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Impact of Exposure on Thin Epoxy Overlay Performance

Abul Fazal Mazumder
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IMPACT OF EXPOSURE ON THIN EPOXY OVERLAY PERFORMANCE

by

Abul Fazal Mazumder

A dissertation submitted to the Graduate College
in partial fulfillment of the requirements
for the degree of Doctor of Philosophy
Civil and Construction Engineering
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Doctoral Committee:

Upul Attanayake, Ph.D., Chair
Xiaoyun Shao, Ph.D.
Neal Berke, Ph.D.
Thin epoxy overlays are used for improving the condition and extending the service life of bridge decks. The tensile bond pull-off strength, evaluated as per the ASTM C1583, is used as the performance indicator. A failure in the substrate with a tensile strength of 250 psi or greater is considered acceptable. However, the performance evaluated on in-service bridge decks shows inconsistent results. Laboratory studies by several researchers documented a distinct performance difference when the overlays are exposed to room temperatures in comparison to elevated temperatures. However, the most influential parameters such as concrete surface profile, thermal compatibility between overlay and concrete, the variation of substrate moisture against temperature, epoxy softening, and mechanical and interface epoxy properties under elevated temperatures were not measured and correlated to the observed performance. The performance of a concrete-overlay system depends on the mechanical and interface properties of epoxy, concrete surface profile, concrete properties, and exposure conditions. This study included experimental and numerical investigations to provide clarifications to the observed performance differences by evaluating the impact of concrete age at the time of epoxy application, concrete mix ingredients, exposure conditions, concrete microstructure development, substrate moisture and temperature,
concrete surface profile, and epoxy properties on the performance of two epoxy overlays. Experimental results confirm that (i) the performance of epoxy overlays improves when the concrete mix contains slag and (ii) substrate moisture vapor pressure and epoxy softening under elevated temperature negatively affect the overlay performance. The concrete/epoxy bond interface undergoes higher degradation when subjected to an elevated temperature. The results obtained from the numerical analyses indicate a concrete surface profile of 6–8 with a height-space ratio of surface irregularities of 0.45 provides the maximum bond capacity for a thin epoxy overlay on a concrete mix with 35% slag and 65% Type I cement.
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Finally, I am very grateful to my beloved wife, daughter, and son for their emotional and moral support throughout my Ph.D. journey. I would like to express my deepest gratitude to my brother, sisters, and other relatives for their love, patience, encouragement, and prayers. I am very
Acknowledgments - Continued

grateful to my beloved father and mother and would like to dedicate my work to their departed souls.

Abul Fazal Mazumder
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CHAPTER 1

INTRODUCTION

1.1 Problem Statement

Bridge decks that are exposed to de-icing salts, harsh environmental conditions, and traffic loading while sheltering the rest of the bridge components from such adverse conditions need to be well maintained to enhance the service life of the structure. The wet and dry curing practices and the quality assurance and quality control (QAQC) procedures implemented on typical concrete mixes used for bridge decks and repairs are expected to result in durable bridge decks. However, randomly dispersed cracking developed in the decks under volume change loads and the constraints provided by the girders and other components are documented (Aktan et al. 2003). The durability of such decks is improved by bridging or sealing the cracks with a flood coating (i.e., a thin epoxy overlay or a healer sealer) (DeRuyver and Schiefer 2016). The deck condition, the intensity of cracks, causes of cracking, need for increased skid resistance, available funding, and project costs are the decision parameters for selecting a flood coating (DeRuyver and Schiefer 2016). Depending on the condition, decks are patched or repaired before the application of a flood coat. The typical practice of the Departments of Transportation (DOTs) is to maintain a total of 28 days of curing (wet and dry curing) for new concrete in patches and repairs before the application of a flood coat. The application of thin epoxy overlays is preferred over healer sealers as a crack bridging flood coating while evaluating the preventive maintenance options (DeRuyver and Schiefer 2016).
The deck surface is shotblasted and cleaned before the application of epoxy overlays. Shotblasting removes surface contaminants and develops a surface profile by exposing large size aggregates, as per the International Concrete Repair Institute (ICRI) guidelines, to ensure adequate bonding of the overlay with the concrete substrate (DeRuyver and Schiefer 2016). After preparing the deck surface, the substrate moisture condition is evaluated. With an acceptable moisture content and the presence of satisfactory conditions stipulated by the highway agency and the epoxy manufacturer, the epoxy overlay is applied in two coats. A layer of aggregate is broadcasted following the application of each layer to maintain friction. After maintaining the specified curing duration, overlay performance is evaluated using the tensile bond pull-off strength test described in the American Society for Testing and Materials (ASTM) C1583 (2013).

Sprinkel et al. (1993) evaluated the performance of thirteen epoxy overlays applied on 24 bridge decks located across seven states. The average bond strength values recorded at different ages are shown in Figure 1.1a. As shown in the figure, the average bond strength values recorded in subsequent years following the application are lower than 250 psi. Wilson and Henley (1995) documented similar observations when the performance of four epoxy overlays applied on 13 bridges was evaluated (Figure 1.1b). Unfortunately, none of these data sets included substrate temperature and moisture conditions at the time of testing and the ambient condition histories to evaluate the potential impact of such parameters on the performance.

The typical recommendation of epoxy manufacturers and the practice of highway agencies are to maintain a 28-day curing period for new concrete in patches and repairs. This curing duration typically involves 7 days of wet curing and 21 days of dry curing. Even though the wet curing duration is sometimes extended beyond 7 days for concrete mixes with certain supplementary
cementitious materials the total curing duration is still limited to 28 days. This practice requires closing a facility, such as a bridge, for at least 28 days. Therefore, there is an interest to evaluate the possibility of applying thin epoxy overlays within the dry curing period and opening the facilities to their typical operations after 28 days. To evaluate the possibility of applying thin epoxy overlays within the dry curing duration, Shearrer et al. (2015) developed an experimental program including five epoxy overlays. Concrete slabs were prepared using three concrete mixes and wet cured for 14 days. The mix designs of these mixes are presented in Table 1.1. Among the concrete mixes, the fly ash concrete mix contains 25% Class F fly ash. The overlays were applied after dry curing the slabs for 3, 7, 14, and 21-days following 14 days of wet curing. One set of slabs with overlays was cured at 73°F (room temperature – RT) while the other set was cured at 122–125°F (elevated temperature – HS). Figures 1.1c and d show performance comparison based on concrete mixes and epoxy types under different overlay application age and exposure conditions. As shown in the figures, the bond strength under room temperature was greater than the specified minimum of 250 psi, irrespective of the concrete mix and the concrete age at the time of overall application. However, the bond strength was lower when the slabs were subjected to an elevated temperature but increased with an extended dry curing period. Shearrer et al. (2015) concluded that the possible cause for the lower bond strength under elevated temperature could be the moisture vapor pressure developed at the interface. Unfortunately, the variation of moisture within the slabs was not measured to support this conclusion. Out of the three mixes used for the evaluation, the bond strength was higher in the mix with fly ash compared to the mixes with Type I cement. One possible reason for this observation could be the lower rate of moisture migration in the concrete with fly ash. The investigation by Shearrer et al. (2015) was limited to assessing the performance immediately after overlay application and curing.
Although the overlays are applied after a specified curing period as per the highway agency and manufacturer specifications the field performance is inconsistent. The performance of a concrete-overlay system depends on many parameters including mechanical and interface properties of epoxy, concrete surface profile, concrete properties, and exposure conditions. The studies conducted so far led to inconclusive conclusions since inadequate data were reported. Therefore, there is a need to understand the performance of epoxy overlays under different exposure conditions and measure the epoxy overlay performance impacting parameters.

Figure 1.1 Performance of epoxy overlays under field and laboratory conditions
Note: RT = room temperature; HS = elevated temperature (heated slabs).
Table 1.1  Mix Design of Concrete Mixes Used by Shearrer et al. (2015)

<table>
<thead>
<tr>
<th>Material</th>
<th>Control</th>
<th>Low-cracking</th>
<th>Fly ash</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse aggregate (lb)</td>
<td>1.837</td>
<td>1.858</td>
<td>1.884</td>
</tr>
<tr>
<td>Fine aggregate (lb)</td>
<td>1.250</td>
<td>1.264</td>
<td>1.282</td>
</tr>
<tr>
<td>Cement-Type I (lb)</td>
<td>550</td>
<td>550</td>
<td>412.5</td>
</tr>
<tr>
<td>Fly ash(^a) (lb)</td>
<td>0</td>
<td>0</td>
<td>137.5</td>
</tr>
<tr>
<td>Water-cementitious material ratio</td>
<td>0.50</td>
<td>0.44</td>
<td>0.50</td>
</tr>
<tr>
<td>Water reducer (fl oz/lb-cementitious material)</td>
<td>20.25</td>
<td>27.08</td>
<td>0</td>
</tr>
</tbody>
</table>

\(^a\)25% Class F fly ash was used in Fly ash concrete.

1.2 Research Objectives and Tasks

The research objective is to evaluate the impact of concrete age on thin epoxy overlay performance. To achieve the objective, the following specific tasks were performed:

1. Perform a comprehensive literature review to document epoxy overlay performance and the parameters influencing the performance.
2. Develop a testing plan and evaluate the impact of identified parameters on the performance of thin epoxy overlays.
3. Analyze the results and provide conclusions and recommendations.

To achieve the objective, a research methodology was developed and presented in Chapter 2.

1.3 Research Scope

The scope of this research is limited to evaluating the tensile bond strength as the performance parameter of two thin epoxy overlays. Two concrete mixes were used as the substrate. Overlays were applied on new concrete at 14, 21, and 28 days of concrete age. Tensile bond strength was evaluated under laboratory and outdoor exposure. Epoxy properties such as dynamic viscosity and epoxy softening under elevated temperature and moisture were evaluated to provide clarifications to the observed performance. A numerical study was performed to evaluate the
influence of mechanical and interface properties of epoxy and concrete surface profiles on the
tensile bond strength.

1.4 Organization of the Study

This dissertation is organized into 7 chapters.

Chapter 1 includes the problem statement, research objectives, and scope.

Chapter 2 describes the research methodology.

Chapter 3 documents guidelines and practices of highway agencies, manufacturer requirements,
the performance of epoxy overlays, epoxy and concrete properties affecting epoxy
overlay performance, and methods to evaluate epoxy and concrete property and
performance of epoxy overlays.

Chapter 4 describes the testing plan to evaluate concrete and epoxy properties, experimental
results, and observations.

Chapter 5 describes the evaluation of system performance through numerical investigations and
results.

Chapter 6 includes a summary, conclusions, and recommendations.

Chapter 7 presents the cited references.
CHAPTER 2

METHODOLOGY

A research methodology was developed to accomplish the objective of this study. Figure 2.1 shows the research methodology. As shown in the figure, six tasks (Task-1 to Task-6) were accomplished to achieve the objective.

![Research methodology diagram]

Figure 2.1 Research methodology

Task-1: Literature Review

A comprehensive review of DOT manuals and guides and national and international literature was completed to document the state-of-the-art and practice of thin epoxy overlay application and
performance. Several epoxy product datasheets were reviewed to document the manufacturers’ recommendations on the thin epoxy overlay application. The performance evaluation, factors affecting the overlay performance, and experimental and numerical investigation on epoxy adhesives were also documented. The impact of epoxy and concrete properties on the overlay performance was summarized and presented. The testing methods and procedures of epoxy and concrete properties, and overlay performance were documented. The findings are documented in Chapter 3.

**Task-2: Develop a Testing Plan**

A testing plan was developed to evaluate the epoxy and concrete properties, and overlay performance under different exposure conditions following the testing methods and procedures identified in Task-1. The goal of the testing plan was to evaluate the impact of concrete mixes, epoxy application ages, and exposure conditions and duration on the overlay performance. The testing plan is presented in Chapter 4.

**Task-3: Prepare Specimens and Conduct QAQC Testing**

To fulfill the goal of Task-2, cylinder, beam, and slab specimens were fabricated to evaluate the concrete properties and overlay performance. The fresh concrete properties were evaluated on specimen fabrication day. Specimens to evaluate the epoxy properties were also fabricated. All the specimens were fabricated following the standard procedures. The specimen fabrication and description are presented in Chapter 4.
Task-4: Evaluate the Epoxy and Concrete Properties, and Overlay Performance

The fabricated specimens were tested following the standard procedures to evaluate the epoxy and concrete properties and the performance of epoxy overlays. The obtained results were analyzed and documented in Chapter 4.

Task-5: Numerical Simulation in ABAQUS Environment

Numerical models were developed in ABAQUS Environment to understand the concrete/overlay bond interface behavior under different exposure conditions. The concrete-epoxy system was simulated in a flat contact model and a contact model with surface irregularities. The mechanical and interface properties of epoxy were obtained from the literature review performed in Task-1. The results obtained from this task are documented in Chapter 5.

Task-6: Summary, Conclusions, and Recommendations

Based on the outcome of Task-4 and Task-5, the summary, conclusions, and recommendations were added in Chapter 6.
CHAPTER 3

LITERATURE REVIEW

3.1 Overview

Epoxy is a mixture of two components: a resin and a binder. Usually, the mixing proportions vary from 1:1 to 4:1. The mixture of these two parts produces a thermosetting resin that can tolerate substrate moisture influence to a certain extent (Potter 1975). The overlay system can bridge micro-cracks and create a good skid-resistant driving surface when an aggregate layer is broadcasted. The typical thickness of an epoxy overlay is \( \frac{3}{8} \) to \( \frac{1}{2} \) in. (Sika Corporation 2011). An epoxy overlay application requires shotblasting the deck surface following a minimum specified concrete curing duration, cleaning the surface, and maintaining a period for overlay curing before opening to traffic. This chapter discusses thin epoxy overlay application practice of state highway agencies, requirements in epoxy manufacturer technical datasheets, the performance of epoxy overlays, factors affecting overlay performance, the experimental and numerical investigation on epoxy adhesive, epoxy and concrete property affecting epoxy overlay performance, and standard methods to evaluate epoxy and concrete properties, and the performance of epoxy overlays.

3.2 Thin Epoxy Overlay Application: Practice of State Highway Agency

Wet and dry curing requirements, substrate preparation methods, application requirements, and performance evaluation methods of 11 state highway agencies were reviewed and summarized in Table 2.1. The information presented in the table is primarily compiled from the publications.
available on the respective highway agency websites and the information collected through limited communications. The epoxy overlay application process starts after completing a specified wet and dry curing period. As an example, Florida, Illinois, Michigan, and New York require 28 days of curing as the standard practice. This duration includes 7 days of wet and 21 days of dry curing. Even though the Michigan Department of Transportation (MDOT) standard wet curing duration is listed as 7 days, the current stipulations in the Standard Specifications for Construction (MDOT 2012) provide flexibility for extending the curing duration beyond 7 days by specifying 7-day minimum compressive and flexural strength requirements. Similarly, Alabama, California, Indiana, Ohio, Iowa, and Pennsylvania evaluate concrete compressive strength to decide on the wet curing duration. Even though the typical wet curing duration specified by a majority of the agencies is 7 days, Wisconsin and Pennsylvania specify 14 days while Iowa specifies only 4 days. Following the specified wet and dry curing periods, the concrete surface is prepared for the epoxy overlay application. The most common surface preparation method is shotblasting since it exposes large size aggregates for ensuring a sufficient bond between the epoxy overlay and the substrate. After shotblasting, the surface is cleaned using a vacuum. The next step is to evaluate the concrete surface profile and moisture content. A concrete surface profile (CSP) of 5, 6, or 7 is commonly used. The American Concrete Institute (ACI) recommended minimum CSP for epoxy overlay application is 5 (ACI 548.8 2019). As shown in the table, certain states are very strict, and only one profile is specified. Overlay performance is influenced by surface and near-surface moisture, which is most commonly evaluated following the procedures described in the ASTM D4263. The specification requires using a 4 mil thick 18 × 18 in. polythene sheet of which the perimeter is sealed using an adhesive tape to check moisture accumulation during a period of 16 hours. As shown in the table, the highway agencies modified the duration for practical purposes. As an
example, Florida performs a capillary moisture test for 5 hours, whereas Michigan moisture test duration is the greater of 3 hours or a period recommended by the epoxy manufacturer. As an alternative to ASTM D4263 procedures, Wisconsin and New York implement ASTM F2659 procedures to measure substrate moisture using electrical impedance meters. Wisconsin allows overlay applications when the substrate moisture content is less than 4.5%, whereas the limit in New York is 5%. With an acceptable moisture content, an epoxy overlay is applied following the procedures and other requirements stipulated in highway agency manuals, guides, and special provisions, or manufacturer technical datasheets. Other than the CSP and substrate moisture requirements, ambient conditions (temperature, humidity, and wind), rain forecast, substrate temperature, and material temperature are considered. As shown in the table, ambient humidity and wind speed are not considered by many agencies. Several agencies specified the maximum limit of substrate temperature to 100°F while the Ohio limit is 120°F. An epoxy overlay is a two-layer coating system. The thickness of each layer is \( \frac{3}{16} \) in. A layer of aggregate is broadcasted following an application of each epoxy layer. Typically, trap rock, chipped flint, bauxite, or silica sand is used (DeRuyver and Schiefer 2016). At the end of the specified epoxy overlay curing period, a tensile bond pull-off strength test is conducted as per the ASTM C1583 procedure to evaluate the overlay performance.
<table>
<thead>
<tr>
<th>State</th>
<th>Application time (days)</th>
<th>Substrate preparation method</th>
<th>Application requirements</th>
<th>Performance evaluation</th>
</tr>
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<td>AL</td>
<td>7 (min) + f&lt;sub&gt;c&lt;/sub&gt;, 1</td>
<td>28 - WC</td>
<td>N&lt;sup&gt;1&lt;/sup&gt; Y&lt;sup&gt;4&lt;/sup&gt; N</td>
<td>na&lt;sup&gt;3&lt;/sup&gt; N</td>
</tr>
<tr>
<td>CA</td>
<td>7 (min) + f&lt;sub&gt;c&lt;/sub&gt;</td>
<td>28 - WC</td>
<td>N Y N na</td>
<td>N</td>
</tr>
<tr>
<td>FL</td>
<td>7</td>
<td>14 (+21)&lt;sup&gt;2&lt;/sup&gt;</td>
<td>N Y N MS&lt;sup&gt;6&lt;/sup&gt;</td>
<td>ASTM D4263 (5 h)</td>
</tr>
<tr>
<td>IA</td>
<td>4 (min) + f&lt;sub&gt;c&lt;/sub&gt;</td>
<td>28 - WC</td>
<td>N Y N 6 or 7</td>
<td>ASTM D4263 (2 h)</td>
</tr>
<tr>
<td>IL</td>
<td>7</td>
<td>21</td>
<td>N Y N na</td>
<td>ASTM D4263 (2 h)</td>
</tr>
<tr>
<td>IN</td>
<td>7 (min) + f&lt;sub&gt;c&lt;/sub&gt;</td>
<td>28 - WC</td>
<td>N Y N 5, 6, or 7</td>
<td>ASTM D4263</td>
</tr>
<tr>
<td>MI</td>
<td>7 (min) + f&lt;sub&gt;c&lt;/sub&gt;, f&lt;sub&gt;r&lt;/sub&gt;</td>
<td>28 - WC</td>
<td>N Y N 7</td>
<td>ASTM D4263 (Longer of 3 h or MS)</td>
</tr>
<tr>
<td>NY</td>
<td>7</td>
<td>21</td>
<td>N Y N 5 or 6</td>
<td>ASTM D4263 (2 h) or ASTM F2659&lt;sup&gt;7&lt;/sup&gt; (&lt; 5% moisture)</td>
</tr>
<tr>
<td>OH</td>
<td>7 (min) + f&lt;sub&gt;c&lt;/sub&gt;</td>
<td>28 - WC</td>
<td>N Y N na</td>
<td>na</td>
</tr>
<tr>
<td>PA</td>
<td>14 (min) + f&lt;sub&gt;c&lt;/sub&gt;</td>
<td>28 - WC</td>
<td>N Y N 5, 6, or 7</td>
<td>ASTM D4263 (2 h)</td>
</tr>
<tr>
<td>WI</td>
<td>14</td>
<td>14</td>
<td>N Y N 5</td>
<td>ASTM D4263 (2 h) or ASTM F2659 (&lt; 4.5% moisture)</td>
</tr>
</tbody>
</table>

1. f<sub>c</sub> and f<sub>r</sub> denotes the required compressive and flexural strengths at the end of the specified wet curing duration.
2. In 2018, FDOT developed specification 403 to implement a 21-day DC period.
3. No
4. Yes
5. Not available
6. Manufacturer specifications
7. Electrical impedance meter
8. California Testing Methods
9. Indiana Testing Methods
3.3 Manufacturer Recommendations

Table 3.2 summarizes the application requirements of several epoxy overlays supplied by BASF, E-Bond, E-Chem, Euclid Chemical, Poly-Carb, Sika, Transpo, and Unitex. These products are MDOT approved epoxy overlays (MDOT 2018). The minimum age of concrete, concrete surface profile, optimum moisture content, and ambient and substrate temperature are the listed parameters. Epoxy overlays supplied by Sika and Unitex can be applied on 21 days or older concrete. Concrete must be at least 28 days or older to receive overlays supplied by the other manufactures. The application of an epoxy overlay requires a CSP of 5–7. The required level of substrate moisture content or moisture vapor emission rate (MVER) is not stated in many technical datasheets. Even though E-Chem EP50 is insensitive to moisture, the application of Euclid Chemical products requires a lower MVER. Only Unitex has indicated moisture content requirements for overlays. Moisture content of less than 4% is required for a Pro-Poxy Type III DOT overlay application.

<table>
<thead>
<tr>
<th>Supplier</th>
<th>Product</th>
<th>Minimum age of concrete (days)</th>
<th>CSP</th>
<th>Moisture content</th>
<th>Substrate temperature (°F)</th>
<th>Ambient temperature (°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BASF</td>
<td>MasterSeal 350</td>
<td>28</td>
<td>5</td>
<td>na</td>
<td>≥ 50</td>
<td>≥ 50</td>
</tr>
<tr>
<td>E-Bond</td>
<td>526 Lo-Mod</td>
<td>28</td>
<td>5</td>
<td>na</td>
<td>≥ 50</td>
<td>≥ 50</td>
</tr>
<tr>
<td>E-Chem</td>
<td>EP50</td>
<td>28</td>
<td>5</td>
<td>Insensitive</td>
<td>na</td>
<td>≥ 50</td>
</tr>
<tr>
<td>Euclid Chemical</td>
<td>Flexolith Summer Grade</td>
<td>28</td>
<td>4–6</td>
<td>MVER should not be high</td>
<td>40–90</td>
<td>40–90</td>
</tr>
<tr>
<td></td>
<td>Flexolith HD</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Poly-Carb</td>
<td>Flexogrid Mark-163</td>
<td>na</td>
<td>na</td>
<td>na</td>
<td>≥ 50</td>
<td>≥ 50</td>
</tr>
<tr>
<td></td>
<td>Flexogrid Mark-154</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sika</td>
<td>Sikadur 22-Lo Mod</td>
<td>21–28</td>
<td>3–4</td>
<td>na</td>
<td>≥ 40</td>
<td>≥ 40</td>
</tr>
<tr>
<td>Transpo</td>
<td>T-48 Chip Seal</td>
<td>na</td>
<td>5</td>
<td>na</td>
<td>50–100</td>
<td>50–100</td>
</tr>
<tr>
<td>Unitex</td>
<td>Pro-Poxy Type III DOT</td>
<td>21–28</td>
<td>6–7</td>
<td>&lt; 4%</td>
<td>≥ 50</td>
<td>≥ 50</td>
</tr>
</tbody>
</table>

Note: CSP = concrete surface profile; na = not available; MVER = moisture vapor emission rate.
3.4 Epoxy Overlay Performance

3.4.1 Performance Evaluation under Field and Laboratory Conditions

Sprinkel (1983) conducted an experimental study using two types of epoxy overlays to determine the thermal compatibility between concrete and thin polymer epoxy overlays. The scope of the study included the evaluation of dynamic modulus of elasticity, coefficient of thermal expansion, shear strength, tensile bond pull-off strength at the interface, rapid chloride permeability, and delamination. The temperature cycles between 10° F to 100° F were maintained. The increase in the number of thermal cycles reduced shear strength and bond strength at the concrete/overlay interface and increased delamination and permeability.

Gama (1999) studied the durability of thin epoxy overlays. Gama’s study included the following tests on concrete specimens with overlays: a falling-head water permeability test, a rapid chloride ion penetration test, a water absorption test, a flexure strength test of saturated specimens, a thermal compatibility test under -58° F to 104° F temperature for 103 cycles, and the interface water vapor pressure test. The impact of water vapor pressure on the integrity of the overlay bond was evaluated using ultrasonic pulse velocity (UPV) and tensile bond pull-off strength tests. The concrete portion of the specimens was submerged in water, and the overlay was exposed to an elevated temperature of 122° F using an ultraviolet heat lamp for two weeks. The UPV and bond strength tests were conducted before placing the specimens in water and after the specimens cooled down to room temperature and immediately after removal from the water bath. According to Gama (1999), the integrity of the concrete-overlay system was not affected by the temperature cycles of -58° F to 104° F or the water vapor pressure. However, wet and dry curing periods,
concrete age at the time of overlay application, surface preparation methods, and surface profiles were not described.

Sprinkel et al. (1993) evaluated the performance of overlay systems and epoxy sealants by considering chloride ion ingress, corrosion of reinforcing bars, skid resistance and wear, direct bond and shear strengths at the interface, cracking, delamination, and spalls as the performance indicators. The results indicated that 13, 25, and 77 years of exposure are required to achieve a chloride content of 1 lb/yd³ at a depth of 1.75 in. from the top surface for concrete without any protection, concrete with epoxy sealers, and concrete with epoxy overlays, respectively. Tensile bond pull-off strength tests were performed on 24 in-service bridges across 7 states with 13 different epoxy overlays. The data collected in subsequent years following epoxy applications indicated inconsistent performance. Figure 1.1a shows the average bond strength values recorded at different ages. Unfortunately, additional data such as substrate temperature and moisture condition at the time of overlay application and testing are not available to evaluate the potential impact of such parameters on overlay performance or to clarify the reasoning behind performance inconsistencies.

Wilson and Henley (1995) evaluated the performance of epoxy overlays and methyl methacrylate (MMA) by considering the resistance to chloride ion penetration (AASHTO T277), friction, and tensile bond pull-off strength (ACI 503R). Both polymers provided excellent resistance to chloride ingress. The tensile bond pull-off strength was evaluated on 13 bridge decks with 4 epoxy overlays. The average bond strength evaluated immediately following application shows a significant variation, especially the bond strength of E4 epoxy. The bond strength of the E4 epoxy overlay degraded significantly after it was in service for 3 to 4 years (Figure 1.1b). Unfortunately,
adequate information, including the substrate and ambient temperature histories, is not available to evaluate the possible causes for lower bond strengths.

To evaluate the possibility of applying thin epoxy overlays within the dry curing period, Shearrer et al. (2015) developed an experimental program using five epoxy overlays and three different concrete mixes. The mix designs are presented in Table 1.1. Among these mixes, the fly ash concrete mix contains 25% Class F fly ash. Concrete slabs were wet cured for 14 days. The moisture content of the slabs was measured using an electrical impedance meter before applying epoxy overlays. The overlays were applied after dry curing the slabs for 3, 7, 14, and 21-days following 14 days of wet curing (i.e., at 17, 21, 28, and 35 days of concrete age). The concrete moisture content was almost consistent and ranged between 3.576~3.433% between 17 and 35 days of concrete age. One set of slabs with epoxy overlays was cured at 73° F (room temperature – RT) while the other sets were cured at 122–125° F (elevated temperature – HS). Figures 1.1a and b show the performance of overlays with respect to concrete mixes, epoxy types, overlay application age, and exposure conditions. As shown in the figures, the bond strength under room temperature is greater than the specified minimum of 250 psi irrespective of concrete mixes, application ages, and epoxy types. The bond strength was lower when the slabs were subjected to elevated temperatures. However, the bond strength under elevated temperatures increased with the increase in the dry curing duration. The moisture vapor pressure at the concrete/overlay interface was identified as the possible cause for the lower bond strength under elevated temperatures (Shearrer et al. 2015). Unfortunately, moisture variation within the slabs was not measured to support this conclusion. Out of the three mixes used in this study, the bond strength was consistently higher on the specimens prepared with the fly ash mix compared to the other two mixes with Type I cement. One possible reason for this observation could be the lower rate of
moisture migration in the concrete with fly ash. The investigation was limited to the evaluation of bond strength immediately after overlay application and curing. According to Shearrer et al. (2015), epoxy can be applied after 24–28 days of concrete age depending on the acceptable moisture content of the substrate.

The performance of epoxy overlays on two adjacent bridges near I-57 in Clifton, Illinois, was evaluated by Pfeifer and Kowalski (1999) considering chloride permeability, bond pull-off strength, and skid resistance as performance parameters. The results indicated that the epoxy overlays have the potential to perform as impermeable layers with high skid resistance for at least 15 years. Adam and Gansen (2001) evaluated the friction number and percent of delamination on one bridge deck with a MARK-163 Flexogrid epoxy overlay system. The overlay was applied in 1986, and the friction number and percent delamination were measured over 5 years. The friction number remained almost unchanged after epoxy application while the percent of delamination increased to 3.8% in 1991. The blisters in the overlay allowed moisture ingress and freezing caused delamination. Soltesz (2010) evaluated skid resistance and delamination of eight thin polymer overlay systems applied on two bridge decks. The products included Mark 154, Flexolith, Safetrack HW, Kwik Bond PPC MLS, Tyregrip, SafeLane HDX, Urefast PF60, and Unitex Pro-Poxy Type III DOT. The skid resistance was measured in the field using ASTM E274 procedures. After 3 years of service, only Tyregrip showed skid numbers of 50 and 54 in both bridges. Other epoxy overlays showed skid numbers less than the bare concrete. The overlay condition was visually inspected after 33 to 35 months following application. Tyregrip, Safetrack HW, and Unitex Pro-Poxy Type III DOT showed the highest numbers of delaminated areas. Fifteen (15) percent of Safetrack HW epoxy coated wheel paths were worn out after about 3 years of service. Soltesz (2010) evaluated the water absorption of epoxy resin and abrasion resistance of the overlay
system. The Urefast PF60 and Mark 154 epoxy resins absorbed the highest amount of water, 5.0% and 4.5% respectively. The water absorption of other products was less than 2.5%. The SafeLane HDX epoxy with Dolomitic limestone aggregate showed the highest weight loss of 1.2 g after 10 minutes of grinding during the abrasion resistance test. Other epoxy overlays showed a weight loss of 0.3~0.8 g. Soltesz (2010) evaluated mechanical properties such as tensile strength and tensile elongation of epoxy resin, along with flexural and compressive strengths of the overlay system. These properties were evaluated at 0, 70, and 140º F. The tensile strength and tensile elongation were also measured at 70º F after 0, 500, 1000, and 1500 hours of simulated sunlight exposure. The terrestrial sunlight exposure was simulated using ultraviolet light following ASTM G155. The tensile strength of resin along with the flexural and compressive strengths of overlay systems were significantly reduced under elevated temperatures. Even though the tensile elongation increased with temperature, the tensile elongation capacity decreased with the exposure duration to elevated temperatures. Pantelides and Weber (2011) evaluated tensile bond pull-off strength (ASTM C1583) and the water-soluble chloride content (ASTM C1218) along the depth of concrete to assess the performance of epoxy overlays on precast deck panels. The bond strength was evaluated before and after placing the panels on the bridge. The bond strength was more than the Utah DOT specified limit of 200 psi. Specimens for chloride content tests were ponded with a 3% NaCl solution for 90 days. The overlays were able to prevent chloride ingress. Young et al. (2014) evaluated the performance of SafeLane and Flexogrid. The tensile bond pull-off strength test (ASTM C1583) caused a failure in the substrate at a tensile strength greater than 250 psi. The acid-soluble chloride content test (ASTM C1152) results indicated that the overlays were effective in sealing concrete from chloride ingress. Tabatabai et al. (2016) evaluated the performance of thin polymer overlays. The tensile bond pull-off strength tests were performed after exposing the
specimens to freeze-thaw cycles, elevated temperatures, ultraviolet rays, and rain exposure cycles. Also, the accelerated corrosion test and tire wear test were conducted to assess the performance. The results indicated that the epoxy overlay systems provide the best performance compared to the healer sealer systems.

3.4.2 Performance Evaluation under Field Inspection and Survey

Issa et al. (1995) visually inspected 24 bridges (2 bridges in Illinois, 1 in Connecticut, 1 in Virginia, 1 in Maryland, 1 in Iowa, 2 in California, 8 in New York, 2 in Alaska, 1 in Ohio, and 4 in Pennsylvania) with latex-modified overlays, silica fume concrete overlays, epoxy overlays, and high-molecular-weight methacrylate crack sealants. The bridge decks with epoxy overlays and sealer materials performed better than the other overlays. However, the product names of epoxy overlays and sealing materials were not documented in the publication. Alger et al. (2003) administered a questionnaire to understand the anti-icing performance on bridge decks with epoxy overlays. Based on the results, a total of 37 bridges were selected to investigate the current coating conditions and the ease of snow removal, frost resistance, and skid resistance during winter. Also, a limited number of tensile bond pull-off strength tests were performed on 2 bridge decks. The bond strength of well-bonded epoxy overlays was more than the specified limit of 250 psi. The poorly bonded epoxy overlay strength was lower than 250 psi. It was presumed that an epoxy overlay coating would last for 15 years and a third layer applied by the end of 15 years would seal the deck for another 10 to 15 years, providing significant savings in terms of maintenance costs and safety. Nelson (2005) surveyed highway agency transportation engineers and maintenance specialists to understand the decision-making process for selecting urethanes, silicon-based sealers, and epoxy overlays for protecting bridge decks from chloride ingress and maintaining an
acceptable level of skid resistance. Nelson (2005) suggested applying epoxy overlays when both chloride barrier and improved skid resistance are desired. Harper (2007) studied 98 bridge decks with epoxy overlays in Missouri and documented cracking, pitting, delamination, peeling, missing areas of epoxy, cracks, spalling, and post overlay patches as defects. The recommendations to improve overlay performance include (i) avoiding an epoxy polymer overlay application when more than 5% of the deck area needs to be repaired, (ii) performing bond strength on patches and repairs to ensure adequate bond strength between concrete and repair/patch material, (iii) performing a moisture patch test following ASTM D4263, and (iv) properly mixing epoxies to remove air bubbles.

3.4.3 Anticipated Fix Life with Overlays

ElBatanouny et al. (2017) developed a service life model and conducted a life-cycle cost analysis (LCCA) to determine the best capital preventive maintenance options for bridge decks. For Northern bridge decks with 50 years of expected service life, penetrating silane sealers are recommended to be applied immediately after deck construction. Epoxy overlays are applied within 5 years of service. For a bridge deck with 100 years of expected service life, the epoxy overlays are applied immediately after construction and reapplied at every 25-year interval. Balakumaran and Weyers (2019) studied the long-term performance of epoxy overlays on 133 bridge decks in Virginia. The year built or reconstructed for the deck, roadway type, chloride application rate, and superstructure type (simple span or continuous span) and material were identified through multiple regression analysis as the major parameters affecting the overlay service life. The results indicated the range of service life to be 18 to 22 years at a 95 percent confidence level. According to the MDOT Bridge Deck Preservation Matrix (MDOT 2017), the
anticipated fix life with epoxy overlays range from 15 to 20 years, respectively. The anticipated fix life of Michigan decks with epoxy overlays is comparable to the average service life of epoxy overlays on Virginia bridge decks. Alger et al. (2003) evaluated 37 Michigan bridge decks with epoxy overlays and presumed that an epoxy overlay would last for 15 years and a third layer applied at the end of 15 years would seal the deck for another 10 to 15 years.

As discussed in Section 3.4.1, 3.4.2, and 3.4.3, the epoxy overlay performance is evaluated using the tensile bond pull-off strength test and the resistance to chloride ingress. The strength of the substrate is examined to assure adequate strength for the integrity of the system.

3.4.4 Factors Affecting Epoxy Performance

Thin epoxy overlays applied on bridge decks are exposed to various weather conditions. During winter, epoxy overlays undergo freezing. Epoxies typically operate well below -67°F temperature (Epotek 2017). The typical cryogenic temperature of epoxy is -238°F to the absolute zero temperature of -459°F (Epotek 2017). At cryogenic temperature, the molecular motion theoretically stopped completely (Britannica 2021). However, the epoxy properties and performance are fully reversible when the temperature is increased from cryogenic to room temperature (Epotek 2017). Therefore, freezing temperature does not impact significantly the epoxy properties and performance. The epoxy overlays show an adequate performance under weather conditions in spring and fall since the temperature is near 73°F. The epoxy performance is highly impacted due to summer conditions. Elevated temperature, moisture, and ultraviolet (UV) radiation during summer impact the properties and performance of epoxy overlays.

Figure 3.1 shows a heat flow curve of an epoxy. The figure shows a glass transition, a crystallization, and a melting temperature region. The flexible chain segments and side groups of
epoxy polymer start moving with a little applied thermal energy. These movements provide room for larger and rigid segments of cross-linked polymer chains to move. At the glass transition temperature region, the mobility of cross-linked polymer chain increases significantly and the epoxy polymer transforms from a hard-glassy material to a compliance state and behaves like a soft-rubbery material (Epotek 2012 and Epotek 2016). This is an endothermic state change. The epoxy properties and performance does not degrade when the epoxy is cooled to room temperature from the glass transition temperature (Epotek 2016). The polymer chains form an ordered arrangement and undergo crystallization when epoxy is heated to a temperature more than the glass transition temperature (Mettler-Toledo AG 2013). The crystallization is an exothermic state change. For further heating above crystallization temperature, the polymer chains move freely and undergo melting (Mettler-Toledo AG 2013). The melting is an endothermic state change.

![Figure 3.1 Heat flow curve of an epoxy](image)

During an elevated temperature, overlay shows lower performance because of (i) the reduction in mechanical and adhesion properties of an epoxy overlay, (ii) shear stress developed at the interface due to thermal incompatibility, (iii) moisture vapor pressure built up at the interface, or a combination thereof (Sprinkel 1983, Gama 1999, and Shearrer et al. 2015). Also, the tensile strength decreases, the elongation capacities increases, and the epoxy softens during prolonged
and repeated elevated temperature exposure resulting in bond failure at the interface (Soltesz 2010).

During rain or an elevated temperature, epoxy can absorb moisture. The absorbed moisture interacts with the polymer and acts as a plasticizer (Sperling 1986). Therefore, the mobility of the cross-linked polymer chains increases, and the epoxy starts softening at a much lower temperature than the glass transition temperature range (Sperling 1986). Therefore, the glass transition temperature is significantly reduced (Epotek 2012).

The UV radiation consists of UV-A, UV-B, and UV-C radiations. Among these rays, the ozone layer removes most of the UV-B and completely removes the UV-C. Therefore, the unremoved part of the UV-B and the UV-A comes to the earth. These UV radiations are harmful to epoxy polymer and affect the physical, chemical, and mechanical properties (Nikafshar et al. 2017). The UV radiations impact the key properties of epoxy such as cohesive and adhesive strengths of polymer and glass transition temperature. This effect is known as photodegradation. The UV rays have energy more than the chemical bond strength of epoxy polymer and form free radicals on the polymer surface (Asmatulu et al. 2007). Therefore, chemical bonds break during the photodegradation thus cohesive strength is reduced (Asmatulu et al. 2010). The UV rays also react with hydroxyl groups which are responsible for adhesion properties. The reduction in hydroxyl group concentration due to the reaction with UV rays reduces the adhesion strength. During photodegradation, the polar groups are formed in the polymer which prevents cross-linked polymer chain movement thus increase the glass transition temperature. Therefore, the polymer exhibits reduced flexibility and behaves similar to a brittle material. The rate of photodegradation
significantly increases because of many factors including humidity, temperature, oxygen, and pollutants.

3.4.5 Investigation on Epoxy Adhesive Performance

Epoxy adhesives are being used in automotive, ship, sports, and aerospace. These epoxy adhesives are exposed to the extreme environmental conditions such as photodegradation and elevated temperature. Numerous experimental and numerical studies have been conducted to evaluate the behavior of epoxy adhesive under such extreme conditions. The performance of adhesives was evaluated using single lap shear, double lap shear, end notched flexure, mixed-mode flexure, and double cantilever bending test under elevated and moisture exposure conditions (Loh et al. 2002, Banea 2012, Fernandez 2013, Sugiman 2012, Sugiman et al. 2013, Li and Li 2015, and Liu et al. 2016). Sugiman et al. (2013) and Liu et al. (2016) experimentally and numerically investigated the hygrothermal effect on epoxy adhesive performance. The mechanical and interface properties were experimentally evaluated using dog bone and double lap shear joint tests following ASTM D638 (modified) and D3528, respectively, under room temperature, elevated temperature dry, and elevated temperature wet conditions. The bilinear traction-separation law was used to model the cohesive interface between adhesive and adherents. The experimental and numerical work shows good agreement results in terms of stress at failure and failure modes.

3.5 Impact of Epoxy and Concrete Properties and Practices on the Epoxy Overlay Performance

The focus of this study is to understand the performance of epoxy overlays under different exposure conditions and evaluate epoxy overlay performance impacting factors. Epoxy and concrete properties and practices that are critical to the epoxy overlay performance are discussed below.
Thin epoxy overlays are applied on bridge decks with new concrete in patches and repairs after a 28-day prescribed curing period (MDOT 2018). Within this period, it is expected that the new concrete undergoes a majority of (anticipated) shrinkage, develops related cracking, and establishes an acceptable level of internal moisture. Attaining an acceptable internal moisture level depends on several parameters including concrete mix ingredients, curing conditions, moisture diffusion coefficient, the moisture profile along with the depth, and exposure conditions. The substrate moisture is evaluated before epoxy overlays placement. Once an overlay is applied and the required conditions and duration are maintained for curing, tensile bond pull-off strength tests are performed as per the ASTM C1583 (2013) to evaluate the performance.

Four different failure modes are observed during tensile bond pull-off strength tests (ASTM C1583 2013). A failure in the substrate is preferred at any age of concrete. A failure in the substrate occurs during a tensile bond pull-off strength test when the tensile strength of concrete is lower than the tensile strength and bond strength of the epoxy overlay (Sprinkel 1983). The bond failure at the concrete/overlay interface occurs when the bond strength is lower than the tensile strength of the epoxy overlay and concrete (Sprinkel 1983).

Failure in substrate depends on the tensile strength of concrete. Seventy percent (70%) of the specified design strength of a typical concrete is achieved within the wet curing duration (Basnayake et al. 2020). Therefore, concrete achieves tensile strength of more than 250 psi before the specified concrete age to apply an epoxy overlay. Bond failure at concrete/overlay interface is mostly observed under elevated temperatures with a bond strength lower than the specified limit. According to Sprinkel (1983), Gama (1999), and Shearrer et al. (2015), overlay bond failure under an elevated temperature is observed due to (i) the reduction in mechanical and adhesion properties
of an epoxy overlay, (ii) shear stress developed at the interface due to thermal incompatibility, (iii) moisture vapor pressure built up at the interface, or a combination thereof (Mazumder et al. 2021). Also, the epoxy resin loses the tensile strength and increases elongation capacities as well as softens during prolonged and repeated exposure to elevated temperatures resulting in bond failure at the interface (Soltesz 2010). To understand the softening behavior of epoxy, it is required to evaluate epoxy state changes under elevated temperature and develop a heat flow curve of epoxy under a suitable elevated temperature range. Another possible reason for interface bond failure is the reduction of an effective bond area because of concrete cracking after epoxy overlay application (Bakhsh 2010).

Concrete and epoxy overlay properties (such as modulus of elasticity, tensile strength, shear strength, and the coefficient of thermal expansion) are dissimilar. When the concrete-epoxy combined system is subjected to an elevated temperature, the magnitude of expansion in epoxy and concrete is different. This results in shear stresses at the interface. When concrete is exposed to an elevated temperature, moisture vapor travels towards the heated surface through connected capillary pores (Lyon 2014). The rate of moisture migration increases with the rise of surface temperature, and the rate is faster after concrete reaches a certain threshold temperature. The moisture accumulates at the interface when an impermeable barrier is placed on the surface. As a result, the accumulated moisture creates vapor pressure which negatively affects the bond strength.

The moisture migration in concrete depends on many parameters including concrete mix ingredients, moisture content along with the depth of concrete, pore structure, exposure condition, and drying period (Lawler et al. 2007). As an example, supplementary cementitious materials (SCMs) impact moisture migration in fresh and hardened concrete. The bleeding rate of Class C and Class F fly ash and silica fume concrete is much lower than Type I cement concrete while the
effect of Ground Granulated Blast Furnace Slag (GGBFS) on bleeding varies (IMCP 2007). The rapid chloride permeability (RCP) and the apparent chloride diffusion coefficient may or may not be lower in concrete mixes with SCMs than Type I cement. Lawler et al. (2007) fabricated specimens using four concrete mixes to evaluate RCP values as per AASHTO T277 at 56 days of concrete age and the apparent chloride diffusion coefficients as per AASHTO T259/T260 (modified). A set of $12 \times 12 \times 6$ in. specimens were ponded with a 15% NaCl solution after wet and dry curing them for 14 and 28 days, respectively. Following 6 months of ponding, acid-soluble chloride content was evaluated down to a depth of 3 in. from the top of the specimen by following AASHTO T260 procedures. Table 3.3 shows RCP values and the apparent chloride diffusion coefficients. As shown in the table, the chloride diffusion is lower in concrete with SCMs; thus, the moisture migration through the pore structure is lower. Even though the chloride diffusion is lower in concrete with SCMs, the magnitude depends on the type and the amount of SCMs. This difference can be attributed to the capillary pore structure discontinuity and the total permeable void volumes. The rate of strength and microstructure development is different with the type and the amount of SCMs. Therefore, it is required to evaluate the concrete porosity to understand the moisture migration under an elevated temperature.

**Table 3.3 RCP and Apparent Chloride Diffusion Coefficients for Mixes with SCMs (Lawler et al. 2007)**

<table>
<thead>
<tr>
<th>Cement (lbs/yd$^3$)</th>
<th>w/cm</th>
<th>SCM (%)</th>
<th>RCP data at 56 days (Coulomb)</th>
<th>Apparent chloride diffusion coefficient ($\times 10^{12}$ in.$^2$/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>658</td>
<td>0.40</td>
<td>NA</td>
<td>2878</td>
<td>1.221</td>
</tr>
<tr>
<td>560</td>
<td>0.37</td>
<td>15% Class C fly ash</td>
<td>3398</td>
<td>1.088</td>
</tr>
<tr>
<td>395</td>
<td>0.37</td>
<td>40% Class F fly ash</td>
<td>2072</td>
<td>1.106</td>
</tr>
<tr>
<td>428</td>
<td>0.37</td>
<td>35% GGBFS</td>
<td>1136</td>
<td>0.251</td>
</tr>
</tbody>
</table>

Note: NA = not applicable.

As discussed in this section, several epoxy and concrete properties and practices are important to understand the performance of epoxy overlays under different exposure conditions. Table 3.4
shows epoxy and concrete properties and practices that needed to be evaluated to understand the behavior of epoxy overlays. As an example, the heat flow curve is required to be developed to understand the softening behavior of epoxy under elevated temperatures.

Table 3.4 Epoxy and Concrete Properties and Practices to Understand the Behavior and Performance of Epoxy Overlays

<table>
<thead>
<tr>
<th>Epoxy</th>
<th>Concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) Epoxy softening</td>
<td>a) Concrete microstructure development</td>
</tr>
<tr>
<td></td>
<td>b) Substrate moisture condition</td>
</tr>
</tbody>
</table>

3.6 Epoxy and Concrete Properties and Overlay Performance Evaluation

Table 3.4 shows the epoxy and concrete properties to be evaluated to understand the performance of epoxy overlays under different exposure conditions. The performance of epoxy overlays is evaluated using a tensile bond pull-off strength test. The evaluation methods of epoxy and concrete properties and the performance of epoxy overlays are discussed in the following sections.

3.6.1 Epoxy Softening

The epoxy properties and performance are affected due to elevated temperature. Therefore, it is required to understand the behavior of epoxy under elevated temperature. The ASTM E1356 is a suitable method to develop a heat flow curve for the epoxy to understand the softening of epoxy under elevated temperature. The standard suggests using a differential scanning calorimeter.

3.6.2 Concrete Microstructure Development

The moisture migration of concrete depends on several parameters including concrete pore structure. The porosity test described in ASTM C642 is suitable to evaluate the microstructure development and the volume of total permeable voids in concrete.
3.6.3 Substrate Moisture Condition

Most highway agencies evaluate substrate moisture by following a modified version of the procedure described in ASTM D4263. However, several qualitative and quantitative methods are available to assess substrate moisture. The qualitative techniques include a capillary moisture patch test, a mat bond test, a primer or adhesive strip test, and an electrical resistance test using an electrical conductance meter. The quantitative methods include (i) using an electrical impedance meter, a nuclear gauge, and the gravimetric process, (ii) a moisture vapor emission rate (MVER) measurement, (iii) a surface relative humidity (RH) measurement, and (iv) an internal relative humidity (IRH) measurement. These qualitative and quantitative methods have limitations. The flooring industry uses MVER, surface RH, and IRH measurement techniques. Wisconsin and New York DOTs use electrical impedance meters.

3.6.4 Tensile Bond Pull-Off Strength

The performance of epoxy overlays is evaluated using the tensile bond pull-off strength test following ASTM C1583. The test is conducted after a 24-hour epoxy curing period. The other available test standards are ACI 503R, ASTM D4541, and ASTM D7234. ACI 503R and ASTM C1583 are similar.

Table 3.5 lists the parameters presented in Section 3.6 and several other parameters are required to evaluate through experimental procedures to collect necessary data to understand the performance of epoxy overlays. Other parameters include the dynamic viscosity of epoxy and quality assurance and quality control (QAQC) properties of concrete. One of the methods to evaluate the dynamic viscosity of epoxy is ASTM D2983 (Procedure D) using a Brookfield Viscometer. Concrete fresh and hardened properties are evaluated as QAQC testing.
Temperature, slump, density, and air content are concrete fresh properties evaluated following ASTM C1064, C143, C138, and C231, respectively. Compressive and flexural strengths are concrete hardened properties evaluated following ASTM C39 and C78, respectively.

Table 3.5  Epoxy and Concrete Properties and Epoxy Overlay Performance Evaluation Parameters and Measurands

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Measurand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Viscosity of epoxy</td>
<td>Dynamic viscosity</td>
</tr>
<tr>
<td>Epoxy softening</td>
<td>Heat flow against temperature</td>
</tr>
<tr>
<td>QAQC</td>
<td>Concrete fresh properties</td>
</tr>
<tr>
<td></td>
<td>Temperature</td>
</tr>
<tr>
<td></td>
<td>Slump</td>
</tr>
<tr>
<td></td>
<td>Density</td>
</tr>
<tr>
<td></td>
<td>Air content</td>
</tr>
<tr>
<td>Concrete hardened properties</td>
<td>Compressive strength</td>
</tr>
<tr>
<td></td>
<td>Flexural strength</td>
</tr>
<tr>
<td>Concrete microstructure development</td>
<td>Porosity</td>
</tr>
<tr>
<td>Concrete moisture condition</td>
<td>Moisture vapor emission rate (MVER)</td>
</tr>
<tr>
<td></td>
<td>Moisture content</td>
</tr>
<tr>
<td></td>
<td>Internal relative humidity (IRH)</td>
</tr>
<tr>
<td>Overlay performance</td>
<td>Tensile bond pull-off strength</td>
</tr>
</tbody>
</table>

3.7 Summary

Epoxy overlays have been used since the 1990s to extend the service life by protecting bridge decks from chloride-laden moisture ingress. Epoxy overlay applications require completing a 28-day curing period, preparing the substrate surface, and meeting application requirements set by the respective highway agency and the product manufacturer. Epoxy overlay performance is evaluated using the tensile bond pull-off strength test. The performance of epoxy overlays is documented in the literature. Unfortunately, none of the publications presents the most influential overlay performance impacting parameter to support the conclusions. The performance of a concrete-overlay system depends on many parameters including mechanical and interface properties of epoxy, concrete surface profile, concrete properties, and exposure conditions. The parameters listed in Table 3.5 are required to evaluate experimentally to understand the
performance of epoxy overlays under different exposure conditions. The influence of epoxy mechanical and interface properties and concrete surface profile is evaluated using numerical simulation models. However, the impact of UV radiation is not considered in this study.
CHAPTER 4

EXPERIMENTAL INVESTIGATION

4.1 Overview

The field performance of thin epoxy overlays is inconsistent although overlays are applied after a specified curing period as per the highway agency and manufacturer specifications. The studies conducted so far led to inconclusive conclusions since the most influencing overlay performance impacting parameters were reported not systematically investigated. Therefore, it is necessary to bring clarity to the current understanding by evaluating the impact of two different concrete mixes, epoxy application ages, and exposure conditions and duration on the performance of two epoxy overlays. This chapter presents the experimental studies conducted to evaluate the performance of two thin epoxy overlays under different exposure conditions, and the findings.

4.2 Epoxy and Concrete Properties and Overlay Performance Evaluation

The epoxy properties and the performance of two epoxy overlays were evaluated under different exposure conditions. The selected epoxies are Pro-Poxy Type III DOT of Unitex (Unitex 2015) and 526 Lo-Mod of E-Bond (E-Bond Epoxies, Inc.). These epoxies were selected from the MDOT approved product list (MDOT 2018). These epoxies are labeled as E1 and E2 throughout this dissertation. Both epoxies require pre-mixing of resin and binder before application. The resin and binder undergo an exothermic chemical reaction and maintains a gel time of about 19 minutes before setting at a temperature closer to 180°F. Table 4.1 presents the overlay properties such as
dynamic viscosity, tensile strength, elongation at break, tensile bond pull-off strength, slant shear bond strength, and thermal compatibility. These properties vary in the field depending on various parameters including the ambient conditions during the epoxy overlay application. Tensile strength, elongation at break, slant shear bond strength, and thermal compatibility presented in Table 4.1 are collected from the manufacturers’ technical datasheets. These epoxies satisfied the thermal compatibility requirements evaluated within the temperature range of -6~73.5º F following ASTM C884.

The viscosity and softening of epoxy were evaluated as epoxy properties. The performance of these epoxy overlays was evaluated on the bridge deck joint repair (BDJR) and Grade DM concrete mixes under three epoxy application ages and laboratory and outdoor exposure conditions. These are standard concrete mixes of MDOT. The BDJR is an expansion joint repair and deck patching material. Grade DM is the standard bridge deck concrete mix. The mix designs of both concrete mixes are presented in Table 4.2. As shown in the table, the Grade DM concrete mix contains 35% GGBFS while BDJR contains only Type I cement. A hydration controlling admixture was used in Grade DM concrete to increase the setting time during casting. Table 4.3 shows the epoxy and concrete properties, performance evaluation, and associated experimental parameters for one concrete mix and one epoxy overlay. As shown in the table, the dynamic viscosity and heat flow were evaluated, the basic QAQC testing was performed, concrete microstructure development was evaluated, substrate moisture was measured, and the epoxy overlay performance was evaluated under laboratory and outdoor exposure conditions. A continuously submerged wet curing was provided according to ASTM C192 through the testing ages for ASTM specimens. All the other specimens were moist cured for 7 days. The testing plan for each evaluation parameter is discussed in the following sections.
Table 4.1 Properties of Thin Epoxy Overlays

<table>
<thead>
<tr>
<th>Property</th>
<th>ASTM standard</th>
<th>E1</th>
<th>E2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile strength (psi)</td>
<td>D638</td>
<td>&gt; 3000</td>
<td>2500–5000</td>
</tr>
<tr>
<td>Elongation at break (%)</td>
<td></td>
<td>≥ 30</td>
<td>30–80</td>
</tr>
<tr>
<td>Slant shear bond strength (psi)b</td>
<td>C882</td>
<td>≥ 2500</td>
<td>1600</td>
</tr>
<tr>
<td>Thermal compatibility</td>
<td>C884</td>
<td>Pass</td>
<td>No delamination</td>
</tr>
</tbody>
</table>

Note: ASTM = American Society for Testing and Materials.

Table 4.2 Mix Design of BDJR and Grade DM Concrete

<table>
<thead>
<tr>
<th>Material</th>
<th>Quantity (per yd³)</th>
<th>BDJR</th>
<th>Grade DM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse aggregate (SSD) (lbs)</td>
<td>1,488</td>
<td>1,644</td>
<td></td>
</tr>
<tr>
<td>Fine aggregate (SSD) (lbs)</td>
<td>1,557</td>
<td>1,356</td>
<td></td>
</tr>
<tr>
<td>Cement--Type I (lbs)</td>
<td>656</td>
<td>397</td>
<td></td>
</tr>
<tr>
<td>GGBFS (lbs)</td>
<td>NA</td>
<td>214</td>
<td></td>
</tr>
<tr>
<td>Water (lbs)</td>
<td>246</td>
<td>235</td>
<td></td>
</tr>
<tr>
<td>Air entraining admixture (fl oz)</td>
<td>5.07</td>
<td>10.78</td>
<td></td>
</tr>
<tr>
<td>Hydration controlling admixture (fl oz)</td>
<td>NA</td>
<td>18.56</td>
<td></td>
</tr>
<tr>
<td>Water reducing admixture (fl oz)</td>
<td>58.67</td>
<td>54.44</td>
<td></td>
</tr>
<tr>
<td>Water-cementitious material ratio</td>
<td>0.38</td>
<td>0.39</td>
<td></td>
</tr>
</tbody>
</table>

Note: BDJR = bridge deck joint repair concrete mix; Grade DM = standard concrete mix for Michigan bridge decks; SSD = saturated surface dry; NA = not applicable.
<table>
<thead>
<tr>
<th>Evaluation parameter (a)</th>
<th>Measurand (b)</th>
<th>ASTM standard (c)</th>
<th>Size of the specimen (in.) (d)</th>
<th>Concrete age at the time of overlay application (e)</th>
<th>Exposure conditions (f)</th>
<th>Concrete age at the time of testing (days) (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Epoxy property</td>
<td>Dynamic viscosity</td>
<td>D2983 (Procedure D)</td>
<td>As per the ASTM</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td></td>
<td>Heat flow against temperature</td>
<td>E1356</td>
<td>As per the ASTM</td>
<td>NA</td>
<td>Without moisture</td>
<td>NA</td>
</tr>
<tr>
<td></td>
<td>Heat flow against moisture</td>
<td>E1356</td>
<td>As per the ASTM</td>
<td>NA</td>
<td>With moisture</td>
<td>NA</td>
</tr>
<tr>
<td>QAQC</td>
<td>Temperature</td>
<td>C1064</td>
<td>As per the ASTM</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td></td>
<td>Slump</td>
<td>C143</td>
<td></td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td></td>
<td>Density</td>
<td>C138</td>
<td></td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td></td>
<td>Air content</td>
<td>C231</td>
<td></td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Hardened properties</td>
<td>Compressive strength</td>
<td>C39</td>
<td>4 × 8</td>
<td>NA</td>
<td>NA</td>
<td>7, 14, 21, and 28</td>
</tr>
<tr>
<td></td>
<td>Flexural strength</td>
<td>C78</td>
<td>6 × 6 × 20¹</td>
<td>NA</td>
<td>NA</td>
<td>7, 14, 21, and 28</td>
</tr>
<tr>
<td>Concrete microstructure development</td>
<td>Porosity</td>
<td>C642</td>
<td>4 × 8</td>
<td>NA</td>
<td>NA</td>
<td>3, 7, 14, 21, and 28</td>
</tr>
<tr>
<td>Substrate moisture</td>
<td>Moisture vapor emission rate (MVER)</td>
<td>F1869</td>
<td>40 × 40 × 9</td>
<td>NA</td>
<td>NA</td>
<td>14, 21, and 28</td>
</tr>
<tr>
<td></td>
<td>Moisture content</td>
<td>F2659</td>
<td></td>
<td>NA</td>
<td>NA</td>
<td>7, 14, 21, and 28</td>
</tr>
<tr>
<td></td>
<td>Internal relative humidity (IRH)</td>
<td>F2170</td>
<td>(Probe depths – 1 and 3.6 in.)</td>
<td>NA</td>
<td>NA</td>
<td>Starting from 7-day until the end of testing</td>
</tr>
<tr>
<td>Evaluation parameter</td>
<td>Measurand</td>
<td>ASTM standard</td>
<td>Size of the specimen (in.)</td>
<td>Concrete age at the time of overlay application (e)</td>
<td>Exposure conditions (f)</td>
<td>Concrete age at the time of testing (days) (g)</td>
</tr>
<tr>
<td>------------------------</td>
<td>----------------------------------</td>
<td>----------------</td>
<td>-----------------------------</td>
<td>-----------------------------------------------</td>
<td>------------------------</td>
<td>-----------------------------------------------</td>
</tr>
<tr>
<td>Epoxy overlay</td>
<td>Tensile bond pull-off strength</td>
<td>C1583</td>
<td>40 × 40 × 9</td>
<td>14</td>
<td>RT</td>
<td>Lab: 17, 21, 28, 42, and 105 Outdoors^c</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>HS</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>WD^b</td>
<td>Lab: 17, 28, 42, and 105 Outdoors</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>RT</td>
<td>Lab: 24, 28, 35, 49, and 112 Outdoors</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>HS</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>WD</td>
<td>Lab: 24, 35, 49, and 112 Outdoors</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>RT</td>
<td>Lab: 31, 35, 42, 56, and 119 Outdoors</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>HS</td>
<td>31, 42, 56, 119, and outdoors</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>WD</td>
<td></td>
</tr>
</tbody>
</table>

Note: QAQC = quality assurance and quality control; ASTM = American Society for Testing and Materials; NA = not applicable; RT = room temperature; HS = elevated temperature; WD = one-week alternate wet and dry cycles.

^a Beam specimens of 4 × 4 × 14 in. were used for Grade DM.

^b WD specimens are used at 14, 21, and 28-days application ages for Grade DM and only at 28-days application age for BDJR.

^c The epoxy performance at outdoor exposure condition was evaluated on BDJR concrete specimens on 226, 227, 337, 477, 479, 483, and 484 days and Grade DM concrete specimens were tested on 268, 269, 385, 519, 521, 525, and 526 days of concrete age.
4.2.1 Epoxy Properties

The epoxies used in this study are non-Newtonian thixotropic fluid. Therefore, the dynamic viscosity was evaluated for different spindle speed to obtain a flow curve and determine the dynamic viscosity and associated critical spindle speed. The dynamic viscosity of both epoxies was measured using a Brookfield Viscometer (Model DVEERVTJO) following ASTM D2983 (Procedure D) at spindle speeds of 6, 10, 12, 20, 30, 50, 60, and 100 rpm under standard laboratory conditions at about 73\(^\circ\) F and 35% relative humidity (RH). The variation of dynamic viscosity was also evaluated with time for the critical spindle speed until the epoxy reaches the gel time.

The heat flow against the temperature of both epoxies was measured, with and without moisture exposure, using a PerkinElmer Pyris I Differential Scanning Calorimeter. Figure 4.1a shows some specimens used for the test. The heat flow curve was developed using a set of specimens without moisture exposure following ASTM E1356. Two sets of specimens were conditioned, immersed under water at 122\(^\circ\) F temperature, and reconditioned as per ASTM D570. During conditioning, the specimens were dried in an oven at 122\(^\circ\) F temperature for 24 hours. Following drying, the specimens were cooled in a desiccator, and weight was measured. The specimens were immersed under water using a container and placed in an oven under 122\(^\circ\) F temperature. Following 48 hours, the weight of the specimens was measured under SSD condition and the heat flow curve was developed using one set of specimens following ASTM E1356. The other set of specimens was dried (reconditioning) in an oven at 122\(^\circ\) F temperature for 24 hours as per ASTM D570. The specimens were cooled in a desiccator. Following cooling, specimen weight was measured and the heat flow curve was developed as per ASTM E1356. The absorbed moisture content was
evaluated using the weights measured after conditioning, immersed under water at 122° F temperature, and reconditioning.

The heat flow vs. temperature measurement testing using the differential scanning calorimeter was completed using five steps. In the first step, the specimens were held at 68° F for 1 minute. Following the first step, the specimens were heated to 392° F using the 50° F/minute heating rate. In the third step, specimens were held at 392° F for 1 minute. Following holding, the specimens were cooled down to 68° F using a 68° F/minute cooling rate. At the last step, the specimens were held at 68° F for 1 minute. Figure 4.1b shows the thermal steps during the test.

4.2.2 QAQC

Temperature, slump, density, and air content by pressure method were measured as fresh properties of concrete on the casting day as per the Manual for the Michigan Test Methods (MTM 2018) and the MDOT Standard Specifications for Construction (MDOT 2012). Compressive and flexural strengths were evaluated as hardened properties. Concrete cylinders and beams were fabricated and cured as per the ASTM C192 for compressive and flexural strength testing.
4.2.3 Concrete Microstructure Development

Concrete microstructure development was evaluated by measuring porosity (the volume of total permeable voids) following ASTM C642. Concrete specimens of 4 × 8 in. cylinders were fabricated using BDJR and Grade DM concrete mixes. The porosity was measured using 3, 7, 14, 21, and 28 days aged concrete specimens. A single cylindrical specimen provided two 4 × 2 in. specimens to conduct the porosity test at each testing age. The top 0.5 in. of the cylinder was discarded. Two 4 × 2 in. cylindrical sections were cut from the remaining part of the cylinder to obtain specimens as per the ASTM standard.

4.2.4 Substrate Moisture and Overlay Performance

The MVER, moisture content, and internal relative humidity (IRH) were measured to assess the substrate moisture condition. Tensile bond pull-off strength was evaluated as the overlay performance indicator. Thirty-four (34) 40 × 40 × 9 in. slab specimens were fabricated. Figure 4.2 shows a formwork, specimen curing, specimen arrangement for shotblasting, the top surface after shotblasting and cleaning, the surface with a single coat of epoxy, and a specimen after completing overlay application. In January 2019, 19 slabs were fabricated with Grade DM concrete. Fifteen (15) slabs were fabricated with BDJR concrete in March 2019. Following 7 days of wet curing, the formwork was removed and all the surfaces of the slab, except the top surface, were epoxy painted to replicate the one-dimensional moisture transfer in the presence of stay-in-place formwork. Subsequently, the slabs were dry-cured under standard laboratory conditions at about 73°F and 35% RH. One slab from each mix was selected to measure MVER and moisture content. The remaining 32 slabs (14 BDJR and 18 Grade DM) were used for tensile bond pull-off strength evaluation and IRH measurements. Epoxy overlays were applied at 14, 21,
and 28 days of concrete age. The top surface of all the slabs was shotblasted and cleaned at the age of 14 days. The resin and binder of both epoxies were mixed following manufacturer recommendations and the first coat of epoxy on the 14 days old slabs was applied on the same day and a layer of aggregate was broadcasted. Figure 4.2e shows a specimen with the first layer of epoxy. The second epoxy layer and aggregate were applied on the following day. This allowed a 24-hour curing period for the first layer. A similar process was followed when applying overlays on 21 and 28 days old slabs. Figure 4.2f shows a specimen with a two-coat epoxy overlay.
4.2.4.1 Substrate Moisture Evaluation

MVER was measured following ASTM F1869 at 14, 21, and 28 days of concrete age. Moisture content was measured using an electrical impedance meter as per the ASTM F2659 at 7, 14, 21, and 28 days of concrete age. IRH probes were installed in epoxy coated slabs at 1 and 3.6 in.
depths from the top surface. The probes at 1 in. depth provided IRH near the top surface. The probes at 3.6 in. depth provided IRH at 40% depth of the specimen for one-way drying as per the ASTM F2170 (2019). IRH measurement was started at the beginning of dry curing.

### 4.2.4.2 Epoxy Overlay Performance Evaluation under Laboratory Conditions

The overlay performance was evaluated following ASTM C1583 (2013) procedures under three exposure conditions; (i) room temperature (RT), (ii) elevated temperature (heated slab – HS), and (iii) one-week alternate wet and dry cycle (WD). The RT specimens were cured at 73°F after epoxy application. According to the American Association of State Highway and Transportation Officials (AASHTO) LRFD Bridge Design Specifications, the maximum design temperatures of 100°F and 110°F are used in Michigan for concrete decks with prestressed girders and steel girders, respectively (AASHTO 2016). Therefore, one specimen from each application age was heated to approximately 110°F using two infrared lights before conducting a pull-off strength test to evaluate the impact of hot summer conditions on the overlay bond strength. Figure 4.3a shows the insulated heating chamber. The temperature was continuously controlled and recorded using an auto-shutoff temperature controller and recorder, respectively. Figures 4.3b and c show the temperature controller and recorder, respectively. The bond strength was also evaluated after allowing the slabs to cool down to room temperature following a heat cycle. The WD specimens were exposed to one-week of alternate wet and dry cycles after epoxy application. During the wetting period, 3% NaCl solution was used to flood the top surface continuously to evaluate the impact of salt solution on overlay performance. Bond strength tests were performed at 3, 7, 14, 28, and 91 days following epoxy application. As an example, the concrete age at testing of 14-day epoxy coated slabs was 17, 21, 28, 42, and 105 days. Table 4.3 shows the concrete age at the
time of testing. Each pull-off strength test area was sealed using epoxy paint to prevent moisture loss.

![Insulated heating chamber with infrared lights](image)

Figure 4.3 Insulated chamber for performance evaluation under elevated temperature

4.2.4.3 Epoxy Overlay Performance Evaluation under Outdoor Exposure Conditions

In June and July 2019, all thirty-two (32) specimens were moved to an uncovered parking area to get them exposed to southwest Michigan weather (Figure 4.4). The overlay performance was evaluated during fall, winter, and summer. Testing of slabs fabricated using both concrete mixes was performed on the same day, except during the winter cycle. Tensile bond pull-off strength tests were conducted at 226, 227, 337, 477, 479, 483, and 484 days of concrete age on the BDJR concrete specimens that received overlays at the concrete age of 14 days. Since the Grade DM specimens were fabricated 42 days before BDJR specimens, concrete ages at the time of epoxy
overlay performance evaluation on 14-day Grade DM specimens were 268, 269, 385, 519, 521, 525, and 526 days.

The bond strength was evaluated in October 2019 on RT and HS specimens. The ambient temperature during testing was 48~50°F. Among the three application ages, the slabs that received overlays at the age of 14 days (i.e. 7 days after 7-day wet curing) were expected to retain the highest amount of internal moisture and had the greatest potential to be damaged under freezing conditions. Hence, bond strength on those slabs was evaluated in February 2020. The BDJR and Grade DM slabs were subjected to 89 and 96 freezing cycles, respectively. The ambient temperature during the testing was 34~38°F. The last sets of bond strength tests were conducted in July 2020 since the ambient temperature is maximum from June to August in a year. One set of data was collected during 12:00~4:00 p.m. of a daytime when the ambient temperature was 87~91°F and ultraviolet radiation is maximum. The other data set was collected in the morning when the ambient temperature was about 73°F. By July 2020, these slabs were subjected to 149 freezing cycles. One cycle of bond strength tests was performed on the WD slabs. The WD slabs were continuously exposed to 3% NaCl solution for 135 days before evaluating the bond strength. Tensile bond pull-off strength tests on the WD slabs were performed in the morning of summer days when the ambient temperature was about 73°F. Each pull-off strength test area was sealed using epoxy paint to prevent moisture loss.
Figure 4.4 Slabs in the open parking lot and getting exposed to southwest Michigan weather
4.3 Results and Discussion

4.3.1 Epoxy Properties

4.3.1.1 Dynamic Viscosity

Figures 4.5a(i) and b(i) show the variation of dynamic viscosity and torque (as a percentage of the full scale) with the spindle speed. As shown in the figures, the dynamic viscosity and torque change with the spindle speed since these epoxies are non-Newtonian thixotropic fluids. According to ASTM D2983, the torque should be between 20 to 80% of full scale. The torque exceeds the 80% limit at 100 rpm and 60 rpm for E1 and E2, respectively. As per the ASTM D2983, the dynamic viscosity measured within the acceptable torque range and at the highest spindle speed is reported. Accordingly, the dynamic viscosities reported at 60 rpm for E1 and 50 rpm for E2 epoxies are 1850 and 3070 cP, respectively. The dynamic viscosity, torque, and temperature were measured until the gel time and shown in Figures 4.5a(ii) and b(ii). As shown in the figures, the dynamic viscosity of both epoxies decreases with the temperature and demonstrates a thixotropic behavior. The dynamic viscosity of E1 and E2 epoxies at the gel time were 500 and 853 cP, respectively. The gel time of E1 and E2 epoxies are 19.75 and 19.30 minutes, respectively. The temperature at the gel time was close to 180°F. As shown in Figure 4.5, the viscosity of E2 is 1.7 to 2.2 times greater than that of E1.
4.3.1.2 Heat Flow Against the Temperature

Table 4.4 shows the water absorption results for both epoxies. The average water absorption for E1 and E2 epoxy is 2.06% and 1.62%, respectively. The reconditioned specimens were not completely dried after 24 hours of drying at 122° F temperature. Therefore, there is residual moisture in the specimens. The residual moisture is 0.29% and 0.51% for E1 and E2 epoxy, respectively. Following wetting and reconditioning, specimens 2, 3, 6, and 7 of E1 epoxy were used for heat flow against the temperature measurement testing under wet and reconditioned conditions. Similarly, specimens 1, 3, 5, and 7 were used for E2 epoxy. The heat flow against the temperature was also measured for both epoxies for another set of specimens that were not considered for moisture absorption test and marked as control specimens.
<table>
<thead>
<tr>
<th>Epoxy</th>
<th>Specimen no.</th>
<th>Conditioned weight (mg)</th>
<th>Wet weight (mg)</th>
<th>Reconditioned weight (mg)</th>
<th>Increase of weight after wet (%)</th>
<th>Average increase of weight after wet (%)</th>
<th>Increase of weight after reconditioning (%)</th>
<th>Average increase of weight after reconditioning (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E1</td>
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<td>87.4</td>
<td>1.15</td>
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<td></td>
</tr>
</tbody>
</table>

\(^a\)Outlier
\(^b\)Specimens used for heat flow curve development
Figures 4.6a and b show the heat flow curves for E1 and E2 epoxies, respectively, under control, wet, and reconditioned states. In these figures, the change in heat flow denotes the polymer chain movement. As shown in the figures, all the control specimens show a change of heat flow at a temperature of about 100~120° F. This is because of the movement of flexible chain segments and side groups. The rigid segments of cross-linked polymer chains start to move at a temperature about 300° F and the glass transition temperature region ends at about 365° F temperature. The wet and reconditioned specimens show an increased movement of cross-linked polymer chains, indicated by the steep gradient of heat flow curves of these specimens compared to control specimens. The absorbed moisture interacts with the polymer and acts as a plasticizer (Sperling 1986). Therefore, these specimens could have started softening at a much lower temperature than the control specimens. The glass transition temperature region of both wet and reconditioned specimens is similar to control specimens. Among the wet and reconditioned specimens, wet specimens of E1 epoxy show higher order of polymer chain movement than reconditioned specimens since the wet specimens have higher water absorption. One wet specimen of E1 epoxy undergoes crystallization at about 364° F temperature. The reconditioned specimens of E1 epoxy desorbed approximately 86% of the absorbed moisture and regains the softening property. However, the reconditioned specimens of E2 epoxy desorbed approximately 68% of the absorbed moisture and show a similar polymer chain movement as the wet specimens. Therefore, a comparatively higher degradation due to elevated temperature and moisture is expected in E2 epoxy.
4.3.2 QAQC

Fresh properties of BDJR and Grade DM concretes are presented in Table 4.5. These results comply with MDOT specifications. Figures 4.7a and b show the variation of compressive and flexural strengths along with the MDOT strength requirements. In these figures, the best-fit lines are used to represent the variation of compressive and flexural strengths against time by excluding some outliers. The strengths of BDJR and Grade DM concretes are greater than the specified values. In the presence of 35% of GGBFS, the early-age strength of Grade DM is lower than that of BDJR concrete.

<table>
<thead>
<tr>
<th>Measurand</th>
<th>ASTM standard</th>
<th>Result</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (° F)</td>
<td>C1064</td>
<td>BDJR</td>
<td>Grade DM</td>
</tr>
<tr>
<td></td>
<td></td>
<td>69</td>
<td>69</td>
</tr>
<tr>
<td>Slump (in.)</td>
<td>C143</td>
<td>4.50</td>
<td>6.50</td>
</tr>
<tr>
<td>Density (lbs/yd³)</td>
<td>C138</td>
<td>144.4</td>
<td>143.0</td>
</tr>
<tr>
<td>Air content (%)</td>
<td>C231</td>
<td>5.5</td>
<td>5.7</td>
</tr>
</tbody>
</table>

Note: ASTM = American Society for Testing and Materials; BDJR = bridge deck joint repair concrete mix; Grade DM = standard concrete mix for Michigan bridge decks.
4.3.3 Concrete Microstructure Development

Figure 4.7c shows the volume of total permeable voids against the age of concrete for both concrete mixes. The volume of total permeable voids reduces with the continuation of cement hydration and reaches a constant value signifying the development of a discontinuous microstructure. As shown in the figure, the volume of total permeable voids is lower in Grade DM with GGBFS than in the BDJR concrete mix.

4.3.4 Substrate Moisture

Figure 4.7d shows the variation of MVER against the age of concrete. The specified MVER limit is 3 lb/1000 ft²/24 h (Gaughen 1999). The MVER in Grade DM was lower up to 23 days compared to BDJR. The BDJR concrete mix achieved the specified limit just before 28 days, but the Grade DM could not satisfy the limit within that time period. Figure 4.7e shows the variation of moisture content with the age of concrete. In the figure, the best-fit lines are used to represent the moisture content variation against time by excluding some outliers. The specified limits of moisture content by Wisconsin and New York DOT are 4.5 and 5%, respectively. The BDJR and Grade DM mixes achieved a moisture content of less than 4.5% at 18 and 13 days of concrete age, respectively.
Figure 4.7 Variation of concrete strength, porosity, and moisture with respect to the age of concrete

Note: BDJR = bridge deck joint repair concrete mix; Grade DM = standard concrete mix for Michigan bridge decks; MVER = moisture vapor emission rate; WisDOT = Wisconsin department of transportation; NYDOT = New York department of transportation.
4.3.4 Epoxy Overlay Performance

Figures 4.8 and 4.9 show the tensile bond pull-off strength for both epoxy overlays applied to the slabs fabricated using BDJR and Grade DM mixes. Figures 4.10 and 4.11 show the variation of IRH and concrete temperature within the slabs under laboratory and outdoor exposure conditions, respectively. The performance of E1 and E2 epoxy overlays under laboratory and outdoor exposure conditions are discussed in the following sections.

4.3.4.1 Performance under Laboratory Conditions

The tensile bond pull-off strength variation against time for 14, 21, and 28 days of epoxy application ages under three different exposure conditions is presented in Figures 4.8 and 4.9 for BDJR and Grade DM concrete mixes, respectively. When evaluated under room temperature (RT), the average bond strength of more than 250 psi was recorded with a failure in the substrate, regardless of the epoxy application ages, concrete mixes, epoxy types, or substrate moisture at the time of overlay application.

When evaluated under room temperature following a series of wet and dry (WD) exposure cycles, the average bond strength of more than 250 psi was recorded with a failure in the substrate, regardless of the epoxy application ages, concrete mixes, epoxy types, substrate moisture at the time of overlay application, or the presence of 3% NaCl for a duration of 90 days.

When evaluated under elevated temperature (HS), the average bond strength was always lower than 250 psi, regardless of the epoxy application ages, concrete mixes, epoxy types, or substrate moisture at the time of overlay application. Concrete/overlay interface failure was observed from all the tests performed under elevated temperatures. Exposure to elevated temperature increases
energy in the pore system and draws up moisture vapor through connected capillary pores towards the heated top surface (Lyon 2014). The moisture migration increases with temperature, and the rate rapidly increases after concrete reaches a certain threshold temperature (Attanayake and Mazumder 2021, Mazumder et al. 2021). Figures 4.10a(i) and a(ii) show the moisture migration in the slabs prepared with BDJR and Grade DM concrete mixes. As shown in the figures, a noticeable change in moisture migration is observed when the slab temperature reaches approximately 90° F and the moisture migration rate increases in BDJR and Grade DM slabs when the temperature reaches approximately 102 and 100° F, respectively. Figures 4.10b(i) and b(ii) show the percentage increase of IRH and slab temperature at 1 in. depth during the first three heating cycles for BDJR and Grade DM, respectively. The slab temperature was more than 110° F for approximately 6 hours. As shown in the figures, the IRH increased by 12.0~13.5% in BDJR and 5.0~5.5% in Grade DM concrete. As a result, moisture accumulates at the concrete/overlay interface. This condition was observed during testing. The accumulated moisture possibly creates vapor pressure at the interface. A certain degree of epoxy softening was observed under prolonged exposure to a temperature greater than 110° F. These factors could have contributed to the reduction in bond strength. The magnitude of moisture increase is lower in Grade DM than BDJR concrete since the volume of total permeable voids is lower (as shown in Figure 4.7c). Further, the amount of moisture inside the pores of Grade DM is lower than BDJR since the pore size is smaller in concrete with supplementary cementitious materials (SCMs) (Meddah and Tagnit-Hamou 2009). Therefore, the bond strength of both epoxies was higher on Grade DM than BDJR concrete. Regardless of the epoxy application age and concrete mix, the E1 epoxy overlay showed higher average bond strength than the E2 epoxy overlay for the first three heating cycles under similar temperatures and the amount of moisture change. The average bond strength of the last
two heating cycles showed approximately similar results for both overlays. The bond strength under elevated temperature reduces during each testing cycle, shows a similar trend for all three application ages, and converges to about 80 psi. This might be due to the repeated exposure to elevated temperatures (Soltesz 2010).

The bond strength was also evaluated after allowing the slab temperature to reach room temperature following a heat cycle. The data is presented using pink and red bullets with blue borders. Failure in the substrate, bond failure at the concrete/overlay interface, and a partial failure in the bond and the substrate were observed. The results show a recovery of the bond strength. The magnitude of recovered bond strength was higher in Grade DM concrete for both epoxy overlays. The recovered bond strength of the E1 epoxy overlay is higher than the E2 epoxy overlay for both concrete mixes.

4.3.4.2 Performance under Outdoor Exposure Conditions

Figures 4.8 and 4.9 present overlay performance under outdoor exposure for BDJR and Grade DM concrete mixes, respectively. Regardless of the epoxy application ages, concrete mixes, epoxy types, and substrate moisture at the time of overlay application, the average bond strength was more than the specified limit when the performance was evaluated in October (fall 2019) with a concrete surface temperature of about 50°F. Substrate failure was observed. Figures 4.11a(i) and a(ii) show IRH and internal temperature variation in the slabs under fall conditions. Even though the IRH increased by approximately 2.5 and 3.5% in BDJR and Grade DM slabs, the epoxies did not soften since the concrete temperature was below 73°F. A similar performance was recorded in February (winter 2020) with a concrete surface temperature close to 32°F. Figures 4.11b(i) and
b(ii) show IRH and internal temperature variation in the slabs under winter conditions. The IRH increased by approximately 5.0 and 4.5% in BDJR and Grade DM slabs, respectively.

The average bond strength evaluated in July (summer 2020) with a concrete surface temperature of 112~124°F was lower than 250 psi, but it was greater than the strength observed under simulated heated conditions in the lab. Partial failure in overlay, bond, and substrate was commonly observed. Figures 4.11c(i) and c(ii) show IRH and internal temperature variation in the slabs under summer conditions. Even though the slab temperature was more than 110°F for about 8 hours, the IRH increased by approximately 2% and 1% in BDJR and Grade DM slabs, respectively. As concrete age increases, the internal moisture content decreases without an external moisture source. This might be the reason for having a greater bond strength under summer conditions than the simulated conditions in the lab. The moisture migration was lower in the Grade DM than in the BDJR concrete mix. Figures 4.12a and b show the failure surface of the E1 and E2 epoxy overlay, respectively. A higher degree of softening was visible in the E2 epoxy under elevated temperatures. The bond strength was also evaluated in the morning (July, summer 2020) with a concrete surface temperature close to 78°F. The bond strength is more than the specified limit.

The bond strength of both epoxy overlays exposed to 3% NaCl solution for 135 days under outdoor exposure conditions was more than 250 psi when the surface temperature at the time of testing was about to 73°F. Most of the tests showed failure in the substrate. However, in a few cases, the failure was through the concrete/overlay interface and the substrate.

Both epoxies showed comparatively similar performance; however, E1 had a slightly better overall performance. Low permeable concrete (such as Grade DM) improves overlay performance. Slabs
with overlays subjected to an elevated temperature at an early age result in lower bond strength due to high internal moisture.
Figure 4.8 Variation of tensile bond pull-off strength of both epoxies on slabs prepared with BDJR mix

Note: RT = room temperature; HS = elevated temperature; WD = one-week alternate wet and dry cycles.
i) E1 epoxy overlay

ii) E2 epoxy overlay

a) 14-day epoxy application age

b) 21-day epoxy application age

c) 28-day epoxy application age

Legend

- E1 – RT
- E1 – HS/Summer (Hot)
- E1 – HS/Summer (cool)
- E1 – WD
- E1 – Fall
- E1 – Winter
- E2 – RT
- E2 – HS/Summer (Hot)
- E2 – HS/Summer (cool)
- E2 – WD
- E2 – Fall
- E2 – Winter

Figure 4.9 Variation of tensile bond pull-off strength of both epoxies on slabs prepared with Grade DM mix

Note: RT = room temperature; HS = elevated temperature; WD = one-week alternate wet and dry cycles.

60
Figure 4.10 Variation of IRH and slab temperature at 1 in. depth of the slab under heated condition in laboratory

Note: BDJR = bridge deck joint repair concrete mix; Grade DM = standard concrete mix for Michigan bridge decks; IRH = internal relative humidity.
Figure 4.11 Variation of IRH and slab temperature at 1 in. depth of the slab under outdoor exposure conditions

Note: BDJR = bridge deck joint repair concrete mix; Grade DM = standard concrete mix for Michigan bridge decks; IRH = internal relative humidity.
4.4 Summary

Two epoxy overlays were evaluated to understand the behavior under different exposure conditions. The dynamic viscosity and heat flow against temperature were measured as epoxy properties. The performance of these epoxies was evaluated on BDJR and Grade DM concrete mixes. The epoxy overlays were applied at 14, 21, and 28 days of concrete age. The performance was evaluated under laboratory and outdoor exposure conditions. Tensile bond pull-off strength tests were conducted in the laboratory under room temperature (RT) and two simulated exposure conditions: elevated temperatures (HS) and wet-dry (WD) cycles. Bond strength was also evaluated after allowing adequate time for the slabs to reach room temperature following a heat cycle. After completing laboratory investigations, the slabs were moved outdoors and exposed to typical southwest Michigan weather conditions. Tensile bond pull-off strength tests were
conducted in fall, winter, and summer. The bond strength of both overlays was greater than 250 psi under all the exposure conditions, except under elevated temperatures.

The exposure to elevated temperature increases energy in the pore system and draws up moisture vapor through connected capillary pores towards the heated top surface. The moisture migration increases with the rise of temperature and the rate increases after the concrete temperature reaches a certain threshold. As a result, moisture accumulates at the concrete/overlay interface and develops vapor pressure. In addition, a certain degree of epoxy softening was observed under prolonged and repeated exposure to above 100° F temperature. These factors could have contributed to the reduction in bond strength under elevated temperatures.
CHAPTER 5

STUDY OF SYSTEM BEHAVIOUR THROUGH SIMULATION

5.1 Overview

The influence of epoxy properties and concrete surface profile on the concrete/epoxy bond interface behavior was investigated through simulations. Numerical models were developed in ABAQUS Environment and simulated under different exposure conditions. The mechanical and interface properties of epoxy were adopted from a literature. A mesh sensitivity analysis was performed to evaluate the optimum mesh size for different models. The models were developed using SI units. However, the results are presented in the imperial unit, where applicable. This chapter discusses the numerical models and results.

5.2 Numerical Models

Chapter 4 discusses the performance of epoxy overlays under different exposure conditions. As discussed in Chapter 4, epoxy overlays show a bond strength of more than 250 psi under room temperature. The performance of epoxy overlays was impacted due to elevated temperature and concrete moisture. At an early age (up to 120 days of concrete age), epoxy overlays show an average bond strength of approximately 80 psi due to a high magnitude of moisture accumulation at the concrete/overlay interface and prolong heating under repeated elevated temperature cycles. However, the epoxy overlays show an average bond of approximately 180 psi at a later age (at 477 days of concrete age) due to a negligible magnitude of moisture accumulation at the
concrete/overlay interface and prolong heating under outdoor summer exposure. The concrete/overlay interface was dry under room temperature and elevated temperature at later age since the moisture accumulation at the concrete/epoxy interface was negligible. At an early age, the concrete/overlay interface was wet due to a high magnitude of moisture accumulation at the concrete/epoxy interface. The accumulated moisture creates vapor pressure. According to Haberam and John (1989), a fully-saturated system develops a water vapor pressure of 1.6927 psi at a temperature of 122°F. However, epoxy can absorb the accumulated moisture. When epoxy absorbs moisture, the cross-linked polymer chains start moving at a low temperature. Therefore, epoxy loses the adhesive properties and softens at a much lower temperature.

The numerical simulation models were developed to investigate the concrete/epoxy bond interface behavior under room temperature-dry (RT-Dry) and elevated temperature-dry (HS-Dry) exposure conditions. These conditions were simulated in a flat concrete/epoxy interface. The mechanical and interface epoxy properties under these exposure conditions are adopted from Liu et al. (2016). Liu et al. (2016) show the mechanical and interface epoxy properties for room temperature-dry, elevated temperature-dry, and elevated temperature-wet conditions. The mechanical and interface properties of epoxy under elevated temperature-wet conditions were evaluated after specimens were submerged under deionized water for 60 hours at 194°F. However, the epoxy overlays applied on concrete are not exposed to concrete moisture similar to the conditions stated in Liu et al. (2016). Besides, the bond strength evaluated at a later age showed better overlay performance than early age because of negligible moisture accumulation at the interface which indicates the moisture desorption from the epoxy. Therefore, the elevated temperature-wet conditions were not considered in the numerical simulation of this study. The coefficient of thermal expansion of epoxy was adopted from the epoxy manufacturer datasheet (Transpo Industries Company Inc.)
2013). The modulus of elasticity of concrete was calculated from the compressive strength of Grade DM concrete. The coefficient of thermal expansion of concrete was adopted from AASHTO LRFD (2016) and FHWA (2016). In addition, the influence of concrete surface profile was investigated by introducing cubes, cylinders, and spherical caps in the concrete/epoxy interface. To evaluate the optimum mesh size, a mesh sensitivity analysis was performed before developing models for concrete/epoxy interface behavior evaluation. The mesh sensitivity analysis was performed on flat and concrete surface profile contact models with spherical caps.

Table 5.1 shows the simulation plan. Table 5.2 shows the dimensions and spacing of cube, cylinder (narrow base), cylinder (wide base), and spherical cap used in concrete surface profile contact models. Table 5.3 shows the concrete and epoxy properties used in the models for different exposure conditions. Figures 5.1 and 5.2 show the models. The geometric dimensions of concrete and epoxy were selected similar to the dimensions of the testing area of a tensile bond pull-off strength test. Steps to develop the models for mesh sensitivity analysis and bond interface behavior evaluation are described in the following sections. Tables 5.1 and 5.3, and Figures 5.1 and 5.2 are constantly referenced in these sections.

5.2.1 Mesh Sensitivity Analysis

The following steps were used to develop the simulation models in ABAQUS Environment for mesh sensitivity analysis.

1. **Geometry:**
   
   a. **Flat contact models:** A cylindrical geometry with 55 mm diameter and 25 mm height was developed as concrete. Figure 5.1a shows the concrete geometry.
b. **Concrete surface profile contact models:** A cylindrical geometry with 55 mm diameter and 25 mm height was developed as concrete. Five spherical caps with 2 mm height and 8 mm diameter were added to the concrete top surface. One spherical cap was added at the center of the top surface and the other four caps were added along the plane axes at a 16 mm distance from the center of the top surface. Figure 5.2e shows the location of the spherical caps and the concrete geometry. Similar to this model, concrete geometries were developed for different spherical cap sizes.

2. **Material property:** Concrete material properties, as shown in Table 5.3, were assigned to the geometry.

3. **Boundary condition:** The center of the bottom surface of the geometry was restrained in translation in all three directions. The rest of the bottom surface was restrained in translation along the vertical direction (Y-direction).

4. **Displacement load:** A tensile displacement, along the vertical direction, of 0.004 mm and 0.007 mm was assigned at the top surface to the flat and concrete surface profile contact models, respectively.

5. **Mesh:** The flat contact models were meshed using hex (C3D8R) elements and concrete surface profile contact models were meshed using tetrahedron (C3D10) elements. Mesh sizes of 1.5, 2.5, 5.0, 7.5, 10, 20, 30, 40, 50, and 55 mm were used to evaluate the optimum mesh size.

6. **Analysis:** Linear elastic analysis was performed.
5.2.2 Concrete/Epoxy Bond Interface Modeling

The steps involved to develop a flat and a concrete surface profile contact model with spherical caps of 2 mm height are presented below. These steps were followed to develop models for concrete/epoxy bond interface behavior evaluation.

1. **Geometry:**
   
   a. *Flat contact models:* A cylindrical geometry with 55 mm diameter and 25 mm height was developed as concrete. Figure 5.1a shows the concrete geometry. Another cylindrical geometry with 55 mm diameter and 6.35 mm height was added as epoxy. Figure 5.1b shows the epoxy geometry. Both geometries were assembled. Figure 5.1c shows the assembly.

   b. *Concrete surface profile contact models:* A cylindrical geometry with 55 mm diameter and 25 mm height was developed as concrete. Five spherical caps with 2 mm height and 8 mm diameter were added to the concrete top surface. One spherical cap was added at the center of the top surface and the other four caps were added along the plane axes at a 16 mm distance from the center of the top surface. Figure 5.2e shows the location of the spherical caps. Another cylindrical geometry with 55 mm diameter and 10.35 mm height was added as epoxy. Five spherical caps with 2 mm height and 8 mm diameter were cut from the bottom epoxy surface at the same location. Both geometries were assembled. Figure 5.2g shows the assembly.

2. **Material property:** Concrete and epoxy material properties, as shown in Table 5.3, were assigned to the designated geometries.
3. *Interaction property:* The cohesive interaction properties, as shown in Table 5.3 under epoxy interface properties, were assigned to the model. The epoxy bottom contact surface was assigned as the master surface and the concrete top contact surface was assigned as the slave surface.

4. *Boundary condition:* The bottom surface of the concrete was restrained in translation in all three directions.

5. *Load:*
   
   a. *Thermal load:* Except RT-Dry model, a temperature load was applied to all models. The initial temperature was set to 22.8° C. The final temperature was assigned as 50° C.
   
   b. *Displacement load:* A tensile displacement of 0.13 mm and 0.06 mm was assigned at the epoxy top surface to flat and concrete surface profile contact models, respectively.

6. *Mesh:* The flat contact models were meshed using hex elements (C3D8R) and concrete surface profile contact models were meshed using tetrahedron (C3D10) elements. Based on the outcome of the mesh sensitivity analysis (discussed in Section 5.3.1) and the limitation of the license of ABAQUS Environment, the flat contact models were meshed with a 2.5 mm, and concrete surface profile contact models were meshed with 3.5 mm element size. Figures 5.1d and 5.2h show a meshed flat and a meshed concrete surface profile contact model, respectively.

7. *Analysis:* Linear elastic analysis was performed.
Table 5.1 Simulation Plan

<table>
<thead>
<tr>
<th>Models</th>
<th>Exposure condition</th>
<th>Shape for concrete surface profile contact model</th>
<th>Number of models</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat contact(^1)</td>
<td>Room temperature (RT) and elevated temperature (HS)</td>
<td>NA</td>
<td>2</td>
</tr>
<tr>
<td>Concrete surface profile contact</td>
<td>Elevated temperature (HS)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cylinder-narrow base</td>
<td>2 × 10 = 20</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cylinder-wide base</td>
<td>2 × 4 = 8</td>
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</tr>
<tr>
<td></td>
<td>Spherical cap(^1)</td>
<td>2 × 4 = 8</td>
<td></td>
</tr>
</tbody>
</table>

\(^1\) The mesh sensitivity analysis was performed for all types of models.

Note: NA = not applicable.

Table 5.2 Dimensions and Spacing of Different Shapes Used in Concrete Surface Profile Contact Models

<table>
<thead>
<tr>
<th>Shape</th>
<th>Height (mm)</th>
<th>Base diameter (mm)</th>
<th>Spacing (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cube</td>
<td>2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0, 6.0, 7.0</td>
<td>NA</td>
<td>14.0, 13.5, 13.0, 12.5, 12.0, 11.5, 11.0, 10.0, and 9.0</td>
</tr>
<tr>
<td>Cylinder (narrow base)</td>
<td>2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0, 6.0, 7.0</td>
<td>2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0, 6.0, 7.0</td>
<td>14.0, 13.5, 13.0, 12.5, 12.0, 11.5, 11.0, 10.0, and 9.0</td>
</tr>
<tr>
<td>Cylinder (wide base)</td>
<td>2.0, 2.5, 3.0, and 3.5</td>
<td>8, 10, 12, and 14</td>
<td>8, 6, 4, and 2</td>
</tr>
<tr>
<td>Spherical cap</td>
<td>2.0, 2.5, 3.0, and 3.5</td>
<td>8, 10, 12, and 14</td>
<td>8, 6, 4, and 2</td>
</tr>
</tbody>
</table>

Note: NA = not applicable.

Table 5.3 Concrete and Epoxy Properties

<table>
<thead>
<tr>
<th>Properties</th>
<th>Room temperature (RT) – IP1</th>
<th>Elevated temperature (HS) – IP2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Concrete</strong></td>
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<tr>
<td>Modulus of elasticity (MPa)</td>
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<td>31,000</td>
</tr>
<tr>
<td>Poisson ratio</td>
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<td>0.2</td>
</tr>
<tr>
<td>Coefficient of thermal expansion (mm/mm/°C)</td>
<td>10 × 10(^{-6})</td>
<td>10 × 10(^{-6})</td>
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<td><strong>Epoxy mechanical</strong></td>
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<td>1140</td>
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<tr>
<td>Coefficient of thermal expansion (mm/mm/°C)</td>
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<td>40 × 10(^{-6})</td>
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<td><strong>Epoxy interface</strong></td>
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<td>Normal stiffness (N/mm(^3))</td>
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<td>35,000</td>
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<tr>
<td>Shear stiffness (N/mm(^3))</td>
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<td>12,500</td>
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<td>Maximum normal stress (MPa)</td>
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<td>38</td>
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<tr>
<td>Maximum shear stress (MPa)</td>
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<tr>
<td>Fracture energy (N/mm)</td>
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<td>0.7</td>
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</table>
Figure 5.1 Geometries, assembly, and mesh of a flat contact model
a) A cube of 2 mm height
b) A cylinder (narrow base) of 2 mm height
c) A cylinder (wide base) of 2 mm height
d) A spherical cap of 2 mm height
e) Concrete top surface with location after 2 mm height spherical caps were added to the geometry
f) Epoxy bottom surface with location after 2 mm height spherical caps were cut from geometry
g) Assembly
h) Mesh

Figure 5.2 Geometries, assembly, and mesh of concrete surface profile models

5.3 Results and Discussion

The results of the mesh sensitivity analysis and the concrete/epoxy bond interface behavior evaluation are discussed in the following sections.
5.3.1 Mesh Sensitivity Analysis

Figure 5.3a(i) shows the normalized tensile stress against the mesh size and Figure 5.3a(ii) shows the output location in a flat contact model by a red dot. Eq. 5.1 shows the equation to calculate the tensile stress. Using the assigned material properties, dimension, and displacement load, a tensile stress of 719.39 psi was calculated using Eq. 5.1. Regardless of the mesh size, ABAQUS output shows the same results because of the simplicity of the geometry. Therefore, a mesh size of 1.5 mm to 55.0 mm can be used for flat contact models.

Figure 5.3b(i) shows the normalized tensile stress against the mesh size and Figure 5.3b(ii) shows the output location in a concrete surface profile contact model by a red dot. Regardless of the spherical cap size, the ABAQUS output shows similar results for a mesh size less or equal to 10 mm. Therefore, a mesh size of 10 mm or less can be used for concrete surface profile contact models.

\[ \sigma = \frac{\delta E}{L} \] (5.1)
5.3.2 Concrete/Epoxy Bond Interface Behavior

5.3.2.1 Flat Contact

Figure 5.4 shows the contact pressure and shear stress distribution under room and elevated temperatures. A similar stress distribution is observed under room and elevated temperatures. Figure 5.5 shows the normalized contact open (vertical separation) and contact slip (lateral separation) under room and elevated temperatures. Higher interface degradation is evident under elevated temperature. The gray areas show the higher contact open and slip compared with the results under room temperature. Therefore, the performance of epoxy overlays is reduced under elevated temperature due to the reduction of mechanical and interface properties of epoxy. Hence,
improvement of mechanical and interface epoxy properties under elevated temperature (at least up to 150° F) is required.

Eq. 5.2 shows Van Vlack’s equation to calculate the interface shear stress under elevated temperature due to the thermal incompatibility between two bonded materials (Sprinkel et al. 1983). The derivation of this equation is presented in the Appendix A. At 122° F, a shear stress of 130.13 psi is developed at the concrete/epoxy interface that can be calculated using concrete and epoxy properties presented in Table 5.3. A reduction in the coefficient of thermal expansion of epoxy would reduce the developed shear stress and contact deformation. As an example, shear stress of 7.8 psi would reduce per in./in./° F reduction of coefficient of thermal expansion of epoxy. Figure 5.6 shows the reduction of interface shear stress and contact deformation due to the decrease of thermal coefficient ratio of epoxy to concrete.

\[
\tau = \frac{(\alpha_{overlay} - \alpha_{concrete}) E_{overlay} E_{concrete} \Delta T}{E_{overlay} + E_{concrete}}
\]  

(5.2)
i) Room temperature

ii) Elevated temperature

a) Contact pressure

i) Room temperature

ii) Elevated temperature

b) Contact shear stress

Figure 5.4 Contact pressure and shear stress distribution in flat contact models subjected to tensile loads under room and elevated temperatures.
Figure 5.5 Contact open (vertical separation) and slip (lateral separation) distribution in flat contact models subjected to tensile load under room and elevated temperatures.

Figure 5.6 Variation of shear stress and contact deformation with respect to the thermal coefficient ratio of epoxy to concrete.
5.3.2.2 Concrete Surface Profile Contact

Figure 5.7 shows the normalized maximum contact pressure and shear stress vs. height-space ratio diagram for cube and cylinder (narrow base) shapes. Figure 5.8 shows the normalized maximum contact pressure and shear stress vs. height-space ratio diagram for cylinder (wide base) and spherical cap. The maximum contact pressure and shear stress of these shapes are normalized with the maximum contact pressure and shear stress of the flat contact model. Irrespective of the concrete/epoxy interface properties, the normalized maximum contact pressure is similar for all the shapes. However, the magnitude of the normalized maximum shear stress changes with the shapes and aspect ratio. The magnitude of normalized maximum shear stress in the cylinder (narrow base) is slightly higher than the cube shape for concrete/epoxy interface properties considered under room temperature (Table 5.3) although these shapes have the same aspect ratio (height over base width) of 1. However, the normalized maximum shear stress for cube and cylinders (narrow base) for concrete/epoxy interface properties considered under elevated temperature (Table 5.3) shows a similar magnitude. The normalized maximum shear stress in the cylinder with a wide base and spherical cap is lower than the cylinder with a narrow base and cube because of the lower aspect ratio and larger circular area. The aspect ratio of cylinders with a wide base and spherical cap shapes is 0.25. The lower aspect ratio and larger circular area reduce stress concentrations. Therefore, cylinders with a wide base and spherical cap shaped aggregates would yield higher bond strength. Hence, aggregates with a lower aspect ratio reduce the contact shear stress thus increase the bond strength of an epoxy overlay. The cube and cylinder (narrow base) shaped aggregates with relatively higher aspect ratios would promote failure at the concrete/overlay interface because of the higher combined stresses.
For cube and cylinder (narrow base), the minimum contact pressure is developed for the height-space ratio of 0.19–0.45, irrespective of the concrete/epoxy interface properties, under the same thermal and displacement loads (Figure 5.7). Within this height-space ratio range, the bond interface enables better mechanical interlocking of the concrete-epoxy system and uniform stress distribution (Luković et al. 2013). Therefore, the contact pressure capacity is maximum for the height-space ratio of 0.19–0.45. The contact shear remains almost the same for the height-space ratio of 0.19–0.45 under the same thermal and displacement loads. The contact shear increases significantly for a height-space ratio of more than 0.45. Therefore, the contact shear capacity is maximum for the height-space ratio up to 0.45. Hence, the contact pressure and shear capacity are maximum for a height-space ratio of 0.19–0.45.

For cylinder (wide base) and spherical cap, the contact pressure and shear show a similar trend irrespective of epoxy interface properties (Figure 5.8). Under the same thermal and displacement loads, the cylinder (wide base) contact models show minimum contact pressure and shear stress at a height-space ratio of 0.41. The spherical cap contact models show the minimum contact shear stress at a height-space ratio of 0.75. Therefore, the contact pressure and shear capacity are maximum at 0.41 and 0.75 height-space ratio for cylinder (wide base) and spherical cap, respectively.
The cube and cylinder (narrow base) show the higher bond interface capacity for a mean profile depth of 5.0 mm which is close to CSP 8 (TCC Materials 2016). The cylinder (wide base) and spherical cap show the higher bond interface capacity for a mean profile depth of 2.5–3.0 mm which is close to CSP 6 (TCC Materials 2016). Therefore, CSP 6–8 would yield better concrete/epoxy bond interface capacity thus bond strength since the shotblasted concrete surface exposes aggregate with different sizes and shapes.
5.4 Summary

The flat and concrete surface profile contact models were developed in ABAQUS Environment to evaluate the influence of epoxy properties and concrete surface profile on concrete/epoxy interface behavior under different exposure conditions. The epoxy properties are impacted by elevated temperatures. The concrete/epoxy bond interface undergoes higher degradation when subjected to elevated temperature thus reduction of overlay performance. The reduction in coefficient of thermal expansion of epoxy would reduce the interface shear stress under elevated temperature resulting increase in bond capacity. The concrete surface profile contact models show a CSP of 6–8 with a height-space ratio of surface irregularities of 0.45 would provide the maximum bond capacity for an epoxy overlay.
CHAPTER 6

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

6.1 Summary

Thin epoxy overlays are expected to bridge the cracks and protect the entire deck surface to prevent the ingress of chloride ions and other harmful chemicals. A tensile bond pull-off strength test is used to evaluate the system performance. The performance is satisfactory when the bond strength is greater than or equal to 250 psi. However, the performance evaluated on in-service bridge decks shows inconsistent results. Such studies failed to record and correlate the parameters that influence overlay performance during testing to clarify the observed variations. Laboratory studies by several researchers documented a distinct performance difference when the overlays are exposed to room temperatures in comparison to elevated temperatures. However, the most influential parameters such as concrete properties, concrete surface profile, thermal compatibility between overlay and concrete, the variation of substrate moisture against temperature, epoxy softening under elevated temperatures, and mechanical and interface epoxy properties were not measured and correlated to the observed performance. Therefore, this study was developed to bring clarity to the current understanding by evaluating the epoxy properties and the impact of two different concrete mixes, epoxy application ages, along with exposure conditions and duration on the bond strength. The performance of two epoxy overlays was evaluated under laboratory and outdoor exposure conditions. Following the experimental investigation, a numerical investigation was performed in ABAQUS Environment. The concrete-epoxy system was simulated with a flat
contact and a contact with various surface irregularities under different exposure conditions to understand the impact of epoxy properties and concrete surface profile on the overlay performance.

6.2 Conclusions and Recommendations

6.2.1 Conclusions

The following conclusions are derived from this study:

- The overlay bond strength evaluated at or below 73° F was more than the specified limit of 250 psi regardless of the epoxy application age, concrete mix, and epoxy products.

- Irrespective of the application age, the bond strength under elevated temperatures was less than 250 psi with a failure at the concrete/overlay interface. The exposure to elevated temperatures increases energy in the pore system and draws up moisture vapor through connected capillary pores towards the heated top surface. The moisture migration increases with temperature, and the rate increases after the concrete temperature reaches a certain threshold. As a result, moisture accumulates at the concrete/overlay interface. The accumulated moisture creates a vapor pressure and increases the polymeric chain movement of epoxy resulting epoxy softening. A certain degree of epoxy softening was observed under prolonged and repeated exposure to above 100° F.

- The accumulated moisture redistributed at room temperature following a heating cycle. As a result, the created vapor pressure is dissipated and increased polymeric chain movement is ceased. Therefore, the epoxy overlay recovers the bond strength and
shows a performance of more than 250 psi. Hence, there is no evidence of having permanent damage to the integrity of the system.

- The bond strength of both overlays under elevated temperatures is higher on concrete with slag compared to the mix with Type I cement. The concrete with slag has a low volume of total permeable voids and a smaller pore size that results in a negligible increase in the IRH under elevated temperatures.

- The BDJR concrete mix achieved the specified MVER limit of 3 lb/1000 ft²/24 h at about 28 days whereas Grade DM did not achieve the specified limit within 28 days. However, both concrete mixes achieved a moisture content of less than 4.5% at 18 and 13 days of concrete age: per the readings of an electrical impedance meter, a technology used by a limited number of highway agencies. Hence, the available methods for moisture content evaluation under field conditions need to be evaluated and introduced to highway agencies for substrate moisture measurement.

- A shear stress is developed at the concrete/overlay interface under elevated temperatures because of the differential magnitude of the coefficient of thermal expansion of epoxy and concrete. Reduction in the coefficient of thermal expansion of epoxy would decrease the concrete/epoxy interface shear stress develops under elevated temperature conditions. The interface shear stress of 7.8 psi would reduce per in./in./°F reduction in the coefficient of thermal expansion of epoxy.

- The concrete surface profile (CSP) of 6–8 with a height-space ratio of surface irregularities of 0.45 shows the lowest contact stresses and deformations thus improves thermal compatibility.
6.2.2 Recommendations

The following recommendations are derived from this study:

- Low permeable concrete, such as mixes with SCMs, is recommended to apply for repair and patching to improve bridge deck durability and overlay performance.

- An epoxy overlay can be applied on or after 7 days following 7 days of moist curing of concrete with slag. However, the cracking age of concrete needs to be considered for the application of epoxy overlays.

- Slabs with overlays subjected to an elevated temperature at an early age result in lower bond strength due to high internal moisture. Therefore, applying overlays on new concrete in the fall is recommended to provide adequate time to stabilize internal moisture before the subsequent summer months. However, this is not practical in most of the climatic regions where seasonal changes are not favorable to maintain a bridge deck temperature below 95 to 100°F. Therefore, epoxy properties need to be enhanced to sustain under high temperatures, at least up to 150°F, since the maximum slab temperature was 124°F when the ambient temperature was 91°F.

- The coefficient of thermal expansion of epoxy is recommended to decrease for reducing the concrete/epoxy interface shear stress develops under elevated temperature conditions.

- The concrete surface profile (CSP) of 6–8 with a height-space ratio of surface irregularities of 0.45 is recommended to improve the performance of an epoxy overlay.
6.3 Recommendations for Further Studies

The following further studies are recommended.

- The performance of epoxy overlays was evaluated for about a year. During the evaluation time, the specimens were exposed to room temperature, elevated temperature, and wet-dry cycle under laboratory conditions for 120 days. Following laboratory investigation, the specimens were exposed to southwest Michigan outdoor conditions. The performance evaluation of the overlays for a couple of more years is recommended to develop a better understanding.

- The impact of other environmental parameters such as ultraviolet radiations on overlay performance is recommended to evaluate.

- The neat epoxy material properties were used in the ABAQUS simulation models and the properties were adopted from a literature. The epoxy used in the bridge decks has different mechanical and interface properties than the epoxy properties available in that specific literature. Besides, the epoxy overlay applied to bridge decks contains flint aggregate. Therefore, the combined material properties are recommended to experimentally investigate for simulation models.

- A numerical investigation is recommended to perform by assigning the concrete ingredient material properties of coarse aggregate and cement paste to understand the impact of mechanical and physical properties of aggregates and cement paste on the overlay performance.

- A numerical study is recommended incorporating the fatigue induced stresses on the concrete-overlay system under different exposure conditions and predicting the epoxy degradation and overlay performance for the remaining service life.
• A further study is recommended to investigate the behavior of a thin epoxy overlay under field conditions with temperature and traffic loading.
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APPENDIX

A. Derivation of Van Vlack’s Equation

A shear stress is developed at the bond interface due to the thermal incompatibility when a composite of two elements with different materials properties is subjected to a temperature change. The equation to calculate the shear stress is derived using the basic solid mechanics principles.

According to the equilibrium of forces principle, the summation of forces in the composite is equal to zero. Eq. A-1 shows the force equilibrium principle.

\[ F_1 + F_2 = 0 \quad (A-1) \]

\[ \Rightarrow F_1 = -F_2 \]

where:

\( F_1 \) is the force in element 1
\( F_2 \) is the force in element 2

According to the compatibility of deformation principle, both elements of a composite undergo same magnitude of expansion or contraction. Eq. A-2 shows the compatibility of deformation principle.

\[ (\Delta_p)_1 + (\Delta_T)_1 = (\Delta_p)_2 + (\Delta_T)_2 \quad (A-2) \]

where:

\( \Delta_p \) is the expansion or contraction due to internal forces
\( \Delta_T \) is the expansion or contraction due to thermal change
The Eq. A-2 is equivalent to:

\[
\frac{F_1 \cdot L_1}{A_1 \cdot E_1} + \alpha_1 \cdot L_1 \cdot \Delta T = \frac{F_2 \cdot L_2}{A_2 \cdot E_2} + \alpha_2 \cdot L_2 \cdot \Delta T
\]  

(A-3)

where:

\(L_1\) is the length of element 1

\(L_2\) is the length of element 2

\(A_1\) is the cross-sectional area of element 1

\(A_2\) is the cross-sectional area of element 2

\(\alpha_1\) is the coefficient of thermal expansion of element 1

\(\alpha_2\) is the coefficient of thermal expansion of element 2

\(\Delta T\) is the temperature change

Further simplifying Eq. A-3:

\[
\frac{F_1 \cdot L_1}{A_1 \cdot E_1} - \frac{F_2 \cdot L_2}{A_2 \cdot E_2} = \alpha_2 \cdot L_2 \cdot \Delta T - \alpha_1 \cdot L_1 \cdot \Delta T
\]

Considering the same length and cross-sectional area for both elements:

\[
\frac{F_1 \cdot L}{A \cdot E_1} - \frac{F_2 \cdot L}{A \cdot E_2} = \alpha_2 \cdot L \cdot \Delta T - \alpha_1 \cdot L \cdot \Delta T
\]

\[
\Rightarrow \frac{F_1}{A \cdot E_1} - \frac{-F_1}{A \cdot E_2} = \alpha_2 \cdot \Delta T - \alpha_1 \cdot \Delta T
\]

\[
\Rightarrow \frac{F_1}{A \cdot E_1} + \frac{F_1}{A \cdot E_2} = (\alpha_2 - \alpha_1) \cdot \Delta T
\]

\[
\Rightarrow \frac{F_1}{A} \left( \frac{1}{E_1} + \frac{1}{E_2} \right) = (\alpha_2 - \alpha_1) \cdot \Delta T
\]

\[
\Rightarrow \frac{F_1}{A} \left( \frac{E_1 + E_2}{E_1 E_2} \right) = (\alpha_2 - \alpha_1) \cdot \Delta T
\]

\[
\Rightarrow \tau = \frac{(\alpha_2 - \alpha_1)E_1 E_2}{E_1 + E_2} \Delta T
\]

Where \(\tau\) is the interface shear stress.

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