mL) of AgNO\(_3\) at the equivalent point of the sample; \( V_2 \) is the volume of AgNO\(_3\) of the blank solution (just water); \( N \) is the normality of the AgNO\(_3\) solution used in titration and correlates the volume of AgNO\(_3\) to NaCl content. The normality of the solution was checked every day of titration and the average solution normality was used in the equation; \( \text{w} \) is the weight of the ground up concrete sample.

4.0 DATA EVALUATION

4.1 Cyclic Test

Strain values were set to zero prior to testing each day. The location of the top reinforcing mat and the applied displacements produced a small tensile strain in the reinforcing steel on the top longitudinal mat. Figure 26 shows the maximum strains of the bottom longitudinal strain gauge for each specimen for the fifth day cyclic testing. The average strain was approximately one half of the theoretical yield strength of the steel reinforcement. Hairline cracks on the underside of the specimens were detected after cyclic loading. These cracks were spaced at approximately 8 in. apart and extend the entire width of the specimen.
4.2 Temperature Test

The temperature on the bottom surface of the concrete specimen and inside the dry ice box were recorded. Figures 27 and 28 show typical temperature readings found on the bottom concrete surface and inside the dry ice box during the temperature cycles.

Figure 27: Typical Temperature for Dry Ice Cycle
4.3 Pull-off Test Values

Pull-off tests were performed and the corresponding values and failure modes are recorded in Tables 3 through 15. Tables 3 through 5 show the results for the three bridges. Tables 6 through 15 shows the results for the laboratory specimens. Failure of the epoxy corresponds to failure in the metal/concrete epoxy used in the pull-off test. Failure of the overlay corresponds to the bond between the overlay and the concrete deck. There was no clear correlation between the number of cycles the specimen underwent and the values of the bond strength. A comparison between the average valid (non-epoxy) pull test values can be found in Table 16. The pull tests from the lab testing performed better on average than those taken from existing bridges. This could be caused by the difference between field and laboratory preparation and loading conditions and the compressive strength of the concrete deck.

The pull-off test results for the bridges tested are shown in Figures 29 through 31. Figures 32 through 35 show pull-off results for non-epoxy failures for laboratory specimens.
Table 3: S1 Bridge pull-off values

<table>
<thead>
<tr>
<th>Force (lb)</th>
<th>Stress (psi)</th>
<th>Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>PULL 1</td>
<td>745</td>
<td>237 EPOXY*</td>
</tr>
<tr>
<td>PULL 2</td>
<td>1035</td>
<td>329 OVERLAY</td>
</tr>
<tr>
<td>PULL 3</td>
<td>990</td>
<td>315 EPOXY</td>
</tr>
<tr>
<td>PULL 4</td>
<td>1350</td>
<td>430 EPOXY</td>
</tr>
</tbody>
</table>

Epoxy Failure refers to failure of the epoxy or glue used in the pull-off test

- Total Average Pull-Off Test Stress: 328 psi
- Average Valid (Non-Epoxy) Stress: 329 psi
- Average Overlay Stress: 329 psi
- Percent Concrete Failure of Valid Tests: 0%

Table 4: S3 Bridge pull-off values

<table>
<thead>
<tr>
<th>Force (lb)</th>
<th>Stress (psi)</th>
<th>Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>PULL 1</td>
<td>1120</td>
<td>357 CONCRETE/OVERLAY</td>
</tr>
<tr>
<td>PULL 2</td>
<td>925</td>
<td>294 OVERLAY</td>
</tr>
<tr>
<td>PULL 3</td>
<td>910</td>
<td>290 OVERLAY</td>
</tr>
<tr>
<td>PULL 4</td>
<td>920</td>
<td>293 OVERLAY</td>
</tr>
</tbody>
</table>

Epoxy Failure refers to failure of the epoxy or glue used in the pull-off test

- Total Average Pull-Off Test Stress: 2 psi
- Average Valid (Non-Epoxy) Stress: 2 psi
- Average Overlay Stress: 2 psi
- Percent Concrete Failure of Valid Tests: 0%

Table 5: S4 Bridge pull-off values

<table>
<thead>
<tr>
<th>Force (lb)</th>
<th>Stress (psi)</th>
<th>Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>PULL 1</td>
<td>1120</td>
<td>357 CONCRETE/OVERLAY</td>
</tr>
<tr>
<td>PULL 2</td>
<td>925</td>
<td>294 OVERLAY</td>
</tr>
<tr>
<td>PULL 3</td>
<td>910</td>
<td>290 OVERLAY</td>
</tr>
<tr>
<td>PULL 4</td>
<td>920</td>
<td>293 OVERLAY</td>
</tr>
</tbody>
</table>

Epoxy Failure refers to failure of the epoxy or glue used in the pull-off test

- Total Average Pull-Off Test Stress: 308 psi
- Average Valid (Non-Epoxy) Stress: 308 psi
- Average Overlay Stress: 308 psi
- Percent Concrete Failure of Valid Tests: 0%
Table 6: S1 Type I pull-off values

<table>
<thead>
<tr>
<th>Force (lb)</th>
<th>Stress (psi)</th>
<th>Failure</th>
<th>Force (lb)</th>
<th>Stress (psi)</th>
<th>Failure</th>
<th>Average Stress (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial</td>
<td>0</td>
<td>CONCRETE (LOST VALUE)</td>
<td>0</td>
<td>CONCRETE (LOST VALUE)</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Day 1</td>
<td>1605</td>
<td>511</td>
<td>1895</td>
<td>603</td>
<td>CONCRETE</td>
<td>557</td>
</tr>
<tr>
<td>Day 2</td>
<td>1595</td>
<td>508</td>
<td>1345</td>
<td>428</td>
<td>AGGREGATE IN EPOXY</td>
<td>468</td>
</tr>
<tr>
<td>Day 3</td>
<td>1125</td>
<td>358</td>
<td>1530</td>
<td>487</td>
<td>CONCRETE</td>
<td>423</td>
</tr>
<tr>
<td>Day 4</td>
<td>2395</td>
<td>762</td>
<td>2120</td>
<td>675</td>
<td>EPOXY*</td>
<td>719</td>
</tr>
<tr>
<td>Day 5</td>
<td>2050</td>
<td>653</td>
<td>2370</td>
<td>754</td>
<td>CONCRETE</td>
<td>703</td>
</tr>
</tbody>
</table>

Total Average Pull-Off Test Stress: 574 psi
Average Valid (Non-Epoxy) Stress: 580 psi
Average Overlay Stress: NA psi
Percent Concrete Failure of Valid Tests: 100%

*Epoxy Failure refers to failure of the epoxy or glue used in the pull-off test. No Overlay failure: all failures occurred in concrete or epoxy.

Table 7: S2 Type I pull-off values

<table>
<thead>
<tr>
<th>Force (lb)</th>
<th>Stress (psi)</th>
<th>Failure</th>
<th>Force (lb)</th>
<th>Stress (psi)</th>
<th>Failure</th>
<th>Average Stress (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial</td>
<td>710</td>
<td>226</td>
<td>835</td>
<td>266</td>
<td>EPOXY</td>
<td>246</td>
</tr>
<tr>
<td>Day 1</td>
<td>2150</td>
<td>684</td>
<td>1410</td>
<td>449</td>
<td>CONCRETE</td>
<td>567</td>
</tr>
<tr>
<td>Day 2</td>
<td>2785</td>
<td>886</td>
<td>1575</td>
<td>501</td>
<td>CONCRETE</td>
<td>694</td>
</tr>
<tr>
<td>Day 3</td>
<td>1785</td>
<td>568</td>
<td>1345</td>
<td>428</td>
<td>CONCRETE</td>
<td>498</td>
</tr>
<tr>
<td>Day 4</td>
<td>1395</td>
<td>444</td>
<td>2000</td>
<td>637</td>
<td>CONCRETE</td>
<td>540</td>
</tr>
<tr>
<td>Day 5</td>
<td>2155</td>
<td>686</td>
<td>2750</td>
<td>875</td>
<td>CONCRETE AT OVERLAY</td>
<td>781</td>
</tr>
</tbody>
</table>

Total Average Pull-Off Test Stress: 554 psi
Average Valid (Non-Epoxy) Stress: 621 psi
Average Overlay Stress: NA psi
Percent Concrete Failure of Valid Tests: 100%

*Epoxy Failure refers to failure of the epoxy or glue used in the pull-off test. No Overlay failure: all failures occurred in concrete or epoxy.
Table 8: S3 Type I pull-off values

<table>
<thead>
<tr>
<th></th>
<th>Force (lb)</th>
<th>Stress (psi)</th>
<th>Failure</th>
<th>Force (lb)</th>
<th>Stress (psi)</th>
<th>Failure</th>
<th>Average Stress (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial</td>
<td>1160</td>
<td>369</td>
<td>EPOXY*</td>
<td>790</td>
<td>251</td>
<td>EPOXY</td>
<td>310</td>
</tr>
<tr>
<td>Day 1</td>
<td>825</td>
<td>263</td>
<td>EPOXY</td>
<td>1095</td>
<td>349</td>
<td>EPOXY</td>
<td>306</td>
</tr>
<tr>
<td>Day 2</td>
<td>1385</td>
<td>441</td>
<td>EPOXY</td>
<td>725</td>
<td>231</td>
<td>EPOXY</td>
<td>336</td>
</tr>
<tr>
<td>Day 3</td>
<td>-</td>
<td>-</td>
<td>NOT TESTED</td>
<td>-</td>
<td>-</td>
<td>NOT TESTED</td>
<td>-</td>
</tr>
<tr>
<td>Day 4</td>
<td>65</td>
<td>21</td>
<td>EPOXY</td>
<td>480</td>
<td>153</td>
<td>EPOXY</td>
<td>87</td>
</tr>
<tr>
<td>Day 5</td>
<td>0</td>
<td>0</td>
<td>EPOXY</td>
<td>695</td>
<td>221</td>
<td>EPOXY</td>
<td>111</td>
</tr>
<tr>
<td>DST TEST</td>
<td>1050</td>
<td>334</td>
<td>EPOXY</td>
<td>1490</td>
<td>474</td>
<td>CONCRETE</td>
<td>404</td>
</tr>
<tr>
<td>DST TEST</td>
<td>1115</td>
<td>355</td>
<td>OVERLAY</td>
<td>1215</td>
<td>387</td>
<td>OVERLAY</td>
<td>371</td>
</tr>
<tr>
<td>DST TEST</td>
<td>2135</td>
<td>680</td>
<td>OVERLAY</td>
<td>1540</td>
<td>490</td>
<td>OVERLAY</td>
<td>585</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Total Average Pull-Off Test Stress</th>
<th>314</th>
<th>psi</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Valid (Non-Epoxy) Stress</td>
<td>477</td>
<td>psi</td>
<td></td>
</tr>
<tr>
<td>Average Overlay Stress</td>
<td>478</td>
<td>psi</td>
<td></td>
</tr>
<tr>
<td>Percent Concrete Failure of Valid Tests</td>
<td>20</td>
<td>%</td>
<td></td>
</tr>
</tbody>
</table>

*Epoxy Failure refers to failure of the epoxy or glue used in the pull-off test.

Table 9: S4 Type I pull-off values

<table>
<thead>
<tr>
<th></th>
<th>Force (lb)</th>
<th>Stress (psi)</th>
<th>Failure</th>
<th>Force (lb)</th>
<th>Stress (psi)</th>
<th>Failure</th>
<th>Average Stress (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial</td>
<td>1360</td>
<td>433</td>
<td>CONCRETE/OVERLAY</td>
<td>2245</td>
<td>715</td>
<td>CONCRETE</td>
<td>574</td>
</tr>
<tr>
<td>Day 1</td>
<td>1405</td>
<td>447</td>
<td>EPOXY*</td>
<td>790</td>
<td>251</td>
<td>EPOXY</td>
<td>349</td>
</tr>
<tr>
<td>Day 2</td>
<td>2030</td>
<td>646</td>
<td>EPOXY</td>
<td>2435</td>
<td>775</td>
<td>CONCRETE</td>
<td>711</td>
</tr>
<tr>
<td>Day 3</td>
<td>2425</td>
<td>772</td>
<td>CONCRETE</td>
<td>1745</td>
<td>555</td>
<td>CONCRETE</td>
<td>664</td>
</tr>
<tr>
<td>Day 4</td>
<td>2485</td>
<td>791</td>
<td>CONCRETE</td>
<td>1725</td>
<td>549</td>
<td>EPOXY</td>
<td>670</td>
</tr>
<tr>
<td>Day 5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Total Average Pull-Off Test Stress</th>
<th>495</th>
<th>psi</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Valid (Non-Epoxy) Stress</td>
<td>673</td>
<td>psi</td>
<td></td>
</tr>
<tr>
<td>Average Overlay Stress</td>
<td>433</td>
<td>psi</td>
<td></td>
</tr>
<tr>
<td>Percent Concrete Failure of Valid Tests</td>
<td>83</td>
<td>%</td>
<td></td>
</tr>
</tbody>
</table>

*Epoxy Failure refers to failure of the epoxy or glue used in the pull-off test.
Table 10: S5 Type I pull-off values

<table>
<thead>
<tr>
<th></th>
<th>Force (lb)</th>
<th>Stress (psi)</th>
<th>Failure</th>
<th>Force (lb)</th>
<th>Stress (psi)</th>
<th>Failure</th>
<th>Average Stress (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial</td>
<td>910</td>
<td>290</td>
<td>EPOXY*</td>
<td>1960</td>
<td>624</td>
<td>MIDDLE OF OVERLAY</td>
<td>457</td>
</tr>
<tr>
<td>Day 1</td>
<td>1150</td>
<td>366</td>
<td>EPOXY</td>
<td>1020</td>
<td>325</td>
<td>EPOXY</td>
<td>345</td>
</tr>
<tr>
<td>Day 2</td>
<td>0</td>
<td>0</td>
<td>EPOXY</td>
<td>1225</td>
<td>390</td>
<td>EPOXY</td>
<td>195</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1335</td>
<td>425</td>
<td>PARTIAL DEPTH OF OVERLAY</td>
<td>451</td>
</tr>
<tr>
<td>Day 4</td>
<td>1280</td>
<td>407</td>
<td>EPOXY</td>
<td>1390</td>
<td>442</td>
<td>EPOXY</td>
<td>425</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>MIDDLE OF OVERLAY</td>
<td>2035</td>
<td>648</td>
<td>MIDDLE OF OVERLAY (GLUE MAY HAVE ATTACHED TO REST OF DECK)</td>
<td>558</td>
</tr>
<tr>
<td>POST TESTING</td>
<td>1670</td>
<td>532</td>
<td>CONCRETE AND OVERLAY</td>
<td>2315</td>
<td>737</td>
<td>OVERLAY</td>
<td>634</td>
</tr>
</tbody>
</table>

Total Average Pull-Off Test Stress: 438 psi
Average Valid (Non-Epoxy) Stress: 572 psi
Average Overlay Stress: 572 psi
Percent Concrete Failure of Valid Tests: 0%

*Epoxy Failure refers to failure of the epoxy or glue used in the pull-off test

Table 11: S1 Type II pull-off values

<table>
<thead>
<tr>
<th></th>
<th>Force (lb)</th>
<th>Stress (psi)</th>
<th>Failure</th>
<th>Force (lb)</th>
<th>Stress (psi)</th>
<th>Failure</th>
<th>Average Stress (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial</td>
<td>1535</td>
<td>489</td>
<td>CONCRETE</td>
<td>1535</td>
<td>489</td>
<td>CONCRETE</td>
<td>489</td>
</tr>
<tr>
<td>Day 1</td>
<td>1530</td>
<td>487</td>
<td>EPOXY W/ FLINT</td>
<td>1250</td>
<td>398</td>
<td>EPOXY W/ FLINT</td>
<td>442</td>
</tr>
<tr>
<td>Day 2</td>
<td>1045</td>
<td>333</td>
<td>CONCRETE</td>
<td>1935</td>
<td>616</td>
<td>CONCRETE</td>
<td>474</td>
</tr>
<tr>
<td>Day 3</td>
<td>800</td>
<td>255</td>
<td>EPOXY*</td>
<td>1920</td>
<td>611</td>
<td>CONCRETE</td>
<td>433</td>
</tr>
<tr>
<td>Day 4</td>
<td>1775</td>
<td>565</td>
<td>CONCRETE</td>
<td>2240</td>
<td>713</td>
<td>EPOXY W/ FLINT</td>
<td>639</td>
</tr>
<tr>
<td>Day 5</td>
<td>1770</td>
<td>563</td>
<td>Epoxy</td>
<td>1070</td>
<td>341</td>
<td>Epoxy</td>
<td>452</td>
</tr>
</tbody>
</table>

Total Average Pull-Off Test Stress: 488 psi
Average Valid (Non-Epoxy) Stress: 517 psi
Average Overlay Stress: NA psi
Percent Concrete Failure of Valid Tests: 100%

*Epoxy Failure refers to failure of the epoxy or glue used in the pull-off test
No Overlay failure: all failures occurred in concrete or epoxy
Table 12: S2 Type II pull-off values

<table>
<thead>
<tr>
<th></th>
<th>Force (lb)</th>
<th>Stress (psi)</th>
<th>Failure</th>
<th>Force (lb)</th>
<th>Stress (psi)</th>
<th>Failure</th>
<th>Average Stress (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial</td>
<td>1125</td>
<td>358</td>
<td>EPOXY*</td>
<td>935</td>
<td>298</td>
<td>CONCRETE</td>
<td>328</td>
</tr>
<tr>
<td>Day 1</td>
<td>1635</td>
<td>520</td>
<td>EPOXY</td>
<td>1740</td>
<td>554</td>
<td>CONCRETE</td>
<td>537</td>
</tr>
<tr>
<td>Day 2</td>
<td>2545</td>
<td>810</td>
<td>EPOXY</td>
<td>2285</td>
<td>727</td>
<td>CONCRETE</td>
<td>769</td>
</tr>
<tr>
<td>Day 3</td>
<td>630</td>
<td>201</td>
<td>OVERLAY</td>
<td>1800</td>
<td>573</td>
<td>EPOXY / OVERLAY / CONCRETE</td>
<td>387</td>
</tr>
<tr>
<td>Day 4</td>
<td>935</td>
<td>298</td>
<td>OVERLAY/CONCRETE</td>
<td>1260</td>
<td>401</td>
<td>CONCRETE</td>
<td>349</td>
</tr>
<tr>
<td>Day 5</td>
<td>1815</td>
<td>578</td>
<td>CONCRETE</td>
<td>1150</td>
<td>366</td>
<td>CONCRETE</td>
<td>472</td>
</tr>
</tbody>
</table>

Total Average Pull-Off Test Stress: 474 psi
Average Valid (Non-Epoxy) Stress: 444 psi
Average Overlay Stress: 357 psi
Percent Concrete Failure of Valid Tests: 67%

Table 13: S3 Type II pull-off values

<table>
<thead>
<tr>
<th></th>
<th>Force (lb)</th>
<th>Stress (psi)</th>
<th>Failure</th>
<th>Force (lb)</th>
<th>Stress (psi)</th>
<th>Failure</th>
<th>Average Stress (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial</td>
<td>1820</td>
<td>579</td>
<td>EPOXY*</td>
<td>690</td>
<td>220</td>
<td>EPOXY</td>
<td>399</td>
</tr>
<tr>
<td>Day 1</td>
<td>1370</td>
<td>436</td>
<td>EPOXY</td>
<td>1515</td>
<td>482</td>
<td>EPOXY</td>
<td>459</td>
</tr>
<tr>
<td>Day 2</td>
<td>935</td>
<td>298</td>
<td>EPOXY</td>
<td>980</td>
<td>312</td>
<td>EPOXY</td>
<td>305</td>
</tr>
<tr>
<td>Day 3</td>
<td>1255</td>
<td>399</td>
<td>OVERLAY</td>
<td>1085</td>
<td>345</td>
<td>EPOXY</td>
<td>372</td>
</tr>
<tr>
<td>Day 4</td>
<td>960</td>
<td>306</td>
<td>EPOXY</td>
<td>540</td>
<td>172</td>
<td>EPOXY</td>
<td>239</td>
</tr>
<tr>
<td>Day 5</td>
<td>665</td>
<td>212</td>
<td>OVERLAY (PULL TEST POSSIBLY OVER GROUT POCKET)</td>
<td>1245</td>
<td>396</td>
<td>EPOXY</td>
<td>304</td>
</tr>
<tr>
<td>O/J TESTIN</td>
<td>1040</td>
<td>331</td>
<td>OVERLAY</td>
<td>1185</td>
<td>377</td>
<td>OVERLAY</td>
<td>354</td>
</tr>
</tbody>
</table>

Total Average Pull-Off Test Stress: 348 psi
Average Valid (Non-Epoxy) Stress: 330 psi
Average Overlay Stress: 330 psi
Percent Concrete Failure of Valid Tests: 0%

*Epoxy Failure refers to failure of the epoxy or glue used in the pull-off test
Table 14: S4 Type II pull-off values

<table>
<thead>
<tr>
<th>Day</th>
<th>Force (lb)</th>
<th>Stress (psi)</th>
<th>Failure</th>
<th>Force (lb)</th>
<th>Stress (psi)</th>
<th>Failure</th>
<th>Average Stress (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial</td>
<td>0</td>
<td>CONCRETE (DID NOT CLEAR VALUES)</td>
<td>2470</td>
<td>786</td>
<td>CONCRETE (EPOXY ON SIDE)</td>
<td>393</td>
<td></td>
</tr>
<tr>
<td>Day 1</td>
<td>1925</td>
<td>613</td>
<td>EPOXY</td>
<td>350</td>
<td>111</td>
<td>CONCRETE</td>
<td>362</td>
</tr>
<tr>
<td>Day 2</td>
<td>1470</td>
<td>468</td>
<td>CONCRETE</td>
<td>1590</td>
<td>506</td>
<td>EPOXY</td>
<td>487</td>
</tr>
<tr>
<td>Day 3</td>
<td>1020</td>
<td>325</td>
<td>EPOXY</td>
<td>-</td>
<td>-</td>
<td>EPOXY</td>
<td>325</td>
</tr>
<tr>
<td>Day 4</td>
<td>2000</td>
<td>637</td>
<td>CONCRETE</td>
<td>1185</td>
<td>377</td>
<td>EPOXY / OVERLAY</td>
<td>507</td>
</tr>
<tr>
<td>Day 5</td>
<td>2210</td>
<td>703</td>
<td>OVERLAY / EPOXY</td>
<td>1960</td>
<td>624</td>
<td>CONCRETE</td>
<td>664</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>450 psi</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>530 psi</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>75 %</strong></td>
</tr>
</tbody>
</table>

Total Average Pull-Off Test Stress: 515 psi
Average Valid (Non-Epoxy) Stress: 530 psi
Average Overlay Stress: 540 psi
Percent Concrete Failure of Valid Tests: 75%

*Epoxy Failure refers to failure of the epoxy or glue used in the pull-off test

Table 15: S5 Type II pull-off values

<table>
<thead>
<tr>
<th>Day</th>
<th>Force (lb)</th>
<th>Stress (psi)</th>
<th>Failure</th>
<th>Force (lb)</th>
<th>Stress (psi)</th>
<th>Failure</th>
<th>Average Stress (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial</td>
<td>1145</td>
<td>364</td>
<td>EPOXY*</td>
<td>720</td>
<td>229</td>
<td>EPOXY</td>
<td>297</td>
</tr>
<tr>
<td>Day 1</td>
<td>2405</td>
<td>766</td>
<td>OVERLAY</td>
<td>0</td>
<td>0</td>
<td>EPOXY Popped OFF</td>
<td>383</td>
</tr>
<tr>
<td>Day 2</td>
<td>2070</td>
<td>659</td>
<td>EPOXY</td>
<td>1200</td>
<td>382</td>
<td>EPOXY</td>
<td>520</td>
</tr>
<tr>
<td>Day 3</td>
<td>1210</td>
<td>385</td>
<td>EPOXY</td>
<td>940</td>
<td>299</td>
<td>EPOXY</td>
<td>342</td>
</tr>
<tr>
<td>Day 4</td>
<td>1650</td>
<td>525</td>
<td>EPOXY</td>
<td>450</td>
<td>143</td>
<td>TOP LAYER OF OVERLAY</td>
<td>334</td>
</tr>
<tr>
<td>Day 5</td>
<td>1460</td>
<td>465</td>
<td>EPOXY</td>
<td>2430</td>
<td>773</td>
<td>EPOXY</td>
<td>619</td>
</tr>
<tr>
<td>DST TEST</td>
<td>1775</td>
<td>565</td>
<td>OVERLAY</td>
<td>1325</td>
<td>422</td>
<td>OVERLAY</td>
<td>493</td>
</tr>
<tr>
<td>DST TEST</td>
<td>1708</td>
<td>544</td>
<td>CONCRETE</td>
<td>2150</td>
<td>684</td>
<td>CONCRETE</td>
<td>614</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>450 psi</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>521 psi</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>474 psi</strong></td>
</tr>
</tbody>
</table>

Total Average Pull-Off Test Stress: 450 psi
Average Valid (Non-Epoxy) Stress: 521 psi
Average Overlay Stress: 474 psi

Percent Concrete Failure of Valid Tests: 33%

*Epoxy Failure refers to failure of the epoxy or glue used in the pull-off test

32
Table 16: Average valid (non-epoxy) pull-off stress

<table>
<thead>
<tr>
<th></th>
<th>S1</th>
<th></th>
<th>S2</th>
<th></th>
<th>S3</th>
<th></th>
<th>S4</th>
<th></th>
<th>S5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Average Pull-Off Stress (psi)</td>
<td>Percent Concrete Failure of Valid Tests (%)</td>
<td>Average Pull-Off Stress (psi)</td>
<td>Percent Concrete Failure of Valid Tests (%)</td>
<td>Average Pull-Off Stress (psi)</td>
<td>Percent Concrete Failure of Valid Tests (%)</td>
<td>Average Pull-Off Stress (psi)</td>
<td>Percent Concrete Failure of Valid Tests (%)</td>
</tr>
<tr>
<td>Bridge</td>
<td>329</td>
<td>0</td>
<td>-</td>
<td>2</td>
<td>0</td>
<td>308</td>
<td>0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Type I</td>
<td>580</td>
<td>100</td>
<td>621</td>
<td>20</td>
<td>673</td>
<td>83</td>
<td>572</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Type II</td>
<td>517</td>
<td>100</td>
<td>444</td>
<td>0</td>
<td>530</td>
<td>75</td>
<td>521</td>
<td>33</td>
<td></td>
</tr>
</tbody>
</table>

Figure 29: Pull-off results for S1 Bridge
Figure 30: Pull-off results for S3 Bridge

Figure 31: Pull-off results for S4 Bridge
Figure 32: S1 Type II concrete failure for laboratory specimen

Figure 33: S2 Type II overlay failure for laboratory specimen
Figure 34: S3 Type II overlay failure for laboratory specimen

Figure 35: S5 Type II overlay failure for laboratory specimen
4.4 Chloride Test Values

Chloride tests were performed after 90 days of ponding. The corresponding values are shown in Figures 36 through 41. The average chloride content of similar holes for each test are recorded in Table 17. A negative value is considered a chloride content of zero.

Figure 36: S1 Chloride Test Values

Figure 37: S2 Chloride Test Values
Figure 38: S3 Chloride Test Values

Figure 39: S4 Chloride Test Values

Figure 40: S5 Chloride Test Values
Figure 41: Plain Concrete Ponded and Non-Ponded Chloride Test Values

Table 17: Average chloride content

<table>
<thead>
<tr>
<th>Average Chloride Content (lbs/yd$^3$)</th>
<th>0 - 1/8 in.</th>
<th>1/8 - 1/4 in.</th>
<th>1/4 - 3/8 in.</th>
<th>3/8 - 1/2 in.</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1T1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S1T2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>S1T3</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>S1T4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S2T1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S2T2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>S2T3</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>S2T4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S3T1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S3T2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>S3T3</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>S3T4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S4T1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>S4T2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>S4T3</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>S4T4</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>S5T1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S5T2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S5T3</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>S5T4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plain - ponded</td>
<td>2.96</td>
<td>2.51</td>
<td>0.07</td>
<td>0.00</td>
</tr>
<tr>
<td>Plain - non-ponded</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>
5.0 CONCLUSIONS

Two properties were tested and compared to determine the performance of different overlay systems for precast bridge decks. Pull-off tests were used to compare the mechanical characteristics of the overlay system, specifically the bond between the overlay and the bridge deck. Ponding tests were also carried out to compare the ability of the overlay system to resist chloride intrusion from de-icing salts.

A valid pull-off test is one in which failure occurred in the overlay or the concrete. All valid pull-off values from the field occurred at the overlay and concrete contact surface; the majority of the valid pull-off results for the S1, S2, and S4 laboratory tests occurred in the concrete. The specimens in the laboratory performed better than those in the field. This difference in strength and failure type is due to the difference of laboratory and field preparation conditions for the application of the overlay. Overlay systems S1, S4 and S5 had higher average valid bond strengths than the other systems.

Ponding results showed an average chloride content of 2.96 lbs/yd³ for the first 1/8 in. below the concrete surface for concrete specimens with no overlay application. An average chloride content of 2.51 lbs/yd³ was found at a depth between 1/8 in. to 1/4 in. for the same specimens. No chlorides were detected in the concrete specimens with any one of the five overlay systems.

6.0 RECOMMENDATIONS AND IMPLEMENTATION

As a result of this research it is recommended that overlay systems should be applied per manufacturer’s specifications and adequate post tensioning between panel joints should be provided.

A field problem observed by UDOT is that application of the overlay is carried out before a complete removal of the concrete curing compound, which is typically done through shot blasting. Bridge decks should be properly cleaned and prepared prior to the installation of the overlay system to ensure an adequate bond between the overlay system and the concrete.
Chloride penetration through any one of the five overlays was not achieved after 90 days of ponding; any further testing for chloride penetration should have an increased time of ponding.
APPENDIX A

SURVEYS

ALABAMA

1) What specific corrosion protection systems do you use on standard concrete bridge decks? (ie epoxy coated bars, high performance concrete, concrete deck overlays (which type) sealant barriers, add mixtures)

   Minimum 2” cover on top mat of reinforcing steel and use fly ash and microsilica in the concrete

2) How have they preformed?

   Alabama bridge decks are very durable and have performed well. But also, we have very mild winters compared to many States and for this reason have to use very little deicing salt during the winter season. It is rare that we replace a deck before replacing the bridge.

3) What are your typical accelerated bridge construction (ABC) methods? (ie Half Depth Deck Panels, precast Deck Panels, SPMT Deck and Superstructure, Slide-in)

   See comments above. Very rarely replace a bridge deck so no experience with ABC for replacing bridge decks.

4) What specific corrosion protection systems do you use on ABC concrete decks? (ie epoxy coated bars, high performance concrete, concrete deck overlays (which type) sealant barriers, add mixtures)

5) How have they preformed?

6) How often is deck sealers re-applied (if used)?

   Alabama does not use sealers on our bridge decks

7) Were corrosion protection systems applied prior to deck installation?

8) What is the typical initial deck deflection and cracking occurring from installation?

   Is there an increase in the percent of corrosion in the bridge decks used in ABC methods due to initial deck cracking from installation?
9) Is there an increase in the percent of corrosion in the bridge decks used in ABC methods due to initial deck cracking from installation?

10) Was there an increase in debonding between ABC concrete subsurface and deck overlays?

11) Where is the majority of debonding between ABC concrete subsurface and deck overlays occurring? (ie Grouted joints, center span…)

12) What are your standard de-icing procedures/protocols (if any)?

   Sanding mostly, maybe a little deicing salt application in northern most counties.

**FLORIDA**

1) What specific corrosion protection systems do you use on standard concrete bridge decks? (ie epoxy coated bars, high performance concrete, concrete deck overlays (which type) sealant barriers, add mixtures)

   On most decks, FDOT does nothing more than use quality concrete. Over salt water, calcium nitrate may be added. Most mixes contain flyash. FDOT does not allow epoxy coated rebar nor overlays. We have no serious deck problems.

2) How have they preformed?

   No problems

3) What are your typical accelerated bridge construction (ABC) methods? (ie Half Depth Deck Panels, precast Deck Panels, SPMT Deck and Superstructure, Slide-in)

   Depends on the project. We use a lot of metal sip forms but little other as the cost is either prohibitive or the project constraints do not warrant such activities. We have used SPMT and are looking at precast deck panels.

4) What specific corrosion protection systems do you use on ABC concrete decks? (ie epoxy coated bars, high performance concrete, concrete deck overlays (which type) sealant barriers, add mixtures)

   Nothing special

5) How have they preformed?
6) How often is deck sealers re-applied (if used)?

None

7) Were corrosion protection systems applied prior to deck installation?

No

8) What is the typical initial deck deflection and cracking occurring from installation?

N/A

9) Is there an increase in the percent of corrosion in the bridge decks used in ABC methods due to initial deck cracking from installation?

N/A

10) Was there an increase in debonding between ABC concrete subsurface and deck overlays?

N/A

11) Where is the majority of debonding between ABC concrete subsurface and deck overlays occurring? (ie Grouted joints, center span…)

N/A

12) What are your standard de-icing procedures/protocols (if any)?

None for Florida

IOWA

1) What specific corrosion protection systems do you use on standard concrete bridge decks? (ie epoxy coated bars, high performance concrete, concrete deck overlays (which type) sealant barriers, add mixtures)

New construction: Epoxy coated bars on all deck, high performance concrete where feasible, and two-course decks on major structures only.

Repair: Concrete deck overlay

2) How have they preformed?

Very good
3) What are your typical accelerated bridge construction (ABC) methods? (ie Half Depth Deck Panels, precast Deck Panels, SPMT Deck and Superstructure, Slide-in)

   Full depth deck panels with overlay on paved roads subject to dicing and without overlay on gravel roads. Stay in place concrete deck panels (3") are allowed only on low volume prestressed concrete girder bridges.

4) What specific corrosion protection systems do you use on ABC concrete decks? (ie epoxy coated bars, high performance concrete, concrete deck overlays (which type) sealant barriers, add mixtures)

   Epoxy coated bars, high performance concrete, and low slump concrete overlay (or HPC overlay).

5) How have they performed?

   This form of ABC is relatively new in Iowa but so far we are not aware of any problems.

6) How often is deck sealers re-applied (if used)?

   Not used

7) Were corrosion protection systems applied prior to deck installation?

   N/A

8) What is the typical initial deck deflection and cracking occurring from installation?

   Not aware of deck cracking problems associated with ABC methods described above.

9) Is there an increase in the percent of corrosion in the bridge decks used in ABC methods due to initial deck cracking from installation?

   See above

10) Was there an increase in debonding between ABC concrete subsurface and deck overlays?

    This form of ABC is relatively new in Iowa but so far we are not aware of any problems.
11) Where is the majority of debonding between ABC concrete subsurface and deck overlays occurring? (ie Grouted joints, center span…)

See above

12) What are your standard de-icing procedures/protocols (if any)?

Various dicing chemicals (salt and brine) are used on regular basis in the winter.

MARYLAND

1) What specific corrosion protection systems do you use on standard concrete bridge decks? (ie epoxy coated bars, high performance concrete, concrete deck overlays (which type) sealant barriers, add mixtures)

   The Maryland State Highway Administration uses epoxy coated bars on all concrete bridge decks. Occasionally we will use a linseed oil protective coating on new bridge decks if time allows for curing. This is a onetime application.

2) How have they preformed?

   We believe the epoxy coated bars are performing well although we do not have any long term field data to prove this since the bridges that have the epoxy coated rebar are still fairly new.

3) What are your typical accelerated bridge construction (ABC) methods? (ie Half Depth Deck Panels, precast Deck Panels, SPMT Deck and Superstructure, Slide-in)

   We do not use any accelerated methods for bridge decks. We do have a bridge system that we use in ABC applications. The bridge system is solid slabs superstructure on which we apply a concrete overlay.

4) What specific corrosion protection systems do you use on ABC concrete decks? (ie epoxy coated bars, high performance concrete, concrete deck overlays (which type) sealant barriers, add mixtures)

   We believe the concrete deck is the most important element contributing to the longevity of a bridge. Therefore, we don’t believe there are benefits to be gained by accelerating the placement of this element, which would only save a few days in the total time for a project. Concrete decks are always constructed in the same manner regardless if the bridge is on an accelerated schedule.

5) How have they preformed?

   Same as all bridge decks.
6) How often is deck sealers re-applied (if used)?

Never

7) Were corrosion protection systems applied prior to deck installation?

No

8) What is the typical initial deck deflection and cracking occurring from installation?

9) Is there an increase in the percent of corrosion in the bridge decks used in ABC methods due to initial deck cracking from installation?

10) Was there an increase in debonding between ABC concrete subsurface and deck overlays?

11) Where is the majority of debonding between ABC concrete subsurface and deck overlays occurring? (ie Grouted joints, center span…)

12) What are your standard de-icing procedures/protocols (if any)?

Since we do not use ABC method for our concrete decks there are no answers to provide to the questions above.

TENESSEE

1) What specific corrosion protection systems do you use on standard concrete bridge decks? (ie epoxy coated bars, high performance concrete, concrete deck overlays (which type) sealant barriers, add mixtures)

We use epoxy coated reinforcing steel and 2-1/2 inch clear cover over the top mat of reinforcing.

2) How have they preformed?

Very well. Our use of epoxy coated reinforcement extends nearly 30-years and repairs to these decks have been practically nil.

3) What are your typical accelerated bridge construction (ABC) methods? (ie Half Depth Deck Panels, precast Deck Panels, SPMT Deck and Superstructure, Slide-in)

We have yet to develop an ABC Bridge project.
4) What specific corrosion protection systems do you use on ABC concrete decks? (ie epoxy coated bars, high performance concrete, concrete deck overlays (which type) sealant barriers, add mixtures)

We would use the same deck protection discussed above.

5) How have they preformed?

N/A

6) How often is deck sealers re-applied (if used)?

N/A

7) Were corrosion protection systems applied prior to deck installation?

N/A

8) What is the typical initial deck deflection and cracking occurring from installation?

N/A

9) Is there an increase in the percent of corrosion in the bridge decks used in ABC methods due to initial deck cracking from installation?

N/A

10) Was there an increase in debonding between ABC concrete subsurface and deck overlays?

N/A

11) Where is the majority of debonding between ABC concrete subsurface and deck overlays occurring? (ie Grouted joints, center span…)

N/A

12) What are your standard de-icing procedures/protocols (if any)?

We use salt brine prior to the onset of a snow or icing event.
1) What specific corrosion protection systems do you use on standard concrete bridge decks? (ie epoxy coated bars, high performance concrete, concrete deck overlays (which type) sealant barriers, add mixtures)

   Epoxy coated rebar in northern part of state 
   Asphalt overlays with a membrane are no longer in use 
   some use of linseed oil or Silane sealers

2) How have they performed?

   Epoxy: not sure – will take about 40 years to know 
   Asphalt overlays: poorly 
   sealers – unsure of effectiveness

3) What are your typical accelerated bridge construction (ABC) methods? (ie Half Depth Deck Panels, precast Deck Panels, SPMT Deck and Superstructure, Slide-in)

   Half-depth deck panels – used on over 90% of all span-type bridges. We don’t really consider this to be an ABC issue because we’ve been using them for 25 years as a standard method

4) What specific corrosion protection systems do you use on ABC concrete decks? (ie epoxy coated bars, high performance concrete, concrete deck overlays (which type) sealant barriers, add mixtures)

   same as for non-ABC decks

5) How have they performed?

   same as for all decks

6) How often is deck sealers re-applied (if used)?

   rarely, if ever

7) Were corrosion protection systems applied prior to deck installation?

   Not sure what this means

8) What is the typical initial deck deflection and cracking occurring from installation?

   Installation of a protection system? None
9) Is there an increase in the percent of corrosion in the bridge decks used in ABC methods due to initial deck cracking from installation?

Too early or impossible to tell

10) Was there an increase in debonding between ABC concrete subsurface and deck overlays?

N/A

11) Where is the majority of debonding between ABC concrete subsurface and deck overlays occurring? (ie Grouted joints, center span…)

N/A

12) What are your standard de-icing procedures/protocols (if any)?

Bare road policy – our maintenance forces will use any tool available.

VIRGINIA

1) What specific corrosion protection systems do you use on standard concrete bridge decks? (ie epoxy coated bars, high performance concrete, concrete deck overlays (which type) sealant barriers, add mixtures)

For new decks we are using high performance concrete in bridge decks along with low permeability specifications. We have stopped using epoxy coated and galvanized reinforcing steel and switch to corrosion resistant reinforcing steels. At present we allow three types: solid stainless, stainless clad and low carbon/chromium (ASTM 1035 – MMFX-2) although there is no domestic production of stainless clad at this time. The type required in bridge decks is dependent on the functional classification of the roadway with an adjustment based on the deicing salts used. (The informational and instructional memorandum is posted on our website).

For older decks we use epoxy overlays when they can be applied before the steel starts to corrode and concrete overlays of latex-modified or 7% silica fume when corrosion induced spalling is significant.

2) How have they preformed?

Performance continues to be good. Both high performance concrete and corrosion resistant reinforcement are expected to provide a service life of more than 100 years. Epoxy overlays typically provide good protection for approximately 20 years. Concrete overlays typically provide good protection for 20 to 40 years.
3) What are your typical accelerated bridge construction (ABC) methods? (ie Half Depth Deck Panels, precast Deck Panels, SPMT Deck and Superstructure, Slide-in)

- Precast concrete panels placed in the transverse direction.
- Composite steel beam (2 beams) and concrete deck units placed in the longitudinal direction.
- Precast slab spans.
- Epoxy overlays.
- Latex-modified concrete very early strength overlays.
- Corrosion resistant reinforcement.

4) What specific corrosion protection systems do you use on ABC concrete decks? (ie epoxy coated bars, high performance concrete, concrete deck overlays (which type) sealant barriers, add mixtures)

Same as response to the earlier questions.

5) How have they preformed?

Same as response to the earlier questions.

6) How often is deck sealers re-applied (if used)?

We rarely use sealers on decks because they need to be reapplied every 5 years and traffic wears the sealer off.

7) Were corrosion protection systems applied prior to deck installation?

Only when corrosion resistant reinforcement is used.

8) What is the typical initial deck deflection and cracking occurring from installation?

High performance concrete often cracks which is the reason we use corrosion resistant reinforcement.

9) Is there an increase in the percent of corrosion in the bridge decks used in ABC methods due to initial deck cracking from installation?

Reinforcement corrodes in cracks unless it is corrosion resistant reinforcement.

10) Was there an increase in debonding between ABC concrete subsurface and deck overlays?

Only when the contractor failed to meet the specification with respect to surface preparation and placing and curing the overlay.
11) Where is the majority of debonding between ABC concrete subsurface and deck overlays occurring? (ie Grouted joints, center span…)

   Along joints and cracks and wheel paths.

12) What are your standard de-icing procedures/protocols (if any)?

   Historically we have applied a mixture of sand and calcium chloride. In recent years we are using more liquid chloride.

WASHINGTON

1) What specific corrosion protection systems do you use on standard concrete bridge decks? (ie epoxy coated bars, high performance concrete, concrete deck overlays (which type) sealant barriers, add mixtures)

   1. New construction: Epoxy in top and bottom of the deck with 2.5” rebar cover.
   2. Existing Decks:
      a. Modified Concrete Overlays: Flyash, Microsilica, or Latex
      b. Rapid construction: Rapid Set LMC or Polyester

2) How have they preformed?

   Concrete overlays have about 40%-60% of the lifespan of a new deck. New decks have a wearing surface lifespan of about 30-50 years.

3) What are your typical accelerated bridge construction (ABC) methods? (ie Half Depth Deck Panels, precast Deck Panels, SPMT Deck and Superstructure, Slide-in)

   Half deck prestressed panels

4) What specific corrosion protection systems do you use on ABC concrete decks? (ie epoxy coated bars, high performance concrete, concrete deck overlays (which type) sealant barriers, add mixtures)

   One layer of epoxy coated rebar with 2.5” rebar cover.

5) How have they preformed?

   Generally these systems have increased reflective cracking at the edge of panels. As compared to cast in place decks, the difference in performance is unproven at this time.

6) How often is deck sealers re-applied (if used)?
Deck sealers systems have not been implemented in Washington State. Manufacturers recommended re-application rates is one of the reasons they have not been used.

7) Were corrosion protection systems applied prior to deck installation?

8) What is the typical initial deck deflection and cracking occurring from installation?

    Unknown.

9) Is there an increase in the percent of corrosion in the bridge decks used in ABC methods due to initial deck cracking from installation?

    Unknown.

10) Was there an increase in debonding between ABC concrete subsurface and deck overlays?

    Overlays are not applied during new construction and Washington has not applied a concrete overlay to an existing concrete panel.

11) Where is the majority of debonding between ABC concrete subsurface and deck overlays occurring? (ie Grouted joints, center span…)

12) What are your standard de-icing procedures/protocols (if any)?

    WSDOT uses preemptive brine solutions and salt/sand mixtures.
REFERENCES


ACRONYMS

ABC- Accelerated Bridge Construction
DOT – Department of Transportation
Lb – pound
Psi – Pounds per square inch
SPMT - Self Propelled Modular Transport