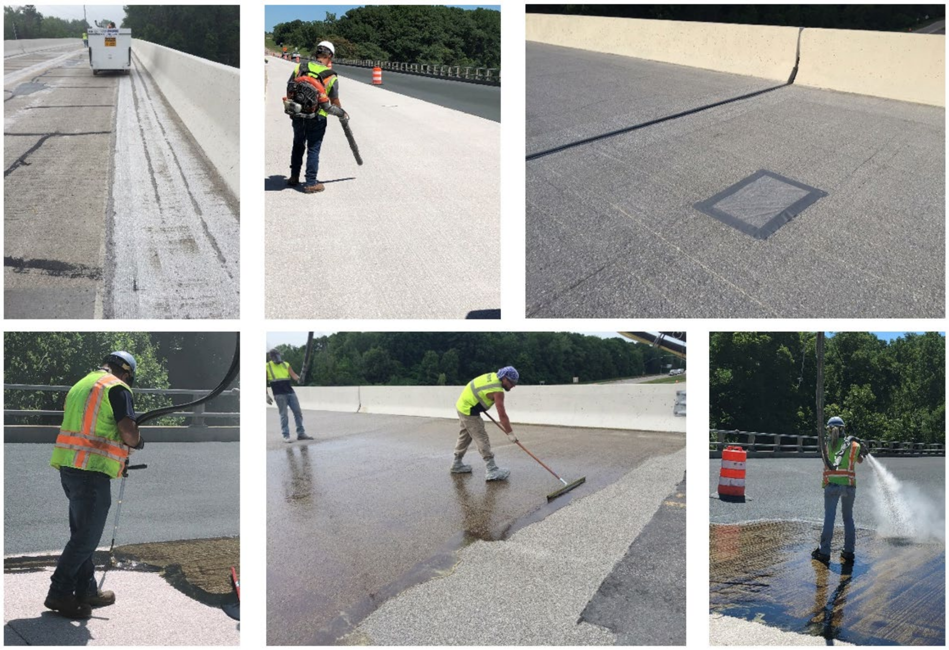
Effects of Concrete Cure Time on Epoxy Overlay and Sealant Performance

FINAL REPORT – DECEMBER 2020



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16. Abstract

Applying flood coats (thin epoxy overlays and healer sealers) improves bridge deck condition and extends service life. The current Michigan Department of Transportation (MDOT) policy is to maintain a total curing period comprising 28 days of wet and dry curing before applying a flood coat on bridge decks with new concrete for patches and repairs. Consequently, the contractors must wait 28 days to start surface preparation for a flood coat application, which increases project completion time, traffic management, and user costs. Therefore, there is an interest to evaluate the possibility of applying a flood coat during the dry curing period. Hence, two performance-based procedures were developed to identify the minimum concrete age to receive a thin epoxy overlay or a healer sealer. Two epoxy overlays and two healer sealers were identified from MDOT approved product lists to evaluate their performance on the standard bridge deck joint repair (BDJR) and Grade DM concrete mixes. The overlay performance was evaluated under standard laboratory conditions, simulated summer exposure conditions, wet and dry conditions, and the outdoor conditions representing southwest Michigan exposure. The performance under outdoor conditions was evaluated during the fall, winter, and summer seasons. The overlay performance was assessed primarily by conducting the tensile bond pull-off strength test. Also, the effectiveness of the overlay against chloride ingress was evaluated. The performance of healer sealers was assessed by evaluating the effectiveness of sealers to prevent chloride ingress through sealed cracks. The experimental results support applying overlays and healer sealers during the dry curing period. The rational and implementable procedures developed through this research evaluate the minimum age of concrete to receive epoxy overlays or healer sealers without compromising concrete durability and overlay/healer sealer performance. Even though the process requires evaluating several parameters, this process needs to be implemented only once per each standard or approved mix resulting in significant savings from project and road user costs.

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EXECUTIVE SUMMARY

INTRODUCTION

The Michigan Department of Transportation (MDOT) applies flood coatings (thin epoxy overlays and healer sealers) as Capital Preventive Maintenance (CPM) and Capital Scheduled Maintenance (CSM) activities to bridge or seal cracks to improve a bridge deck's condition and extend the service life. Depending on the condition, decks are patched or repaired before a flood coating application. The current MDOT policy requires maintaining a total curing period of 28 days (7-days wet and 21-days dry) before applying a flood coating on bridge decks with new concrete for patches and repairs. Consequently, the contractors must wait 28 days to start surface preparation for a flood coat application. This requirement delays project completion time and increases traffic management and user costs. Therefore, there is an interest to evaluate the possibility of applying a flood coat during the dry curing period. This requires identifying the minimum concrete age to receive a flood coat. The minimum concrete age to receive a flood coat and the performance of the system depend on several parameters including concrete cracking, moisture, and strength. Such parameters depend on concrete mixture ingredients and wet and dry curing periods. Therefore, there is an interest to evaluate if a prescription- or a performance-based approach is better for deciding the minimum concrete age to receive a flood coating.

The objective is to determine if a procedure or a set time is better for deciding when to place an epoxy overlay or a healer sealer on MDOT standard concrete materials and special/patching materials. To achieve the objective, the project was organized into six tasks as follows:

1) Research criteria and benefits of epoxy overlay and sealant placement timing with regards to standard materials and special/patching materials.
2) Develop a testing plan that encompasses the material used by MDOT.
3) Prepare specimens and conduct QAQC testing.
4) Evaluate overlay/sealant performance vs. crack development and curing.
5) Analyze results and quantify the cost savings.
6) Recommend a procedure for determining overlay/sealant placement timing based on material/mix design.

PERFORMANCE EVALUATION OF EPOXY OVERLAYS AND HEALER SEALERS

Two performance-based procedures were developed to identify the minimum concrete age to receive a flood coating: one for thin epoxy overlays and the other for healer sealers. The robustness of both procedures was demonstrated through a comprehensive experimental study.

Thin epoxy overlays are expected to bridge the cracks and protect the entire deck surface by preventing 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. The minimum concrete age to receive an overlay depends on concrete wet curing duration, cracking age, concrete age to achieve an acceptable substrate moisture condition, and concrete age to develop the required minimum tensile strength. Thin epoxy overlay performance depends on concrete strength, bond strength, thermal compatibility between overlay and concrete, epoxy performance under various exposure conditions, and workmanship. Considering all these parameters, a comprehensive procedure was developed to evaluate the minimum age of concrete to receive an overlay as a function of (i) concrete wet curing duration, (ii) concrete age at the time of cracking, (iii) concrete age to achieve acceptable substrate moisture, (iv) concrete age to develop the specified minimum tensile strength, and (v) concrete age at the time of epoxy application to develop the specified bond strength. This procedure was implemented using two MDOT standard concrete mixes and two thin epoxy overlays. The bridge deck joint repair (BDJR) and Grade DM standard mixes were selected. E-bond 526 Lo-Mod and Unitex Pro-Poxy Type III DOT epoxy overlays were selected from the MDOT approved product list. Moreover, there is an interest to evaluate the possibility of developing a hybrid bridge deck protection system with penetrating sealers and thin epoxy overlays to complement the overlay performance by retarding chloride ingress into the concrete through pinholes and other anomalies formed during overlay application and while in service. Therefore, the experimental study was extended to evaluate the impact of silane pretreatment on overlay bond strength. SIL-ACT ATS-100, a 100% silane penetrating sealant in the MDOT approved product list, was selected for pretreating the specimens fabricated with BDJR concrete.

Healer sealers are expected to seal the cracks by penetrating and bonding the cracks while maintaining the integrity under repeated loading that demands opening and closing of the sealed cracks. The performance can be assessed by evaluating the ability of the sealed cracks to resist chloride ion ingress and reduce corrosion risk probability of the embedded reinforcing steel. The minimum concrete age to receive a healer sealer depends on concrete wet curing duration, cracking age, and concrete age to achieve an acceptable substrate moisture condition. Several parameters (including concrete moisture, workmanship, etc.) influence healer sealer performance. Considering all these parameters, a comprehensive procedure was developed to evaluate the minimum age of concrete to receive a healer sealer as a function of (i) concrete wet curing duration, (ii) concrete age at the time of cracking, (iii) concrete age to achieve acceptable substrate moisture, and (iv) concrete age at the time of healer sealer application to achieve comparable performance to 28 days. This procedure was implemented using two MDOT standard concrete mixes (BDJR and Grade DM) and two healer sealers (Sikadur 55 SLV and Unitex Pro-Poxy 40 LV LM) selected from the MDOT approved product list.

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions and recommendations were derived from the experimental investigations conducted to evaluate the minimum concrete age to receive thin epoxy overlays and healer sealers:

- Rational and implementable procedures are presented to evaluate the minimum age of concrete to receive epoxy overlays and healer sealers without compromising concrete durability and overlay/sealant performance. Even though the processes require evaluating several parameters, these procedures need to be implemented only once per each standard or approved mix resulting in significant savings from project and road user costs. It is recommended to include the procedures as part of the flood coat acceptance testing program.
- 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 type. The average substrate moisture condition at 14 days was 5.6% and 4.2% for BDJR and Grade DM concretes, respectively. The moisture contents are comparable to the limits specified by New York and Wisconsin DOTs.
- Irrespective of the application age, the bond strength of epoxy overlays under elevated temperature was less than 250 psi. The primary failure type was a bond failure at the concrete/overlay interface. A certain degree of epoxy softening was observed under prolonged and repeated exposure to temperatures above 100° F.

- The bond strength recovers when the temperature reaches room temperature following a heating cycle. However, bond strength decreases under repeated exposure to heating cycles: an evidence of having a certain degree of permanent damages to the integrity of the system.
- The Unitex Pro-Poxy Type III DOT epoxy overlay performed consistently better than the E-bond 526 Lo-Mod epoxy overlay irrespective of concrete mix, epoxy application age, and exposure conditions.
- Pretreatment using SIL-ACT ATS-100, a 100% silane penetrating sealant, shows no adverse impact on the overlay performance; rather, it improves the bond strength under elevated temperature when applied on 21 or 28 days old concrete. Pretreatment improved the recovered bond strength following heating cycles.
- The total chloride content along the depth of concrete evaluated after 135 days following the healer sealer application shows similar values and trends for all three application ages. The total chloride content at least 1.0 in. deep into the sealed crack remains constant and similar to the background chloride content (i.e. 231~270 ppm), an indication of the effectiveness of the crack sealant. The total chloride content at the unprotected crack (reference specimen) is much greater than 500 ppm up to a 3 in. depth.
- Both sealers (Sikadur 55 SLV and Unitex Pro-Poxy 40 LV LM) show similar performance irrespective of the sealant application age and concrete mix.
- Concrete cracking age under standard laboratory exposure conditions became the decisive parameter for determining the concrete age to receive thin epoxy overlays and healer sealers. Since thin epoxy overlays and healer sealers can be applied on 18 days old BDJR concrete and 20 days old Grade DM concrete to achieve comparable performance to 28 days, a 21-day application age is specified. The 18-day and 20-day waiting periods were decided based on the concrete cracking age. The use of non-shrink bridge deck repair and/or patch materials could potentially reduce this waiting period.
- Maintaining traffic on a typical bridge with a 5,000 ft^2 deck area and the average annual daily traffic (AADT) of about 5,000 to 12,000 could save road user costs, in Michigan, of more than \$30,482 to \$84,824 per day. The above cost calculation demonstrates the benefits of completing overlay and healer sealer application operations during the dry curing period rather than extending the bridge closure at least one or two days beyond the 28-day closure.

- The concrete with slag improves overlay bond strength under elevated temperature and reduces chloride ingress. The concrete with slag has a low volume of total permeable voids and smaller pore size that results in lower permeability and very little increase in the internal relative humidity (IRH) under elevated temperature. Therefore, low permeable concrete, such as mixes with supplementary cementitious materials (SCMs), is recommended to improve bridge deck durability, along with overlay and sealant performance.
- Even though the MDOT standard practice is 7 days of moist curing, the current stipulations in the Standard Specifications for Construction provide flexibility for extending the curing duration beyond 7 days by specifying 7-day minimum compressive and flexural strength requirements. However, these curing requirements do not specifically address the extended curing required to develop a discontinuous capillary pore structure with a minimum volume of total permeable voids in concrete with SCMs, a durability performance requirement. Therefore, it is recommended to include the bulk electrical conductivity and porosity testing in the curing specifications to establish moist curing requirements that assure both the strength and durability requirements.

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1 INTRODUCTION

1.1 OVERVIEW

Bridge decks that are exposed to deicing 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. Bridge preservation activities include Capital Preventive Maintenance (CPM), Capital Scheduled Maintenance (CSM), and Rehabilitation and Replacement (MDOT 2008, MDOT 2010, USDOT 2018). The wet and dry curing practices and the quality assurance and quality control (QAQC) procedures implemented on the typical concrete mixes used for bridge decks and repairs are expected to result in durable bridge decks. However, randomly dispersed cracking because of tensile stresses developed in the decks under volume change loads, such as concrete shrinkage and daily temperature changes, and the constraints provided by the girders and other components are documented (Aktan et al. 2003). The durability of such decks can be improved by bridging or sealing the cracks using flood coatings [i.e., thin epoxy overlays or healer sealers] (DeRuyver and Schiefer 2016). The deck condition, cracking intensity, 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). Applying thin epoxy overlays is preferred over healer sealers while evaluating the preventive maintenance options (DeRuyver and Schiefer 2016). The healer sealers are primarily selected "because of [the] present-day required budgetary savings or mobility restrictions" (DeRuyver and Schiefer 2016). Depending on the condition, decks are patched or repaired before a flood coating application. The typical practice of the Departments of Transportation (DOTs) is to maintain a 28-day total wet and dry curing period for new concrete in patches and repairs before applying a flood coat. Consequently, the contractors have to wait for 28 days to start surface preparation for an application. This requirement delays project completion time and increases traffic management and user costs (Yavuz et al. 2017). However, the minimum concrete age to receive a flood coat and the performance of the system depend on several parameters including, but not limited to, concrete cracking intensity, moisture condition, and strength. Such parameters depend on concrete mixture ingredients and wet and dry curing periods. Therefore, prescribing a fixed curing period before a flood coating application is a concern. Hence, there is an interest to evaluate whether a prescription-based or a performance-based approach is better for deciding the application of flood coatings on bridge decks with new concrete in patches and repairs.

1.2 OBJECTIVE AND TASKS

The objective is to determine if a procedure or a set time is better for deciding when to place an epoxy overlay or a healer sealer on Michigan Department of Transportation (MDOT) standard concrete materials and special/patching materials.

To achieve the objective, the project was organized into six tasks as follows:

1) Research criteria and benefits of epoxy overlay and sealant placement timing with regards to standard materials and special/patching materials.
2) Develop a testing plan that encompasses the material used by MDOT.
3) Prepare specimens and conduct QAQC testing.
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5) Analyze results and quantify the cost savings.
6) Recommend a procedure for determining overlay/sealant placement timing based on material/mix design.

1.3 REPORT ORGANIZATION

This report is organized into 7 chapters.

Chapter 1 includes the introduction and research project objectives and tasks.

Chapter 2 documents guidelines and practices of highway agencies, manufacturer requirements, the performance of epoxy overlays and healer sealers, concrete property affecting epoxy overlay and healer sealer performance, and methods to evaluate concrete property and performance of epoxy overlays and healer sealers.

Chapter 3 describes the testing plan to evaluate epoxy overlay performance and results.

Chapter 4 describes the testing plan to evaluate healer sealer performance and results.

Chapter 5 describes potential user cost savings from epoxy overlay and healer sealer application before the end of the specified 28-day curing period.

Chapter 6 includes a summary, conclusions, and recommendations.

Chapter 7 presents the cited references.

2 STATE-OF-THE-ART AND PRACTICE LITERATURE REVIEW

2.1 OVERVIEW

For many years, a mix of fixes has been used to extend the service life of bridges with a minimum cost. In 1950, a single layer of coal tar epoxy was broomed onto the concrete substrate and seeded with fine aggregate. This overlay could not perform as a durable, impermeable layer. To improve the performance, in 1960, an oil-extended epoxy was used. In the mid-1970s, polyester-styrene resins and methyl methacrylate monomer systems were applied (Fowler and Whitney 2011). Since 1990, epoxy overlays and healer sealers have been used to protect and increase the service life of concrete bridge decks. Epoxy is a mixture of two components: a resin and 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 ⅜ to ½ in. (Sika Corporation 2011) while the sealant is $^{3}/_{16}$ in. thick. An epoxy overlay or a healer sealer application requires shotblasting the deck surface following a minimum specified concrete curing duration, cleaning the surface, and maintaining a period for overlay or healer sealer curing before opening to traffic. This chapter discusses guidelines and practices of highway agencies, requirements in epoxy manufacturer technical datasheets, the performance of epoxy overlays and healer sealers, concrete properties affecting epoxy overlay and healer sealer performance, standard methods to evaluate concrete properties, and finally, standard methods to evaluate the performance of epoxy overlays and healer sealers.

2.2 GUIDELINES AND PRACTICE OF HIGHWAY AGENCIES

Wet and dry curing requirements, substrate preparation methods, application requirements, and performance evaluation methods of 11 state highway agencies for epoxy overlays and 3 state highway agencies for healer sealers were reviewed and summarized in Table 2-1 and Table 2-2, respectively. The information is primarily compiled from the respective agency web publications and through limited communications. Applying a flood coating on new concrete starts after completing a specified wet and dry curing period. MDOT's standard practice is to maintain a 28-day curing period (7 days of wet curing and 21 days of dry curing) for standard bridge deck concrete mixes. Even though the MDOT standard practice is 7 days of moist curing, the current stipulations in the Standard Specifications for Construction provide flexibility for extending the curing duration beyond 7 days by specifying 7-day minimum compressive and flexural strength requirements (MDOT 2012). Similarly, Alabama, California, Indiana, Ohio, Iowa, and Pennsylvania measure the compressive strength of concrete after wet curing and decide to continue wet curing when the specified minimum strength requirements are not met. Thus, these agencies have policies for performance-based curing practices, where strength is the performance parameter. Even though the typical wet curing duration specified by most of the agencies is 7 days, Wisconsin and Pennsylvania specify 14 days while Iowa specifies only 4 days for the specific mixes used in those states.

Shotblasting is commonly used as a surface preparation method to expose large size aggregates, remove contaminants, open the cracks, round off the crack edges, and remove any debris present in the cracks (MDOT Wiki 2019). The concrete surface profile (CSP) is evaluated as per the International Concrete Repair Institute (ICRI) guidelines. A CSP of 5–7 is commonly used for epoxy overlays to expose large size aggregates for ensuring a sufficient bond between the epoxy overlay and the substrate. The American Concrete Institute (ACI) recommended a minimum CSP of 5 for epoxy overlay application (ACI 548.8 2019). As shown in the tables, some states are very strict with the CSP requirements and specify only one profile. A CSP of 3–5 is used for healer sealers. An alternative approach for surface profile evaluation for healer sealers is to compare the profile with a selected sandpaper grit size. As an example, Ohio uses 100-grit sandpapers for this purpose. After shotblasting, the surface is cleaned using a vacuum truck and concrete moisture content is evaluated. Surface and near-surface moisture influence the performance of epoxy overlays and healer sealers. The moisture is commonly evaluated following the procedures described in ASTM D4263. According to the standard, a 4 mils thick 18 × 18 in. polythene sheet, with a sealed perimeter, is placed on the concrete surface for a minimum of 16 hours to observe moisture accumulation underneath the plastic sheet. Highway agencies modified the duration for practical purposes. As an example, Florida performs a capillary moisture test for 5 hours, whereas the Michigan test duration is at least 3 hours or a longer 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 an electrical impedance meter. Wisconsin allows overlay application when the substrate moisture content is less than 4.5%, whereas the limit of New York is 5.0%. With an acceptable moisture content, epoxy overlays and healer sealers are applied following the procedures and 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 tables, ambient humidity and wind speed are not considered by many agencies. For epoxy overlays, several agencies specified the maximum limit of substrate temperature to 100^o F while the Ohio limit is 120^o F. An epoxy overlay is a two-layer coating system whereas a healer sealer is a single coat system. The thickness of each epoxy layer is $^3/_{16}$ 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 for epoxy overlays and fine aggregate is used for healer sealers (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 performance. The specified minimum bond strength limit is 250 psi (MDOT 2019a). A field performance evaluation method for healer sealers is not currently available.

Table 2-1. Epoxy Overlay Application Requirements and Performance Evaluation: Highway Agency Practice

State	Application time (days)		Substrate preparation method			Application requirements								Performance evaluation
	Wet curing (WC)	Dry curing (DC)	Acid etching	Shotblasting	Pressurized water	Concrete surface profile (CSP)	Substrate moisture content	Ambient temperature (°F)	Ambient relative humidity (%)	Wind (mph)	Rain forecast (hours from application time)	Substrate temperature (°F)	Material temperature (°F)	Tensile bond pull-off strength
AL	7 (min) + f_c[1]	28 - WC	N[3]	Y[4]	N	na[5]	N	55–90	N	N	+ 24	> 60	60–90	ASTM C1583
CA	7 (min) + f_c	28 - WC	N	Y	N	na	N	N	< 85	N	N	50–100	N	CTM[8] 420
FL	7	14 (+21)[2]	N	Y	N	MS[6]	ASTM D4263 (5 h)	> 55	N	na	na	> 55	> 55	ACI 503R, ASTM C1583
IL	7	21	N	Y	N	na	ASTM D4263 (2 h)	55–90	N	N	– 48	> 60	> 60	Illinois pull-off test
IA	4 (min) + f_c	28 - WC	N	Y	N	6 or 7	ASTM D4263 (2 h)	> 55	N	N	N	60–100	> 60	ASTM C1583, ACI 503R
IN	7 (min) + f_c	28 - WC	N	Y	N	5, 6, or 7	ASTM D4263	55–90	N	N	+ 2	60–100	> 70	ITM[9] 407
MI	7 (min) + f_c, f_r[1]	28 - WC	N	Y	N	7	ASTM D4263 (Longer of 3 h or MS)	> 50	MS	MS	MS	> 50	70–100	ASTM C1583
NY	7	21	N	Y	N	5 or 6	ASTM D4263 (2 h) or ASTM F2659[7] (< 5% moisture)	> 50	N	N	Within cure time	MS	MS	ASTM C1583, ACI 503R
OH	7 (min) + f_c	28 - WC	N	Y	N	na	na	> 50	na	N	-4 to + 12	50–120	65–80	N
PA	14 (min) + f_c	28 - WC	N	Y	N	5, 6, or 7	ASTM D4263 (2 h)	MS	MS	MS	MS	MS	60–90	ASTM C1583
WI	14	14	N	Y	N	5	ASTM D4263 (2 h) or ASTM F2659 (< 4.5% moisture)	50–100	N	N	Within cure time	50–100	65–99	ASTM C1583

1. f_c and f_r 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

Table 2-2. Healer Sealer Application Requirement and Performance Evaluation: Highway Agency Practice

State	Application time (days)		Substrate preparation method			Application requirements								Field performance evaluation
	Wet curing (WC)	Dry curing (DC)	Acid etching	Shotblasting	Pressurized water	Concrete surface profile (CSP)	Substrate moisture content (on the day of placement)	Ambient temperature (°F)	Ambient relative humidity (%)	Wind (mph)	Rain forecast (hours from application time)	Substrate temperature (°F)	Material temperature (°F)	
FL	7	14 (+21)[a]	N	N	N	na	na	na	na	na	-48 to + 6	na	na	na
MI	7 (min) + f_c, f_r	28 – WC	N	Y	N	3	ASTM D4263 (longer of 3 hrs or MS)	> 50	na	na	na	> 50	70–100	na
OH	7 (min) + f_c	28 – WC	Y	Y	Y	ASTM D7682, 100-grit sandpaper	na	> 50	< 80	na	-24 to + 12	40–100	> 50	na

Note: min = minimum; f_c = required compressive strength at the end of specified wet curing duration; f_r = required flexural strength at the end of specified wet curing duration; Y = yes; N = no; MS = epoxy manufacturer specification; na = not applicable; ASTM = American Society for Testing and Materials.

[a] In 2018, FDOT developed specification 403 to implement a 21-day DC period

A detailed discussion on concrete curing, substrate preparation, application requirements, and performance evaluation is given below.

2.2.1 Concrete Curing

Concrete structures, such as bridge decks, are exposed to various loads and harsh exposure conditions during their service life. For this reason, such structures are designed considering both strength and durability. Exposure to deicing salts, surface abrasion, and freeze-thaw conditions contribute to the rapid deterioration of concrete. In the absence of cracks, the amount and rate of moisture and aggressive chemical ingress, such as chlorides, depend on the total volume of permeable voids in concrete and the continuity of the capillary pore structure. Therefore, the concrete wet curing duration needs to be maintained until a discontinuous capillary pore structure with a minimum volume of total permeable voids is developed (Basnayake et al. 2020). The required wet curing duration depends on the content and composition of the concrete mixture, physical and chemical properties of the ingredients, expected hardened concrete properties, and their rate of development (ACI 308R-16 2016). The rate of strength gain is slower in concrete mixes with Class F fly ash or ground granulated blast furnace slag (GGBFS) compared to a concrete mix with Type I cement; thus, 10 to 14 days of wet curing is recommended (Poole 2006, USDOT 2003). On the other hand, concrete mixes with Class C fly ash or silica fume gain strength faster compared to Type I cement concrete (Poole 2006, IMCP 2007). Therefore, specifying a fixed curing period is not suitable for concrete mixes with SCMs.

Curing periods specified by Alabama, Florida, Iowa, Michigan, Pennsylvania, and Rhode Island are presented in Table 2-3. The table lists the specified 28-day strength limits, curing periods, cement content, water-cementitious material (w/cm) ratio, and the percentage of SCMs. Alabama, Iowa, and Pennsylvania perform a minimum of 7, 4, and 14 days of wet curing, respectively. As an example, Pennsylvania evaluates compressive strength after 14 days of wet curing and decides to continue wet curing if the specified compressive strength is not achieved. Rhode Island starts dry curing if the concrete flexural strength is 525 psi or greater after 7 days of wet curing. Similar performance-based specifications are used in several other states, including Michigan (MDOT 2012). However, the performance parameter is limited to strength.

Table 2-3. Specified Curing Duration for Mixes with SCMs

Highway agency	Concrete mix	Specified 28-day strength (psi)	Wet curing period (days)	Cement content (lbs/yd^3) (min/max)	w/cm	Fly ash	GGBFS	Silica fume
Alabama	na[a]	4000	7 + f_c	Contractor[b]	0.45	Max 30	Max 50	Max 10
Florida	Type II	4500	7	611/687	0.40	25	na	na
Iowa	HPC–D	4500–5000	4 + f_c	625/na	0.40	20	Min 30	na
	CV–HPC–D	4500–5000	4 + f_c	651/na	0.40	20	na	na
Michigan	D	4500	7 (min) + f_c/f_r	658/na	0.44	na	na	na
	DM	4500	7 (min) + f_c/f_r	Variable[c]	0.44	Max 35	Max 40	na
	SFMC	4500	7 (min) + f_c/f_r	618/na	0.44	na	na	6
	LMC	4500	24 or 48 hrs	658/na	0.30	na	na	na
Pennsylvania	AAAP	4000	14 + f_c	560/752	0.45	Max 15	Min 25	5–10
	HPC	4000	14 + f_c	560/690	0.45	na	na	na
Rhode Island	HP	4500	7 + f_r	705/799	0.40	na	na	na

Note: Min = minimum; max = maximum; w/cm = water-cementitious material ratio; GGBFS = ground granulated blast furnace slag; f_c = required compressive strength at the end of wet curing; f_r = required flexural strength at the end of wet curing.

[a] na – information is not provided in the literature

[b] Mix design is submitted by the contractor to meet the DOT specifications.

[c] Cement content depends on the fly ash and GGBFS in the mix.

2.2.2 Substrate Preparation

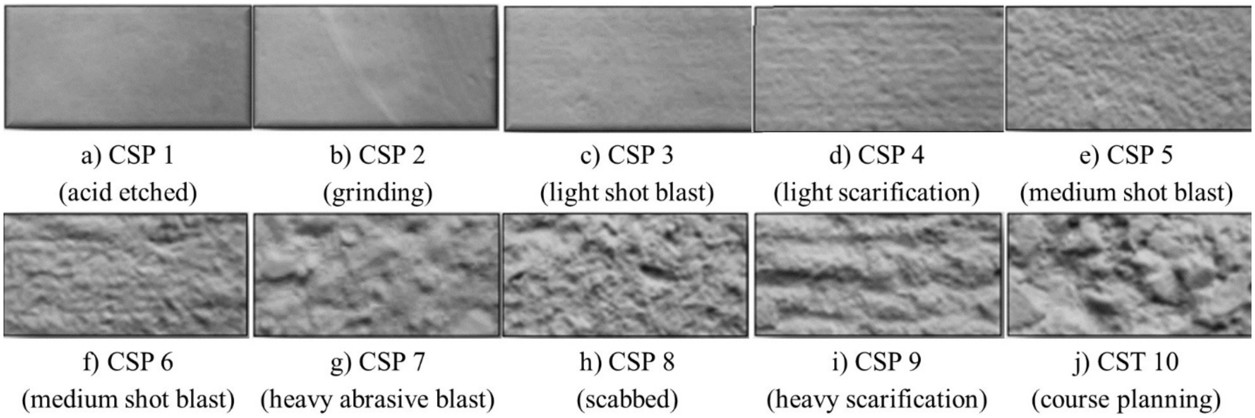
Surface preparation methods include acid etching, shotblasting, and the use of pressurized water. Hydrochloric/muriatic or buffered phosphoric acids are used for acid etching. Acid etching cannot remove curing compounds and oily deposits. It is difficult to predict and control chemical reactions after applying the chemical on the deck surface, and over-etching is possible. Over etching makes the deck surface more porous, promotes moisture ingress during deck cleaning, and accelerates reinforcement corrosion (Mailvaganam et al. 1998). On the other hand, it can only produce CSP 1 or 2. Therefore, ACI Committee 515 (1985) recommends using this method in the absence of other alternatives.

The use of pressurized water increases substrate moisture (Attanayake et al. 2006) and makes it impossible to apply epoxy overlays or healer sealers on the same day. As shown in Table 2-1, this method is not used for surface preparation prior to epoxy overlay applications. Only Ohio uses pressurized water to clean the surface for healer sealer application (Table 2-2).

Shotblasting uses steel balls propelled by a rotating wheel to clean and scour concrete surfaces (Mailvaganam et al. 1998). Shotblasting to a higher CSP, such as 7, exposes large size aggregates and increases the aggregate surface area available for epoxy adhesion. The bond strength can be improved by exposing large aggregates since the adhesion is primarily controlled by the aggregates that are stronger than the cement matrix. Further, moisture migration through aggregates is lower. Shotblasting does not alter surface moisture and allows cleaning the surface using a vacuum truck (DeRuyver and Schiefer 2016). Therefore, shotblasting is the preferred concrete surface preparation method for epoxy overlay or healer sealer application.

2.2.3 Application Requirements

Concrete surface profile, substrate moisture content, overlay material properties, and ambient conditions impact the formation of a concrete/overlay interface zone and the mechanical interlocking between substrate and overlay material to influence interface bond strength (Bissonnette et al. 2012, Garbacz et al. 2004). According to Winkler (2014), one of the major reasons for the protective system/repair failure is poor surface preparation. To improve consistency in practice and specifications, the ICRI developed a CSP classification ranging from CSP 1 (nearly flat) to CSP 10 (amplitude > ¼ in.) (Figure 2-1). The recommended CSP range for epoxy overlays is 5–9, and for healer sealers it is 3–5 (ICRI 2013).


a) CSP 1 (acid etched) b) CSP 2 (grinding) c) CSP 3 (light shot blast) d) CSP 4 (light scarification) e) CSP 5 (medium shot blast)

f) CSP 6 (medium shot blast) g) CSP 7 (heavy abrasive blast) h) CSP 8 (scabbed) i) CSP 9 (heavy scarification) j) CST 10 (course planning)

Figure 2-1. ICRI (2013) concrete surface profile (CSP) classification

Substrate moisture is one of the key parameters that influence the performance of epoxy overlays or healer sealers (Table 2-1 and Table 2-2). The presence of an excessive amount of substrate moisture could influence epoxy overlay bonding and develop vapor pressure at the concrete/overlay interface under elevated temperatures (Shearrer et al. 2015). The polythene sheet test (ASTM D4263) is a qualitative measure of substrate moisture within the top ½ in. (Kanare 2008). This test method could provide false indications when the air above the deck is at the dew point. Wisconsin and New York DOTs use electrical impedance meters to measure concrete moisture as per ASTM F2659 and limit the substrate moisture content to 4.5% and 5.0%, respectively.

2.2.4 Performance Evaluation

The tensile bond pull-off strength test is used to evaluate epoxy overlay performance. All highway agencies implement the procedure in ASTM C1583 or similar practices. A few DOTs include ASTM C1583 procedures with or without modifications in their testing manuals and use agency names to introduce the test rather than directly referring to the ASTM. As an example, Illinois DOT adopted ASTM C1583 procedures and renamed them the Illinois pull-off test. There is no standard or agency-specific test method to evaluate healer sealer performance in the field.

2.3 MANUFACTURER RECOMMENDATIONS

Manufacturers present application requirements and procedures. The MDOT approved epoxy overlays are supplied by BASF, E-Bond, E-Chem, Euclid Chemical, Poly-Carb, Sika, Transpo, and Unitex (MDOT 2018a). The approved healer sealers are supplied by E-Chem, Euclid Chemical, Poly-Carb, Sika, and Unitex (MDOT 2018b). Table 2-4 and Table 2-5 summarize the requirements in technical datasheets. The minimum age of concrete, concrete surface profile, optimum moisture content, along with ambient and substrate temperature are the listed parameters. Epoxy overlays or healer sealers 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 or healer sealers supplied by the other manufacturers. The application of an epoxy overlay requires a CSP of 5–7 while a healer sealer requires a CSP of 2–5. Iowa and Pennsylvania perform acid etching to remove loose material and laitance during deck surface preparation. However, BASF and Euclid Chemical do not recommend acid etching (BASF 2016 and Euclid Chemical 2016). The deck concrete must be neutralized using a water/baking soda or a water/ammonia mixture followed by a clean water rinse before applying an epoxy overlay or a healer sealer when acid etching is used (Euclid Chemical 2016). 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 and healer sealers. The moisture content of < 4% and vapor pressure of ≤ 3 lbs/1000 ft^2 is required for a Pro-Poxy Type III DOT overlay and Pro-Poxy 40 LV LM healer sealer, respectively.

Table 2-4. Application Requirements of MDOT Approved Epoxy Overlays

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

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

Table 2-5. Application Requirements of MDOT Approved Healer Sealers

Supplier	Product	Minimum age of concrete (days)	CSP	Moisture content	Substrate temperature (°F)	Ambient temperature (°F)
E-Chem	EP100	28	na	insensitive	≥ 50	≥ 50
Euclid Chemical	Dural 335 Dural 50 LM	28	2–5	insensitive tolerant	50–90	50–90
Poly-Carb	Mark 127	na	na	na	na	na
Sika	Sikadur 55 SLV	21–28	na	na	40–95	40–95
Unitex	Pro-Poxy 40 LV LM	21–28	na	Vapor pressure ≤ 3 lbs/1000 ft^2	≥ 50	≥ 50

Note: CSP = concrete surface profile; na = not available.

2.4 EPOXY OVERLAY AND SEALANT PERFORMANCE

2.4.1 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 10º F to 100º 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/yd^3 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 2-2 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.

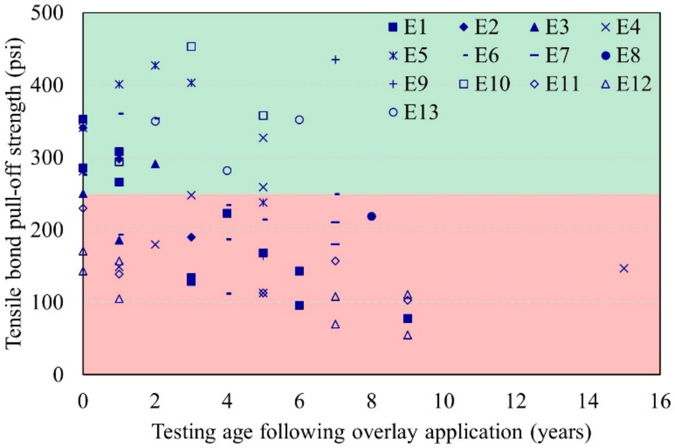


Figure 2-2. Performance of epoxy overlays evaluated by Sprinkel et al. (1993)

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 E4 epoxy overlay degraded significantly after it was in service for 3 to 4 years (Figure 2-3). Unfortunately, adequate information, including the substrate and ambient temperature histories, is not available to evaluate the possible causes for lower bond strengths.

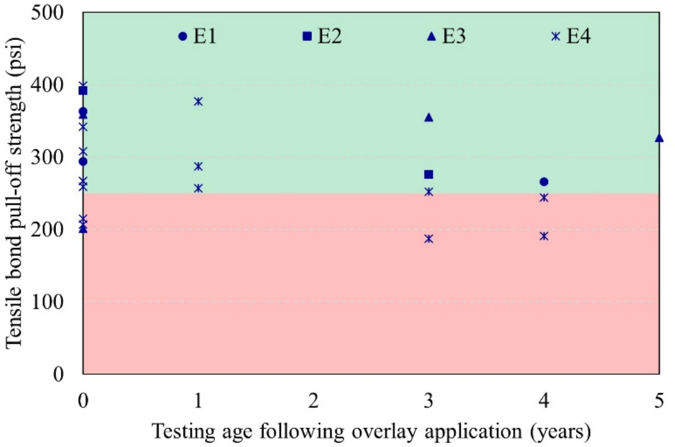
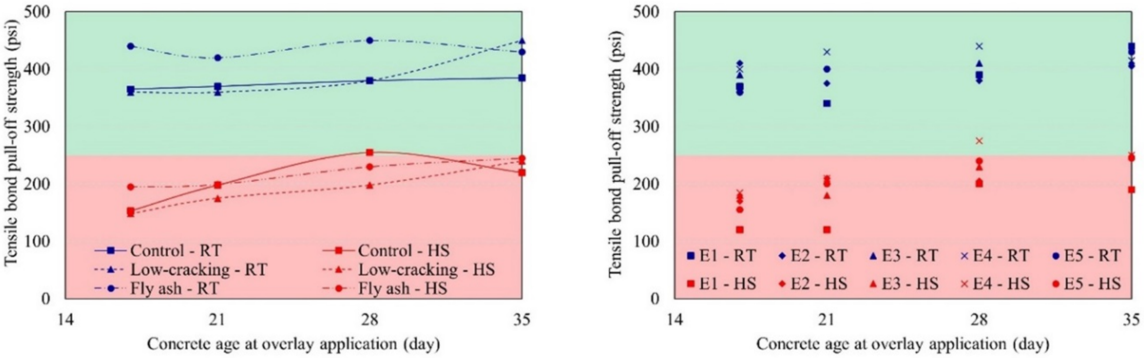


Figure 2-3. Performance of epoxy overlays evaluated by Wilson and Henley (1995)

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 2-6. 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). Figure 2-4a and Figure 2-4b 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.

Table 2-6. Concrete Mix Designs Used by Shearrer et al. (2015)

Material	**Control**	**Low-cracking**	**Fly ash**
Coarse aggregate (SSD) (lbs/yd^3)	1,837	1,858	1,884
Fine aggregate (SSD) (lbs/yd^3)	1,250	1,264	1,282
Cement–Type I (lbs/yd^3)	550	550	412.5
Class F fly ash (lbs/yd^3)	0	0	137.5
Water-cementitious material ratio	0.50	0.44	0.50
Water reducer (fl oz/lbs-cementitious material/yd^3)	20.25	27.08	0
Air content (assumed) (%/yd^3)	2	2	2



a) Performance of epoxies on three concrete mixes   b) Epoxy performance irrespective of concrete mixes

Figure 2-4. Performance of epoxy overlays evaluated by Shearrer et al. (2015)

Note: RT = room temperature; HS = elevated temperature (heated slabs).

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 moisture 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 other overlay systems.

2.4.2 Performance Evaluation by Field Inspection and Surveys

Issa et al. (1995) visually inspected 22 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. Johnson (2013) conducted a survey and an extensive literature review to document the performance evaluation parameters and methods for penetrating silane sealers, film formers, and crack sealants. Considering the extent of cracking, Johnson (2013) recommended using healer sealers to treat bridge decks with randomly dispersed cracking.

2.4.3 Anticipated Fix Life with Overlays and Sealants

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 healer sealers and epoxy overlays ranges from 8 to 10 years and 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.

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. The healer sealer performance is evaluated by considering the resistance to chloride ingress.

2.5 CONCRETE PROPERTIES AND PRACTICES FOR DECIDING THE MINIMUM CONCRETE AGE TO RECEIVE A FLOOD COAT

The focus of this study is to determine the suitability of a prescription-based or a performance-based procedure for deciding the minimum age of concrete to receive an epoxy overlay or a healer sealer. Concrete properties and practices that are critical to identifying the minimum concrete age to receive a flood coat are discussed in the following sections.

2.5.1 Performance of Epoxy Overlays

Thin epoxy overlays are applied on bridge decks with new concrete in patches and repairs after a 28-day prescribed curing period (MDOT 2018a). 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. Therefore, the concrete age at cracking and at the time of achieving an acceptable substrate moisture content are two parameters to decide on the minimum age of concrete to receive an epoxy overlay. This specific concrete age depends on several parameters including concrete mix ingredients, curing conditions, moisture diffusion coefficient, the moisture profile along the depth, and exposure conditions. 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). These failure modes and associated concrete parameters are discussed in the following sections.

2.5.1.1 Failure in the Substrate

A weaker substrate results in a substrate failure with a lower tensile bond pull-off strength than the specified limit (typically, 250 psi). To improve substrate strength, the proper curing conditions and duration need to be maintained. Strength and the rate of strength gain depend on many parameters such as concrete mix ingredients, w/cm ratio, type and quantity of SCMs, along with exposure and curing conditions (Poole 2006, IMCP 2007). A longer wet curing period is required for concrete mixes with SCMs to ensure adequate strength development. Recent studies suggest 10 to14 days of wet curing for such mixes (Poole 2006, USDOT 2003). The duration of curing for a specific mix needs to be established based on the rate of strength development (ACI 308R-01 2008). Therefore, the curing duration needs to be a parameter when deciding the minimum concrete age to receive an overlay.

2.5.1.2 Bond Failure at the Concrete/Overlay Interface

Bond failure at the concrete/overlay interface is mostly observed under elevated temperatures due to (i) the reduction in mechanical and adhesion properties of the epoxy overlay, (ii) shear stress development 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 epoxy resin loses tensile strength and elongation capacities as well as softening during prolonged and repeated exposure to elevated temperatures resulting in failure at the concrete/overlay interface bond (Soltesz 2010). Another possible reason for interface bond failure is the reduction of an effective bond area because of concrete cracking after an 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 the moisture content along the depth of concrete specimen, pore structure, exposure conditions, and drying period (Lawler et al. 2007). A discontinuous capillary pore structure with a minimum volume of total permeable voids is expected to be developed within the wet curing period. The development of a discontinuous capillary pore structure and a minimum volume of total permeable voids depends on concrete mix ingredients and wet curing duration and conditions. As an example, a concrete mix with Type I cement and a 0.45 water-cement (w/c) ratio develops a discontinuous capillary pore structure within 7 days of wet curing; while a mix with 65% Type I cement and 35% GGBFS takes about 10 days to develop such a pore structure (Powers et al. 1959, Hearn et al. 2006, Basnayake et al. 2020). Therefore, wet and dry curing periods need to be defined for the mixes used in patches and repairs to minimize moisture influence on the overlay performance.

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 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 in Type I cement. Lawler et al. (2007) fabricate 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 × 12 × 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 2-7 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. Since the rate of strength and microstructure development is different with the type and the amount of SCMs, the required curing duration to develop a discontinuous capillary pore structure with a minimum volume of total permeable voids need to be evaluated and maintained.

Table 2-7. RCP and Apparent Chloride Diffusion Coefficients for Mixes with SCMs (Lawler et al. 2007)

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

Note: NA = not applicable.

Concrete cracking after an overlay application reduces the effective bonded area between overlay and substrate (Bakhsh 2010). The cracked concrete has a greater surface area for moisture migration. Further, moisture migration through cracks is faster and easier. Thus, concrete cracking after overlay application could result in lower bond strength because of (i) reduction in the effective bonded area and (ii) a greater amount of moisture accumulation at the concrete/overlay interface. Therefore, it is necessary to consider the concrete cracking age as a parameter for deciding the minimum concrete age to receive an epoxy overlay.

2.5.2 Performance of Healer Sealers

A healer sealer is applied on a bridge deck with new concrete after a 28-day prescribed curing period (MDOT 2018b). Within this period, it is expected that a majority of shrinkage cracks will develop along with an acceptable level of internal moisture content within the concrete. Therefore, concrete cracking age and time to achieve acceptable substrate moisture are selected as two decision parameters for healer sealer application. The concrete cracking age and the time to achieve acceptable substrate moisture depend on several parameters as discussed in Section 2.5.1. With an acceptable moisture content, a flood coating healer sealer is applied to seal the cracks for preventing chloride laden moisture ingress. Therefore, the resistance to chloride ion ingress is a performance parameter (Sprinkel et al. 1993). Chloride content along the depth is evaluated using acid-soluble and/or water-soluble chloride content tests following ASTM C1152 and ASTM C1218, respectively. The decks become vulnerable to chloride since the coating wears off due to traffic. Subsequently, the chloride diffuses through concrete within such unprotected areas and starts corroding reinforcing steel, although the cracks are sealed from chloride ingress. Since chloride ingress is faster through a continuous pore structure, wet curing needs to be continued until a discontinuous capillary pore structure is developed with a minimum volume of total permeable voids (Basnayake et al. 2020). The development of a discontinuous capillary pore structure with a minimum volume of total permeable voids depends primarily on concrete mix ingredients and wet curing duration and conditions. Therefore, the minimum concrete age for healer sealer application depends on concrete wet curing duration, cracking age, and substrate moisture condition.

As discussed in Section 2.5.1 and 2.5.2, several concrete properties and practices are important to assess the need of developing a prescription-based or a performance-based approach to identify the minimum concrete age to receive an epoxy overlay or a healer sealer. Table 2-8 shows concrete properties and practices that need to be evaluated to identify the minimum concrete age to receive a flood coat. As an example, concrete wet curing duration, cracking age, moisture condition, and tensile strength are the parameters to be considered for deciding the minimum concrete age to receive an epoxy overlay.

Table 2-8. Concrete Properties and Practices to Decide the Minimum Concrete Age to Receive a Flood Coat

Epoxy overlay	Healer sealer
a) Wet curing duration	a) Wet curing duration
b) Concrete cracking age	b) Concrete cracking age
c) Substrate moisture condition	c) Substrate moisture condition
d) Concrete tensile strength	

2.6 CONCRETE PROPERTY AND FLOOD COAT PERFORMANCE EVALUATION

Table 2-8 shows the concrete properties to be evaluated for deciding the minimum concrete age receiving epoxy overlays or healer sealers. The performance of epoxy overlays is evaluated using a tensile bond pull-off strength test and the performance of healer sealers is evaluated by measuring the chloride content along the depth. The evaluation methods for concrete properties and the performance of epoxy overlays and healer sealers are discussed in the following sections.

2.6.1 Concrete Wet Curing Duration

Concrete structures, such as bridge decks, are exposed to various loads and harsh conditions during their service life. For this reason, such structures are designed considering both strength and durability. Exposure to deicing salts, surface abrasion, and freeze-thaw conditions contribute to the rapid deterioration of concrete. In the absence of cracks, the amount and rate of moisture and aggressive chemical ingress, such as chlorides, depend on the total volume of permeable voids in concrete and the continuity of capillary pore structure. Therefore, permeability is a major parameter that defines concrete durability. The coefficient of permeability is used as a measure of permeability. For a freshly mixed cement paste, the coefficient of permeability is in the order of 4×10^{-4} to 4×10^{-5} in./s and reduces with the degree of cement hydration (Mehta and Monteiro 2006). The reduction in permeability is attributed to the increase in capillary pore discontinuity (Powers et al. 1959). Powers et al. (1959) developed a semi-theoretical equation to represent the development of a discontinuous capillary pore structure with the degree of hydration. Hearn et al. (2006) presented a relationship between permeability and porosity. This relationship was graphically presented with available data to demonstrate that the permeability-porosity relationship of mixes with various w/cm ratios follows a specific line once the mixes develop discontinuous capillary pore structures. Nokken (2004) used concrete mixes with SCMs and various w/cm ratios to evaluate the concepts presented by Powers et al. (1959). The presence of a capillary pore structure discontinuity relationship for mortar and concrete mixes was confirmed by measuring the electrical conductivity of the samples using the rapid chloride permeability test (Nokken 2004). All the work presented in these references (Powers et al. 1959, Hearn et al. 2006, Nokken 2004) indicates very little change in permeability once a discontinuous capillary pore structure is developed. Therefore, the curing duration for a given concrete mix can be determined by knowing the time required to develop a discontinuous capillary pore structure (Nokken 2004).

The formation of a discontinuous capillary pore structure is evaluated through permeability and porosity. The saturated water permeability test and ionic diffusion test are two common methods for evaluating concrete permeability. The solvent displacement technique (water, isopropanol, methanol, etc.) and mercury intrusion porosimetry are two common methods used to quantify porosity. These test methods have their own merits and demerits (Hearn et al. 2006, Nokken 2004, Abell et al. 1998). Even though most of the listed methods provide a direct permeability reading, the implementation of such methods for repeated measurements is laborious. As a result, nondestructive evaluation of concrete properties using electrical methods is becoming popular. Conductivity or resistivity measurements are used to indirectly evaluate concrete permeability. The conductivity of concrete is influenced by the volume and connectivity of pores, and the conductivity of pore solution. With the development of pore structure over time, the conductivity of concrete decreases. Bulk electrical conductivity was proposed as a suitable indicator of concrete permeability and as a potential method to determine the required wet curing duration (Nokken 2004). Typically, a reduction in the bulk electrical conductivity is expected with the concrete age (Nokken 2004). A significant decrease in the rate of reduction of electrical conductivity is observed after achieving the capillary discontinuity. Therefore, the bulk electrical conductivity test method specified in the ASTM C1760 is a suitable test method to evaluate the required time for achieving capillary discontinuity. In addition, the porosity test described in ASTM C642 is suitable to determine the time to achieve a minimum volume of total permeable voids. Therefore, the required wet curing duration can be considered as the maximum of (i) time to achieve the specified strength, (ii) time to achieve a discontinuous pore structure, and (iii) time to achieve a minimum volume of total permeable voids.

2.6.2 Concrete Cracking Age

Epoxy overlays and healer sealers are applied to enhance the durability of cracked concrete. Therefore, the age of concrete cracking must be determined so that the epoxy overlay and healer sealer can be applied after concrete cracks. The restrained shrinkage test (ASTM C1581) is commonly used to identify the cracking age of concrete. The cracking age obtained from the restrained shrinkage test can be correlated to the field conditions (Fu 2013).

2.6.3 Substrate Moisture Condition

The substrate moisture is another parameter considered for flood coat application. 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.

2.6.4 Strength Development of Concrete

The compressive and flexural strength tests are conducted to evaluate the concrete strength development against the age of concrete by following ASTM C39 and ASTM C78, respectively. These tests are conducted primarily for quality assurance and quality control purposes. Both compressive and flexural strengths are important to assure adequate substrate strength during shotblasting to minimize concrete damage and provide sufficient tensile strength for satisfying the minimum tensile bond pull-off strength requirements.

2.6.5 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.

2.6.6 Resistance to Chloride Ingress

Healer sealers are applied on bridge decks to seal cracks and prevent moisture-laden chloride ingress. Several methods are available to measure chloride content in concrete. The acid-soluble and water-soluble chloride content is evaluated following ASTM C1152 and C1218 procedures, respectively. The ASTM C1152 procedure is used to measure the total chloride content bound on aggregate and hydrated cement as well as the available chloride to cause corrosion. The threshold total chloride content to initiate steel corrosion is 500 ppm (parts per million). The ASTM C1218 procedure is used to measure the water-soluble chloride content available to cause steel corrosion. This test does not evaluate the bound chloride in aggregates and hydrated cement. However, the chloride content evaluated following ASTM C1218 can show higher chloride content due to aggregate crushing and highly variable data depending on the particle size and core extraction time and temperature (Concrete Construction 1998). ACI 222R-19 (2019) defines the threshold limit for water-soluble chloride content as 75–80% of the acid-soluble limit of 500 ppm. Therefore, the threshold limit for the water-soluble chloride content is 375–400 ppm.

Section 2.5 listed several parameters for deciding on the minimum concrete age to receive a flood coating. However, several additional parameters need to be evaluated using experimental procedures to support the decisions. Table 2-9 lists the parameters for deciding the minimum concrete age to receive a flood coating, parameters evaluated through experimental procedures to collect necessary data, and the relevance of the parameters to make decisions on overlay and healer sealer applications.

Table 2-9. Parameters for Deciding the Minimum Concrete Age to Receive a Flood Coating

Parameter for deciding the minimum concrete age to receive a food coating	Parameters evaluated using experimental methods	Epoxy overlay	Healer sealer
Wet curing duration	Compressive and flexural strengths Bulk electrical conductivity Porosity	Yes	Yes
Concrete age at cracking	Restrained shrinkage	Yes	Yes
Substrate moisture condition	Moisture vapor emission rate (MVER) Moisture content Internal relative humidity (IRH)	Yes	Yes
Tensile strength	Flexural strength	Yes	No
Bond strength	Tensile bond pull-off strength	Yes	No
Chloride content	Acid- and water-soluble chloride content	No	Yes

2.7 SUMMARY

Epoxy overlays and healer sealers have been used since the 1990s to extend the service life by protecting bridge decks from chloride-laden moisture ingress. Epoxy overlay and healer sealer 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. Healer sealer performance is evaluated by measuring the resistance to chloride ingress. The performance of epoxy overlays and sealers is documented in the literature. Unfortunately, none of the publications presents substrate temperature and moisture conditions or the ambient exposure histories to support the conclusions. The minimum concrete age to receive a flood coating and the flood coat performance depends on several parameters such as concrete cracking, moisture, and strength. Such parameters depend on concrete mix design and wet and dry curing periods. Therefore, the parameters listed in Table 2-9 can be considered to develop a performance-based procedure for deciding the minimum concrete age to receive a flood coat.

3 PERFORMANCE OF THIN EPOXY OVERLAYS

3.1 OVERVIEW

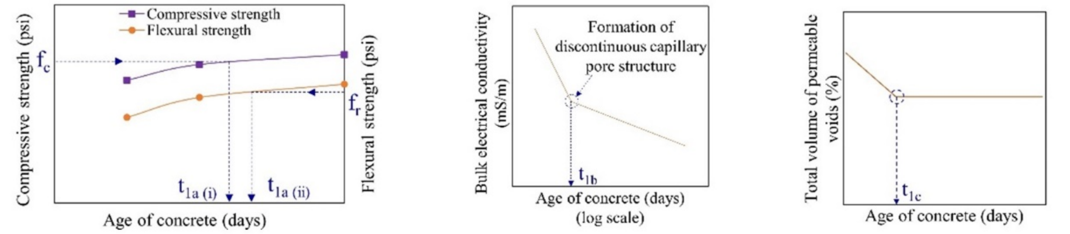
The specifications and special provisions require 28 days of curing for new concrete before applying a thin epoxy overlay. This requirement extends project duration, impacts mobility, and increases the overall cost. Thus, it is necessary to evaluate the possibility of applying epoxy overlays (for patches and repairs) earlier than 28 days on decks with new concrete without compromising the intended performance. This chapter presents a performance-based procedure to evaluate the minimum age of concrete to receive an overlay, implementation of the procedure, and the results. Meanwhile, there is an interest in evaluating the possibility of developing a hybrid bridge deck protection system with penetrating sealers and thin epoxy overlays to complement the overlay performance by retarding chloride ingress into the concrete through pinholes and other anomalies formed during overlay application and damages during service. This chapter also presents the experimental studies conducted to evaluate the overlay bond strength performance in the presence of a penetrating sealant, along with the findings of said studies.

3.2 EVALUATION OF THE MINIMUM CONCRETE AGE TO RECEIVE A THIN EPOXY OVERLAY

3.2.1 Procedure for Deciding the Minimum Concrete Age

The objective of this study is to identify the minimum concrete age to receive a thin epoxy overlay. The decision depends on concrete wet curing duration, cracking age, concrete age to achieve an acceptable substrate moisture condition, and concrete age to achieve a required minimum tensile strength. Thin epoxy overlay performance depends on concrete strength, bond strength, thermal compatibility between overlay and concrete, and epoxy performance under various exposure conditions. 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 (MDOT 2019a). Figure 3-1 depicts the procedure to evaluate the minimum age of concrete to receive an overlay (*t*), which is defined as a function of (i) concrete wet curing duration, (ii) concrete age at the time of cracking, (iii) concrete age to achieve acceptable substrate moisture, (iv) concrete age to develop the specified minimum tensile strength, and (v) concrete age at the time of epoxy application to achieve the specified bond strength. The significance of each parameter is described in the following sections.

The minimum age of concrete to receive a thin epoxy overlay, t (days) = max

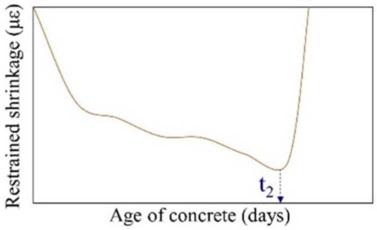


(i) Concrete age to satisfy the specified strength requirements (**t_{1a}**)

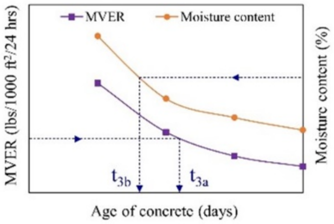
(ii) Concrete age to develop a discontinuous pore structure (**t_{1b}**)

(iii) Concrete age to develop a minimum volume of total permeable voids (**t_{1c}**)

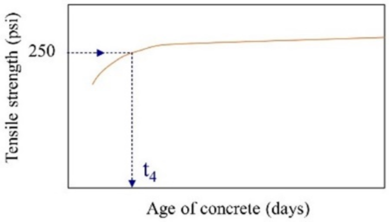
a) Concrete wet curing duration (**t_1 = max (t_{1a}, t_{1b}, and t_{1c})**)



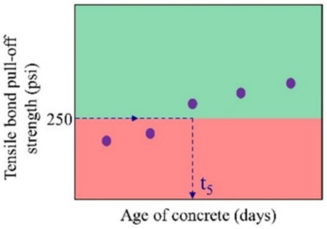
b) Concrete age at the time of cracking (**t_2**)



c) Concrete age to achieve acceptable substrate moisture (**t_3**)



d) Concrete age to develop the specified minimum tensile strength (**t_4**)



e) Concrete age at the time of epoxy overlay application to develop the specified bond strength (**t_5**)

Figure 3-1. Procedure for deciding the minimum concrete age to receive a thin epoxy overlay

Note: QAQC = quality assurance and quality control; max = maximum; MVER = moisture vapor emission rate.

3.2.1.1 Concrete Wet Curing Duration

The wet curing duration is typically defined based on the time to achieve the specified compressive and/or flexural strength of concrete. Figure 3-1a(i) shows the variation of concrete strength against time. This relationship can be used to decide on the wet curing duration (t_{1a}) to achieve the required strength. However, a favorable curing condition needs to be maintained until a discontinuous pore structure with a minimum volume of total permeable voids is developed for assuring durability and managing moisture transfer. Figure 3-1a(ii) shows the variation of bulk electrical conductivity against time. The time to develop a discontinuous pore structure (t_{1b}) is represented by the change in slope. Figure 3-1a(iii) shows the variation of the total volume of permeable voids against time. The time to achieve a minimum volume of total permeable voids (t_{1c}) is represented by the change in slope. Hence, the wet curing duration (t_1) should be continued beyond the longest duration of t_{1a}, t_{1b}, and t_{1c} to satisfy both the strength and durability requirements.

3.2.1.2 Concrete Age at the Time of Cracking

An overlay is decided based on concrete crack density and propensity for future crack growth. Even though the ASTM C1581 test does not simulate field conditions, this method allows evaluating the cracking propensity of different mixes and the time it takes to crack under restraint conditions. This method is expected to provide the earliest possible concrete cracking time for a given mix under similar exposure conditions. Figure 3-1b shows the variation of strain in the steel ring due to concrete shrinkage against time and the criterion used to select the cracking time (t_2). The concrete age at the time of epoxy overlay application needs to be equal or greater than t_2.

3.2.1.3 Concrete Age to Achieve Acceptable Substrate Moisture

The third parameter considered for overlay application is substrate moisture. Most of the highway agencies evaluate substrate moisture by following a modified version of the procedure described in ASTM D4263. The standard practice of the flooring industry is to evaluate the moisture vapor emission rate (MVER) with a maximum limit of 3 lbs/1000 ft^2/24 hrs (Gaughen 1999). A few highway agencies, such as New York and Wisconsin, evaluate substrate moisture using electrical impedance meters. New York applies epoxy overlays when the substrate moisture content is less than 5.0%, whereas the Wisconsin limit is 4.5%. Figure 3-1c shows the procedure to determine the time to reach the required maximum permissible MVER or substrate moisture (t_3).

3.2.1.4 Concrete Age to Develop the Specified Minimum Tensile Strength

Concrete needs to develop a direct tensile strength greater than the required minimum bond strength evaluated using the tensile bond pull-off strength test. This can be a requirement above and beyond the typical QAQC specifications. As an example, MDOT special provision 12SP-712C-03 specifies a minimum bond strength of 250 psi (MDOT 2019a). Hence, adequate time should be allowed for concrete to develop this required strength.

The flexural strength is evaluated using a four-point bending test on 6 × 6 × 20 in. beams (ASTM C78). Recommendations by Lin et al. (2013) can be implemented to estimate, the direct tensile strength from the flexural strength evaluated following ASTM C78. Since the direct tensile strength is approximately 63~73% of the flexural strength (Lin et al. 2013), 60% of the flexural strength can be conservatively used as the direct tensile strength of concrete to estimate the minimum required curing duration. The time requirement is depicted in Figure 3-1d. The concrete age at the time of epoxy overlay application (*t*) should be greater than t_4 to achieve a minimum flexural strength of 417 psi (i.e., 250/0.6).

3.2.1.5 Concrete Age at the Time of Epoxy Overlay Application to Achieve the Specified Bond Strength

Several other parameters, including the amount of moisture in concrete, moisture profile, moisture vapor transmission under elevated temperatures, workmanship, etc., influence overlay bond strength. Hence, bond strength needs to be evaluated after applying overlays on concrete at different ages. Satisfactory performance is achieved when the bond strength is equal to or greater than 250 psi, as shown in Figure 3-1e. The concrete age at the time of overlay application to achieve the specified bond strength (*t*) should be equal to or great than t_5, the concrete age at the time of receiving an overlay to satisfy the performance requirement.

3.2.2 Implementation of the Proposed Procedure

E-bond 526 Lo-Mod and Unitex Pro-Poxy Type III DOT were selected from the MDOT approved product list (MDOT 2018a). These products were selected based on their application frequency on Michigan bridge decks. The performance of these overlays was evaluated on specimens fabricated using bridge deck joint repair (BDJR) and the Grade DM concrete mixes. The BDJR mix is used for expansion joint repair and deck patching. Grade DM is the standard bridge deck concrete mix. Table 3-1 shows the mix designs. As shown in the table, the BDJR mix contains only Type I cement while the Grade DM mix contains 35% ground granulated blast furnace slag (GGBFS). A hydration controlling admixture was used in Grade DM concrete to increase the setting time during casting. The basic QAQC testing on fresh properties was performed on the casting day as per the Manual for the Michigan Test Methods (MTM 2018). Table 3-2 presents the experimental plan to identify the minimum concrete age to receive an overlay. The table columns *a* to *g* list the evaluation parameter, measurand, ASTM standard, size of the specimen, concrete age at the time of overlay application, curing and exposure condition, along with concrete age at the time of testing. For the specimens that required ASTM curing (column *f*), submerged wet curing was provided continuously through the testing ages according to ASTM C192. All the other specimens were dry-cured at 73° F in the laboratory following 7 days of moist curing. The testing plan included the evaluation of epoxy overlay performance against chloride ingress and the impact of epoxy application during the dry curing period. The testing plan for each evaluation parameter is discussed in the following sections.

Table 3-1. Mix Design: BDJR and Grade DM Concrete (per yd^3)

Material	BDJR	Grade DM
Coarse aggregate (SSD) (lb)	1,488	1,644
Fine aggregate (SSD) (lb)	1,557	1,356
Cement–Type I (lb)	656	397
GGBFS (lb)	0	214
Air entraining admixture (fl oz)	5.07	10.78
Hydration controlling admixture (fl oz)	0	18.56
Water reducing admixture (fl oz)	58.67	54.44
Water (lbs)	246	238
Water-cementitious material ratio	0.38	0.39

Table 3-2. Experimental Plan to Assess the Minimum Concrete Age to Receive an Epoxy Overlay

Evaluation parameter (a)	Measurand (b)	ASTM standard (c)	Size of the specimen (in.) (d)	Concrete age at the time of overlay application (e)	Curing and exposure condition (f)[c]	Concrete age at the time of testing (days) (g)
Concrete wet curing duration (t_1)	Compressive strength	C39	4 × 8	NA	ASTM	7, 14, 21, and 28
	Flexural strength[a]	C78	6 × 6 × 20	NA	ASTM	7, 14, 21, and 28
	Bulk electrical conductivity[b]	C1760	4 × 8	NA	ASTM	1, 3, 7, 14, 21, and 28
	Porosity	C642	4 × 2	NA	ASTM	3, 7, 14, 21, and 28
Concrete age at the time of cracking (t_2)	Restrained shrinkage	C1581	As per the ASTM	NA	RT	Until cracking
Concrete age to achieve acceptable substrate moisture (t_3)	Moisture vapor emission rate (MVER)	F1869	40 × 40 × 9	NA	RT	14, 21, and 28
	Moisture content	F2659	40 × 40 × 9	NA	RT	7, 14, 21, and 28
	Internal relative humidity (IRH)	F2170	40 × 40 × 9	NA	RT	Starting from 7-day until the end of testing
Concrete age to develop the specified minimum tensile strength (t_4)	Flexural strength[a]	C78	6 × 6 × 20	NA	ASTM	7, 14, 21, and 28
Concrete age at the time of epoxy application to develop the specified bond strength (t_5)	Tensile bond pull-off strength	C1583	40 × 40 × 9	14	RT–RT	17, 21, 28, 42, 105, and outdoor[d]
					RT–HS	17, 21, 28, 42, 105, and outdoor[d]
					RT–WD[e, f]	17, 28, 42, 105, and outdoor
			40 × 40 × 9	21	RT–RT	24, 28, 35, 49, 112, and outdoor
					RT–HS	24, 28, 35, 49, 112, and outdoor
					RT–WD	24, 35, 49, 112, and outdoor
			40 × 40 × 9	28	RT–RT	31, 35, 42, 56, 119, and outdoor
					RT–HS	31, 35, 42, 56, 119, and outdoor
					RT–WD	31, 42, 56, 119, and outdoor

Note: ASTM = American Society for Testing and Materials; NA = not applicable

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

[b] One-day data was recorded only for the BDJR concrete mix.

[c] ASTM, RT, HS, and WD represent curing conditions. ASTM – continuous submerged wet curing until testing, RT – room temperature, HS – elevated temperature, and WD – one-week alternate wet and dry cycles. RT–RT, RT–HS, and RT–WD represent concrete during following the 7-day wet curing and overlay exposure before or during testing.

[d] The overlay performance under outdoor conditions was evaluated on BDJR concrete specimens at 226, 227, 337, 477, 479, 483, and 484 days of concrete age and Grade DM concrete specimens at 268, 269, 385, 519, 521, 525, and 526 days of concrete age.

[e] WD specimens are used at 14, 21, and 28-day application ages for Grade DM and only at 28-day application age for BDJR.

[f] The performance under outdoor conditions was evaluated on WD slabs fabricated with BDJR mix at 337 days and Grade DM mix on 385 days of concrete age.

3.2.2.1 QAQC Testing

Temperature, slump, density, and air content were measured on the day of casting as per the ASTM C1064, C143, C138, and C231 specifications. Concrete cylinders and beams were fabricated and cured through testing ages as per ASTM C192 to evaluate compressive and flexural strengths. The required QAQC tests and the number of tests were decided as per the Manual for the Michigan Test Methods (MTM 2018) and the MDOT Standard Specifications for Construction (MDOT 2012).

3.2.2.2 Concrete Wet Curing Duration

In addition to compressive and flexural strengths, bulk electrical conductivity and porosity tests were performed to evaluate the required wet curing duration to develop a discontinuous pore structure with a minimum volume of total permeable voids. The bulk electrical conductivity test was performed according to ASTM C1760 on 4 × 8 in. cylinders. The total volume of permeable voids was evaluated following the porosity test procedures described in ASTM C642. A single 4 × 8 in. cylindrical specimen provides two 4 × 2 in. specimens for porosity tests. The top 0.5 in. of the cylinder is discarded, and two 4 × 2 in. cylindrical sections are cut from the remaining part of the cylinder to obtain the specimens.

3.2.2.3 Concrete Age at the Time of Cracking

A restrained shrinkage test was performed following the ASTM C1581 procedure to determine the cracking age of concrete. The specimens were covered with wet burlaps and plastic during the 7-day moist curing period. Following moist curing, specimens were exposed to 73° F and 50% relative humidity (RH). The steel ring strain data was recorded until the concrete rings cracked.

3.2.2.4 Concrete Age to Achieve Acceptable Substrate Moisture

Substrate moisture variation against time was evaluated using MVER and moisture content measurements following ASTM F1869 and F2659 procedures, respectively. A 40 × 40 × 9 in. slab specimen was used for this purpose. Following a 7-day wet curing, all the surfaces of the slab, except the top surface, were epoxy painted to simulate one-dimensional moisture transfer. After the wet curing period, the slab was placed under standard laboratory conditions for dry curing through the testing ages. MVER and moisture content were measured at 14, 21, and 28 days of concrete age. Internal relative humidity (IRH) of the slabs with epoxy overlays was measured by placing RH probes. The same probes were used to evaluate moisture migration under elevated temperature and moisture redistribution under room temperature following a heat cycle. The probes were installed at 1.0 and 3.6 in. depths from the top surface. The probes at 1.0 in. provided IRH near the top. The probes at 3.6 in. provided IRH at a depth of 40% of the specimen thickness for one-way drying (ASTM F2170). IRH measurements started on the 7th day following sample fabrication and continued until the end of testing.

3.2.2.5 Concrete Age to Develop the Specified Minimum Tensile Strength

Flexural strength was evaluated by following the procedures given in ASTM C78. Four-point bending was performed at 7, 14, 21, and 28 days of concrete age to evaluate flexural strength. All the specimens were moist cured following ASTM C192 procedures until the testing age. As described in Section 3.2.1.4, recommendations by Lin et al. (2013) were implemented to estimate the direct tensile strength from the flexural strength evaluated following ASTM C78.

3.2.2.6 Concrete Age at the Time of Epoxy Application to Develop the Specified Bond Strength

A total of thirty-two (32) 40 × 40 × 9 in. slab specimens were fabricated. Eighteen (18) slabs were fabricated with Grade DM concrete in January 2019. Fourteen (14) slabs were fabricated with BDJR concrete in March 2019. Epoxy overlays were applied at 14, 21, and 28 days of concrete age. Figure 3-2 shows 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. The one-way moisture migration was ensured by sealing all the sides, except the top surface, with epoxy paint, to replicate the presence of stay-in-place formwork. Following the 7-day wet curing period, the slabs were cured under standard laboratory conditions. At 14 days of concrete age, the top surface of all the slabs was shotblasted and cleaned. The slabs that were designated to receive an overlay at 14 days received the first coat on the same day. Figure 3-2e shows a specimen with the first layer of epoxy. The second coat was applied on the 15th day. This allowed a 24-hour curing period for the first coat. A layer of flint aggregate was broadcasted following the application of each epoxy layer. A similar process was followed for the specimens that were designated to receive overlays at 21 and 28 days of concrete age. Figure 3-2f shows a specimen with a two-coat epoxy overlay. The overlay performance was evaluated primarily by conducting direct pull-off strength tests under laboratory and outdoor exposure conditions.

a) Formwork
b) Moist curing with wet burlap

c) Specimen arrangement for shotblasting
d) Surface after shotblasting and cleaning

e) First coat of epoxy application
f) Specimen after two coats of epoxy application

Figure 3-2. Slab specimen fabrication and preparation procedures

3.2.2.7 Performance Evaluation under Simulated Exposure Conditions

The overlay performance was evaluated under three exposure conditions: (i) room temperature (RT), (ii) elevated temperature (heated slab – HS), and (iii) one-week alternate wet and dry cycles (WD). The RT specimens were stored at 73° F after epoxy application. The maximum design temperature for Michigan bridges with prestressed girders and steel girders is 100° F and 110° F, respectively (AASHTO 2016). Therefore, one specimen from each application age was heated to about 110° F using two infrared lights to evaluate the impact of hot summer conditions on overlay bond strength. Figure 3-3a shows the insulated heating chamber. The temperature was continuously controlled and recorded using an auto-shutoff temperature controller and recorder, respectively. Figure 3-3b and Figure 3-3c show the temperature controller and recorder, respectively. The bond strength was evaluated at the elevated temperature and 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, a 3% NaCl solution was used to flood the top surface continuously to evaluate the impact of salt solution on overlay performance. Bond strength was evaluated at 3, 7, 14, 28, and 91 days following epoxy application. As an example, the concrete age at testing for a 14-day epoxy coated slab was 17, 21, 28, 42, and 105 days. Table 3-2 shows the concrete age at the time of testing. Each pull-off strength test area was immediately sealed using epoxy paint to prevent moisture loss.

a) Insulated heating chamber with infrared lights

b) Temperature controller c) Temperature recorder

Figure 3-3. Insulated chamber for performance evaluation under elevated temperature

3.2.2.8 Performance Evaluation under Outdoor Exposure Conditions

In June and July of 2019, all 32 slabs were moved to an uncovered parking area to get them exposed to southwest Michigan weather (Figure 3-4). The overlay performance was evaluated during fall 2019 and winter and summer 2020. Testing on 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 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 (with a 6-day delay), 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., on the 7th day after a 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 at the time of testing was 34~38° F. The last sets of bond strength tests were conducted in July 2020. One set of data was collected when the ambient temperature was 87~91° F. The other data set was collected in the morning when the temperature was about 73° F. One cycle of bond strength tests was performed on the WD slabs. The WD slabs were continuously exposed to a 3% NaCl solution for 135 days before evaluating the bond strength. Tensile bond pull-off strength tests on WD slabs were performed on summer mornings when the ambient temperature was about 73° F. Each pull-off strength test area was sealed using epoxy paint.

3.2.2.9 Epoxy Overlay Performance Against Chloride Ingress

Thin epoxy overlays are expected to work as impermeable barriers against chloride ingress to protect bridge decks. Therefore, the ability of overlays to protect concrete from chloride ingress was also evaluated. Two 2.13 in. diameter and 2 in. deep cores were extracted from two WD slabs fabricated with BDJR concrete at the concrete age of 503 days. The top 0.25 in. of each core, measured from the top of the overlay, was discarded. The chloride content was evaluated from 0.25 in. to 1.75 in. at an interval of 0.5 in. following ASTM C1152 procedures. Similarly, chloride content on six WD slabs, fabricated with Grade DM concrete, was evaluated at the concrete age of 545 days. The background chloride content was also evaluated to identify the increase in chloride content due to 42 days of 3% NaCl exposure under laboratory conditions (6 weeks during wet-dry cycles) and 135 days of continuous exposure to outdoor conditions.

a) October 2019

b) January 2020

c) August 2020

d) Slabs ponded with NaCl solution

Figure 3-4. Slabs in the open parking lot and getting exposed to southwest Michigan weather

3.2.2.10 Impact of Epoxy Overlay Application on Concrete Strength and Durability

Applying epoxy overlays at 14, 21, and 28 days of concrete age, following a 7-day moist curing, causes the slabs to retain varying amounts of moisture. The availability of moisture could promote the hydration of the remaining cementitious material to improve microstructure and strength. Nevertheless, having a great amount of moisture entrapped within the slab could cause damages to concrete under freezing conditions. Therefore, compressive strength and pore structure integrity were evaluated. A set of 4 × 8 in. cylinders were extracted from bare slabs and the slabs with epoxy overlays applied at 14, 21, and 28 days of concrete age. Bare slabs were cored at 28, 120, and 539 days of concrete age to extract cylinders for strength tests. In addition, cylinders were extracted from the slabs with overlays at 120 and 539 days of concrete age. Moreover, compressive strength tests were conducted a day after core extraction, except for the testing of cores extracted from the 28-day old concrete.

The age of BDJR and Grade DM concrete was 454 and 406 days when the cores were extracted to evaluate pore structure integrity. By that time, the BDJR and Grade DM slabs were subjected to 149 and 116 freezing cycles, respectively. The top 0.5 in. of each specimen was saw cut and discarded. The remaining portion of the specimens was used for testing. A subset of specimens was used to evaluate porosity. The remaining specimens were used to evaluate the resistance to chloride ingress. One specimen from each mix was selected for background chloride testing. The circumferential area of the remaining cylinders was epoxy painted and ponded with 3% NaCl at the top. Chloride content down to a depth of 3.0 in. was evaluated at the end of 137 days of ponding by following ASTM C1152 procedures.

3.2.3 Results and Discussion

3.2.3.1 QAQC Testing

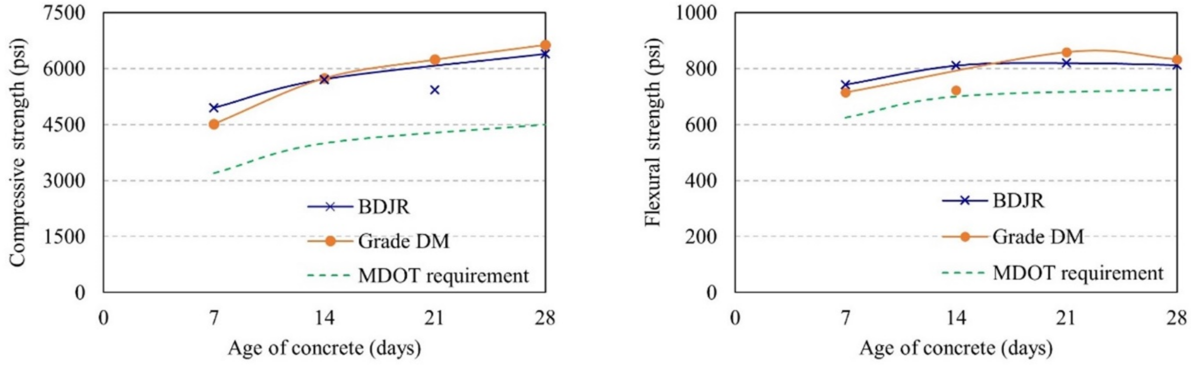
Table 3-3 presents fresh concrete properties. These results comply with MDOT specifications. Figure 3-5 and Figure 3-5b show the variation of the compressive and flexural strength with time. Both BDJR and Grade DM concrete mixes showed greater strengths than the minimum required. Since Grade DM contains 35% of GGBFS, the early-age strength is lower than BDJR.

Table 3-3. QAQC Results: Fresh Concrete Properties

Measurand	ASTM standard	BDJR	Grade DM
Temperature (°F)	C1064	69	69
Slump (in.)	C143	4.50	6.50
Density (lbs/yd^3)	C138	144.4	143.0
Air content (%)	C231	5.5	5.7

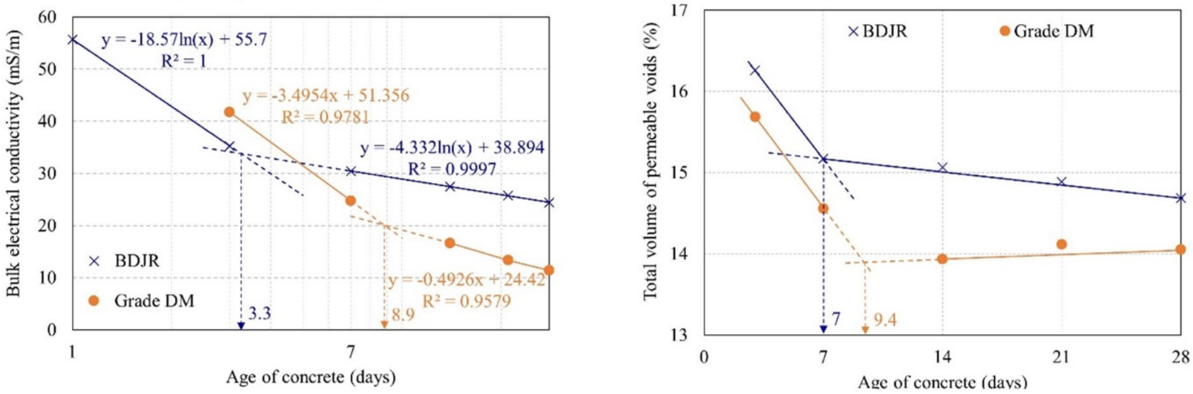
3.2.3.2 Concrete Wet Curing Duration

Figure 3-5a and Figure 3-5b show the compressive and flexure strengths of the mixes along with the MDOT requirements. Since both mixes satisfied the requirements with the 7-day moist curing, t_{1a} is 7 days. Figure 3-5c shows the variation of bulk electrical conductivity against the age of concrete. The required curing duration (t_{1b}) to develop a discontinuous capillary pore structure in BDJR concrete is 4 days since the straight trendline changed the slope at about 3.3 days. Similarly, the required curing duration to develop a discontinuous capillary pore structure in Grade DM concrete is 9 days. Figure 3-5d shows the variation of porosity against the age of concrete. The required curing duration (t_{1c}) to develop a minimum volume of total permeable voids for BDJR and Grade DM concrete is 7 and 10 days, respectively. The longest duration among these three curing durations is 7 days for BDJR and 10 days for Grade DM. Therefore, wet curing durations (t_1) of 7 and 10 days are required for BDJR and Grade DM mixes, respectively.



a) Compressive strength

b) Flexural strength



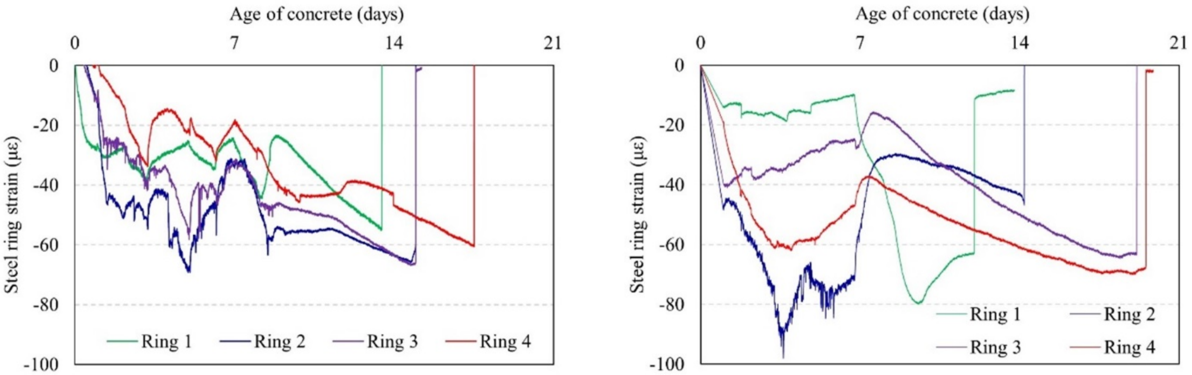
c) Bulk electrical conductivity

d) Porosity

Figure 3-5. Experimental results to determine wet curing duration

3.2.3.3 Concrete Age at the Time of Cracking

Figure 3-6a and Figure 3-6b show the variation of steel ring strain against the age of BDJR and Grade DM concrete. Four specimens were fabricated from each mix. Since the rings made of BDJR concrete cracked on the 14th, 15th (two specimens), and 18th-day following fabrication, the age of BDJR concrete at cracking (t_2) is conservatively assumed as 18 days. The rings made of Grade DM concrete cracked on the 13th, 15th, and 20th (two specimens) day following casting. Therefore, the age of Grade DM concrete at cracking (t_2) is conservatively assumed as 20 days. However, Ring 1 and 2 data for Grade DM mix showed a somewhat uncommon variation of strain against time, and the data did not influence the selected cracking age.



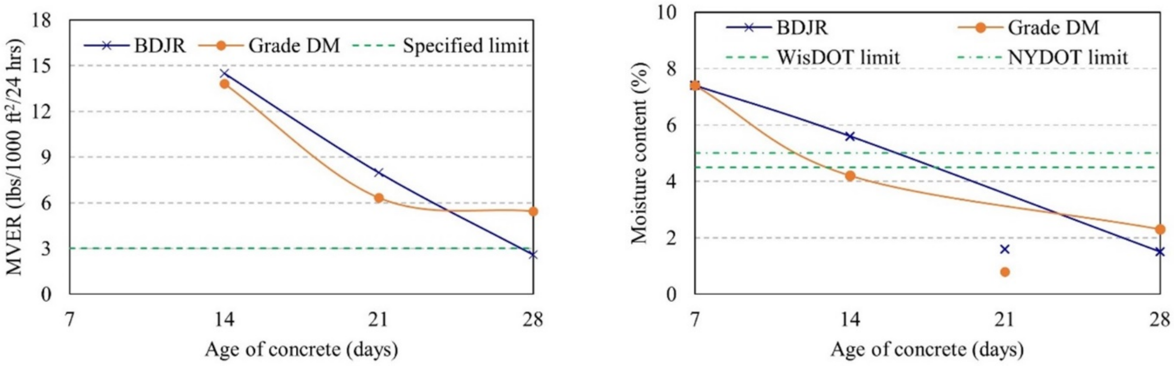
a) BDJR concrete ring data

b) Grade DM concrete ring data

Figure 3-6. Steel ring strain variation with time

3.2.3.4 Concrete Age to Achieve Acceptable Substrate Moisture

Figure 3-7a shows the variation of MVER against concrete age. The specified MVER limit is 3 lbs/1000 ft^2/24 hrs (Gaughen 1999). The BDJR concrete mix achieved the limit by the 28th day. The Grade DM concrete shows a plateau, just lower than 6 lbs/ 1000 ft^2/ 24 hrs, beyond the 21st day. Therefore, the age of concrete to achieve the specified limit of MVER (t_{3a}) for the BDJR mix is 28 days, while it is more than 28 days for the Grade DM mix. The MVER was lower in Grade DM through 23 days than BDJR as it contains GGBFS. Figure 3-7b shows moisture content variation with the age of concrete. The maximum allowable moisture content limits specified by Wisconsin and New York DOT are 4.5 and 5%, respectively. The BDJR and Grade DM mixes achieved a moisture content less than 5% in 17 and 12 days of concrete age, respectively. Therefore, the age of concrete to achieve the specified limit of moisture content (t_{3b}) for the BDJR and Grade DM mixes is 17 and 12 days, respectively.



a) MVER vs. age of concrete

b) Moisture content vs. age of concrete

Figure 3-7. MVER and moisture content variation with the age of concrete

3.2.3.5 Concrete Age to Develop the Specified Minimum Tensile Strength

Figure 3-5b shows the variation of flexural strength against the age of concrete for both concrete mixes. The average flexural strength at 7 days of concrete age for BDJR and Grade DM mixes was 742 and 715 psi, respectively. As discussed in Section 3.2.1.4, recommendations by Lin et al. (2013) can be implemented to estimate the direct tensile strength from the flexural strength evaluated following ASTM C78. Accordingly, a flexural strength of 417 psi is required to develop a direct tensile strength of 250 psi. Since both concrete mixes achieved a flexural strength of more than 417 psi within 7 days of wet curing, the concrete age to achieve the specified tensile strength (t_4) is less than 7 days.

3.2.3.6 Concrete Age at the Time of Epoxy Application to Develop the Specified Bond Strength

Figure 3-8 and Figure 3-9 show the tensile bond pull-off strength for both epoxy overlays applied to the slabs fabricated using BDJR and Grade DM mixes. Figure 3-10 shows the failure modes under different exposure conditions. Figure 3-11 shows the variation of IRH and concrete temperature within the slabs. 'E1' and 'E2' are the labels given to E-bond 526 Lo-Mod and Unitex Pro-Poxy Type III DOT, respectively. The performance of E1 and E2 epoxy overlays under laboratory and outdoor exposure conditions are discussed in the following sections.

3.2.3.6.1 Performance under Simulated Exposure Conditions

The tensile bond pull-off strength variation against time for 14, 21, and 28-day epoxy application ages under three different exposure conditions is presented in Figure 3-8 and Figure 3-9 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. Figure 3-10a(i) shows the failure mode under room temperature. Therefore, the concrete age for overlay application (t_5) can be as early as 14 days if the overlay is subjected to room temperature (73° F) or similar conditions.

When evaluated under room temperature following a series of wet (3% NaCl) 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 NaCl for a duration of 90 days. Figure 3-10a(ii) shows the failure mode under WD exposure conditions. Therefore, the concrete age for overlay application (t_5) can be as early as 14 days if the overlay is subjected to room temperature (73^o F) or similar conditions in the presence of 3% NaCl.

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 (Figure 3-10a(iii)). 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 (Lyon 2014). The moisture migration increases with temperature, and the rate rapidly increases after concrete reaches a certain threshold temperature. Figure 3-11a(i) and Figure 3-11a(ii) show the moisture migration in the slabs prepared with BDJR and Grade DM concrete mixes. As shown in the figures, the concrete pore microstructure starts to pull up moisture as the slab temperature reaches approximately 90^o F, and the moisture migration rate is faster in BDJR and Grade DM concrete mixes after the slab temperature reached approximately 102 and 100^o F, respectively. Figure 3-11b(i) and Figure 3-11b(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^o 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. It was also observed that both epoxies had a certain degree of softening under prolonged exposure to a temperature greater than 110^o 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 3-5d). 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 in Grade DM than BDJR concrete. Regardless of the epoxy application age and concrete mix, the E2 epoxy overlay showed higher average bond strength than the E1 epoxy overlay for the first three heating cycles under similar magnitudes of temperature and moisture migration. The average bond strength of the last two heating cycles showed approximately similar results for both overlays. The bond strength under elevated temperature reduces in each testing cycle and 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 temperature (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 red and pink bullets with a blue border. Failure in the substrate, bond failure at the concrete/overlay interface, and a partial failure in the bond and the substrate were observed. Figure 3-10a(iv) shows the combined failure mode at room temperature following a heat cycle. 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 E2 epoxy overlay is higher than the E1 epoxy overlay for both concrete mixes.

3.2.3.6.2 Performance under Outdoor Exposure

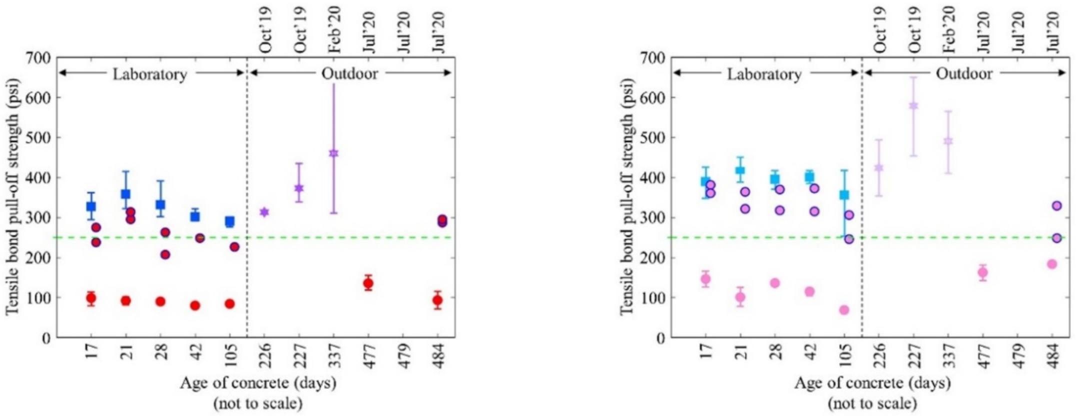
Figure 3-8 and Figure 3-9 present overlay performance under outdoor exposure for BDJR and Grade DM concrete mixes, respectively. Regardless of the epoxy application ages, concrete mixes, epoxy types, and substrate moisture at the time of overlay application, the average bond strength is more than the specified limit when the performance was evaluated in October (fall 2019). Substrate failure was observed. A similar performance was recorded in February (winter 2020).

The average bond strength evaluated in July (summer 2020) under 87~91° F is lower than 250 psi, but it is greater than the strength observed under simulated heated conditions in the lab. Partial failure in overlay, bond, and substrate was commonly observed. Figure 3-11c(i) and Figure 3-11c(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 ages, the internal moisture content decreases if no external moisture source is provided. This might be the reason for having a greater bond strength under summer conditions than the simulated conditions in the lab. The moisture migration is lower in the Grade DM than in the BDJR concrete mix. Figure 3-10b and Figure 3-10c show the failure surface of the E1 and E2 epoxy overlay, respectively. A higher degree of softening is visible in the E1 epoxy under elevated temperatures. The bond strength was also evaluated in the morning (July, summer 2020) when the temperature was close to 73° 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. Most of the tests showed failure in the substrate.

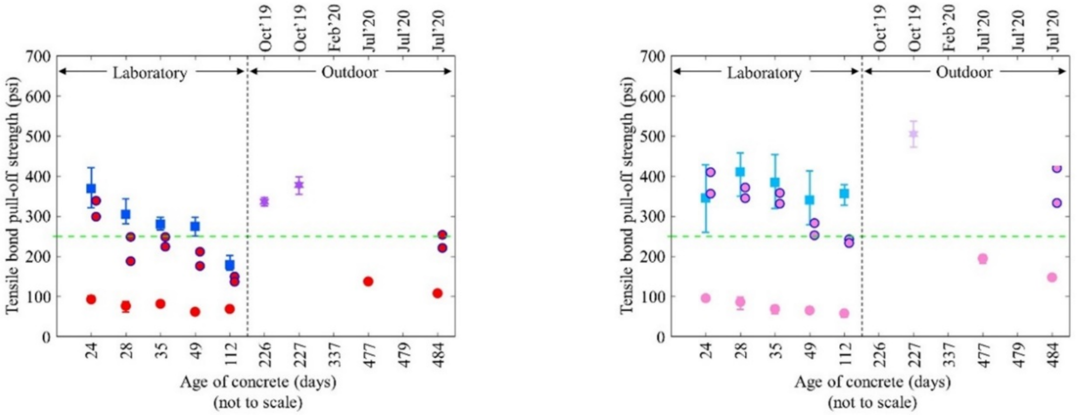
However, in a few cases, the failure was through the concrete/overlay interface and the substrate. This might be due to the elevated temperature exposure in the outdoors.

Both epoxies showed comparatively similar performance; however, E2 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. 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. Hence, the use of concrete with a dense microstructure (lower permeability) is recommended. Further, epoxy properties need to be enhanced to sustain under high temperatures, at least up to 150° F.



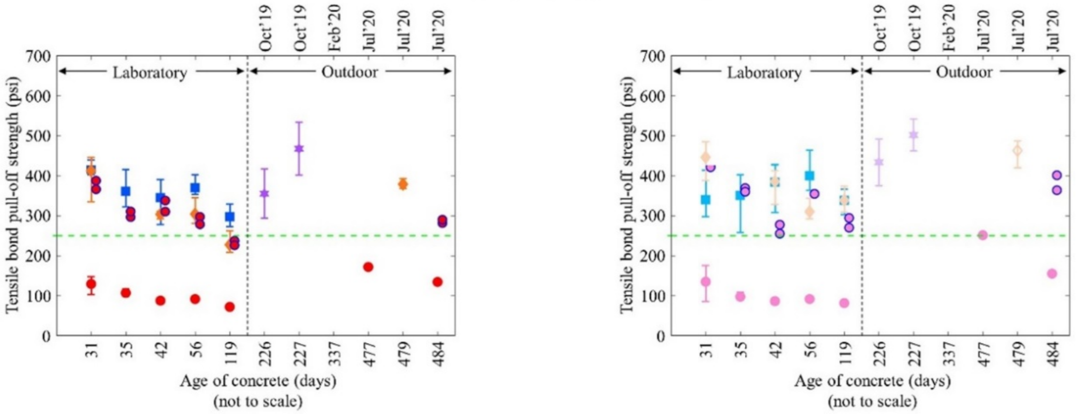
i) E1 Epoxy ii) E2 epoxy

a) 14-day epoxy application age



i) E1 Epoxy ii) E2 epoxy

b) 21-day epoxy application age

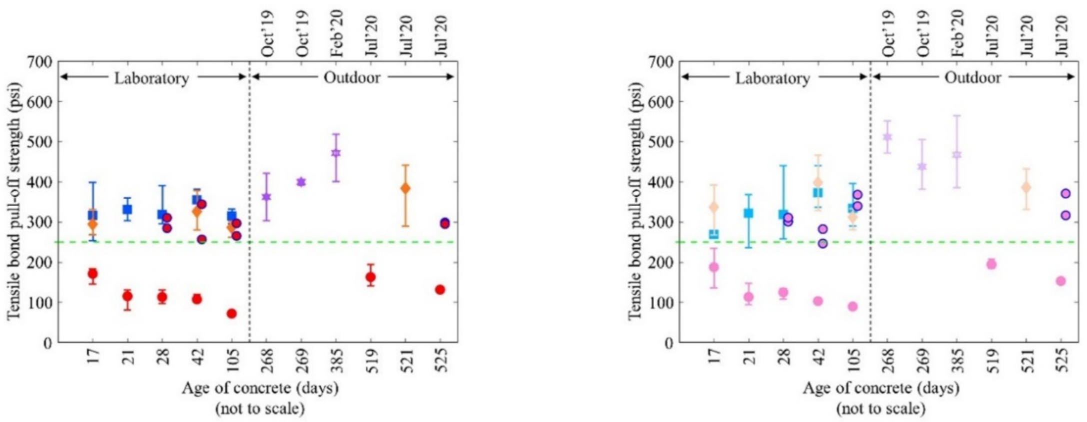


i) E1 Epoxy ii) E2 epoxy

c) 28-day epoxy application age

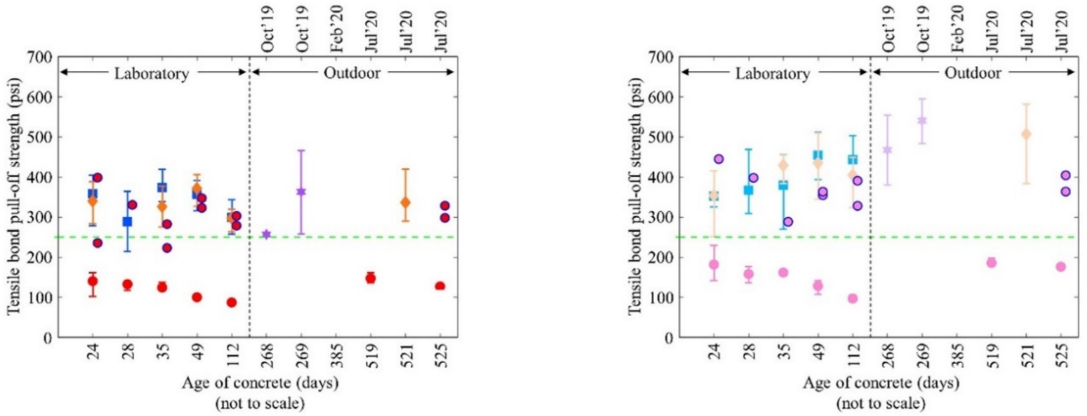
Figure 3-8. Thin epoxy overlay bond strength performance on BDJR concrete slabs

Note: RT = room temperature; HS= elevated temperature; WD = wet-dry cycle.



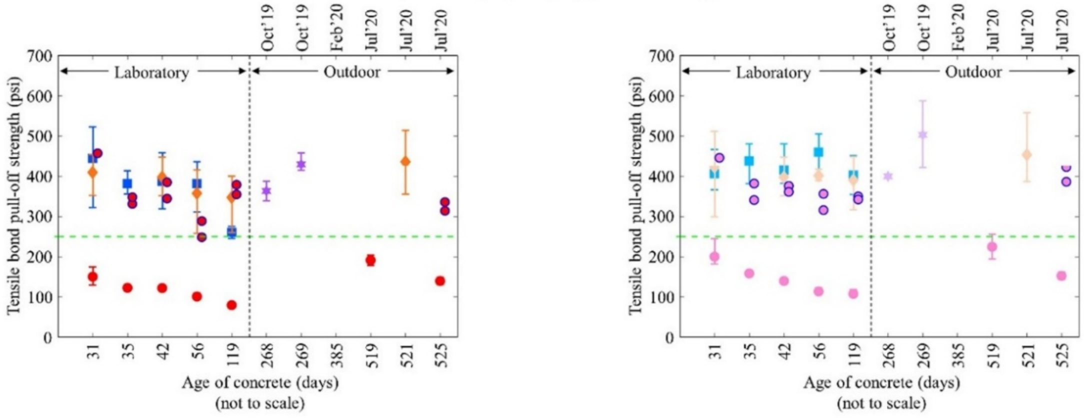
i) E1 Epoxy ii) E2 epoxy

a) 14-day epoxy application age



i) E1 Epoxy ii) E2 epoxy

b) 21-day epoxy application age



i) E1 Epoxy ii) E2 epoxy

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 3-9. Thin epoxy overlay bond strength performance on Grade DM concrete slabs

Note: RT = room temperature; HS= elevated temperature; WD = wet-dry cycle.

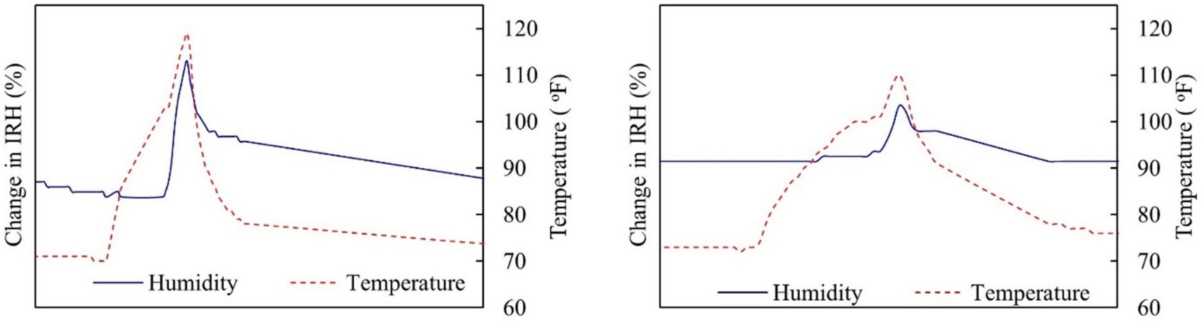
i) Failure in room temperature ii) Failure at room temperature following a wet cycle

iii) Failure at an elevated temperature iv) Failure at room temperature following a heat cycle

a) Failure modes under simulated laboratory exposure conditions

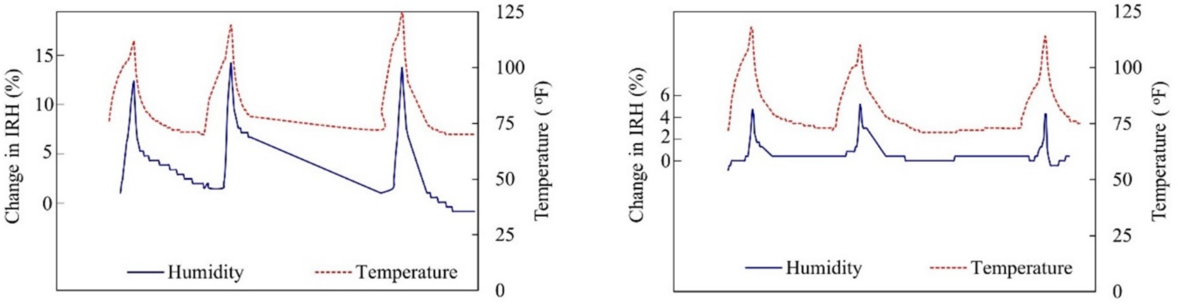
b) E1 epoxy overlay under outdoor summer exposure c) E2 epoxy overlay under outdoor summer exposure

Figure 3-10. Failure modes under different exposure conditions



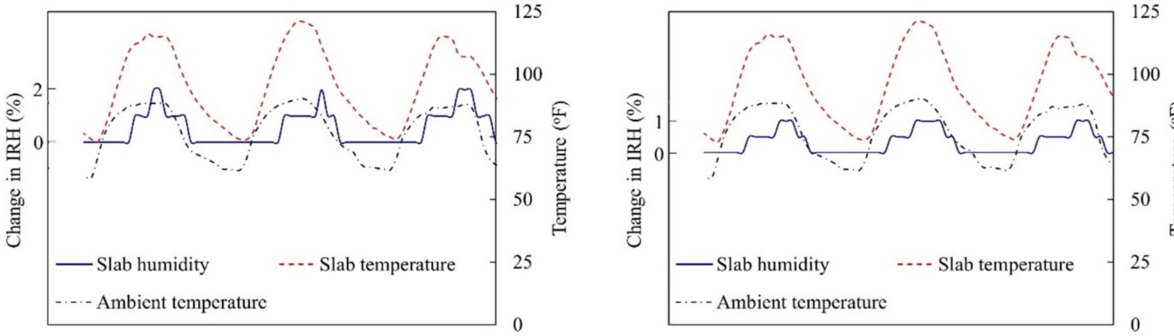
i) BDJR ii) Grade DM

a) IRH and temperature variation during a heating cycle in the laboratory



i) BDJR ii) Grade DM

b) IRH and temperature variation during multiple heating cycles in the laboratory



i) BDJR ii) Grade DM

c) IRH and temperature variation during 3 summer days under outdoors exposure conditions

Figure 3-11. IRH and temperature variation during elevated temperature cycles

3.2.3.7 Epoxy Overlay Performance Against Chloride Ingress

The total average background chloride content along the depth of BDJR and Grade DM specimens is 231 ppm and 270 ppm, respectively. Table 3-4 and Table 3-5 show the chloride content along the depth of the slabs, overlaid with the E1 and E2 epoxies, and ponded with 3% NaCl. Each data point represents the chloride content within a half-inch depth. Since the top 0.25 in. was discarded after extracting the cores to remove overlays, the chloride content at a depth of 0.75 in. represents the average chloride content between a depth of 0.25 in. to 0.75 in. Table 3-4 shows the total chloride content evaluated using the cores extracted from the slabs that were fabricated with the BDJR mix and overlaid with the E1 and E2 epoxies at 28 days of concrete age. The total chloride content was evaluated at 503 days of concrete age after ponding the slabs with a 3% NaCl solution for a total duration of 177 days (42 days with wet-dry cycles and 135 days under outdoor conditions). As shown in the table, the total chloride content in the slab with the E1 overlay ranged from 224 ppm to 231 ppm. Similarly, the total chloride content in the slab with the E2 overlay ranged from 239 ppm to 293 ppm. Considering the typical variability in chloride testing data, the measured chloride contents are similar to the background chloride content of 231 ppm. Table 3-5 shows the total chloride content evaluated using the cores extracted from the slabs that were fabricated with the Grade DM mix and overlaid with the E1 and E2 epoxies at 14, 21, and 28 days of concrete age. The total chloride content was evaluated at 545 days of concrete age after ponding the slabs with a 3% NaCl solution for a total duration of 177 days. As shown in the table, the measured chloride contents are similar to the background chloride content of 270 ppm. Therefore, irrespective of the concrete mixes, application ages, and epoxy types, both epoxy overlays worked as effective barriers for chloride ingress.

Table 3-4. Total Chloride Content (ppm) in the Slabs Fabricated with BDJR Mix

Depth (in.)	28-day slab with overlays (E1/E2)
0.75	224/293
1.25	228/273
1.75	231/239

Table 3-5. Total Chloride Content (ppm) in the Slabs Fabricated with Grade DM Mix

Depth (in.)	14-day (E1/E2)	21-day (E1/E2)	28-day (E1/E2)
0.75	270/244	242/245	277/264
1.25	261/228	260/139	235/238
1.75	274/232	236/247	259/240

3.2.3.8 Impact of Epoxy Overlay Application on Concrete Strength and Durability

Table 3-6 shows the average compressive strength evaluated using the cores extracted from bare slabs and the slabs with epoxy overlays. As shown in the table, the compressive strength of the cores extracted from the slabs that received overlays at the concrete age of 14 days is greater than the slabs that received overlays at the concrete age of 28 days. Therefore, applying overlays as early as 14 days of concrete age has no adverse impact on strength and strength development.

Table 3-6. The Average Compressive Strength Evaluation Using Cylinders Extracted from Slabs Fabricated with BDJR and Grade DM Concrete Mixes

Concrete age at the time of testing (days)	Specimen description	Average compressive strength in BDJR slabs (psi)	Average compressive strength in Grade DM slabs (psi)
28	Bare concrete	5290	6593
121	Bare concrete	6463	7683
	14-day	6353	7867
	21-day	6243	7203
	28-day	5890	7633
539	Bare concrete	7463	8023
	14-day	7497	8050
	21-day	7547	7930
	28-day	7427	7780

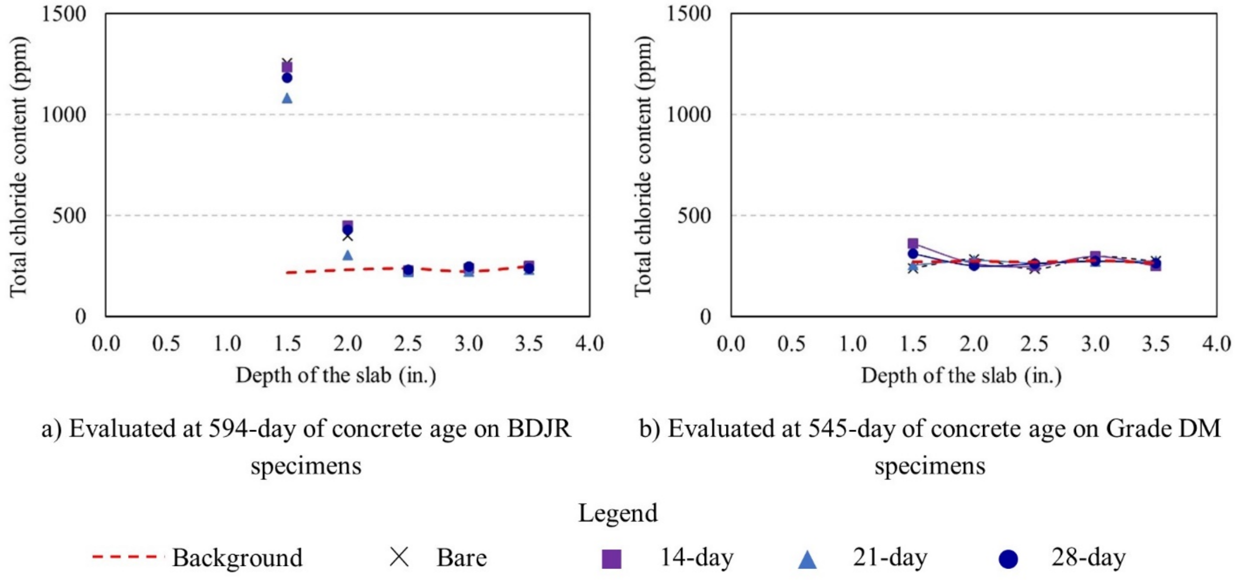
Cores were extracted from BDJR and Grade DM concrete at 454 and 406 days of concrete age. By that time, the BDJR and Grade DM slabs were subjected to a total of 149 days and 116 days of freezing, respectively. The top 0.5 in. of each specimen was saw cut and discarded. The remaining portion of the specimens was used for testing. A subset of specimens was used to evaluate porosity. Table 3-7 shows the total volume of permeable voids evaluated using the cores extracted from bare concrete slabs and the slabs with overlays. As shown in the table, the total volume of permeable voids is similar in all the slabs. Therefore, the slabs show no damage due to freezing or exposure to adverse weather conditions.

The remaining specimens were used to evaluate the resistance to chloride ingress. One specimen from each mix was selected for background chloride testing. The circumferential area of the remaining cylinders was epoxy painted. After allowing 2 to 3 days of drying, the specimens were ponded with 3% NaCl at the top. The chloride content of up to a 3.0 in. depth was evaluated at the end of 137 days of ponding by following ASTM C1152 procedures. By that time, the age of BDJR and Grade DM slabs was 594 days and 545 days, respectively.

Figure 3-12a and Figure 3-12b show the total chloride content along the depth of the bare slabs and the slabs with epoxy overlays. The background chloride contents of the slabs are also presented in the figures. Each data point represents the chloride content within a 0.5 in. depth. Since the top 0.5 in. was discarded after extracting the cores, the chloride content at a 1.0 in. depth is the amount determined using a core extended from a 0.5 in. to 1.0 in. depth. A half-inch depth represents the surface that was ponded after removing 0.5 in. from the cored specimens. Therefore, the total chloride content at 1.0 in. includes the surface chloride content, and it should not be considered for performance evaluation. As shown in the figures, the chloride between 1.0 in. and 1.5 in. depth is higher in BDJR concrete compared with Grade DM since the BDJR concrete porosity is higher than Grade DM (as shown in Figure 3-5d). Irrespective of concrete mix designs and application ages, the total chloride content along the depth of bare concrete slabs and the slabs with epoxy overlays are similar. Hence, the early application of epoxy overlays did not impact concrete durability.

Table 3-7. Total Volume of Permeable Voids (%) in BDJR and Grade DM Concrete Slabs

Specimen description	454 days old BDJR concrete	406 days old Grade DM concrete
Bare concrete	14.9	13.6
14-day	14.8	13.9
21-day	15.0	14.3
28-day	15.0	14.3



a) Evaluated at 594-day of concrete age on BDJR specimens

b) Evaluated at 545-day of concrete age on Grade DM specimens

Figure 3-12. Total chloride content in the slabs fabricated with BDJR and Grade DM concrete mixes

3.2.4 Minimum Concrete Age to Receive a Thin Epoxy Overlay

Table 3-8 shows the parameters selected for epoxy overlay performance evaluation, specification limits, age of concrete (when the evaluation parameter limits are satisfied), and the recommended minimum concrete age to receive an epoxy overlay. For BDJR concrete, the wet curing duration to achieve the required minimum strength and a discontinuous capillary pore structure with a minimum volume of total permeable voids for durability (t_1) is 7 days. Similarly, the Grade DM concrete needs 10 days of wet curing to satisfy the minimum strength and durability requirements. Therefore, the required minimum wet curing duration (t_1) for Grade DM concrete is 10 days. Concrete age at the time of cracking (t_2) is conservatively selected for BDJR and Grade DM concrete as 18 and 20 days, respectively. The age of concrete to achieve an acceptable MVER (t_{3a}) is not considered since the specified MVER limit was not achieved until 28 days, and the performance of the epoxy overlay was not impacted by high MVER. As an example, bond strength was higher on Grade DM slabs compared to BDJR slabs even though MVER was higher in Grade DM slabs. However, Grade DM concrete moisture content was less than 5% when the concrete age was 12 days. The moisture content of BDJR concrete reached the 5% limit in 17 days. New York DOT allows overlay application when the moisture content is equal to or less than 5%. Considering the moisture content limit of 5%, the concrete age to achieve an acceptable moisture content (t_{3b}) for BDJR and Grade DM concrete mixes is selected as 17 and 12 days, respectively. The concrete age to develop the specified minimum tensile strength (t_4) for both mixes is 7 days. Epoxy overlays can be applied on the BDJR and Grade DM concrete in 14 days if only the performance of the overlays against bond strength is considered. However, concrete age needs to be at least 18 and 20 days for the BDJR and Grade DM concrete mixes to allow adequate time to develop cracking, the primary reason for the epoxy overlay application. Even though the epoxy overlay application on uncracked concrete could delay cracking, the overlay would not be able to prevent it from happening. As a result, the system integrity is compromised since concrete cracking after overlay application is difficult to identify through visual inspection. Hence, the cracking age is the decisive parameter for determining the concrete age to receive a thin epoxy overlay. Considering all the parameters, the minimum age of the BDJR and Grade DM concrete to receive an epoxy overlay needs to be 18 and 20 days, respectively.

Table 3-8. The Minimum Age of Concrete to Receive a Thin Epoxy Overlay

Evaluation parameter	**Specified limit**	**Age of concrete (days) (BDJR/Grade DM)**	**Minimum age of concrete to receive an overlay [max (t_1, t_2, t_3, t_4, and t_5)] (BDJR/Grade DM) (days)**
Concrete wet curing duration (t_1)	nd	7/9	18/20
Concrete age at the time of cracking (t_2)	nd	18/20	
Concrete age to achieve acceptable substrate moisture (t_3)	MVER ≤ 3 lbs/1000 ft^2/24 hrs and/or Moisture content ≤ 5%	≅ 28/> 28 ≅ 17/≅ 12	
Concrete age to develop the specified minimum tensile strength (t_4)	250 psi	< 7/< 7	
Concrete age at the time of epoxy application to develop the specified bond strength (t_5)	28 days	14/14	

Note: nd = not defined.

3.3 IMPACT OF PENETRATING SEALANT PRETREATMENT ON THIN EPOXY OVERLAY PERFORMANCE

This section describes the methods and findings of experimental studies conducted to evaluate overlay bond strength performance in the presence of a penetrating sealant pretreatment.

3.3.1 Overlay Performance Evaluation

SIL-ACT ATS-100, a 100% silane penetrating sealant, was selected from the MDOT approved product list (MDOT 2018c). The breathability of concrete in the presence of the sealant (vapor transmission) is 85.4%. (ACT 2019). E-bond 526 Lo-Mod and Unitex Pro-Poxy Type III DOT thin epoxy overlays were selected for developing hybrid systems (i.e., an epoxy overlay on silane pretreated concrete). Fourteen (14) concrete slab specimens of 40 × 40 × 9 in. were fabricated in October 2019 using BDJR concrete. Table 3-9 presents the mix design. All the specimens were moist cured for 7 days according to ASTM C192. Following 7 days of wet curing, all the surfaces of the slabs, except the top surface, were epoxy painted to simulate one-dimensional moisture transfer to replicate the presence of stay-in-place formwork. After the wet curing period, the slabs were dry-cured at 73° F in the laboratory. Table 3-10 lists the experimental plan including QAQC testing, substrate moisture measurement, and the tensile bond pull-off strength tests under laboratory and outdoor exposure conditions. The impact of silane pretreatment on the performance of epoxy overlays placed during the dry curing period was investigated.

Temperature, slump, density, and air content were measured as fresh concrete properties. The top surface of each specimen was shotblasted to CSP 7 and cleaned when the age of concrete was 14 days. Thin epoxy overlays were applied on the silane pretreated slabs at 14, 21, and 28 days of concrete age. Four slabs were selected for each application age. Two slabs were treated with silane before the overlay application and labeled as ST (i.e., Silane Treated). Following the sealant drying period as per the manufacturer's specifications, the first coat of epoxy overlay was applied on the same day. The other two slabs were overlaid with epoxies without any pretreatment and labeled as RS (i.e., Reference Specimen). The second epoxy layer was applied on the following day. This allowed a 24-hour curing period for the first epoxy layer. A layer of flint aggregate was broadcasted following the application of each epoxy layer. The tensile bond pull-off strength was conducted according to ASTM C1583 (2013) under laboratory and outdoor exposure conditions to evaluate the impact of silane pretreatment on the bond strength.

After selecting 4 slabs for each overlay application age, two slabs remained from the total of 14. One of those slabs was used without any treatment (i.e., with a bare concrete surface). The other slab was treated with the penetrating sealant at the concrete age of 14 days. MVER was measured on both slabs at 14, 21, and 28 days of concrete age. The moisture content of both slabs was measured from the end of the 7-day wet curing. IRH was measured starting at the end of the 7-day wet curing until the end of testing by placing probes at the depths of 1 and 3.6 in. from the top surface. IRH of the slabs with epoxy overlays was measured to evaluate moisture migration and redistribution under different exposure conditions.

Table 3-9. BDJR Concrete Mix Design (per yd^3)

Material	Quantity
Coarse aggregate (SSD) (lb)	1,500
Fine aggregate (SSD) (lb)	1,553
Cement – Type I (lb)	655
Water (lb)	235
Hydration controlling admixture (fl oz) (to increase setting time during casting)	33.33
Water reducing admixture (fl oz)	58.33
Air entraining admixture (fl oz)	6.33
Water-cement ratio	0.36

Table 3-10. Experimental Plan to Assess the Influence of Silane Pretreatment on Epoxy Overlay Performance

Evaluation parameter (a)	Measurand (b)	ASTM standard (c)	Specimen dimensions (in.) (d)	Concrete age at the time of overlay application (e)	Treatment conditions (f)	Concrete age at the time of testing (days) (g)
QAQC	Temperature	C1064	As per the ASTM	NA	NA	NA
	Slump	C143				
	Density	C138				
	Air content	C231				
Substrate moisture	MVER	F1869	40 × 40 × 9	NA	RS[a] and ST[b]	14, 21, and 28
	Moisture content	F2659	40 × 40 × 9	NA	RS and ST	7, 14, 21, and 28
	IRH	F2170	40 × 40 × 9	NA	RS and ST	Starting from 7-day until the end of testing
Tensile bond pull-off strength	Tensile bond pull-off strength	C1583	40 × 40 × 9	14	RS and ST	Lab: 17[c], 24[d], 28[d], 42[d], and 70[d] Outdoors[e]: 146, 156, 271, 274, and 275
			40 × 40 × 9	21	RS and ST	Lab: 24, 28, 35, 49, and 77 Outdoors: 271, 274, and 275
			40 × 40 × 9	28	RS and ST	Lab: 31, 35, 42, 56, and 84 Outdoors: 271, 274, and 275

Note: NA = not applicable

[a] RS – Reference specimen. Overlays were placed without silane pretreatment.

[b] ST – Silane treated specimen. Overlays were placed with silane pretreatment.

[c] Tensile bond pull-off strength tests were performed at room temperature in the laboratory.

[d] Tensile bond pull-off strength tests were performed under simulated elevated temperature in the laboratory.

[e] Slabs were moved outdoors when the concrete age was 100 days and exposed to southwest Michigan weather through the testing age.

3.3.2 Epoxy Overlay Performance

3.3.2.1 Performance Evaluation under Simulated Exposure Conditions

The performance of both epoxy overlays was evaluated in the laboratory using (i) slabs under room temperature (RT) (73° F) and (ii) elevated temperature (Heated Slabs - HS) (~110° F). The tensile bond pull-off strength tests were performed on each RS and ST specimen for five cycles. The first cycle of testing was performed under room temperature, and the remaining four cycles were performed under the elevated temperature. The bond strength was also evaluated after allowing the slabs to cool down to room temperature following a heat cycle. The performance was evaluated at 3, 7, 14, 28, and 56 days following epoxy overlay application. As an example, the 14-day slabs were tested at 17, 24, 28, 42, and 70 days of concrete age. Among these testing ages, the first cycle of testing at day 17 was performed under room temperature. Testing at 24, 28, 42, and 70 days was performed under elevated temperature. Each pull-off strength test area was sealed using epoxy paint to prevent moisture loss.

3.3.2.2 Performance Evaluation under Outdoor Exposure Conditions

Following the performance evaluation under simulated exposure conditions in the laboratory, all 12 slabs were moved to an open parking lot in January 2020 to get them exposed to elements. The tensile bond pull-off strength tests were performed under winter and summer exposure conditions. The slabs that received overlays at the age of 14 days were expected to retain the highest amount of internal moisture and had the greatest potential to be damaged under freezing conditions. Hence, bond strength was evaluated in March 2020 after these slabs were subjected to 44 and 52 freezing cycles. The ambient temperature during testing was 34~38° F. The last sets of bond strength tests were conducted in July 2020. One set of data was collected when the ambient temperature was 87~91° F. The other data set was collected in the morning when the temperature was about 73° F. The performance of both epoxy overlays was evaluated on 14-day slabs at 146, 156, 271, 274, and 275 days of concrete age. The other slabs were tested at 271, 274, and 275 days of concrete age. Each pull-off strength test area was sealed using epoxy paint.

3.3.2.3 Impact of Hybrid Protective System on Concrete Durability

Among the three application ages considered in this study, the slabs that received the overlay hybrid system earlier than 28 days of concrete age had a greater potential to be damaged under freezing conditions. This was due to the high amount of internal moisture retained by the time the slabs were moved outdoors in January 2020. Therefore, the durability of concrete was investigated using 4 × 8 in. cores extracted from the bare slab, the 14-day silane treated slab, and the slabs that received overlays and hybrid protective systems at 14, 21, and 28 days of concrete age. Cores were extracted at 245 days of concrete age, and the top 0.5 in. from the finished surface was saw cut and discarded. The circumferential area of the specimens was epoxy painted. A set of specimens was used to evaluate background chloride content. The other specimens were ponded continuously at the top with a 3% NaCl solution. Following 137 days of ponding, chloride content of a depth down to 3.0 in. was evaluated according to ASTM C1152.

3.3.3 Results and Discussion

The fresh concrete properties, substrate moisture, and tensile bond pull-off strength were evaluated. The results are discussed in the following sections.

3.3.3.1 QAQC Testing

Table 3-11 shows the fresh properties of BDJR concrete. These results comply with the MDOT specifications.

Table 3-11. Fresh Properties of BDJR Concrete

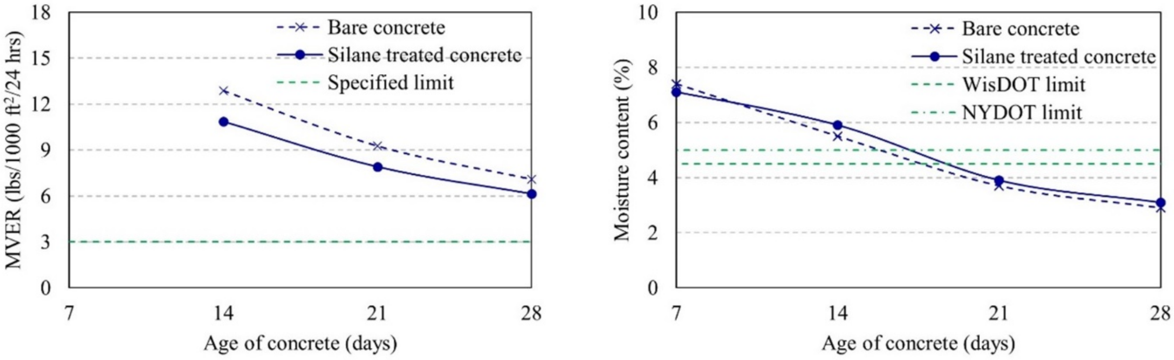
Measured value	ASTM standard	Result
Temperature (°F)	C1064	78
Slump (in.)	C143	5.25
Density (lbs/yd^3)	C138	144.7
Air content (%)	C231	6.2

3.3.3.2 Substrate Moisture

Figure 3-13 shows MVER and moisture content measured on the bare concrete and silane treated slabs. Even though none of the specimens had the MVER lower than 3 lbs/1000 ft^2/24 hrs, the industry standard (Gaughen 1999), the MVER of the silane treated specimen was lower than the bare concrete specimen since the vapor transmission of the penetrating sealant is 85.4%. The MVER test measures the moisture emission rate within the top ½ in. near the surface (Kanare 2008); thus, the presence of penetrating sealant could impact the moisture vapor emission rate. The difference between MVER measured on the bare slab and the silane treated slab on the day of silane application was 2.03 lbs/1000 ft^2/24 hrs. However, the difference was reduced to 0.94 lbs/1000 ft^2/24 hrs after 14 days. The results presented in Figure 3-13a indicate that the MVER of

100% silane treated and bare concrete surfaces could be similar at the lower internal moisture contents.

Moisture content was measured using an electrical impedance meter and recorded as shown in Figure 3-13b. The first measurement was taken at the end of the 7-day moist curing period and shows nearly identical results (7.4% and 7.1%) because both slabs had bare concrete surfaces until 14 days of concrete age. As shown in the figure, moisture content measurements on or after 14 days of concrete age are similar. Electrical impedance meters measure the moisture content of concrete up to 2.0 in. deep from the surface. Since the impact of a penetrating sealant on moisture content within the 2.0 in. depth is insignificant, both slabs show similar results.



a) MVER b) Moisture content

Figure 3-13. MVER and moisture concrete variation with the age of concrete

3.3.3.3 Epoxy Overlay Performance

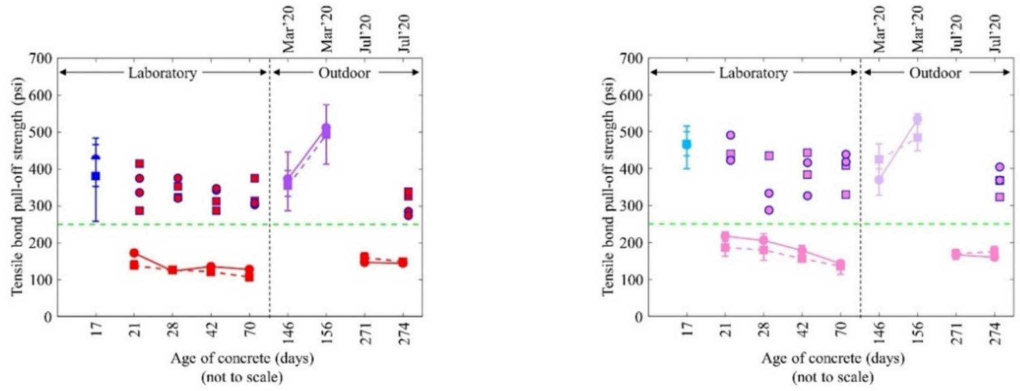
Figure 3-14 shows the variation of tensile bond pull-off strength against time for 14, 21, and 28-day application ages under laboratory and outdoor exposure conditions. Figure 3-15 shows the variation of IRH and concrete temperature with time.

3.3.3.3.1 Performance under Simulated Exposure Conditions

The performance was evaluated in the laboratory under elevated and room temperature conditions. One set of data was collected from the specimens under room temperature (RT) while 4 sets of data were collected from the heated slabs (HS). Figure 3-14 shows overlay performance under all the exposure conditions. As shown in the figure, the average bond strength is more than 250 psi for all the tests performed under room temperature, and the failure was in the substrate (Figure 3-10a(i)). The overlay bond strength with silane pretreatment is greater than the bond strength of overlay on bare concrete specimens. The bond strength is lower than 250 psi for all the tests performed under elevated temperature, and the failure was at the concrete/overlay interface (Figure 3-10a (iii)). Figure 3-15a shows the change in IRH and slab temperature for three heating cycles simulated in the laboratory. The slab temperature was more than 110° F for approximately 6 hours. The IRH increased by approximately 9%. As shown in the figure, the concrete pore microstructure started to pull up moisture when the slab temperature was approximately 90° F, and moisture migration is faster after the slab temperature was approximately 102° F. As a result, moisture accumulates at the concrete/overlay interface and possibly creates vapor pressure on the overlay. In addition, a certain degree of epoxy softening was observed under prolonged and repeated exposure to elevated temperature. These factors could have been the reasons for lower bond strengths observed under elevated temperatures. However, the bond strength of both epoxies on silane pretreated slabs of the 28-day application age is greater than 250 psi during the first heating cycle. Irrespective of the application age and epoxy type, the bond strength of overlay on silane pretreated specimens was greater than the bond strength of overlay on bare concrete specimens when evaluated at an early age under similar exposure and substrate moisture conditions. However, the bond strength was almost the same when evaluated at 70 days following overlay placement. As shown in Figure 3-13a, the impact of silane on MVER decreases with the reduction in concrete moisture. Therefore, the positive impact of silane on bond strength is reduced. The E2 overlay resulted in a higher bond strength than the E1 overlay regardless of the application age and pretreatment condition. The bond strength was also performed after allowing adequate time for the slabs to reach room temperature following a heating cycle. The data is presented using red and pink bullets with blue borders. Failure in substrate, bond failure at the concrete/overlay interface, and partial failure in the bond and substrate were observed. The results show a recovery of the bond strength. The magnitude of recovered bond strength was higher in silane treated specimens irrespective of epoxy application age and epoxy type. Therefore, the presence of silane on concrete shows no adverse impact on the overlay performance rather than improving the bond strength at an early age. The magnitude of recovered bond strength was higher with the E2 overlay than with the E1 overlay, regardless of the treatment condition. In general, the E2 epoxy overlay performed consistently better than the E1 epoxy overlay under simulated exposure conditions in the laboratory.

3.3.3.4 Performance under Outdoor Exposure Conditions

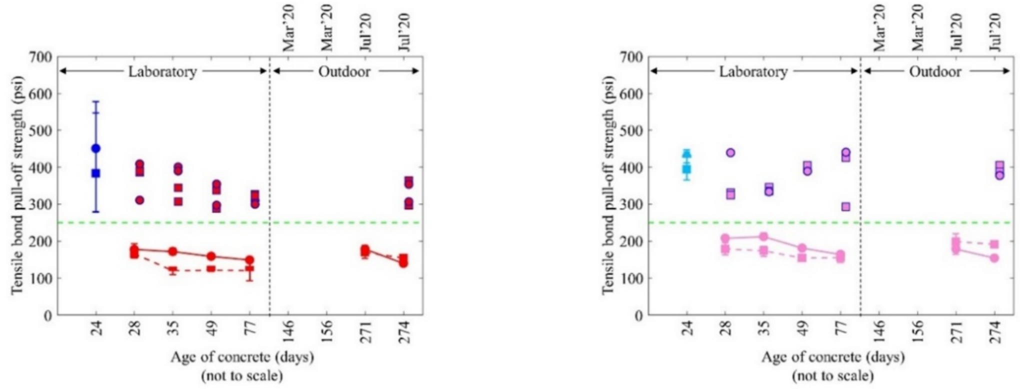
Figure 3-14 shows the overlay bond strength performance under outdoor exposure conditions. In March 2020, the bond strength was evaluated after the specimens were subjected to 44 and 52 freezing cycles. The temperature at the time of testing was 34~38° F. As shown in the figure, the average bond strength is greater than 250 psi, with a failure in the substrate. Irrespective of application age, epoxy type, and treatment condition, the average bond strength evaluated in July (summer 2020) under 87~91° F is lower than the specified minimum of 250 psi. Combined failure in the substrate and bond failure at the concrete/overlay interface was observed in most cases regardless of the application age, epoxy type, and surface treatment. Figure 3-15b shows the change in slab moisture and temperature under outdoor exposure conditions for three consecutive days. As shown in the figure, IRH increased by 4.5~5%. The slab temperature was more than 110° F for a duration of approximately 8 hours. Both bare concrete and silane treated specimens show similar bond strengths under elevated temperature, regardless of the application age and epoxy type. Irrespective of the application age, epoxy type, and treatment condition, the recovered bond strength following a heating cycle is more than 250 psi when evaluated at about 73° F. Therefore, the silane treatment shows no negative impacts on bond strength under hot weather conditions in summer.



i) E1 Epoxy

ii) E2 epoxy

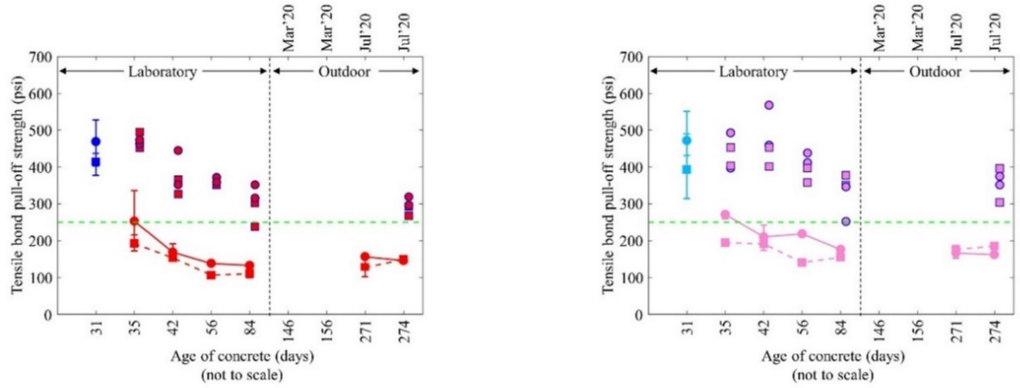
a) 14-day epoxy application age



i) E1 Epoxy

ii) E2 epoxy

b) 21-day epoxy application age



i) E1 Epoxy

ii) E2 epoxy

c) 28-day epoxy application age

Legend

■ E1 – RS – RT
● E1 – ST – RT
■ E2 – RS – RT
● E2 – ST – RT

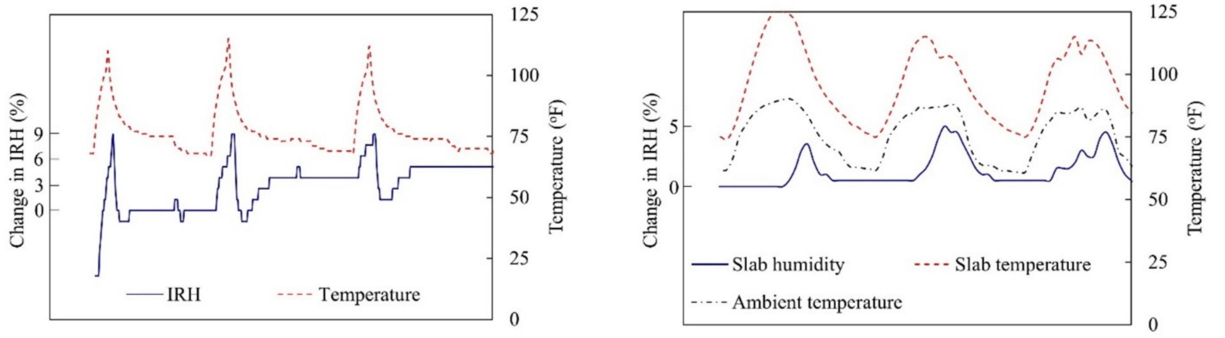
■ E1 – RS – HS/Summer (Hot)
● E1 – ST – HS/Summer (Hot)
■ E2 – RS – HS/Summer (Hot)
● E2 – ST – HS/Summer (Hot)

▣ E1 – RS – HS/Summer (Cool)
◉ E1 – ST – HS/Summer (Cool)
▣ E2 – RS – HS/Summer (Cool)
◉ E2 – ST – HS/Summer (Cool)

■ E1 – RS – Winter
● E1 – ST – Winter
■ E2 – RS – Winter
● E2 – ST – Winter

Figure 3-14. Impact of silane pretreatment on thin epoxy overlay bond strength

Note: RS = reference specimen; ST = silane treated; RT = room temperature; HS= elevated temperature.



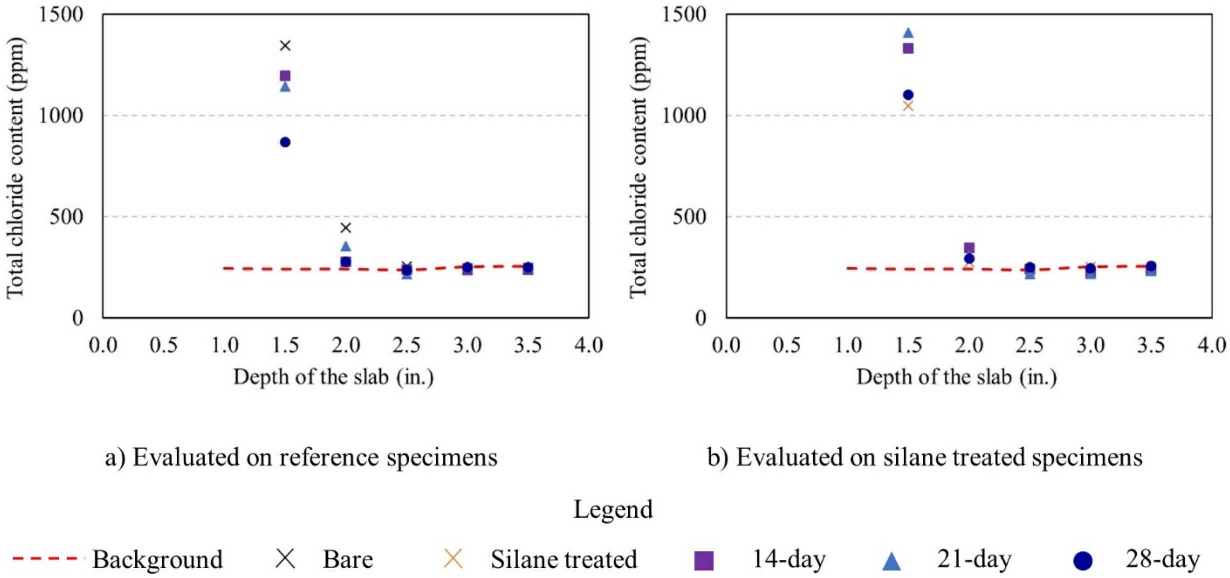
a) first three simulated heating cycles in the laboratory

b) three heating cycles recorded under outdoor summer exposure conditions

Figure 3-15. IRH and temperature variation during three elevated temperature cycles

3.3.3.5 Impact of Hybrid Protective System on Concrete Durability

Figure 3-16a and Figure 3-16b show the total chloride content along the depth of the bare and silane treated slabs, respectively, with and without an epoxy overlay. The background chloride contents along the depth of the slabs are also presented in the figures. Each data point represents the chloride content within a 0.5 in. depth. The top 0.5 in. was discarded following coring and ponded with a 3% NaCl solution at the top. The chloride content reported at a 1.0 in. depth represents the average chloride content between a depth of 0.5 in. to 1.0 in., which is influenced by the surface chloride at a 0.5 in. depth. Hence, the data reported at a 1.0 in. depth was excluded from further consideration. The total chloride content presented in the graph at a 2 in. depth represents the average chloride content within a 1.5 to 2 in. depth. Hence, it is safe to state that the total chloride content beyond a 1.75 in. depth is similar to the background chloride content. Applying overlays with and without silane pretreatment during the dry curing period has no adverse impact on concrete durability because all the specimens have similar chloride profiles after being subjected to more than 40 freezing cycles and ponded with 3% NaCl.



a) Evaluated on reference specimens

b) Evaluated on silane treated specimens

Figure 3-16. Total chloride content along the depth of the slab with and without silane pretreatment

3.4 SUMMARY

A procedure was developed to identify the minimum age of concrete to receive an epoxy overlay. The procedure was demonstrated using two concrete mixes and two thin epoxy overlays. These overlays were applied on concrete specimens fabricated using BDJR and Grade DM concrete mixes 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 elements. Tensile bond pull-off strength tests were conducted in fall, winter, and summer to evaluate the performance under different exposure conditions. The bond strength of both overlays was greater than 250 psi under all the exposure conditions, except under elevated temperatures. The findings support applying overlays on BDJR and Grade DM concrete on or after 18 and 20 days of concrete age, respectively.

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 100º F temperature. These factors could have contributed to the reduction in bond strength under elevated temperatures. Bond strength evaluation of silane pretreated BDJR concrete specimens shows no adverse impact of silane sealers on thin epoxy overlay performance. Bond strength of silane pretreated specimens is slightly better under elevated temperatures. The results encourage applying silane sealers when overlays are applied on concrete during the dry curing period. The early age performance of the E2 epoxy overlay is slightly better than the performance of the E1 overlay.

4 PERFORMANCE OF HEALER SEALERS

4.1 OVERVIEW

The current specifications and special provisions require contractors to maintain a 28-day curing period before applying healer sealers on bridge decks with new concrete in partial or full-depth deck patches and repairs. There is an interest in evaluating the possibility of applying healer sealers on decks with new concrete before 28 days without compromising the intended performance. Therefore, a performance-based procedure was developed to evaluate the minimum concrete age to receive healer sealers. This chapter presents the performance-based procedure to evaluate the minimum concrete age to receive a healer sealer, the implementation of the procedure, and the findings.

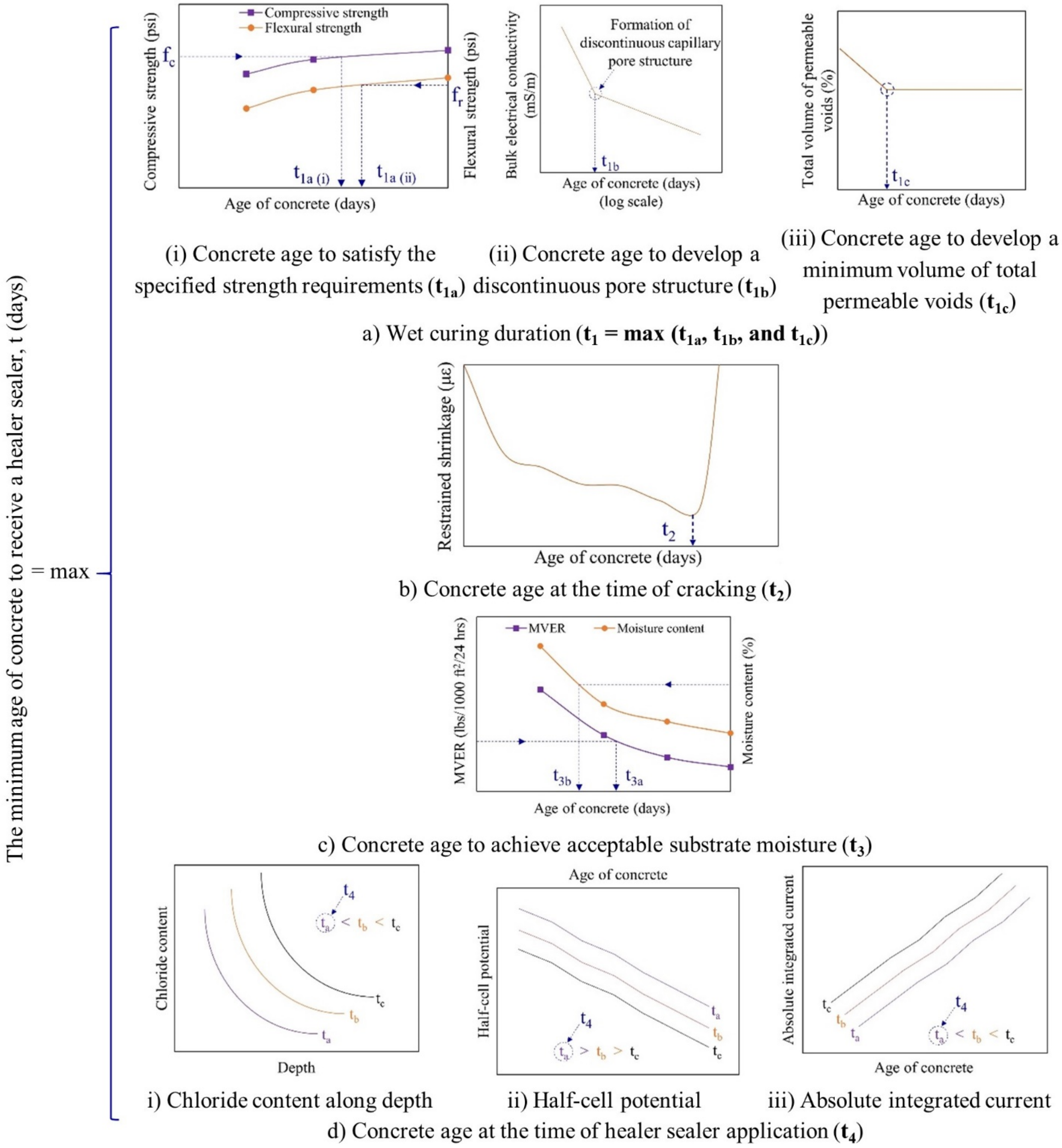
4.2 EVALUATION OF THE MINIMUM CONCRETE AGE TO RECEIVE A HEALER SEALER

The objective of this study is to identify the minimum concrete age to receive a healer sealer. The decision depends on concrete wet curing duration, cracking age, and concrete age to achieve an acceptable substrate moisture condition. Figure 4-1 depicts the procedure to evaluate the minimum age of concrete to receive a healer sealer application (t), which is a function of (i) concrete wet curing duration, (ii) concrete age at the time of cracking, (iii) concrete age to achieve acceptable substrate moisture, and (iv) concrete age at the time of healer sealer application to achieve a performance comparable to the 28 days (t_4) standard.

The significance of all the parameters is described in Chapter 3, except the concrete age at the time of healer sealer application to achieve a performance comparable to the 28 days standard.

4.2.1 Concrete Age at the Time of Healer Sealer Application

Several parameters, including concrete moisture, workmanship, etc., influence healer sealer performance. The performance of a sealer is evaluated considering its ability to resist chloride ion ingress and reduce corrosion risk probability of embedded reinforcing steels, as shown in Figure 4-1d. The chloride content, half-cell potential, and voltage difference across a 10 Ω resistor connected to embedded reinforcement steel can be measured to evaluate the performance after a healer sealer is applied on concrete at specific ages of concrete. This data will indicate the effectiveness of healer sealers in reducing chloride ingress and corrosion potential of reinforcing steel. The data collected from the specimens that were treated with a healer sealer at the concrete age of 28 days can be used as the benchmark. Therefore, the concrete age at the time of healer sealer application (t) should be equal to or greater than t_4, the concrete age at the time of receiving a healer sealer and performing equal to or better than the concrete that received the sealer at the concrete age of 28 days.



(i) Concrete age to satisfy the specified strength requirements (**t_{1a}**)

(ii) Concrete age to develop a discontinuous pore structure (**t_{1b}**)

(iii) Concrete age to develop a minimum volume of total permeable voids (**t_{1c}**)

a) Wet curing duration (**$t_1 = \max(t_{1a}, t_{1b}, \text{and } t_{1c})$**)

b) Concrete age at the time of cracking (**t_2**)

c) Concrete age to achieve acceptable substrate moisture (**t_3**)

i) Chloride content along depth

ii) Half-cell potential

iii) Absolute integrated current

d) Concrete age at the time of healer sealer application (**t_4**)

Figure 4-1. The procedure for deciding the minimum concrete age to receive a healer sealer

4.3 IMPLEMENTATION OF THE PROPOSED PROCEDURE

Sikadur 55 SLV and Unitex Pro-Poxy 40 LV LM healer sealers were selected from the MDOT approved product list (MDOT 2018b). These products were selected based on their application frequency on the Michigan bridge decks. Throughout this report, Sikadur 55 SLV and Unitex Pro-Poxy 40 LV LM are labeled as ‘S1’ and ‘S2’, respectively. The performance of these sealers was evaluated on specimens fabricated using BDJR and Grade DM concrete mixes. Table 3-1 shows the mix design for both concrete mixes. The basic QAQC testing of fresh properties was performed on the casting day as per the Manual for the Michigan Test Methods (MTM 2018). The bond strength of healer sealers was evaluated following ASTM C882 and manufacturer requirements. Table 4-1 shows the experimental program to evaluate the bond strength and the minimum concrete age to receive a healer sealer. The table columns *a* to *g* list the evaluation parameter, measurand, ASTM standard, specimen size, concrete age at the time of healer sealer application, curing condition, and concrete age at the time of testing. For the specimens that required ASTM curing (column *f*), submerged wet curing was provided continuously through the testing ages according to ASTM C192. All the other specimens were dry-cured at 73° F in the laboratory following a 7-day moist curing period.

The testing plan for all evaluation parameters is described in Chapter 3 except the bond strength and the concrete age at the time of the healer sealer application.

Table 4-1. Experimental Program to Assess the Bond Strength and the Minimum Concrete Age to Receive a Healer Sealer

Evaluation parameter (a)	Measurand (b)	ASTM standard (c)	Specimen size (in.) (d)	Concrete age at the time of healer sealer application (e)	Curing condition (f)	Concrete age at the time of testing (days) (g)
Bond strength[a]	Slant shear bond strength	C882	3 × 6	28	RT	30
Concrete wet curing duration (t_1)	Compressive strength	C39	4 × 8	na	ASTM	7, 14, 21, and 28
	Flexural strength[b]	C78	6 × 6 × 20	na	ASTM	7, 14, 21, and 28
	Bulk electrical conductivity[c]	C1760	4 × 8	na	ASTM	1, 3, 7, 14, 21, and 28
	Porosity	C642	4 × 2	na	ASTM	3, 7, 14, 21, and 28
Concrete age at the time of cracking (t_2)	Restrained shrinkage	C1581	As per the ASTM	na	RT	Until cracking
Concrete age to achieve acceptable substrate moisture (t_3)	MVER	F1869	40 × 40 × 9	na	RT	14, 21, and 28
	Moisture content	F2659	40 × 40 × 9	na	RT	7, 14, 21, and 28
Concrete age at the time of healer sealer application (t_4)	Chloride content	C1152 and C1218	6 × 6 × 20	14	RT	149 and 286
			6 × 6 × 20	21	RT	156 and 293
			6 × 6 × 20	28	RT	163 and 300
			6 × 6 × 20	RS	RT	163 and 300
	Half-cell potential[d, e] and voltage[d, f]	C876 and G109 (modified)	6 × 6 × 20	14	RT	28, 42, 56, 84, 112, 126, and 140
			6 × 6 × 20	21	RT	35, 49, 63, 91, 119, 133, and 147
			6 × 6 × 20	28	RT	42, 56, 70, 98, 126, 140, and 154
			6 × 6 × 20	RS	RT	42, 56, 70, 98, 126, 140, and 154

Note: na = not applicable; RS = Reference specimen without healer sealer protection; RT = Room temperature (standard laboratory conditions, 73 °F).

[a] Specimens were fabricated with the BDJR mix.

[b] Beam specimens of 4 × 4 × 14 in. were used for Grade DM.

[c] One-day data was not recorded for Grade DM concrete.

[d] Specimens were fabricated with the BDJR mix.

[e] A copper sulfate electrode was used for half-cell potential measurement.

[f] The voltage was measured against a 10 Ω resistor.

4.3.1 Bond Strength

Cylindrical specimens of 3 × 6 in. were fabricated and moist cured for 7 days. Each specimen was cut into two pieces to make a 30° slant surface from the longitudinal axis of the specimen (ASTM C882). At 28 days of concrete age, each slant shear bond strength specimen was fabricated by connecting two sections using a healer sealer applied on the slanted surfaces. The specimens were dry-cured for 2 days under standard laboratory conditions, as per the manufacturer's recommendations. The bond strength tests were conducted at the end of the dry curing period.

4.3.2 Concrete Age at the Time of Healer Sealer Application

A total of forty-one (41) 6 × 6 × 20 in. beams were fabricated. Twenty-one (21) and 20 specimens were fabricated using the BDJR and Grade DM concrete mixes, respectively. Three (3) beams from the BDJR concrete and 5 beams from the Grade DM concrete were considered as one set of specimens. Therefore, a total of 7 sets of specimens were fabricated using BDJR concrete and 4 sets from Grade DM concrete. One set of specimens from each mix was selected as the reference. Healer sealers were applied on the remaining sets at 14, 21, and 28 days of concrete age. Both sealers (S1 and S2) were evaluated on BDJR concrete while only one sealer (S1) was evaluated using Grade DM concrete. Table 4-2 shows the specimen description.

Table 4-2. Specimen Description

Concrete mix	Specimen	Concrete age at the time of healer sealer application	Sealant type (S1/S2)
BDJR	Reference	na	na
	Sealed	14	S1/S2
		21	S1/S2
		28	S1/S2
Grade DM	Reference	na	na
	Sealed	14	S1
		21	S1
		28	S1

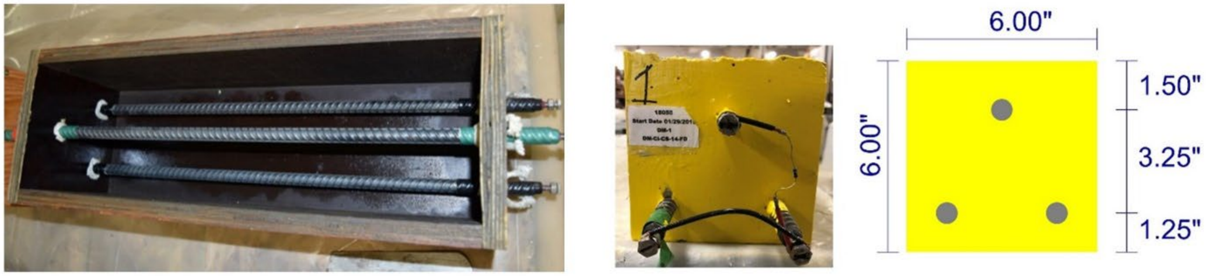
Note: na = not applicable.

Each specimen included three reinforcing steel bars, one at the top layer and two at the bottom layer, based on a slightly modified version of ASTM G109. Figure 4-2a shows the arrangement of 0.5 in. diameter reinforcing steel bars in a beam mold. Figure 4-2b shows a beam cross-section and the cover dimensions. Beams were moist cured for 7 days. At the end of moist curing, all the surfaces, except the top surface, were sealed using an epoxy paint to simulate one-way moisture migration in the presence of a stay-in-place bridge deck formwork (Figure 4-2c). The specimens were dry-cured at 73° F until testing. On the 14th day, two sets of BDJR and one set of Grade DM specimens were selected, and a 0.2 in. wide by 0.25 in. deep notch (a saw cut) was provided at mid-length and across the uncoated top surface of each specimen. The beams were loaded using a four-point loading configuration to develop a crack at the saw-cut. Figure 4-2d shows the loading configuration. Figure 4-2e shows the simulated crack. A shim was placed in the crack to maintain a crack width of 0.0125 in. through the sealant application and testing ages. The top surface of the beams was cleaned using a wire brush and a vacuum. Healer sealers were applied on the top surface using a brush. A similar process was followed for the other specimens.

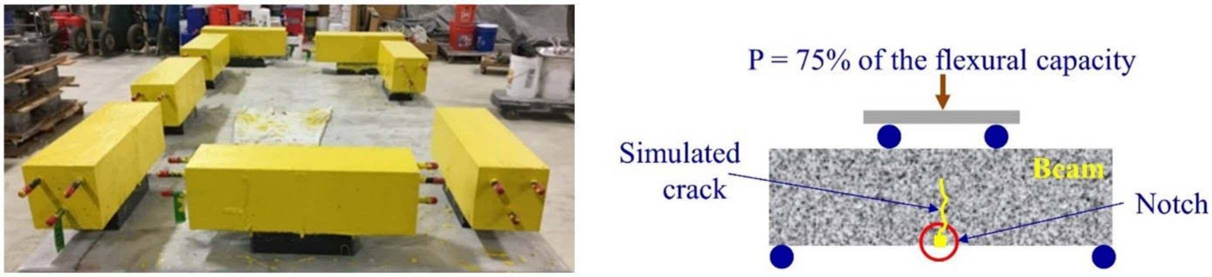
Following the sealant application, the beams were dry-cured at room temperature for one week. During the dry curing period, a plastic pond was attached to the top surface of the beam, as shown in Figure 4-2e. At the end of the one-week dry curing period, the pond was filled with a 3% NaCl solution, and ponding was maintained for one week. Subsequently, the NaCl solution and the pond were removed to flex the beams up to 75% of the 28-day flexural strength for five cycles using the four-point loading setup (Figure 4-2d) to simulate crack opening and closing under loads. After one-week of dry curing, the pond was attached for the next ponding cycle. This process was continued for a period of 135 days from sealant application. At the end of these 135 days, chloride content was tested to evaluate the performance of healer sealers as a crack sealant. Following this period, all the specimens were stored and allowed to dry-cure under room temperature. The chloride content of a selected number of specimens was evaluated after 272 days following sealant application. The same process was implemented for the specimens that received a sealant upon reaching 21 and 28 days of concrete age. The beams were subjected to nine dry-wet exposure cycles and four cycles of flexing before being evaluated for chloride content along the depth of the beam. The dry-wet exposure cycles and flexing schedules were the same for the reference and the 28-day treated specimens.

Four 1.86 in. diameter cores were extracted within the ponded area of each specimen for the testing conducted after 135 days of sealant application: two 3.5 in. deep cores from the top surface and two 2.0 in. deep cores from the bottom surface. Figure 4-2f and Figure 4-2g show the coring locations on the top and bottom surfaces, respectively. Cores were extracted directly over the crack and 3.86 in. away from the crack. The cores were sliced at 0.5 in. intervals and oven-dried for 24 hours. Figure 4-2h shows a few 0.5 in. slices. The slices were ground and the particles passing US sieve #20 were used for chloride testing. For the 135th-day testing, the chloride content from 3.0 in. below the top surface and at 1.0–1.5 in. from the bottom surface was evaluated using the acid-soluble chloride content test method described in ASTM C1152. The chloride content at 1.0–1.5 in. from the bottom surface was also evaluated using the water-soluble chloride content test method as per ASTM C1218. The exposed areas due to coring were epoxy coated, and the specimens were stored under room temperature. Another set of cores was extracted after 272 days of sealant application, one over the crack and the other 3.86 in. away from the crack. The chloride content was evaluated at 1.0–1.5 in. from the top surface using the acid-soluble chloride content test following ASTM C1152.

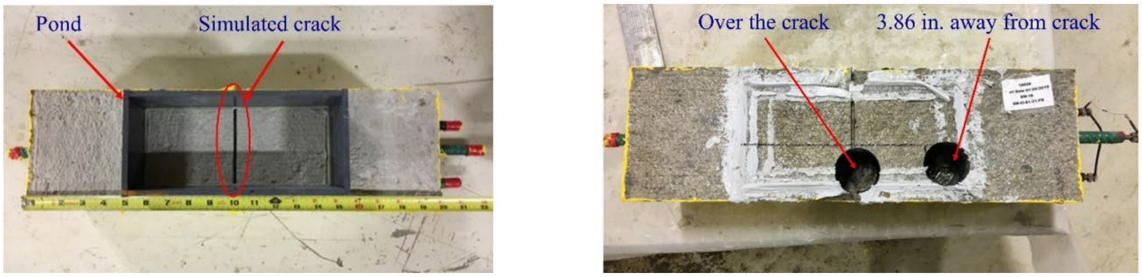
The half-cell potential and the voltage across a 10 Ω resistor were measured after completing each dry-wet cycle, i.e., at 14, 28, 42, 70, 98, 112, and 126 days following sealant application. As an example, the measurements on 14-day treated specimens were recorded at 28, 42, 56, 84, 112, 126, and 140 days of concrete age. The measurements were taken immediately after draining the NaCl solution. The half-cell potential measurements were recorded using a copper sulfate electrode at three locations inside the ponded area – at the crack and on either side of the crack. The procedures described in ASTM C876 (2015) and ASTM G109 (2013) were slightly modified as per the project objectives and schedule. As an example, the voltage measurements were taken once every two weeks during this project for the first 3 cycles, whereas the ASTM G109 (2013) suggested frequency is once every four weeks.



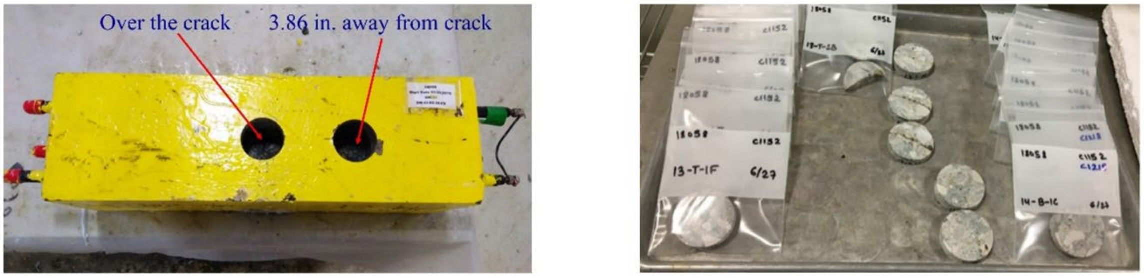
a) Rebar arrangement in the mold b) Beam cross-section showing rebar arrangement



c) Specimens coated with epoxy paint d) Four-point loading configuration



e) Pond and the simulated crack f) Top surface coring locations



g) Bottom surface coring locations h) 0.5 in. thick slices

Figure 4-2. Healer sealer performance evaluation – specimen detail and coring locations

4.4 RESULTS AND DISCUSSION

The basic QAQC and bond strength tests were conducted along with the required activities to determine the minimum concrete age to receive a healer sealer. The results of several evaluation parameters are described in Chapter 3. This section presents (i) bond strength, chloride content, half-cell potential, and the total integrated current data, (ii) the condition of the rebars removed from the beams at the end of testing, and (iii) a discussion of the results. As noted in Section 4.3, ‘S1’ and ‘S2’ are the labels assigned to Sikadur 55 SLV and Unitex Pro-Poxy 40 LV LM, respectively.

4.4.1 Bond Strength

The 2-day, air-dried minimum bond strength of 2,000 psi is specified in the manufacturer’s datasheet. Table 4-3 shows the slant shear bond strength test results. The average slant shear bond strength for S1 and S2 healer sealers are 2,339 and 2,141 psi, respectively. Healer sealers satisfy the manufacturer’s requirements.

Table 4-3. Slant Shear Bond Strength of Healer Sealers

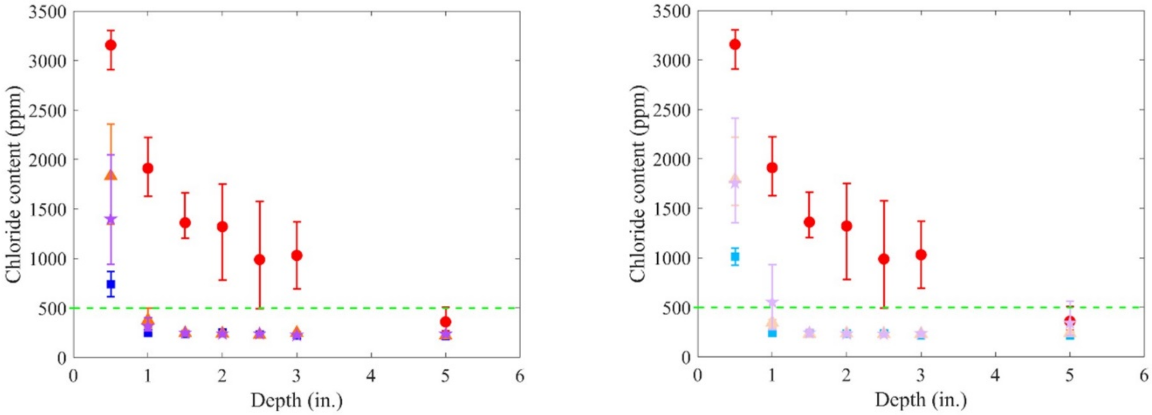
Healer sealer	Specimen no.	Slant shear bond strength (psi)	Average slant shear bond strength (psi)
S1	1	2413	2339
	2	2379	
	3	2224	
S2	1	1584	2141
	2	2870	
	3	1968	

4.4.2 Concrete Age at the Time of Healer Sealer Application

Two healer sealers were applied at 14, 21, and 28 days of concrete age. The chloride content along the depth of concrete, half-cell potential, and potential difference (voltage) across a 10 Ω resistor were evaluated as performance parameters of the sealers. The results are presented in the following sections. Using the acid-soluble chloride content at a 2.5–3.0 in. depth, the time to start reinforcing steel corrosion is calculated and presented. At the end of testing, the reinforcing steel bars were extracted from the reference and treated specimens to document their condition.

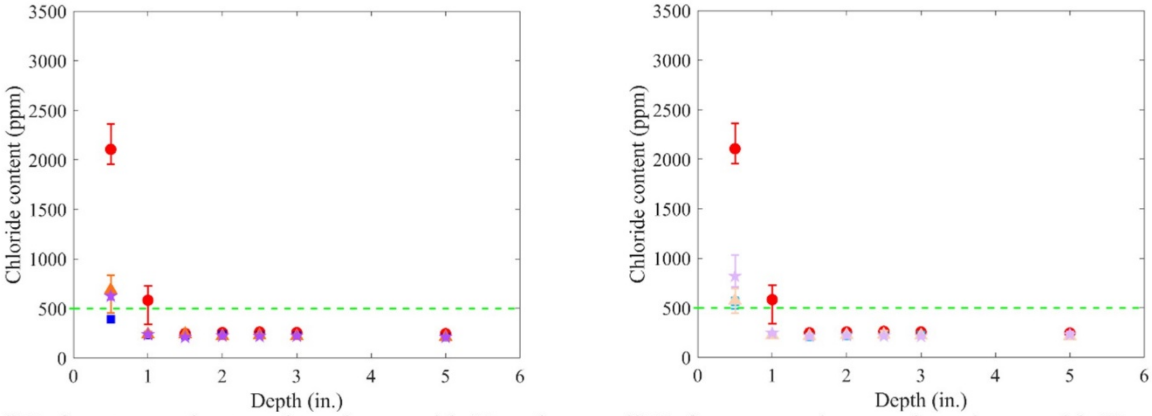
4.4.2.1 Total Chloride Content (ASTM C1152) – 135th-Day Measurement

As noted in Section 2.6.6, ASTM C1152 measures the total chloride content bound on aggregate and hydrated cement as well as the available chloride to initiate corrosion. The total average background chloride content along the depth of BDJR and Grade DM specimens is 231 ppm and 270 ppm, respectively. Figure 4-3a and Figure 4-3b show the chloride content in parts per million (ppm) for BDJR concrete specimens, which include the reference specimen and the specimen treated with two healer sealers. Each data point represents the chloride content within a 0.5 in. depth. As an example, the chloride content at 0.5 in. is the amount determined using a core that extended from the surface to a depth of 0.5 in. Figure 4-3a shows the chloride profile along the depth of the crack. Figure 4-3b shows the chloride profile along the beam depth, as recorded at 3.86 in. away from the crack. Figure 4-4a and Figure 4-4b show the chloride content along the depth of Grade DM specimens, which are the reference specimen and the specimen treated with a healer sealer. Figure 4-4a shows the chloride profile along the depth of the crack. Figure 4-4b shows the chloride profile along the beam depth, as recorded at 3.86 in. away from the crack. The threshold chloride level of 500 ppm, required to initiate reinforcing steel corrosion, as per ACI 222.R-19 (2019), is also indicated in the figures. The chloride content at 3.86 in. away from the crack and at a 1 in. depth is relatively higher in BDJR concrete compared to Grade DM. This is expected since the BDJR concrete porosity is higher than Grade DM, as shown in Figure 3-5d. As shown in Figure 4-3 and Figure 4-4, both sealers show similar performance. Irrespective of concrete mixes, the chloride content along the unprotected cracks is much higher and far exceeds the threshold even at a 3 in. depth. The treated cracks show consistent performance after a 1.5 in. depth in BDJR concrete and after a 1 in. depth in Grade DM concrete. Even though the chloride content data at a 0.5 in. depth is presented in the graph, this data point should not be used for product performance evaluation since the reading is highly influenced by the surface chloride content. As shown in the figures, irrespective of the application age, healer sealer type, concrete mix, and the location of testing (along the crack or away from the crack), the chloride content at or below a 1.5 in. depth remains constant. This shows the effectiveness of the healer sealers in protecting cracked concrete. Hence, the concrete age at the time of healer sealer application (t_4) can be as early as 14 days.



i) Reference specimen and specimens with S1 sealer ii) Reference specimen and specimens with S2 sealer

a) Average chloride content at the crack



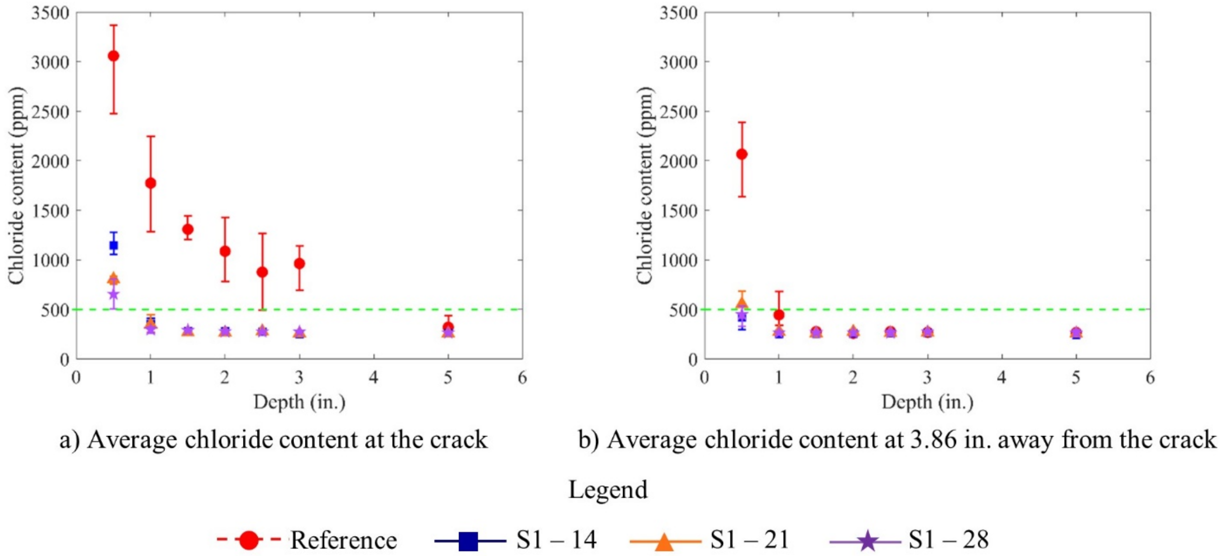
i) Reference specimen and specimens with S1 sealer ii) Reference specimen and specimens with S2 sealer

b) Average chloride content at 3.86 in. away from the crack

Legend

Figure 4-3. Chloride content along the depth of BDJR concrete specimens

Note: ppm = parts per million.



a) Average chloride content at the crack

b) Average chloride content at 3.86 in. away from the crack

Figure 4-4. Chloride content along the depth of Grade DM concrete specimens

Note: ppm = parts per million.

4.4.2.2 Water-Soluble Chloride Content (ASTM C1218) – 135th-Day Measurement

As noted in Section 2.6.6, the ASTM C1218 procedure theoretically measures the water-soluble chloride content that is available to cause corrosion. The threshold limit for water-soluble chloride content to initiate steel corrosion is 375–400 ppm.

The water-soluble chloride content was evaluated within a 0.5 in. depth located between 4.5 in. and 5.0 in. depths using the cores extracted from all the beam specimens at the crack and away from the crack. Table 4-4 and Table 4-5 show the chloride content in BDJR and Grade DM specimens, respectively. In all the specimens, the water-soluble chloride content is lower than the threshold limit. Irrespective of the concrete mix proportions, the chloride content of reference specimens is higher at the crack compared to 3.86 in. away from the crack. This shows the impact of the presence of an untreated crack in the concrete. The chloride content of the reference specimen at 3.86 in. away from the crack is similar to the chloride content at the treated cracks. This indicates the effectiveness of healer sealers in protecting cracked concrete.

Table 4-4. 135th–Day Water-Soluble Chloride Content (ppm) Within 4.5 to 5.0 in. Depth of BDJR Concrete Specimens

Specimen description	Specimen-1 (C[a]/A[b])	Specimen-2 (C/A)	Specimen-3 (C/A)	Average (C/A)
Reference	374/35	147/41	262/34	261/37
14-day S1 sealed	33/31	34/34	31/31	33/32
14-day S2 sealed	33/33	33/38	30/30	32/34
21-day S1 sealed	33/33	36/29	42/33	37/32
21-day S2 sealed	31/31	29/34	31/30	31/32
28-day S1 sealed	40/29	33/29	38/31	37/30
28-day S2 sealed	361[c]/46	36/30	31/38	33/38

[a] Average chloride content at the crack.

[b] Average chloride content at 3.86 in. away from the crack

[c] Outlier

Table 4-5. 135th–Day Water-Soluble Chloride Content (ppm) Within 4.5 to 5.0 in. Depth of Grade DM Concrete Specimens

Specimen description	Specimen-1 (C[a]/A[b])	Specimen-2 (C/A)	Specimen-3 (C/A)	Specimen-4 (C/A)	Specimen-5 (C/A)	Average (C/A)
Reference	69/54	99/56	92/51	94/63	192/47	109/54
14-day S1 sealed	62/73	45/35	40/47	50/50	53/294[c]	50/51
21-day S1 sealed	44/46	45/46	92/80	52/47	49/47	56/53
28-day S1 sealed	275[c]/46	54/47	54/49	48/54	51/44	52/48

[a] Average chloride content at the crack

[b] Average chloride content at 3.86 in. away from the crack

[c] Outlier

4.4.2.3 Total Chloride Content (ASTM C1152) – 272nd-Day Measurement

The specimens were dry-cured for 137 days following the 135th-day of chloride testing. On the 272nd-day (i.e., 135 + 137 days), the chloride content within a 1.0 to 1.5 in. depth was also investigated on a selected number of specimens. Two reference specimens from each mix and one specimen representing each sealant type and a treatment age were selected. Table 4-6 and Table 4-7 show the total chloride content within a 1.0 to 1.5 in. depth in the BDJR and Grade DM specimens. The 135th-day data is also included in the tables. The chloride content of the reference specimens measured at the crack is 1432 ppm and 1545 ppm for BDJR and Grade DM specimens, respectively. The chloride content is much higher than the threshold of 500 ppm. Irrespective of the sealant application age, sealant type, and concrete mix, the chloride content of the treated specimens was less than 250 ppm for BDJR and less than 300 ppm for the Grade DM. With a background chloride content of 270 ppm in Grade DM concrete, the chloride content in uncracked concrete and the concrete with sealed cracks is similar.

Table 4-6. Total Chloride Content (ppm) Within 1 to 1.5 in. Depth in BDJR Concrete Specimens

Specimen description	At 135th-day (C[a]/A[b])	At 272nd-day (C/A)
Reference	1438[c]/229[c]	1432[c]/231[c]
14-day S1 sealed	249/230	253/233
14-day S2 sealed	254/206	226/212
21-day S1 sealed	267/244	209/204
21-day S2 sealed	249/208	217/214
28-day S1 sealed	265/206	211/222
28-day S2 sealed	279/223	240/233

[a] Average chloride content at the crack
[b] Average chloride content at 3.86 in. away from the crack
[c] Average of two beams

Table 4-7. Total Chloride Content (ppm) Within 1 to 1.5 in. Depth in Grade DM Concrete Specimens

Specimen description	At 135th-day (C[a]/A[b])	At 272nd-day (C/A)
Reference	1433[c]/299[c]	1545[c]/289[c]
14-day S1 sealed	293/254	287/296
21-day S1 sealed	241/412[d]	297/291
28-day S1 sealed	295/268	283/285

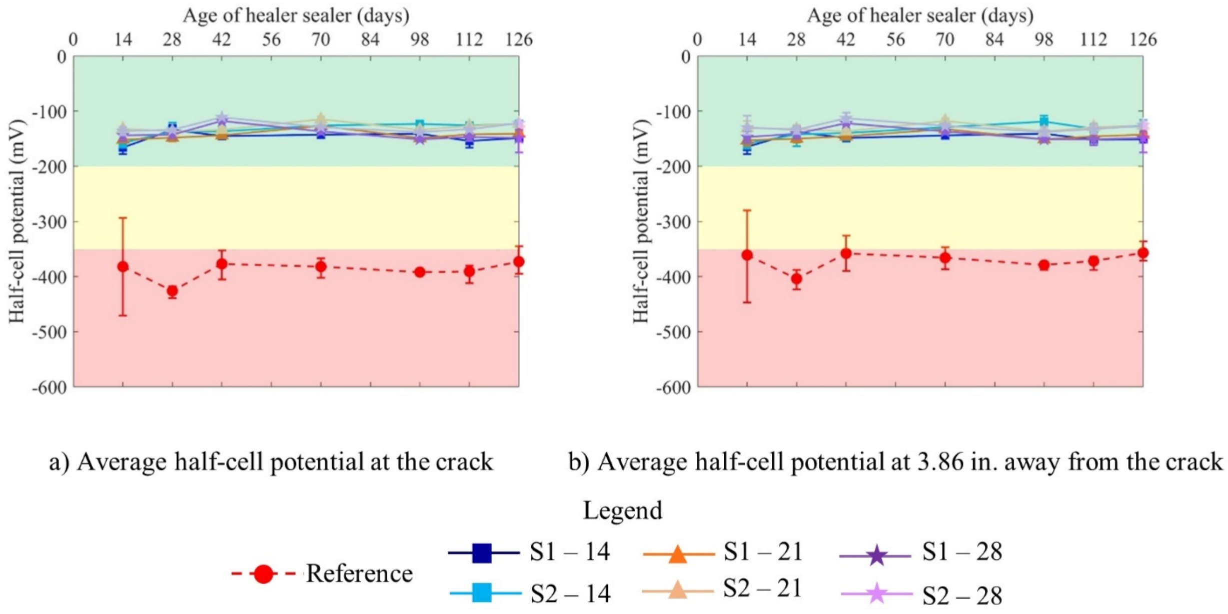
[a] Average chloride content at the crack
[b] Average chloride content at 3.86 in. away from the crack
[c] Average of two beams
[d] Outlier

4.4.2.4 Half-Cell Potential

ASTM C876 (2015) defines the limits for the potentials measured with a copper-copper sulfate reference electrode to identify the probability of reinforcing steel corrosion. Table 4-8 presents a summary of the ASTM limits and definitions. As shown in the table, the probability of not having corrosion is greater than 90% when the half-cell potential is more positive than -200 mV. When the measurements show more negative potentials than -350 mV, the probability of having steel corrosion is greater than 90%. The corrosion potential of reinforcing steel in the beams fabricated with BDJR concrete was evaluated. Beams with untreated cracks were used as the reference specimens. The cracks in the other beams were treated using two healer sealers at the concrete age of 14, 21, and 28 days. The half-cell potentials were measured over the crack and at 3.86 in. away from the crack using a copper-copper sulfate reference electrode. Figure 4-5a shows the half-cell potential measured at the crack with respect to the age of the healer sealer in the crack. Figure 4-5b shows the half-cell potential recorded at 3.86 in. away from the crack with respect to the age of the healer sealer in the crack. Irrespective of the measurement location, the average half-cell potential readings of reference specimens show more negative potentials than -350 mV. Therefore, "there is a greater than 90 % probability that reinforcing steel corrosion is occurring in that area at the time of measurement" (ASTM C876 2015). Regardless of the sealant type, the location of measurements, and the age of the healer sealer in the crack, the half-cell potentials of the specimens treated with healer sealers are more positive than -200 mV. This shows the effectiveness of the healer sealers in protecting cracked concrete. Hence, the concrete age at the time of healer sealer application (t_4) can be as early as 14 days.

Table 4-8. Half-Cell Potential Limits for Evaluating Corrosion Potential (ASTM C876)

Half-cell potential (mV)	Corrosion potential for the copper-copper sulfate reference electrode
> -200	Probability of no corrosion > 90%
-200 to -350	Uncertain
< -350	Probability of corrosion > 90%



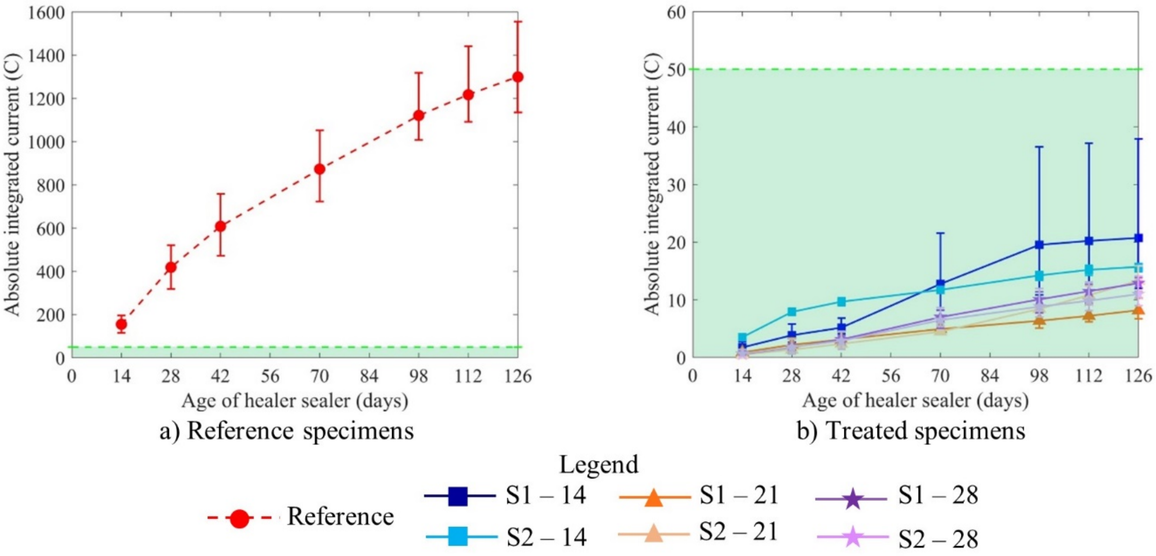
a) Average half-cell potential at the crack

b) Average half-cell potential at 3.86 in. away from the crack

Figure 4-5. Half-cell potential with respect to the age of healer sealer

4.4.2.5 Absolute Integrated Current

Following ASTM G109 (2013) procedures, the voltage across a 10 Ω resistor was measured. The current passing through the resistor was calculated and recorded as a time series. The data was used to calculate the absolute integrated current. The half-cell potential and the voltage across the 10 Ω resistor were measured using the same specimens. Figure 4-6a shows the absolute integrated current evaluated using the reference specimens. Figure 4-6b shows the absolute integrated current evaluated using the specimens with treated cracks. As per ASTM G109 (2013), an integrated current of 150 C is adequate to have a sufficient amount of corrosion for visual evaluation. As shown in Figure 4-6a, the average absolute integrated current recorded during the measurement period is much greater than the threshold of 150 C. As shown in Figure 4-6b, the integrated current recorded on all the treated specimens during the entire measurement period is less than 50 C even though the specimens were subjected to aggressive chloride exposure and 5 cycles of flexing during each drying period. The results prove the effectiveness of healer sealers in protecting cracked concrete. Since all the treated specimens show somewhat similar performance, the concrete age at the time of healer sealer application (t_4) can be as early as 14 days.



a) Reference specimens

b) Treated specimens

Figure 4-6. Variation of absolute integrated current with sealant age

4.4.2.6 Reinforcing Steel Condition

The reference specimens had a chloride content of more than 500 ppm within a 1.0 to 1.5 in. depth at the crack, with the half-cell potential of less than -350 mV, and with an absolute integrated current of more than 150 C. Therefore, the top reinforcing steel of the reference specimens was expected to have sufficient corrosion at the crack for visual evaluation. At the concrete age of 300 days, the reinforcing steel was removed from the reference specimens fabricated using BDJR concrete. Figure 4-7a shows the top and bottom reinforcing steels taken out from one of the reference specimens. As shown in the figure, the top reinforcing steel is corroded at the simulated crack location. The reinforcing steel at the bottom layer was not corroded since the chloride content within the 4.5 to 5.0 in. depth is less than 500 ppm.

On the 272nd-day following healer sealer application, the reinforcing steel at the top and bottom layers of the BDJR concrete specimens was removed. Figure 4-7b shows the condition of top reinforcing steels from a reference specimen and one treated specimen for each healer sealer application ages. None of the reinforcing steels removed from the treated specimens had corrosion. This observation was expected since the chloride content, half-cell potential, and absolute integrated current results presented in the previous sections were well below the corrosion initiation thresholds.

a) Reinforcing steel of a reference specimen

b) Reinforcing steel of reference and treated specimens

Figure 4-7. The condition of reinforcing steel removed from reference and treated BDJR concrete specimens

4.5 MINIMUM CONCRETE AGE TO RECEIVE A HEALER SEALER

Table 4-9 shows the parameters selected for healer sealer performance evaluation, specification limits, age of concrete (when the evaluation parameter limits are satisfied), and the recommended minimum concrete age to receive a healer sealer. For BDJR concrete, the wet curing duration to achieve the required minimum strength and a discontinuous capillary pore structure with a minimum volume of total permeable voids for durability (t_1) is 7 days. Similarly, the Grade DM concrete needs 10 days of wet curing to satisfy minimum strength and durability requirements. Therefore, the wet curing duration (t_1) for Grade DM concrete is 10 days. Concrete age at the time of cracking (t_2) is conservatively selected for BDJR and Grade DM concrete as 18 and 20 days, respectively. The age of concrete to achieve an acceptable MVER (t_{3a}) is not considered since the specified MVER limit was not reached until 28 days, and the healer sealer performance was not impacted by the concrete moisture content at the time of healer sealer application. However, the BDJR and Grade DM concrete mixes achieved the moisture content limit of 5%, specified by the New York DOT, in 17 and 12 days respectively. The moisture content was measured using an electrical impedance meter. Therefore, it is safe to assume that the concrete moisture content of about 5% did not adversely impact the healer sealer performance. Considering the moisture content limit of 5%, the concrete age to achieve an acceptable moisture content (t_{3b}) for BDJR and Grade DM concrete mixes is selected as 17 and 12 days, respectively. The healer sealer can be applied on BDJR and Grade DM concrete in 14 days if only the performance of the sealer against chloride ingress and corrosion probability is considered. However, concrete age needs to be at least 18 and 20 days to develop cracking for BDJR and Grade DM concrete mixes, the primary reason for the healer sealer application. Considering all the parameters, the minimum age of BDJR and Grade DM concrete to receive a healer sealer needs to be 18 and 20 days, respectively.

Table 4-9. The Minimum Age of Concrete to Receive a Healer Sealer

Evaluation parameter	**Specified limit**	**Age of concrete (days) (BDJR/Grade DM)**	**Minimum age of concrete to receive a healer sealer [max (t_1, t_2, t_3, and t_4)] (BDJR/Grade DM) (days)**
Concrete wet curing duration (t_1)	nd	7/10	18/20
Concrete age at the time of cracking (t_2)	nd	18/20	
Concrete age to achieve acceptable substrate moisture (t_3)	MVER ≤ 3 lbs/1000 ft^2/24 hrs and/or Moisture content ≤ 5%	≅ 28/> 28 ≅ 17/≅ 12	
Concrete age at the time of healer sealer application (t_4)	28 days	14/14	

Note: nd = not defined.

4.6 SUMMARY

A procedure was developed to identify the minimum age of concrete to receive a healer sealer. An implementation of the procedure was demonstrated using two concrete mixes and two healer sealers. These sealers were applied on concrete specimens fabricated using BDJR and Grade DM concrete mixes at 14, 21, and 28 days of concrete age. The performance of both sealers was evaluated based on the ability of sealers to resist chloride ingress and reduce the corrosion probability. The findings support applying healer sealers on BDJR and Grade DM concrete on or after 18 and 20 days of concrete age, respectively.

5 ROAD USER COST SAVINGS FROM EARLY APPLICATION OF FLOOD COATINGS

5.1 OVERVIEW

As per the current specifications, thin epoxy overlays and healer sealers are applied on bridge decks after maintaining a 28-day curing period for new concrete in partial or full-depth patches and repairs. Considering the time required under ideal conditions for surface preparation, production, and curing, healer sealer application requires a minimum of a one-day bridge closure beyond 28 days. Similarly, thin epoxy overlay operations require a minimum of a 2-day bridge closure. However, bridge closure duration is extended beyond the required minimum because of several parameters including site-specific weather conditions, capabilities of the equipment, the size of the bridge deck, and curing time (MDOT 2019a). As noted in Chapter 3 and Chapter 4, the findings of the experimental studies conducted for this project strongly support applying a flood coat during the dry-curing period that allows opening the bridge to traffic at the end of the 28-day curing period. This chapter presents the cost savings that could be realized by implementing the recommendations of this project. Even though the cost savings could be realized from many activities, only the road user cost savings are presented using two projects as case studies.

5.2 ROAD USER COST

Several models are available to calculate construction project impact in terms of costs. Aktan and Attanayake (2017) present a comprehensive model to evaluate the impact of construction projects in terms of road user costs, environmental cost, and business revenue change. Aktan and Attanayake (2017) present models to calculate road user costs for passenger and commercial vehicles; environmental costs for air pollution, water pollution, and climate change; and business revenue change for surrounding businesses. This chapter only presents the road user cost (RUC) impact due to complete bridge closure for flood coat application. As shown in Eq. 5-1, RUC includes the delay cost (DC), vehicle operating cost (VOC), and accident cost (AC).

$$RUC = DC + VOC + AC \tag{5-1}$$

The road user cost for a passenger vehicle is calculated using Eq. 5-2 to 5-5. Passenger vehicle related costs include (i) passenger vehicle delay cost (PVDC), (ii) passenger vehicle operating cost (PVOC), (iii) passenger vehicle accident cost (PVAC), and (iv) passenger accident cost (PAC).

Commercial vehicle related costs such as (i) commercial vehicle driver delay cost (CVDDC), (ii) commercial vehicle operating cost (CVOC), and (iii) commercial vehicle accident cost (CVAC) are calculated using Eq. 5-6 to 5-8.

$$PVDC = (T_{Dpv} - T_{WZpv}) \cdot PAADT \cdot AVO \cdot w_{pv} \tag{5-2}$$

$$PVOC = (T_{Dpv} - T_{WZpv}) \cdot PAADT \cdot r_{pv} \tag{5-3}$$

$$PVAC = (L_{Dpv} - L_{WZpv}) \cdot PAADT \cdot A_{npv} \cdot C_a \tag{5-4}$$

$$PAC = (L_{Dpv} - L_{WZpv}) \cdot PAADT \cdot A_{npv} \cdot C_{ap} \cdot (AVO - 1) \tag{5-5}$$

$$CVDDC = (T_{Dcv} - T_{WZcv}) \cdot CAADT \cdot w_{cv} \tag{5-6}$$

$$CVOC = (T_{Dcv} - T_{WZcv}) \cdot CAADT \cdot r_{cv} \tag{5-7}$$

$$CVAC = (L_{Dcv} - L_{WZcv}) \cdot CAADT \cdot A_{ncv} \cdot C_a \tag{5-8}$$

where:

PAADT = volume of passenger vehicle traffic on the roadway to be closed during construction (vehicles/day)

A_{ncv} = normal accident rate for commercial vehicles (accident/100 million vehicle-mile)

A_{npv} = normal accident rate for passenger vehicles (accident/10 million vehicle-mile)

AVO = average vehicle occupancy, including the driver (number of people)

CAADT = volume of commercial vehicle traffic on the roadway to be closed during construction (vehicles/day)

C_a = average cost per accident (includes damage to the driver and the vehicle) (\$/accident)

C_{ap} = average medical cost per accident per person (i.e., accident cost excluding cost of damages to the vehicle) (\$/person/accident)

L_{Dcv} = length of detour for commercial vehicles (miles)

L_{Dpv} = length of detour for passenger vehicles (miles)

L_{WZcv} = length of the road segment closed to commercial vehicles during construction (miles)

L_{WZpv} = length of the road segment closed to passenger vehicles during construction (miles)

r_{cv} = average hourly vehicle operating cost for commercial vehicles ($/hr)

r_{pv} = average hourly vehicle operating cost for passenger vehicles ($/hr)

T_{Dcv} = time to travel via detour for commercial vehicles (hrs)

T_{Dpv} = time to travel via detour for passenger vehicles (hrs)

T_{WZcv} = time to travel along a distance equal to the closed road segment due to construction at the normal posted speed for commercial vehicles (hrs)

T_{WZpv} = time to travel along a distance equal to the road segment closed due to construction at the normal posted speed for passenger vehicles (hrs)

w_{cv} = hourly rate for a commercial vehicle driver ($/hr)

w_{pv} = hourly rate for both passenger and driver ($/hr)

5.3 COST SAVINGS FROM TWO TYPICAL PROJECTS

Two bridge sites were selected to demonstrate the road user cost savings from flood coat applications within the concrete dry curing period.

5.3.1 M-100 Over CN Railroad

This bridge (R01 of 23071) is in Potterville, Michigan and carries M-100 traffic over the CN Railroad (Figure 5-1). The bridge deck length and width are 107 ft – 6 in. and 54 ft. The deck width includes two 12 ft wide traffic lanes, two 10 ft wide shoulders, and a 10 ft wide walkway. The total area of the deck is 5,805 ft^2. When the bridge is closed to traffic, the passenger and commercial vehicles are routed along two different roadways (Figure 5-2). In 2019, the passenger vehicle annual average daily traffic (PAADT) and commercial vehicle annual average daily traffic (CAADT) on the bridge were 4,857 and 123, respectively. The work zone length for passenger and commercial vehicles were 1.6 and 8.5 miles, respectively. The posted speed limit of the road segment is 55 mph. The detour length for passenger vehicles is 4.5 miles and the posted speed limit is 35 mph. The detour length for commercial vehicles is 13.4 miles, with two segments at 60 and 55 mph speeds.

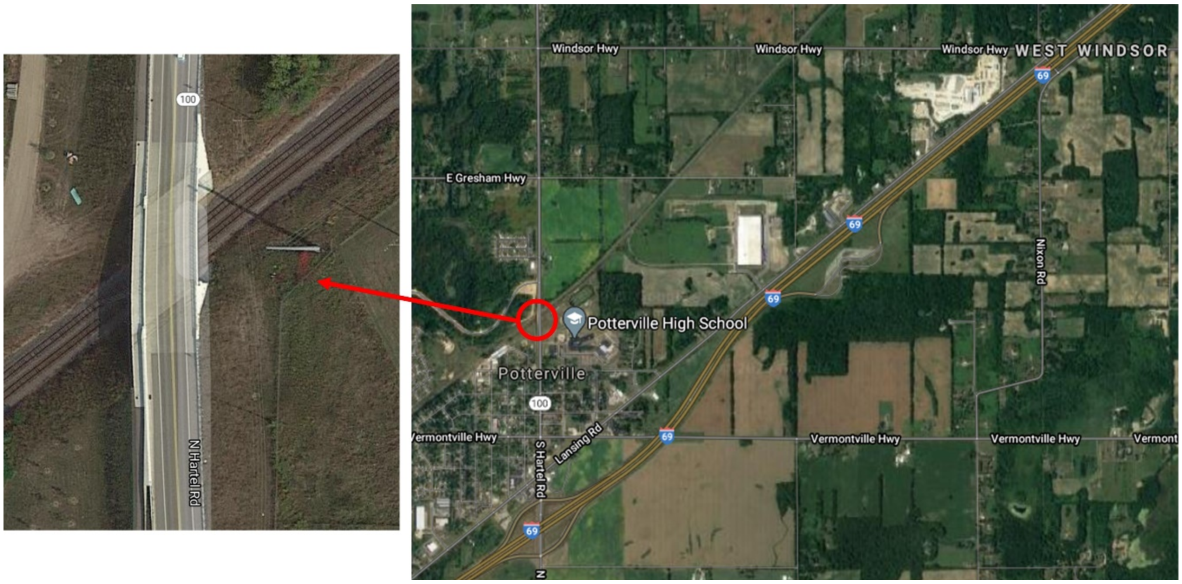
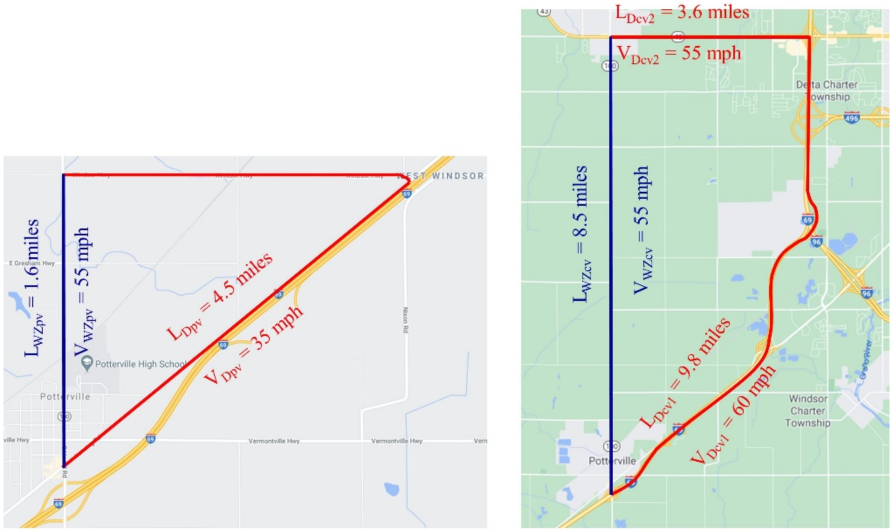


Figure 5-1. M-100 over CN Railroad bridge location (42.632492, -84.739096) (Google map)



Passenger vehicle detour

Commercial vehicle detour

Figure 5-2. Detour assigned to passenger and commercial vehicles

5.3.2 US-131 Over 3 Mile Road

This bridge (S04 of 54013) is in Aetna, Michigan, and carries US-131 freeway traffic over 3 Mile Road (Figure 5-3). The bridge deck length and width are 86 ft and 53 ft – 8 in. The total area of the deck is 4,615 ft^2. When the bridge is closed to traffic, the passenger and commercial vehicles are routed along the same route as shown in Figure 5-4. In 2019, PAADT and CAADT on the northbound (NB) bridge were 11,343 and 1,463, respectively. The length of the work zone is 6.53 miles. The posted speed limit of the road segment is 75 mph for passenger vehicles and 65 mph for commercial vehicles. The length of the detour is 10.28 miles, and the average posted speed limit is 55 mph.

Figure 5-3. US-131 over 3 Mile Road bridge (43.511442, -85.485965) (Google map)

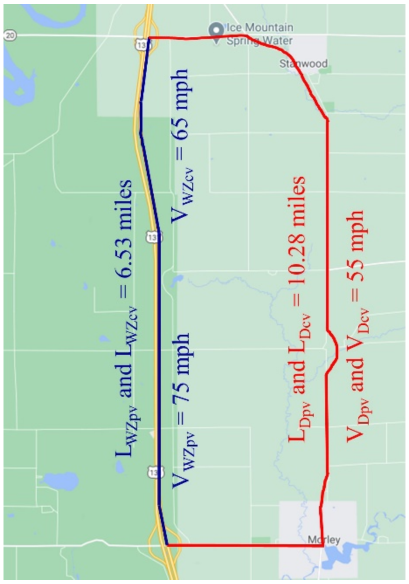


Figure 5-4. Detour assigned to passenger and commercial vehicles

5.3.3 Road User Costs

Table 5-1 shows the road user cost calculation parameters and the data for each bridge site. The PAADT and CAADT are collected from the Annual Average Daily Traffic (AADT) Map of Michigan (MDOT 2020). The length of work zones and detours, speed limits, and travel times were calculated using existing roadway data. The data for the rest of the parameters are determined as described below.

- The average vehicle occupancy (AVO) is 1.7 (FHWA 2018).
- The passenger and passenger vehicle driver hourly rates are assumed to be the same. Since the work zone and detour routes for the M-100 over the CN Railroad bridge site are located within the Eaton County, the hourly rate was calculated using the annual per capita income of the county. The 2018 annual per capita income of \$31,982 (U.S. Census Bureau 2020) was divided by 2080 hours to calculate the hourly rate. The hourly rate of \$14.58 for the US-131 over 3 Mile Road bridge site was calculated using the 2018 statewide annual per capita income of \$30,336 and 2080 hours per year (U.S. Census Bureau 2020).
- Michigan's commercial vehicle driver hourly rate in 2019 was \$20.74 (U.S. Bureau of Labor Statistics 2020a).
- The average operational cost per mile for a passenger vehicle is \$0.575 (IRS 2020) and a commercial vehicle in the Midwest is \$1.727 (Murray and Glidewell 2019). These rates are multiplied with the average vehicle speed of the road segments to calculate the average hourly vehicle operating cost.
- The normal accident rate for passenger vehicles (A_{npv}) is calculated by dividing the number of total injury-level accidents by annual vehicle miles traveled. To calculate a normalized accident rate for passenger vehicles, the ratio is multiplied by the percentage of involvement. In 2019, the total injury-level accidents in Michigan was 54,539 and the percentage involvement for passenger vehicles was 81.8% (MOHSP 2019). In 2018, a total of 101.7 billion miles were recorded by all the vehicles in Michigan (MDOT 2019b). Similarly, the normal accident rate for commercial vehicles (A_{ncv}) is calculated using 6.8% as the percentage involvement.
- The average cost per accident (C_a) and average medical cost per person per accident (C_{ap}) are calculated based on the injury level (serious/moderate/minor). The level of injury was assumed based on the posted speed limit of the detour route. As an example, the injuries from the accidents on road segments with speed limits above 55 mph, at 55 mph, and below 55 mph were assumed to be serious, moderate, and minor. The cost per accident for each injury level was adopted from Kostyniuk et al. (2017).

- The 2020 costs were calculated using the Consumer Price Index (CPI) and Eq. 5-9. Table 5-2 shows CPI for the 2016 to 2020 duration.
- Table 5-3 shows the road user cost per day prorated to the year 2020.

$$\text{Future Value} = \text{Present Value} \times (1 + r)^n \tag{5-9}$$

where:

r = the average CPI

n = the number of years

Table 5-1. Road User Cost Calculation Parameters and Data (2020 Rates)

Parameter	M-100 over CN Railroad	US-131 over 3 Mile Road
PAADT (vehicles/day)	4,857	11,343
CAADT (vehicles/day)	123	1,463
L_{WZpv} (miles)	1.6	6.53
V_{WZpv} (mph)	55	75
T_{WZpv} (hrs)	0.029	0.087
L_{Dpv} (miles)	4.5	10.28
V_{Dpv} (mph)	35	55
T_{Dpv} (hrs)	0.129	0.187
L_{WZcv} (miles)	8.5	6.53
V_{WZcv} (mph)	55	65
T_{WZcv} (hrs)	0.155	0.100
L_{Dcv} (miles)	Segment 1: 9.8 Segment 2: 3.6	10.28
V_{Dcv} (mph)	Segment 1: 60 Segment 2: 55	55
T_{Dcv} (hrs)	0.229	0.187
AVO (person)	1.7	1.7
w_{pv} (\$/hr)	16.09	15.26
w_{cv} (\$/hr)	21.22	21.22
r_{pv} (\$/hr)	31.63	31.63
r_{cv} (\$/hr)	94.99	94.99
A_{npv} (accident/10 million vehicle-mile)	4.39	4.39
A_{ncv} (accident/100 million vehicle-mile)	3.62	3.62
C_a (\$/accident)	Passenger vehicle: 74,705 Commercial vehicle: 541,821	150,013
C_{ap} (\$/person/accident)	69,872	145,181

Table 5-2. Year and Consumer Price Index (CPI) (U.S. Bureau of Labor Statistics 2020b)

Year	Consumer price index (CPI), r (%)
2016	2.1
2017	2.1
2018	1.9
2019	2.3
2020	2.3

Table 5-3. Road User Cost for Two Bridge Sites

Cost component	Equation no.	M-100 over CN railroad	US-131 over 3 Mile Road
Passenger vehicle delay cost (PVDC) ($/day)	5-2	13,285	29,426
Passenger vehicle operating cost (PVOC) ($/day)	5-3	15,363	35,878
Passenger vehicle accident cost (PVAC) ($/day)	5-4	462	2,801
Passenger accident cost (PAC) ($/day)	5-5	302	1,898
Commercial vehicle driver delay cost (CVDDC) ($/day)	5-6	193	2,701
Commercial vehicle operating cost (CVOC) ($/day)	5-7	865	12,090
Commercial vehicle accident cost (CVAC) ($/day)	5-8	12	30
Road user cost (RUC) ($/day)	5-1	30,482	84,824

Table 5-4 shows the typical surface preparation rate, production rate, and curing duration. The deck area that requires a flood coating on M-100 over the CN Railroad and US-131 over the 3 Mile Road bridges is 5,805 ft^2 and 4,615 ft^2, respectively. The time required to complete flood coating jobs on these bridge decks is presented in Table 5-5. Flood coats are required to be applied and cured in daylight. As shown in the table, a healer sealer job on any of these bridges requires closing the bridge for one or two days depending on the deck preparation and production rates. In addition, site-specific weather influences the duration. A thin epoxy overlay job requires closing the bridge for two to three days.

As shown in Table 5-3, the road user costs for M-100 over the CN Railroad and US-131 over the 3 Mile Road projects are $30,482 per day and $84,824 per day, respectively. Therefore, the reduction of one to two days of the road closure, beyond the standard 28-day requirement, could save the users at least $30,482 to $60,964 from the M-100 over the CN Railroad project and $84,824 to $169,648 from the US-131 over the 3 Mile Road project.

Table 5-4. Surface Preparation Rate, Production Rate, and Curing Duration for Epoxy Overlays and Healer Sealers (DeRuyver and Schiefer 2016)

Flood coat	**Surface preparation rate (ft^2/hr) (min/max)**	**Production rate (ft^2/hr) (min/max)**	**Flood coat curing duration (hrs/layer)**
Epoxy overlay	600/850	1,000/3,500	2
Healer sealer	1,600/1,700	1,000/3,500	2

Note: min = minimum; max = maximum.

Table 5-5. Bridge Closure Duration for Epoxy Overlay and Healer Sealer Application

Bridge site	**Flood coat**	**Surface preparation duration (hrs) (min/max)**	**Production duration (hrs) (min/max)**	**Curing duration (hrs)**	**Job duration (hrs) (min/max)**	**Bridge closure duration (days)**
M-100 over CN railroad	Epoxy overlay	6.8/9.7	3.3/11.6	4.0	14.1/25.3	2~3
	Healer sealer	3.4/3.6	1.7/5.8	2.0	7.1/11.4	1~2
US-131 over 3 Mile Road	Epoxy overlay	5.4/7.7	2.6/9.2	4.0	12.0/20.9	2~3
	Healer sealer	2.7/2.9	1.3/4.6	2.0	6.0/9.5	1~2

Note: min = minimum; max = maximum.

5.4 SUMMARY

The objective of this study is to develop a performance-based procedure to identify the minimum concrete age to receive a flood coat. The experimental results support applying a flood coat during the concrete dry curing period without compromising the performance compared to a flood coat applied on the 28 days old concrete. Implementation of this project recommendations could save road users more than \$30,482 to \$84,824 per day on bridge decks of about 5,000 ft^2 in area.

6 SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

6.1 SUMMARY

A flood coating (thin epoxy overlay or healer sealer) application improves bridge deck condition and extends the service life. Depending on the condition, decks are patched or repaired before a flood coating application. Typically, the highway agency policies and manufacturer specifications require maintaining a curing period of 28 days (7-day wet and 21-day dry) before applying a flood coating on bridge decks with new concrete. Consequently, the contractors must wait 28 days to start surface preparation for a flood coat application. Delaying flood coat application increases project completion time, user cost, and the cost of construction and mobility management. Therefore, two performance-based procedures were developed to identify the minimum concrete age to receive a flood coating – one for thin epoxy overlays and the other for healer sealers. The robustness of both procedures was demonstrated through a comprehensive experimental study.

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. The minimum concrete age to receive an overlay depends on concrete wet curing duration, cracking age, concrete age to achieve an acceptable substrate moisture condition, and concrete age to develop the required minimum tensile strength. Thin epoxy overlay performance depends on concrete strength, bond strength, thermal compatibility between overlay and concrete, epoxy performance under various exposure conditions, and workmanship. Considering all these parameters, a comprehensive procedure was developed to evaluate the minimum age of concrete to receive an overlay as a function of (i) concrete wet curing duration, (ii) concrete age at the time of cracking, (iii) concrete age to achieve acceptable substrate moisture, (iv) concrete age to develop the specified minimum tensile strength, and (v) concrete age at the time of epoxy application to develop the specified bond strength. This procedure was implemented using two MDOT standard concrete mixes and two thin epoxy overlays. Bridge deck joint repair (BDJR) and Grade DM concrete mixes were selected for this study. E-bond 526 Lo-Mod and Unitex Pro-Poxy Type III DOT epoxy overlays were selected from the MDOT approved product list. Moreover, there is an interest to evaluate the possibility of developing a hybrid bridge deck protection system with penetrating sealers and thin epoxy overlays to complement the overlay performance by retarding chloride ingress into concrete through pinholes and other anomalies formed during overlay application and service life. Therefore, the experimental study was extended to evaluate the impact of silane pretreatment on overlay bond strength. SIL-ACT ATS-100, a 100% silane penetrating sealant in the MDOT approved product list, was selected for pretreating the concrete specimens fabricated with BDJR concrete.

Healer sealers are expected to seal the cracks by penetrating and bonding the cracks while maintaining the integrity under repeated loading that demands opening and closing of the sealed cracks. The performance can be assessed by evaluating the ability of the sealed crack to resist chloride ion ingress and reduce the probability of corrosion risk on the embedded reinforcing steel. The minimum concrete age to receive a healer sealer depends on concrete wet curing duration, cracking age, and concrete age to achieve an acceptable substrate moisture condition. Several parameters, including concrete moisture, workmanship, etc., influence healer sealer performance. Considering all these parameters, a comprehensive procedure was developed to evaluate the minimum age of concrete to receive a healer sealer as a function of (i) concrete wet curing duration, (ii) concrete age at the time of cracking, (iii) concrete age to achieve acceptable substrate moisture, and (iv) concrete age at the time of healer sealer application to achieve comparable performance to the concrete that received the sealer at the concrete age of 28 days. This procedure was implemented using two MDOT standard concrete mixes (BDJR and Grade DM) and two healer sealers (Sikadur 55 SLV and Unitex Pro-Poxy 40 LV LM) selected from the MDOT approved product list.

6.2 CONCLUSIONS AND RECOMMENDATIONS

6.2.1 Epoxy Overlays

The following conclusions and recommendations were derived from the experimental investigations conducted to evaluate the minimum concrete age to receive an epoxy overlay:

- A rational and implementable procedure is presented to evaluate the minimum age of concrete to receive epoxy overlays without compromising concrete durability and overlay performance. Even though the process requires evaluating several parameters, this process needs to be implemented only once per each standard or approved mix resulting in significant savings on project and road user costs. It is recommended to include the procedures as part of the thin epoxy overlay acceptance testing program.

- Since thin epoxy overlays with comparable properties to E-bond 526 Lo-Mod and Unitex Pro-Poxy Type III DOT can be applied on 18-days old BDJR concrete and 20-days old Grade DM concrete to achieve comparable performance to the 28-days standard, a 21-day application age can be specified. The 18-day and 20-day waiting periods were decided upon based on the concrete cracking age. Even though epoxy overlay application on uncracked concrete could potentially delay cracking, the overlay would not be able to prevent it from happening. As a result, the system integrity is compromised since concrete cracking after an overlay application is difficult to identify through visual inspection. Hence, concrete cracking age under standard laboratory exposure conditions became the decisive parameter for determining the concrete age to receive a thin epoxy overlay.
- 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 type. The average substrate moisture condition at 14 days of concrete age was 5.6% and 4.2% for BDJR and Grade DM concretes, respectively. The moisture contents are comparable to the limits specified by Wisconsin and New York DOTs.
- Irrespective of the application age, the bond strength of epoxy overlays under elevated temperature was less than 250 psi. The primary failure type was a bond failure at the concrete/overlay interface. 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 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 on the overlay resulting in lower bond strength. In addition, a certain degree of epoxy softening was observed under prolonged and repeated exposure to above 100° F.
- The bond strength recovers when the epoxy reaches room temperature following a heating cycle. However, bond strength decreases under repeated exposure to heating cycles, an evidence of having a certain degree of permanent damages to the integrity of the system. The recovered bond strength of E-bond 526 Lo-Mod epoxy overlay on BDJR concrete is consistently lower than 250 psi when applied during the dry curing period.

- The moisture vapor emission rate (MVER) recorded on the slabs fabricated using BDJR and Grade DM mixes did not satisfy the commonly required moisture vapor evaporation rate of 3 lbs/1000 ft^2/24 hrs within 21 days of concrete age. However, the moisture content measured using an electrical impedance meter under standard laboratory conditions was less than 5% by the concrete age of 17 days and 12 days for BDJR and Grade DM mixes, respectively. The 5% moisture content is the limit specified by the New York Department of Transportation.
- 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 smaller pore size that results in very slight increase in the internal relative humidity (IRH) under elevated temperatures. Therefore, low permeable concrete, such as mixes with SCMs, is recommended to improve bridge deck durability and overlay performance.
- The Unitex Pro-Poxy Type III DOT epoxy overlay performed consistently better than the E-bond 526 Lo-Mod epoxy overlay irrespective of concrete mix, epoxy application age, and exposure conditions.
- Pretreatment using SIL-ACT ATS-100, a 100% silane penetrating sealant, shows no adverse impact on the overlay performance; it rather improves the bond strength under elevated temperatures when applied on 21 or 28 days old concrete. Pretreatment improved the recovered bond strength following heating cycles.
- The application of overlays on concrete as young as 14 days did not compromise concrete durability.

6.2.2 Healer Sealers

The following conclusions and recommendations were derived from the experimental investigations conducted to evaluate the minimum concrete age to receive a healer sealer:

- A rational and implementable procedure is presented to evaluate the minimum age of concrete to receive healer sealers without compromising concrete durability and sealant performance. Even though the process requires evaluating several parameters, this process needs to be implemented only once per each standard or approved mix resulting in significant savings from project and road user costs. It is recommended to include the procedures as part of the healer sealer acceptance testing program.

- The total chloride content along the depth of concrete evaluated after 135 days following the healer sealer application shows similar values and trends for all three application ages. The total chloride content measured within the top 0.5 in. needs to be excluded from consideration since it is contaminated with the chloride at the ponded surface. The total chloride content at least 1.0 in. deep into the sealed crack remains constant and similar to the background chloride content (i.e., 231~270 ppm), an indication of the effectiveness of the crack sealant. The total chloride content at the unprotected crack (reference specimen) is much greater than 500 ppm up to a 3 in. depth. The performance data support healer sealer application on or after 14 days of concrete age. However, considering the concrete cracking age under standard laboratory exposure conditions, a 21-day application age can be specified.
- The steel rebars removed from the specimens at the concrete age of 300 days were visually inspected. The top reinforcing steel of the reference specimens had light corrosion while the reinforcing steel removed from the treated specimens showed no sign of corrosion. The measurements of chloride content, half-cell potentials, and the absolute integrated current supported the visual observations.
- Both sealers (Sikadur 55 SLV and Unitex Pro-Poxy 40 LV LM) show similar performance irrespective of application age and concrete mix.

6.2.3 Other

The following additional conclusions and recommendations were derived from the activities completed during this project:

- The use of low permeable concrete improves the bond strength of epoxy overlays.
- Concrete cracking age under standard laboratory exposure conditions became the decisive parameter for determining the concrete age to receive thin epoxy overlays or healer sealers. Therefore, the use of non-shrink bridge deck repair and/or patch material allows for the application of flood coatings much earlier than the 21-day waiting period identified for BDJR and Grade DM concrete.

- Even though the MDOT standard practice is 7 days of moist curing, the current stipulations in the Standard Specifications for Construction provide flexibility for extending the curing duration beyond 7 days by specifying 7-day minimum compressive and flexural strength requirements. However, these curing requirements do not specifically address the extended curing required to develop a discontinuous capillary pore structure with a minimum volume of total permeable voids in concrete with supplementary cementitious materials (SCMs), a durability performance requirement.
- The activities conducted during this project demonstrated the viability of using the bulk electrical conductivity and porosity testing to evaluate the duration of moist curing needed to develop a discontinuous capillary pore structure with a minimum volume of total permeable voids to assure concrete durability. It is recommended to include these two methods in the curing specifications to establish moist curing requirements assuring both the strength and durability requirements.
- Maintaining traffic on a typical bridge with a 5,000 ft^2 deck area and the average annual daily traffic (AADT) of about 5,000 to 12,000 could save road users in Michigan more than \$30,482 to \$84,824 per day.

6.3 RECOMMENDATIONS FOR FURHER STUDIES

The recommendations for further studies are specific to evaluating (i) the minimum age of special concrete mixes as well as the repair and patch materials to receive a thin epoxy overlay or a healer sealer, (ii) thin epoxy overlay and healer sealer application and performance through pilot projects, (iii) thin epoxy overlay performance under outdoor exposure for an extended period and (iv) concrete moisture measurement methods.

- Rational and implementable procedures were developed to evaluate the minimum age of concrete to receive epoxy overlays and healer sealers without compromising concrete durability and overlay/sealant performance. Only two standard concrete mixes (BDJR and Grade DM) were evaluated during this project. It is recommended to implement the procedures to evaluate the suitability of other standard and special concrete mixes as well as the repair and patch materials to receive an overlay or a sealer.
- The minimum concrete age to receive a thin epoxy overlay was established after conducting a comprehensive experimental study using two standard concrete mixes and

two thin epoxy overlays. Even though 56 large concrete slab specimens (40 × 40 × 9 in.) were used for this study to evaluate the overlay performance under various exposure conditions, including the southwest Michigan outdoor exposure, it is recommended to implement the findings on a couple of pilot projects to evaluate the performance before incorporating the recommendations into MDOT standard practice.

- Fifty-six (56) large concrete slab specimens (40 × 40 × 9 in.) were fabricated for this study using BDJR and Grade DM mixes. Two epoxy overlays were applied with and without silane pretreatment. These specimens are currently being exposed to southwest Michigan outdoor conditions. So far, the slabs were in the outdoors for about a year. Initial laboratory data indicated a certain degree of bond strength degradation with exposure to repeated thermal cycles, especially under elevated temperatures. Hence, it is recommended to evaluate the performance of the overlays on those 56 specimens for a couple more years to develop a better understanding of overlay performance.
- The minimum concrete age to receive a healer sealer was established after conducting a comprehensive experimental study using two standard concrete mixes and two healer sealers. It is recommended to implement the finding on a couple of pilot projects to evaluate the healer sealer performance before incorporating the recommendations into MDOT standard practice. In order to evaluate the field performance, cores can be extracted from the treated area to evaluate the depth of penetration and the resistance of the treated cracks to chloride ion ingress. Further, the performance of the bridge decks needs to be monitored for several years to evaluate the effectiveness of the treatments.
- The plastic sheet patch test is widely accepted as a near-surface moisture evaluation method. Due to several challenges associated with this qualitative measurement technique, a few DOTs use moisture content measurements to support the epoxy overlay and healer sealer application decisions. Hence, it is recommended to identify such technologies and evaluate their performance and reliability to be used as a standard method for concrete moisture content measurement.

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APPENDIX A: ABBREVIATIONS

A

AADT	Annual Average Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
AC	Accidental Cost
ACI	American Concrete Institute
ASTM	American Society for Testing and Materials
AVO	Average Vehicle Occupancy

C

CAADT	Commercial Annual Average Daily Traffic
CPI	Consumer Price Index
CPM	Capital Preventive Maintenance
CSM	Capital Scheduled Maintenance
CSP	Concrete Surface Profile
CVAC	Commercial vehicle accident cost
CVDDC	Commercial vehicle driver delay cost
CVOC	Commercial vehicle operating cost

D

DC	Delay Cost
DDC	Driver Delay Cost
DOT	Department of Transportation

F

FHWA	Federal Highway Administration

G

GGBFS	Ground Granulated Blast Furnace Slag

H

HS	Elevated Temperature

I

ICRI	International Concrete Repair Institute

IRH	Internal Relative Humidity
IRS	Internal Revenue Service

M

MDOT	Michigan Department of Transportation
MMA	Methyl Methacrylate
MOHSP	Michigan Office of Highway Safety Planning
MTM	Michigan Test Methods
MVER	Moisture Vapor Emission Rate

N

NA	Not applicable
na	Not available
NB	Northbound
NCHRP	National Cooperative Highways Research Program
nd	Not defined

P

PAADT	Passenger vehicle annual average daily traffic
PAC	Passenger Accident Cost
ppm	Parts Per Million
PVAC	Passenger vehicle accident cost
PVDC	Passenger Vehicle Delay Cost
PVOC	Passenger vehicle operating cost

Q

QAQC	Quality Assurance and Quality Control

R

RAP	Research Advisory Panel
RCP	Rapid Chloride Penetration
RH	Relative Humidity
RS	Reference Specimens

RT	Room Temperature
RUC	Road User Cost
S	
SCM	Supplementary Cementitious Material
ST	Silane Treated
T	
TCG	Tourney Consulting Group
U	
UPV	Ultrasonic Pulse Velocity
USA	United States of America
V	
V	Vehicle Operating Cost
W	
w/c	Water-Cement Ratio
w/cm	Water-Cementitious Material Ratio
WD	Wet and Dry Cycle

APPENDIX B: NOTATIONS

A_{ncv}	Normal accident rate for commercial vehicles
A_{npv}	Normal accident rate for passenger vehicles
C_a	Average cost per accident
C_{ap}	Average medical cost per accident per person
f_c	Specified compressive strength of concrete
f_r	Specified flexural strength of concrete
K	Coefficient of permeability
L_{Dcv}	Length of detour for commercial vehicles
L_{Dpv}	Length of detour for passenger vehicles
L_{WZcv}	Length of the road segment closed to commercial vehicles during construction
L_{WZpv}	Length of the road segment closed to passenger vehicles during construction
n	Number of years
p	Capillary porosity
r	Consumer Price Index (CPI)
r_{cv}	Average hourly vehicle operating cost for commercial vehicles
r_{pv}	Average hourly vehicle operating cost for passenger vehicles
T_{Dcv}	Time to travel via detour for commercial vehicles
T_{Dpv}	Time to travel via detour for passenger vehicles
T_{WZcv}	Time to travel along a distance equal to the closed road segment due to construction at the normal posted speed for commercial vehicles
T_{WZpv}	Time to travel along a distance equal to the road segment closed due to construction at the normal posted speed for passenger vehicles
t	The minimum concrete age to receive an epoxy overlay or a healer sealer
t_1	Concrete wet curing duration
t_{1a}	Time to achieve the specified strengths for QAQC requirements
t_{1b}	Time to achieve a discontinuous pore structure
t_{1c}	Time to achieve a minimum volume of total permeable voids
t_2	Concrete age at the time of cracking
t_3	Concrete age to achieve acceptable substrate moisture

t_4	Concrete age to develop the specified minimum tensile strength
	Concrete age at the time of healer sealer application
t_5	Concrete age at the time of epoxy application to achieve the specified bond strength
V_{Dcv}	Posted speed of detour for commercial vehicles
V_{Dpv}	Posted speed of detour for passenger vehicles
V_{WZcv}	Posted speed of the road segment closed for commercial vehicles during construction
V_{WZpv}	Posted speed of the road segment closed for passenger vehicles during construction
w_{pv}	Hourly rate for both passenger and driver
w_{cv}	Hourly rate for a commercial vehicle driver