Guide to Remediate Bridge Deck Cracking

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GUIDE TO REMEDIATE BRIDGE DECK CRACKING

Final Report

Sponsored by:

The Iowa Highway Research Board
TR-782

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16. Abstract

Bridge decks are known to experience early-age cracking that occurs immediately after or within a few years of construction. Early-age bridge deck cracks are undesirable because they increase deck maintenance needs, and thereby increase costs and traffic disruptions as well. To address this issue, Iowa DOT funded this study to develop a comprehensive guide for characterizing bridge deck cracks and select optimal crack remediation options. The scope of the work included a literature review of crack remediation practices and the decision trees/matrices used by state departments of transportation (DOTs) in the Midwest, as well as the California, Florida, New York State, and Virginia DOTs. Literature from the nuclear and pavement industries was also included. Service life modeling of generic Iowa bridge deck was completed to compare service life estimates of uncracked bridge decks to that of bridge decks with a variety of cracking scenarios and repairs and treatments identified in the literature review. Shallow (1-inch deep) and deep (to rebar) cracks and crack densities between 0.00 ft/ft^2 and 1.00 ft/ft^2 were modeled. Penetrating sealers, flood coats, hot-mix asphalt overlays with waterproofing membranes (HMAWM), thin polymer overlays (TPO), and premixed polymer concrete (PPC) overlays were considered in the models. The results of the service life modeling and costs from the literature review were used to perform life-cycle cost analysis (LCCA) comparing the crack remediation treatments across the various cracking scenarios. Based on the findings of the literature review and results of the service life models and LCCA, a set of data-driven decision trees was developed for selecting effective and cost-efficient repairs or treatments to address early-age cracks in bridge decks between 0 and 2 years in age, at 5 years of age, and at 10 years of age. The utility of the decision trees was demonstrated using an example bridge in Iowa. Implementation of the decision trees in the Iowa Bridge Design Manual and inclusion of the crack repairs and treatments in the Construction Manual or Special Provisions will help the Iowa DOT reduce the impact of early-age bridge deck cracking on deck life and subsequently reduce life-cycle and bridge maintenance costs.

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EXECUTIVE SUMMARY

Cracking of concrete bridge decks is a common issue reported among state departments of transportation (DOTs) and other transportation agencies. Early-age cracking that occurs immediately after or within a few years of construction is particularly undesirable because it compromises the durability of the deck from a young age, increasing deck maintenance needs, costs, and traffic disruptions. To aid the Iowa DOT in effectively and cost-efficiently addressing early-age cracking on bridge decks, this study developed a comprehensive guide for remediating cracks in Iowa bridge decks that addresses a variety of cracking scenarios and provides both high-level discussion for selecting crack repairs and detailed guidance for implementing crack repairs and deck treatments. The scope of the study included a literature review, service life modeling of uncracked, cracked, and repaired bridge decks, life-cycle cost analysis, and synthesis of the findings to develop data-driven decision trees for the Iowa DOT to incorporate in its design manual and specifications.

The literature review focused on how cracks are repaired and how a maintenance strategy is selected. The practices of sixteen state departments of transportation, twelve from the Midwest (Illinois, Indiana, Iowa, Kansas, Michigan, Minnesota, Missouri, Ohio, Nebraska, North Dakota, South Dakota, and Wisconsin) and California, Florida, New York State, and Virginia, were reviewed. Overall, the amount of guidance on crack maintenance varied significantly. Some agencies, such as the South Dakota and North Dakota DOTs, do not discuss crack maintenance in their manuals. Other agencies, such as the Illinois DOT, provide limited discussion in their manuals and several DOTs, such as the New York State DOT, provide small tables for selecting a crack repair based on one or two crack properties. The Indiana, Michigan, Virginia, and Wisconsin DOTs provide comprehensive decision matrices with guidance for selecting a repair or maintenance action broadly based on the condition state of the deck, but these tools do not provide guidance specific to addressing cracks. The Florida DOT provides the most comprehensive and focused tools for selecting a maintenance strategy for early-age bridge deck cracks. Examples of crack maintenance selection tables and matrices were also found in research literature for the bridge, nuclear, and pavement industries. Overall, information considered when selecting crack maintenance strategies included the National Bridge Inventory condition ratings, deck condition state, crack characteristics, and repair options properties. Potential crack repair or treatment strategies included doing nothing, penetrating sealers, crack-chasing methods, flood-coat methods, overlays, and deck replacement.

Service life modeling was conducted to estimate the impact of cracking and crack maintenance strategies on the service life of bridge decks in Iowa. Modeling of chloride-induced corrosion was conducted using WJE CASLE™, a mechanistic service life modeling software developed in-house by WJE. The model inputs were determined based on the Iowa DOT's standard practices, the guidance document *fib Bulletin 34: Model Code for Service Life Design*, and the results of previous inspections and studies conducted on bridges across the United States. Threshold values of 5% damaged area and 20% damaged area were assumed for bridge deck repair and replacement, respectively. Shallow map cracking and deep cracks extending to the reinforcing steel were considered in the models and the estimated time to 20% damage for uncracked areas, shallow crack-affected areas, and deep crack-affected areas was 47, 25, and 17 years, respectively. The impact of crack density was assessed by using weighted combinations of uncracked and crack-affected areas. Crack density was defined as the total crack length divided by the deck area and the crack densities investigated varied from 0.00 ft/ft^2 to 1.00 ft/ft^2. The bridge deck treatments considered in

the models were penetrating sealers, flood coats, hot-mix asphalt overlays with waterproofing membranes (HMAWM), thin polymer overlays (TPO), and premixed polymer concrete (PPC) overlays. The service life models investigated the application of the treatments when the bridge deck is 0, 2, 5, and 10 years old. The benefit of up to 3 applications of a penetrating sealer at regular intervals (4 and 6 years) was also investigated. The findings of the service life modeling are:

- Penetrating sealers are good for extending the time-to-5% damage and time-to-replacement (time to reach 20% damage assumed in this study for simplicity) by 2 to 6 years. They are most beneficial when the crack density is low and must be applied at early ages before crack-affected areas have begun to corrode in order to be effective.
- Flood coats can extend the time-to-5% damage and time-to-replacement by up to 12 to 18 years. They perform at their best when applied at early ages of 0 to 2 years, but can still increase time-to-5% damage or time-to-replacement by at least 5 years when applied at an application age of 5 years for bridge decks with crack densities greater than 0.15 ft/ft^2.
- HMA overlays with waterproofing membranes can extend the time-to-5% damage and time-to-replacement by approximately 5 to 10 years when applied at early ages of 0 to 2 years and are less effective when placed at later ages of 5 or 10 years.
- Thin polymer overlays can increase the time-to-5% damage and time-to-replacement by approximately 17 to 22 years if applied at early ages of 0 to 2 years regardless of crack density. Their benefit decreases with application age, especially when placed at later ages (10 years) or on bridge decks with severe crack densities (1.00 ft/ft^2 in this study).
- Premixed polymer concrete overlays follow the same trends as thin polymer overlays but can increase the time-to-5% damage and time-to-replacement by up to 35 years.
- The key parameters that control when each crack repair or treatment is effective are the corrosion initiation time and the threshold damage percentages at which repair and replacement are triggered.

Life-cycle cost analysis (LCCA) was conducted to estimate the life-cycle cost (LCC) of the crack remediation options. The LCCA relied on initial costs obtained from bid data in the literature review and the time-to-5% damage and time-to-replacement estimated from the service life modeling. Only agency costs were considered.

The results of the literature review, service life modeling, and LCCA were synthesized to develop data-driven decision trees that will aid users in identifying appropriate crack remediation strategies for bridge deck cracking scenarios encountered in Iowa. The decision trees logic assumes that the user's objective is to improve the performance of crack decks in terms of service life or restore the performance to that of an uncracked bridge deck, i.e., to restore the time-to-5% damage and time-to-replacement, at the lowest LCC. The decision trees that were developed consider deck age; crack depth, width, and density; initial and life-cycle costs; and time-to-5% damage and time-to-replacement. Three decision trees were developed overall: one for decks with ages up to 2 years, one for decks approximately 5 years old, and one for decks approximately 10 years old. The decision trees inputs are the crack depth (shallow or deep), width (up to 40 mils [0.040 inches]), and crack density. Crack density was divided into four categories: "Mild" (less than 0.10 ft/ft^2), "Moderate" (0.10 to 0.22 ft/ft^2), "Severe" (0.22 to 0.37 ft/ft^2), and "Very Severe" (greater than 0.37 ft/ft^2). A list of crack remediation options is provided and color-coded to indicate the most suitable option for each cracking scenario. Suitability was determined based on the initial and life-cycle costs, time-to-5% damage, and time-to-replacement. More detailed decision trees showing the percent difference in the cost and life of the bridge deck compared to those of a do-nothing scenario or an uncracked deck are also provided for bridge decks with deep cracks and with shallow cracking. The limitations of the data-driven decision trees include the following:

1. Crack densities exceeding 0.37 ft/ft^2 shall be investigated prior to implementation of repairs.
2. Crack widths between 30 mils and 40 mils (0.030 and 0.040 inches) with a crack density exceeding 0.10 ft/ft^2 shall be investigated prior to implementation of repairs.
3. The decision tree does not apply to crack densities exceeding 0.50 ft/ft^2 or crack widths exceeding 40 mils (0.040 inches).
4. The decision trees only consider bridge decks up to 10 years old.

The findings of this study can be implemented by the Iowa DOT by incorporating the data-driven decision trees presented in this report in the manuals for bridge design and/or maintenance and the standard specifications. Other information that should be included in the manuals and standard specifications includes the inspection procedures provided in this report. The crack repair profiles developed as part of this study and the example specifications for the crack remediation strategies considered in this study from other state DOTs can also be used to develop standard specifications and special provisions for crack remediation treatments that the Iowa DOT would like to implement. Future work in this area should consider how shifts in standard practice, e.g., changes made to concrete mix designs to meet new low-carbon concrete goals, will affect the suitability of the crack remediation strategies. Also, additional studies that measure the impact of repairs and treatments on bridge deck life, particularly in the field, are needed to help the industry develop and refine methods for quantitative modeling of bridge deck repairs and treatments.

CHAPTER 1. INTRODUCTION AND BACKGROUND

1.1. Background

Cracking of concrete bridge decks is a common issue reported among state departments of transportation (DOTs) and other transportation agencies. In a survey of U.S. and international transportation agencies conducted as part of the NCHRP Report 380, *Transverse Cracking in Bridge Decks*, Wiss, Janney, Elstner Associates, Inc. (WJE) found that, on average, transverse cracks initiated within the first month in 53 percent of all bridge decks placed (Krauss & Rogalla, 1996). Since this report, cracking has remained a primary issue for new and existing bridge decks despite continued research studies on mitigation and prevention of bridge deck cracking.

Due to the prevalence of cracking in bridge decks, an understanding of (1) how cracks affect bridge deck durability and service life, and (2) how to best remediate cracks is important. Information on crack remediation techniques that are available, when and under what circumstances they should be applied, and how to optimize their effectiveness is desirable. State DOTs sometimes collect information related to crack width and frequency on concrete decks, and numerous research studies on the effect of cracking and crack parameters on deck corrosion, such as the effect of crack width on chloride and moisture ingress in concrete, have been completed. However, the research has generally been inconclusive, and very few studies have investigated the direct relationship between bridge deck cracking and service life or maintenance requirements of the deck. Regarding crack repair techniques, there has been some research on specific crack repair types and repair materials, and their benefits in terms of preventing chloride intrusion and moisture seepage, but there is a lack of data directly correlating repair effectiveness with service life extension of the bridge deck. In summary, the effects of cracking and crack repair on bridge deck service life are still not understood, and this has been a barrier to the development of a comprehensive guide for bridge decks that carries the user from an assessment characterizing the cracking and bridge deck environment to selecting a general crack maintenance strategy or procedure, then to choosing a specific type of crack repair material. State DOTs, such as the Iowa DOT, require remediation policies that can effectively address bridge deck cracking to prolong service life. Since most deck cracking usually occurs shortly after construction (excluding cracking caused by material degradation and corrosion), remediation of cracks on newly built bridge decks provides an opportunity for significant increases in service life and significant savings in maintenance time and costs over the life of the bridge. In lieu of nation-level industry guidance, state DOTs have developed a variety of policies for the remediation of bridge deck cracking. The purpose of this project is to identify potential best practices for bridge deck crack remediation in Iowa based on the current state of practice, particularly in the Midwest, and our current understanding of the effect of cracks and their repair on bridge deck service life.

1.2. Project Objectives and Scope

The primary objective of this study is to develop a comprehensive guide for remediating cracks in bridge decks in Iowa. The guide will address a variety of cracking scenarios and provide both high-level discussion for selecting crack repairs and detailed guidance for implementing the repairs. Specifically, users will be able to reference the guide for:

- Decision matrices and tables for selecting crack remediation strategies that identify technically appropriate repair methods and materials based on the existing deck condition, deck age, and crack characteristics;
- Guidance for choosing between potential repair strategies based on practical considerations, including ease of installation, expected service life benefit to be experienced by the deck, and costs;
- Suggested crack inspection procedures for acquiring the condition information used by the decision matrices and tables; and
- Guidelines for repair procedures and best practices for each crack repair method considered.

The guide was developed by completing the following scope:

- Literature review of repairs addressing bridge deck cracking and how they are selected and implemented as well as their costs and service life benefits. Practices among the Midwest states were emphasized and recommendations of other agencies were included.
- Extensive service life modeling of generic bridge decks in Iowa with a variety of cracking scenarios and the effects of potential repairs to estimate the typical expected benefit of crack repair strategies on bridge deck service life.
- Benefit-cost analysis of the crack repair strategies.
- Synthesis of the practices and selection criteria identified in the literature review, estimated service life benefits, and initial and life cycle costs to develop a data-driven guide for remediation of cracks on bridge decks with ages up to 10 years.

1.3. Report Organization

This report contains the following chapters and appendices:

- **Chapter 1. Introduction and Background**
  This chapter introduces the project and its objectives and scope.
- **Chapter 2. Literature Review**
  This chapter summarizes the review of literature for guides and decision matrices for bridge deck crack maintenance and repair. The available decision tools used by state DOTs and in other industries, considerations when selecting a crack repair, and the types of repairs used are presented.
- **Chapter 3. Causes, Characterization, and Inspection of Bridge Deck Cracking**

  This chapter provides a summary of common causes of early age cracks and the characteristics of different types of cracks that can be observed in a bridge deck. A classification for the different crack types in terms of their effect on the bridge deck service life is also presented in this chapter.
- **Chapter 4. Effects of Crack Remediation Treatments on Deck Service Life**

  This chapter presents the service life modeling effort that was completed in this study to provide a quantitative estimate of the benefits of the different crack remediation options on the bridge deck service life.
- **Chapter 5. Data-Driven Decision Trees**

This chapter presents the methodology and cost analyses completed to create the data-driven decision trees, which are also presented in this chapter.

- **Chapter 6. Summary and Recommendations**

  This chapter provides a summary of the completed effort along with the main recommendations of the guide.

- **Appendix A. State DOT Decision Tools for Crack Maintenance**
  The matrices and tables used by the state DOTs to select bridge deck crack repairs are compiled in this appendix for reference.

- **Appendix B. Crack Repair Profiles**
  A profile for each of the various crack repairs considered feasible for bridge decks is provided in this appendix for reference. Each profile identifies the repair objectives that can be met, the applicability of the repair to various deck cracking scenarios, construction procedures and materials, and anticipated service life or recommended reapplication frequency as reported in literature. Repair costs are also presented based on bid tabulations.

- **Appendix C. WJE CASLE™ (Corrosion Assessment and Service Life Evaluation) Service Life Modeling Methodology**
  This appendix provides an overview of service life modeling assumptions used in WJE's in-house service life modeling software, which was used to conduct the service life modeling in this study.

- **Appendix D. Summary of Source Data for Decision Tress**
  A summary of the data analysis results for all the crack remediation options considered for different deck conditions is presented in this appendix.

- **Appendix E. Specifications for Bridge Deck Crack Inspection and Repair**
  This appendix contains a compilation of state DOT specifications related to the crack remediation options considered in this guide.

CHAPTER 2. LITERATURE REVIEW

This chapter presents the findings of the literature review, which focused on how cracks are repaired and how a maintenance strategy is selected. The chapter is divided into four sections. The first two describe state practices for maintenance of bridge deck cracking and concrete crack maintenance practices used in other industries, such as the nuclear industry. The third section summarizes the input criteria used by the state DOTs and in other literature for selecting a crack maintenance strategy, and the fourth section summarizes the crack repair or treatment strategies used by the state DOTs to address bridge deck cracking.

2.1. Established Practices According to State DOT Manuals

The practices of sixteen (16) state departments of transportation, twelve from the Midwest (Illinois, Indiana, Iowa, Kansas, Michigan, Minnesota, Missouri, Ohio, Nebraska, North Dakota, South Dakota, and Wisconsin) and California, Florida, New York State, and Virginia, were reviewed for information pertaining to bridge deck crack maintenance. Emphasis was placed on tools, such as decision flowcharts and matrices, for selection of crack maintenance activities and the use of crack characterization data in the decision-making process. The findings are summarized below, and the specific tables and figures provided by the state DOTs included in this review are presented in Appendix A.

The amount of guidance on crack maintenance that is offered by the state DOTs included in this review varied significantly. Some agencies, such as the South Dakota and North Dakota DOTs, do not discuss crack maintenance in their manuals, although a section on bridge maintenance is reportedly in progress for the South Dakota DOT bridge manual. Other agencies discuss select repairs, such as deck sealing and epoxy injection, and repair procedures in their manuals and provide scattered discussion on when implementation of these methods is appropriate. Several DOTs provide tables or matrices offering guidance on selection of a crack maintenance strategy. The inputs and outputs of these tables are summarized in Table 2.1 and the tables are categorized as “crack-focused maintenance selection tools,” “general maintenance selection tools,” or “comprehensive tools for crack repairs.”

“Crack-focused maintenance selection tools” are limited in scope to repairs that can only address cracks and are often selected based on one or two crack properties, typically width and activity. The Minnesota, Missouri, New York, Ohio, and Virginia DOTs provide crack-focused maintenance selection tools in the form of simple tables, or equivalent discussion in their text. These tables do not provide a comprehensive approach as they often overlook some repair options or crack characteristics, such as crack density.

At the highest level, the Indiana, Michigan, Virginia, and Wisconsin DOTs provide “general maintenance selection tools.” These tools are comprehensive decision matrices that provide guidance for selecting a repair or maintenance action based on the condition state of the deck. However, such matrices are broad in scope and do not provide guidance specific to cracks. The repairs listed are used to address all types of bridge deck distress, not just cracking, and the repair options are relatively coarse, such that a crack sealer may be recommended, but the most suitable material or installation procedure is not identified. Additionally, the general maintenance selection tools cannot distinguish between different cracking scenarios. The matrix inputs are often the NBI deck condition rating or element-level condition state data, which theoretically reflect the severity and extent of any cracks present, i.e., crack width and density. Of the state DOTs reviewed, only the Kansas and Indiana DOTs provide guidance for choosing a general deck or wearing surface condition rating based on crack widths and spacing in addition to other factors, as shown in Table 2.2. However, in a study of Pennsylvania bridges, Hopper et al. (2015) found that general deck condition rating and crack severity have a weak to negligible correlation due to the consideration of other defects, such as delaminations and spalls, in the NBI ratings. As a result, while these larger maintenance matrices can provide general guidance, it is advisable to refine the final selection by using tools that directly connect suitable repair strategies to crack conditions, such as the tables provided by the Missouri and New York DOTs (shown in Appendix A).

The Florida DOT is the only DOT reviewed that provides comprehensive but focused guidance for treating cracked bridge decks and as a result, its tools were identified as "comprehensive tools for crack repairs" in Table 2.1. The Florida DOT provides guidance in both the Bridge Maintenance Reference Manual (2018) and the Standard Specifications for Road and Bridge Construction (January 2022). The Bridge Maintenance Reference Manual (BMRM) provides an informative crack sealer summary that bridges the gap between detail-oriented but limited tables and comprehensive but undetailed matrices. The summary table, shown in Table 2.3, covers crack repair methods with a range of robustness, from penetrating sealers to polymer flood coats to a thin epoxy overlay, much like the more comprehensive decision matrices by the Indiana DOT and others. At the same time, the table is specific about the materials used and considers their different properties, encouraging the user to consider the suitability of the material and procedure for their specific scenario, much like the smaller tools by the Minnesota DOT and others. Florida DOT's crack sealer summary additionally includes high-level and practical considerations, notably the "Expected Useful Life" which is often offered in the comprehensive decision matrices as supplementary information (e.g. see the matrices by the Michigan DOT and Wisconsin DOT in Figure A.1, Figure A.2, and Figure A.3). However, while the crack sealer summary balances a comprehensive scope and scenario-specific details well, some additional or alternative information is desirable. Users would likely find more direct information regarding suitable crack widths and characteristics for the listed crack sealers useful rather than inferring suitable cracking scenarios based on the material properties of the crack sealers.

Section 400-21, *Disposition of Cracked Concrete*, of the Florida DOT's Standard Specifications for Road and Bridge Construction provides clear requirements for inspecting bridge deck cracks and then selecting a repair or treatment. The inspection requirements specify the timing of crack inspection and the crack characteristics to be measured (width, length, depth, and activity) and leaves the need for coring and inspection intervals to assess crack growth or activity up to the Engineer. The cracks are classified as structural or non-structural primarily based on crack depth and the environment around the concrete element. The repair of non-structural cracks on bridge decks is then determined based on Table 400-4, *Disposition of Cracked Concrete Bridge Decks*, which is included in Appendix A as Figure A.5 for reference. The crack width and crack density, the latter of which is referred to as the "Cracking Significance," are considered by the matrix. Crack width is divided into relatively fine bins of less than 0.004 inches, 0.004 to 0.008 inches, 0.008 to 0.012 inches, etc. up to 0.028 inches, which may not always be practical. Very fine cracks (less than 0.005 to 0.010 inches) can be challenging to identify and crack width commonly varies along the length of the crack, sometimes by ±0.005 inches. The matrix also considers the elevation of the bridge deck with respect to mean high water and the aggressiveness of the environment, although definitions for the categories ("Slightly Aggressive," "Moderately Aggressive," and "Extremely Aggressive") are not provided in the section. The repairs and treatment options are "no treatment required," "epoxy injection or methacrylate," "penetrant sealer," "investigate to determine appropriate repair or rejection," and "reject and replace." The footnotes indicate that methacrylate are preferred over penetrating sealers and should be chosen if possible. Overlays are also not included in the matrix, although they would likely be considered when investigating to determine appropriate repairs or rejection. In summary, Table 400-4 (Figure A.5) is a highly utilitarian tool that considers a wide range of cracking scenarios and a variety of repairs specifically targeted to bridge deck cracking.

In summary, there are very few comprehensive yet focused decision flowcharts or matrices currently being implemented by the state DOTs for crack maintenance strategies for bridge decks, which aligns with the findings of a previous research study on bridge deck cracking by Balakumaran et al. (2018). The decision matrices that are available are described in Table 2.1, which identifies the agency, the factors considered in the selection, and the maintenance actions that may be selected. Of the DOTs reviewed, only the Florida DOT has a summary tool focused on sealing cracks that presents a wide range of repair options and offers detailed guidance for the specific field scenarios in which they are appropriate. However, additional technical and economical information could improve the utility of the table.

Table 2.1 Summary of decision tools for deck maintenance activities

Agency	Inputs Considered in Selection	Possible Maintenance Activities
Crack-Focused Maintenance Selection Tools/Guidance		
Ohio DOT	Crack location (topside or soffit) Initial cost [1] Expected life [1]	▪ Do nothing ▪ Seal with a silane sealer ▪ Treat crack with a HMWM, a reactive silicate solution, or a gravity-fed resin ▪ Seal top surface with a HMWM, a reactive silicate solution, or a gravity-fed resin
Michigan DOT	Deck condition rating Crack type and depth Expected life [1]	▪ Wash concrete surface ▪ Seal concrete cracks ▪ Apply a thin epoxy overlay
Minnesota DOT	Crack width	▪ Seal with a methacrylate ▪ Seal with an epoxy
Missouri DOT	Crack width	▪ Apply a penetrating concrete sealer (silane) ▪ Apply a low-viscosity polymer crack filler ▪ Apply an in-deck bridge deck crack filler ▪ Apply a chip seal
New York State DOT	Crack width Crack activity Deicer exposure	▪ Do nothing ▪ Apply a penetrating sealer ▪ Seal with a HMWM or by epoxy injection
Virginia DOT	Crack width Crack type (cause) Deck age	▪ Do nothing ▪ Fill cracks
Wisconsin DOT	Crack width and extent Crack activity	▪ Apply a thin polymer overlay
General Maintenance Selection Tools [2]		
Indiana DOT	Deck condition rating Wearing surface condition rating	▪ Penetrating sealer ▪ Seal cracks

Agency	Inputs Considered in Selection	Possible Maintenance Activities
	Superstructure and substructure condition ratings Percent deck deterioration	▪ Conduct partial and full depth patching ▪ Apply a flexible overlay ▪ Apply a rigid overlay
Michigan DOT	Deck condition rating Percent deck deterioration Soffit condition rating Percent soffit deterioration Increase in deck condition rating [1] Increase in soffit condition rating [1] Anticipated fix life [1]	▪ Hold ▪ Seal cracks ▪ Apply a silane treatment ▪ Apply a healer-sealer ▪ Apply an epoxy overlay ▪ Patch the deck ▪ Apply a hot-mixed asphalt overlay with a waterproofing membrane
Virginia DOT	Deck condition rating Percent deck deterioration Deck age Depth of chloride front	▪ Clean and wash the deck ▪ Fill the cracks ▪ Apply an epoxy overlay ▪ Patch the deck ▪ Apply a rigid overlay
Wisconsin DOT [2]	Deck condition rating Percent deck deterioration Percent soffit deterioration Benefit to deck from action [1] Application frequency [1]	▪ Sweep/wash the deck ▪ Seal the deck ▪ Seal the cracks ▪ Patch the wearing surface ▪ Conduct full-depth patching ▪ Apply a thin polymer overlay ▪ Apply a polyester polymer concrete overlay ▪ Apply a rigid concrete overlay ▪ Apply a hot-mixed asphalt overlay with a waterproofing membrane
Comprehensive Tools for Crack Repairs		
Florida DOT (Bridge Maintenance Reference Manual)	Typical applications (qualitative crack widths and density) Viscosity (of repair material) Pot life (of repair material) Minimum cure time Skid resistance strategy Expected useful life	▪ Silane/siloxane ▪ Heavy weight methyl methacrylate, polyurethanes ▪ Epoxy healer sealer ▪ Thin epoxy overlay ▪ Injection epoxy
Florida DOT (Standard Specifications for Road and Bridge Construction)	Elevation (with respect to mean high water) Crack width Cracking significance (crack density) Environment category	▪ No treatment required ▪ Epoxy injection ▪ Methacrylate ▪ Penetrant Sealer ▪ Investigate to determine appropriate repair or rejection ▪ Reject and replace

Notes: [1] *Information is presented after applicable repair(s) is identified as supplementary information.*
[2] *Only inputs and maintenance activities relevant to crack maintenance methods are listed for these tools.*

Table 2.2. Guidance for selecting the general condition rating for an element based on crack characteristics and other deterioration.

Deck Condition Rating	Deck [1]	Deck/Overlay [2]	Rigid Portland Cement Overlay [3]	Polymer Overlay [3]
8	Max. crack width of 0.02″ Max. 2% deterioration	-	-	-
7	Crack width between 0.02″ and 0.04″ Max. 10% deterioration	Light map cracking Max. crack width of 0.02″	Minor cracking Max. crack width of 0.016″ Max. 1% deterioration	Minor cracking Max. crack width of 0.016″
6	Crack width between 0.04″ and 0.06″ Max. 20% deterioration Max. 2% spalling	Moderate map cracking Max. map crack width of 0.04″ Open crack width between 0.04″ and 0.06″ [4] Max. open crack spacing of 5′	Max. crack width of 0.021″ Min. crack spacing of 3′ Max. 5% delamination	Max. crack width of 0.016″ Min. crack spacing of 10′ Max. 0.5% delamination Minor wearing
5	Crack width greater than 0.06″ Max. 40% deterioration Max. 5% spalling	Crack width greater than 0.06″ Cracking has resulted in spalling	Max. crack width of 0.021″ Crack spacing between 1′ and 3′ Max. 10% delamination	Max. crack width of 0.016″ Min. crack spacing of 5′ Max. 1% delamination Minor wearing
4	-	-	Crack width greater than 0.05″ Max. crack spacing of 1′ Between 10% and 25% delamination Unpatched spalls/unsound patching	Crack width greater than 0.016″ Max. crack spacing of 3′ Between 1% and 5% delamination Unpatched spalls/unsound patching Max. 5% worn surface

Notes: [1] From the 2020 Local Bridge Inspection Manual (KDOT 2020).
[2] From the 2020 Local Bridge Inspection Manual, Appendix F (KDOT 2020).
[3] From the Bridge Inspection Manual, Part 4: Additional Inspection Guidance (INDOT 2017).
[4] The maximum crack width permitted for overlays is 0.04 inches.

Table 2.3. Crack Sealer Summary, published by FDOT (2018)

Attribute	Silane/Siloxane	Heavy Weight Methyl Methacrylate, Polyurethanes	Epoxy Healer Sealer	Thin Epoxy Overlay	Injection Epoxy
Typical applications*	Waterproofing good condition concrete	Crack sealers for widespread fine cracking	Crack sealers for widespread fine cracking	Crack sealer for widespread discrete larger crack widths	Crack sealer for widespread discrete larger crack widths
Viscosity (Centipoise)	< 1	20 - 200	50 - 150	1500 - 3000	500 - 2000
Pot Life (Minutes)	NA	5 - 45	20 - 60	15 - 30	15 - 30
Minimum cure Time (Hours)	1 - 4	2 - 12	3	1	2
Skid resistance	Original Surface	Broadcast fine aggregate (sand)	Broadcast fine aggregate (sand)	Broadcast fine aggregate (sand)	Broadcast fine aggregate (sand)
Expected Useful Life (Years)	3 - 5	5 - 10	5 - 10	10 - 15	5 - 10

*Notes: *Sealers should be formulated specifically for the crack(s) being addressed.*

2.2. Crack Maintenance Decision Guides in Research Literature

Comprehensive guidance on bridge deck crack remediation is rare in bridge literature. As a result, the review was expanded beyond concrete bridge deck literature and additional guidance for the selection of crack maintenance strategies was found in documents related to nuclear structures and pavements. While not fully transferable to bridge decks, these tools provide examples and guidance regarding which parameters need to be considered and which maintenance activities are feasible. The following three subsections discuss the resources found in bridge, nuclear, and pavement literature, respectively.

2.2.1. Bridge Industry Literature

Repair decision matrices addressing cracking in bridges were found in two references, one of which focuses on cracking of bridge decks and overlays. The second reference addresses general repair of bridge substructures.

In a 2014 study for the Minnesota DOT, Rettner et al. (2014) evaluated the causes of cracking in newly-constructed bridge decks and overlays and provided recommendations for the prevention and treatment of the observed early-age cracking. Rettner et al. (2014) recommended that a standard treatment schedule be developed and discussed the development of a rational approach to the selection of crack treatments. The researchers stated that the approach should consider whether the crack is structural or non-structural, the cause of the cracking, and the extent and activity of the cracking. Based on their literature review and experience, they recommended deep cracks, which they defined as cracks with a depth of at least 0.25 inches, be sealed. They also noted that shallow cracks would have a negligible effect on overlay permeability, and there is no evidence that their treatment would be beneficial. An example of a "treatment table" or decision matrix for early-age, non-structural cracking was provided and is shown in Figure 2.1. The table recommends either no treatment, treatment with either an epoxy or methyl methacrylate (MM), treatment with an epoxy, treatment with a methyl methacrylate, removal and replacement, or further investigation based on crack width and crack density. In this example, the researchers defined crack density as the sum of the average crack width multiplied by the crack length divided by the area inspected (referred to as the "lot").

<table>
<tr><th></th><th colspan="4">Cracking Density Within Lot</th></tr>
<tr><th>Average Crack Width Range, inches[1]</th><th>Isolated (<0.005%)</th><th>Occasional (0.005% to <0.017%)</th><th>Moderate (0.017% to <0.029%)</th><th>Extensive (>0.029%)</th></tr>
<tr><td><0.004</td><td rowspan="4">No Treatment</td><td rowspan="2">No Treatment</td><td>No Treatment</td><td>MM</td></tr>
<tr><td>0.004 to <0.008</td><td rowspan="2">Epoxy or MM</td><td rowspan="4">Investigate[2]</td></tr>
<tr><td>0.008 to <0.012</td><td rowspan="2">Epoxy or MM</td></tr>
<tr><td>0.012 to <0.016</td><td rowspan="5">Investigate[2]</td></tr>
<tr><td>0.016 to <0.020</td><td>Epoxy or MM</td><td rowspan="4">Investigate[2]</td></tr>
<tr><td>0.020 to <0.024</td><td>Epoxy</td><td rowspan="3">Remove and Replace</td></tr>
<tr><td>0.024 to <0.028</td><td>Epoxy</td></tr>
<tr><td>≥0.028</td><td>Investigate[2]</td></tr>
</table>

[1]Average Crack Width to be determined as the average of 3 representative measures
[2]Investigation should consider the nature and stability of cracking and the probability that repair techniques will effectively prevent future surface deterioration and delamination. *Removal and replacement should be required only when there is a significant probability that all other options will lead to premature failure of the deck*.

Figure 2.1. The example of a treatment table for bridge deck cracking provided by Rettner et al. (2014) in Table 3.1.

In a 2013 study for the Wisconsin DOT, Wan et al. (2013) developed a comprehensive decision matrix for addressing deterioration of reinforced concrete bridge substructures, which is shown in Figure 2.2. One section of the matrix is focused on crack repairs and includes epoxy injection, mortar, jacketing, drilling and plugging, and simple surface repair. Of these repairs, epoxy injection and simple surface repair are considered relevant to bridge decks and jacketing may be considered synonymous to a deck overlay. The decision matrix operates at a high level, and therefore repair decisions are based on the type of substructure element, the estimated cost, and the expected service life. The cost is presented in a unique way in that two estimates, one low and one high, are presented instead of a single value. While the decision matrix does not provide guidance according to crack type and other crack characteristics as is desired in this study, the matrix does highlight the importance of including accurate service life and cost estimates when selecting a crack repair.

	Repair Methods	Piles	Piers	Abutments	Bridge Seats	Unit	Estimated Cost		Service Life	Year of Cost
							Low	High	Years	Estimate
Cathodic Protection Systems	Galvashield CC		X			Each	$24.00	$36.00	15	2012
	Galvashield XP		X	X	X	Each	$21.00	$36.00	15	2012
	Ebonex		X			Each	$29.00	$97.00	25-30	2012
	Norcure Chloride Extraction		X	X		SF	$35.00	$50.00	25-30	2012
	Galvanode DAS	X	X		X	Each	$165.00		10-20	2012
	Galvanode ASZ+		X			SF	$22.00	$27.00	10-20	2012
Crack Repairs	Epoxy Injection		X	X		LF	$20.00	$50.00	20	2012
	Mortar		X	X		LF	$35.00		20	2012
	Jacketing	X	X			LF	$600.00	$1,200.00	20-40	2012
	Drilling and Plugging			X						
	Simple Surface Repair		X	X		SF	$45.00	$77.60	5-10	2012
General Deterioration Repairs	Fiberglass Jackets	X	X			LF	$600.00	$1,200.00	20-40	2012
	FRP Wrap	X	X			SF	$10.00	$50.00	50-75	2012
	Mini Piles	X				LF	$49.00	$53.50		2008
	Underpinning	X				LF	$50.00	$200.00	15	2012
	Pier Widening		X			Each	$10,000.00	$25,000.00		2008
	Encasement	X	X			LF	$20.00		20	2012
	Sprayed-On Concrete		X	X		SF	$7.20	$20.13		2008
Abutment Repairs	Abutment Stability			X						
	Abutment Sliding Repair			X						
	Abutment Settlement Repair			X						
	Abutment Slope-Failure Effect			X						
	Abutment Tensile Repair			X						
Bridge Seat Repairs	Cap Seat Repair				X					
	Concrete Cap Extension				X					
	Beam Saddle Addition		X							

Figure 2.2. Concrete repair decision matrix for substructures developed for Wisconsin DOT (Wan et al. 2013).

2.2.2. Nuclear Industry Literature

Flowcharts developed within the nuclear industry are shown in Figure 2.3 and Figure 2.4 (USACE 1986). The flowchart in Figure 2.3 is for dormant cracks, and the flowchart in Figure 2.4 is for active cracks. Parameters considered in the selection process other than crack activity are the crack type (pattern or isolated) and moisture exposure (none, minor, or severe). The maintenance options include judicious neglect; autogenous healing; dry packing; routing and sealing; flexible sealing; grouting; polymer impregnation; epoxy injection; drilling and plugging; overlay; unbonded overlay; and strengthening. A brief description of each of these options is presented in Table 2.4. These charts focus on cracks in reinforced concrete structures in general and while some crack features (such as seepage with respect to groundwater or containment) and maintenance options (such as dry packing, drilling and plugging, and polymer impregnation) are irrelevant or unsuitable for bridge decks, the general process and many of the details are directly transferable.

In addition to the flowcharts, Naus, Oland and Ellingwood (1996) also present a useful table that aids in the decision-making process by listing the appropriate repair options for different crack types, qualitatively comparing the durability of the potential crack repairs, and providing commentary regarding their applicability. This table is presented in Table 2.5. The types of cracks considered include dormant pattern or fine cracking, dormant isolated large cracking, active cracks, and seepage, only the last of which is not relevant to bridge decks. The potential repair options are similar to those listed in the flowcharts from the nuclear industry and durability of the potential repair options is rated on a scale from 1 to 5 with

1 being the most durable and 5 being the least durable. The commentary includes some qualitative points regarding repair objectives, repair application, suitable crack widths, and repair maintenance needs.

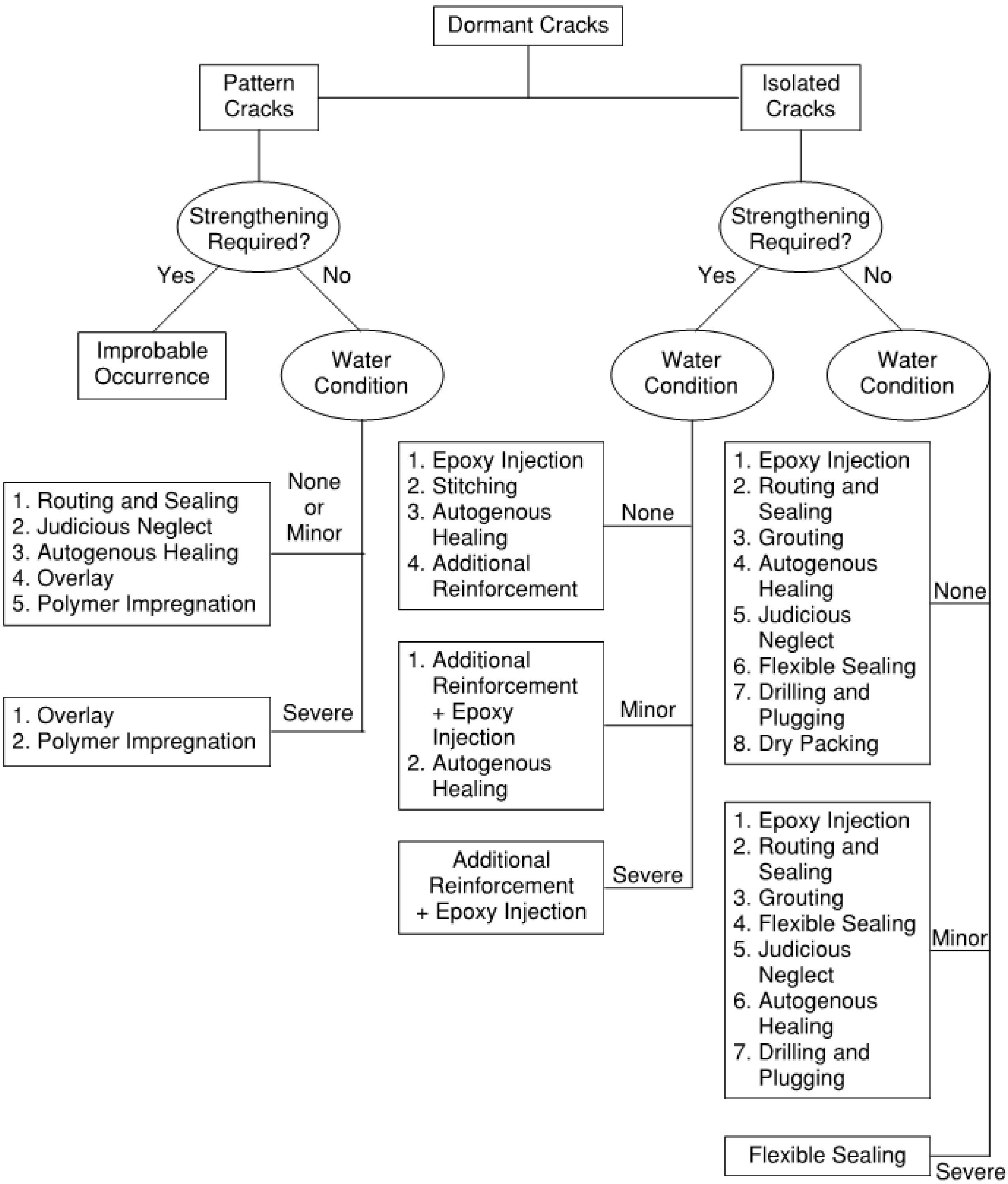

Figure 2.3. Decision flowchart for dormant cracks (USACE 1986).

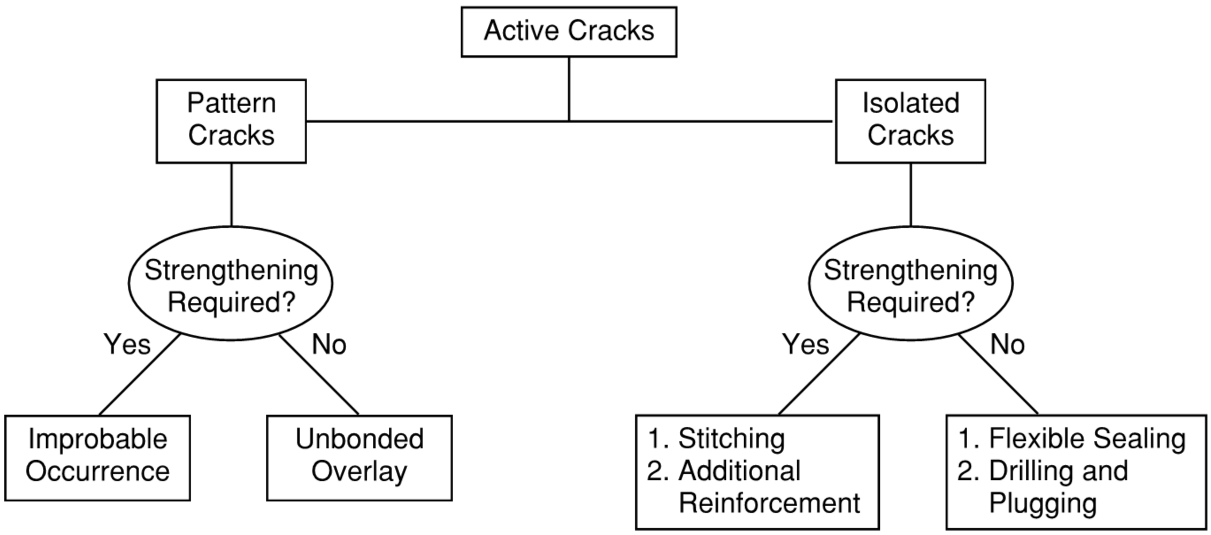

Figure 2.4. Decision flowchart for active cracks (USACE 1986).

Table 2.4. Maintenance Options for Addressing Cracks

Option	Description	Used on Bridge Decks?
Judicious Neglect	If the results of an assessment indicate that the cracking does not cause operational problems or accelerate degradation and time of maintenance, then neglect or "do nothing" may be the most economical and practical choice and judiciously selected. The USACE stresses that this choice must be preempted by consideration of proactive maintenance options.	Yes
Autogenous Healing	Autogenous healing refers to the ability of young concretes to self-heal thanks to their long-term hydration. The newly-formed hydration products fill cracks and carbonation of the products will cause additional precipitates to form. This only occurs if tensile stresses are absent, i.e., the crack is dormant, and if the concrete remains saturated. While similar to a "do nothing" option, a small effort to keep the concrete saturated and encourage further curing may be required.	No
Dry Packing	Dry packing consists of cutting a slot over the crack and ramming or tamping a mortar into the confined area. It can be used for repairing dormant cracks but is not recommended for addressing active cracks.	No
Routing and Sealing	Routing and sealing is commonly used to address dormant cracks. The crack mouth is enlarged (i.e. routed) and then the crack is cleaned and sealed. Alternatively, the crack may simply be sealed (referred to as crack filling in other areas of literature) but this decreases the life of the repair.	Yes
Flexible Sealing	Flexible sealing is similar to routing and sealing but addresses active cracks by turning the crack into a joint. The crack is first routed to	Yes

Option	Description	Used on Bridge Decks?
	produce the reservoir size and shape required to allow the sealant to accommodate the crack's future movements. It is then cleaned and a bond breaker is placed at the crack tip and a seal installed in the reservoir.	
Grouting	Grouting consists of injecting cracks with either hydraulic cement mixtures or chemicals that react to form a gel or solid precipitate. Grouting is considered a more robust alternative to routing and sealing or flexible sealing and is commonly done to address moist cracks experiencing water flow.	No
Polymer Impregnation	In polymer impregnation, a dry concrete surface is flooded and soaked in a monomer, which is permitted to polymerize. Cracks in the concrete surface must be dry as well to permit adequate penetration. The USACE noted that this method had not been successful for addressing fine cracks at that time (1986).	No
Epoxy Injection	Epoxy injection consists of cleaning the crack, placing a confining seal to prevent leaking, installing entry ports, and injecting epoxy. The epoxy is typically injected under high pressure although low pressure may be beneficial in some scenarios. Epoxy injection can restore strength at dormant cracks and is also used to repair delaminations in bridge decks.	Yes
Drilling and Plugging	Drilling and plugging has a limited applicability. Cracks must be relatively straight and accessible at one end such that a hole several inches in diameter can be drilled along the full length of the crack. The hole is then plugged with a rigid material if load transfer across the crack is required, or an asphalt or polyurethane foam if a watertight solution is required.	No
Overlay	Overlaying requires repair of deteriorated substrate concrete and then placement of a fresh layer of concrete. In Ref. [USACE 1986], the USACE acknowledges latex-modified concrete overlays, epoxy concrete overlays, and portland cement overlays.	Yes
Unbonded Overlay	Typically, an overlay is fully restrained along one face by the underlying substrate. An unbonded overlay has a bond breaker separating the overlay from the substrate and may be considered if cracks are active or structural movement is anticipated to prevent reflective cracking.	No
Strengthening	Strengthening is done to allow tensile load transfer across cracks. One method is stitching, in which metal staples or "dogs" are installed across the crack. Another option is to provide additional reinforcement, either by installing conventional reinforcement, prestressing steel, or by posttensioning. Conventional steel is typically embedded in concrete after installation.	No

Source: USACE. (1995). Evaluation and Repair of Concrete Structures. Manual No. 1110-2-2002

Table 2.5. General guide to repair options for concrete cracking (Naus, Oland, & Ellingwood 1996).

Description	Repair Options	Perceived Durability Rating (1-5)[1]	Commentary
Dormant pattern or fine cracking	Judicious neglect	4	Only for fine cracks
	Autogenous healing	3	Only on new concrete
	Penetrating sealers	2	Use penetrating sealer for H_2O, Cl resistance
	Coatings	3	Use coating for abrasion and chemical resistance
	HMWM or epoxy treatment	2	Topical application, bonds cracks
	Overlay or membrane	2	For severely cracked areas
Dormant isolated large cracking	Epoxy injection	1	Needs experienced applicator
	Rout and seal	3	Requires maintenance
	Flexible sealing	4	Requires maintenance
	Drilling and plugging	3	
	Grout injection or dry packing	4	
	Stitching	5	
	Additional reinforcing	4	
	Strengthening	3	
Active cracks	Penetrating sealer	3	Cracks less than 0.5 mm
	Flexible sealing	3	Requires maintenance
	Route and seal	3	Use for wide cracks
	Install expansion joint	2	Expensive
	Drilling and plugging	4	May cause new cracks
	Stitching	4	May cause new cracks
	Additional reinforcing	3	May cause new cracks
Seepage	Eliminate moisture source	1	Usually not possible
	Chemical grouting	2	Several applications may be necessary
	Coatings	4	May have continued seepage
	Hydraulic cement dry packing	4	May have continued seepage

Notes: [1]Scale from 1 to 5, with 1 being most durable.

2.2.3. Pavement Industry Literature

In pavement industry, a decision tree for selecting between crack sealing methods was developed for the Minnesota DOT for asphaltic concrete pavements (Barman, Munch & Arepalli 2019). The tree is shown in Figure 2.5. The repair decision depends on the crack severity (low, moderate or high), pavement type (new HMA or overlay), the analysis period, the design life, the pavement age, and the traffic level. The authors chose to define crack severity by crack width and a width less than 0.25 inches is considered "low," a width between 0.25 and 0.75 inches is considered "moderate," and widths greater than 0.75 inches are considered "high." The crack sealing methods considered are routing and sealing and cleaning and sealing. While the crack widths are too great to be applicable to bridge decks and a much wider selection of crack treatment or repair methods are available to reinforced concrete decks, the features affecting the repair decision including the design life, element age, and traffic level could also be considered in a decision tree for crack repair of bridge decks.

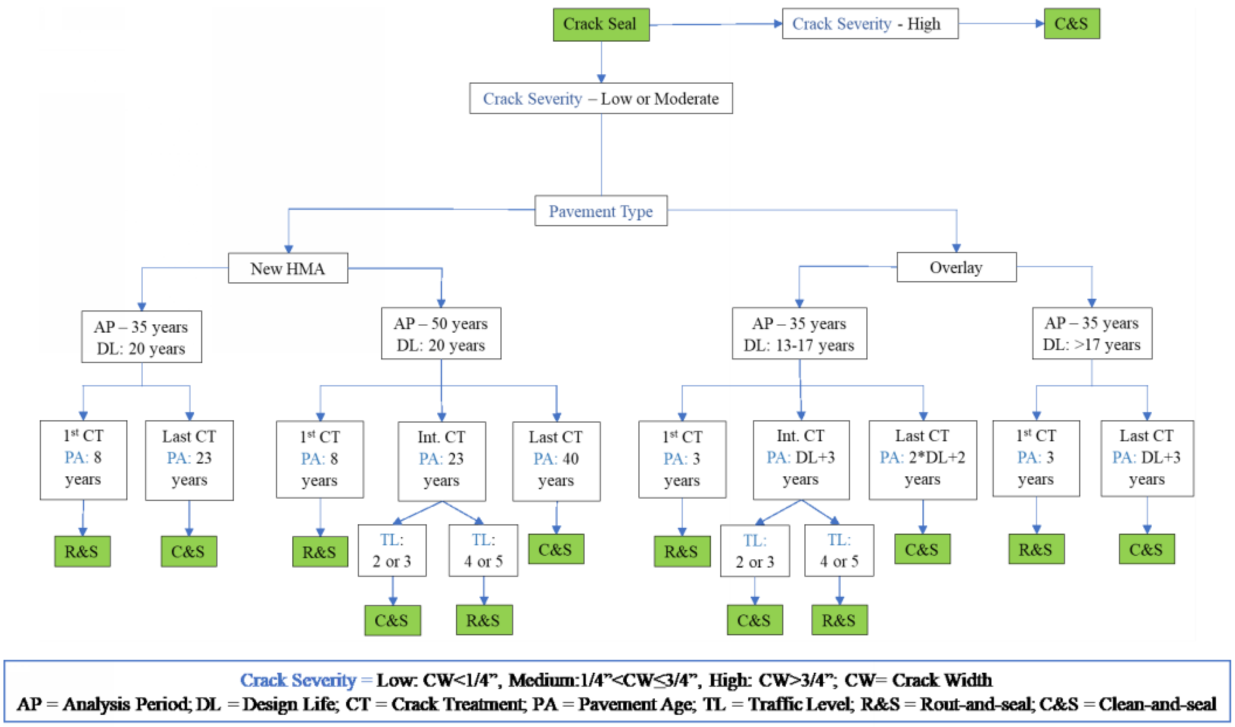

Figure 2.5. Decision tree for selecting a crack sealing method for pavements developed for Minnesota DOT (Barman, Munch, & Arepalli 2019).

2.2.4. Summary of Decision Tools in Research Literature

In summary, only one mature decision matrix, tree, or other tool for crack repair of bridge decks, made by the Florida DOT, was found in the manuals and specifications currently used by the state DOTs included in this literature review. In research literature, a preliminary example for bridge decks and several tools for other bridge components or concrete structures were identified. These examples provide guidance on the factors that could be considered in the decision-supporting tool, including:

- Crack type,
- Crack width,
- Crack density,
- Crack activity,
- Age of deck,
- Design life,
- Durability or service life of the crack repair,
- Cost of the crack repair, and
- Traffic level.

They additionally provide guidance on types of crack repair options that may be considered, including:

- Judicious neglect or no treatment,
- Penetrating sealer,
- High molecular weight methacrylate (HMWM) or epoxy treatment,
- Routing and sealing,
- Cleaning and sealing,
- Epoxy injection,
- Flexible sealing or installation of expansion joint,
- Simple surface repair,
- Overlay,
- Removal and replacement, or
- Investigation.

2.3. Summary of Tool Inputs

The inputs used by the decision tools identified in the state DOT manuals and research literature are listed in Table 2.6. Hopper et al. (2015) also listed factors that should be considered when selecting crack repairs for bridge decks and Krauss (1994) discussed considerations for crack repair selection extensively. The table shows that the most common inputs are deck condition rating and crack width, followed by repair service life. The percent deck deterioration, deck age, and crack activity are the third-most common inputs.

Table 2.6. Number of instances in which each input listed was considered in a crack repair decision methodology.

Input Type	Input	No. of Instances in Crack-Focused Tools	No. of Instances in General Tools	No. of Instances in Comprehensive Tools for Crack Repairs	No. of Instances in Other Tools	Total
NBI Condition Rating	Deck Condition Rating	1	4	-	1	**6**
	Soffit Condition Rating	-	1	-	-	**1**
	Wearing Surface Condition Rating	-	1	-	-	**1**
	Superstructure and/or Substructure Condition Rating	-	1	-	1	**2**
	Percent Deck Deterioration	-	4	-	-	**4**

Input Type	Input	No. of Instances in Crack-Focused Tools	No. of Instances in General Tools	No. of Instances in Comprehensive Tools for Crack Repairs	No. of Instances in Other Tools	Total
Deck Condition State	Percent Soffit Deterioration	-	2	-	-	**2**
	Qualitative Description of Deck and Crack Conditions	-	-	1	-	**1**
	Depth of Chloride Front	-	1	-	-	**1**
Deck Characteristics	Deck Age	1	1	-	2	**4**
	Design Life	-	-	-	2	**2**
	Deicer Exposure	1	-	-	-	**1**
	Elevation w.r.t. Sea Level	-	-	1	-	**1**
	Aggressiveness of Environment	-	-	1	-	**1**
	Traffic Level	-	-	-	2	**2**
	Moisture Exposure	-	-	-	2	**2**
Crack Characteristics	Crack Type	2	-	-	1	**3**
	Crack Location	1	-	-	-	**1**
	Crack Depth	1	-	-	-	**1**
	Crack Width	5	-	1	2	**8**
	Crack Density	-	-	1	1	**2**
	Crack Extent	1	-	-	-	**1**
	Crack Activity	2	-	-	2	**4**
Repair Characteristics	Repair Cost	-	-	-	2	**2**
	Life Cycle Cost	-	-	-	1	**1**
	Repair Service Life	-	-	1	3	**4**
	Analysis Period	-	-	-	1	**1**
	Ease of Application	-	-	-	1	**1**
	Repair Material Properties (Viscosity, Pot Life)	-	-	1	-	**1**
	Minimum Cure Time	-	-	1	-	**1**

Input Type	Input	No. of Instances in Crack-Focused Tools	No. of Instances in General Tools	No. of Instances in Comprehensive Tools for Crack Repairs	No. of Instances in Other Tools	Total
	Available Labor Skills and Equipment	-	-	-	1	**1**
	Final Appearance	-	-	-	1	**1**

The inputs may generally be classified under one of the following five categories:

- **NBI Condition Ratings.** The National Bridge Inventory (NBI) condition ratings are on a scale from 0 to 9, wherein 0 indicates a "failed condition (out of service and beyond corrective action)" and 9 represents an "excellent condition (condition immediately after construction)." Ratings of 7 to 9 are generally considered to be "good" and ratings of 5 or 6 are considered "fair." An NBI condition rating of 4 represents "poor condition (advanced section loss, deterioration, spalling or scour)" and state DOTs typically replace or rehabilitate the bridge component when it reaches a rating of 4.

  The bridge deck, superstructure, and substructure are federally required to be assigned NBI condition ratings during their routine inspection and some state DOTs also use the NBI rating scale to rate the wearing surface, expansion joints, bearings, and other bridge components. These ratings reflect the general condition of the components and while they are a useful and practical high-level metric, they do not typically correlate with the severity of cracking (Hopper et al. 2015).

- **Deck Condition State.** The condition of the deck may be described using element-level inspection data. Element-level inspection of the deck, superstructure, and substructure is currently federally required for bridges on the National Highway System (NHS) and follows the guidance of the Manual for Bridge Element Inspection (MBEI) published by the American Association of Transportation and State Highway Officials (AASHTO). When conducting element-level inspection of the deck, the type of deck distress is identified, its extent, and its severity. The type is identified by a standardized code; for example, Defect 3220 refers to cracking. The extent is represented by an area, and the severity is ranked on a scale from CS1 to CS4, wherein CS refers to "condition state." CS1 represents a good state, CS2 a fair state, CS3 a poor state, and CS4 a severe state. Definitions for each condition state for each defect are published in the MBEI.

  Additionally, the deck condition state may be determined via an in-depth investigation using non-destructive testing, such as half-cell potential surveys, and/or coring to characterize the chloride contamination of the deck. These efforts go beyond the federal inspection and reporting requirements, but can provide valuable information when selecting an appropriate maintenance strategy, particularly for older decks. For example, coring and chloride profiling can provide the chloride front, defined as the depth at which the concentration of chloride ions is high enough to initiate corrosion of the steel reinforcement. The Virginia DOT considers the chloride front in its deck decision matrix for concrete decks.

- **Deck Characteristics.** This category captures general deck characteristics, such as age, traffic, exposure conditions, and design life. Traffic is commonly expressed as average daily traffic (ADT) or average daily truck traffic (ADTT). Exposure to moisture and deicing chemicals, such as sodium chloride brines, and other salts or salt solutions are of concern because they cause corrosion of the steel reinforcement; Iowa bridge decks are typically assumed to have severe exposure to both.
- **Crack Characteristics.** This category includes crack type, location, depth, width, extent, and activity. The crack type may refer to the cause of the crack or the pattern of the cracking; for example, the Virginia DOT makes a point of identifying if the cracking is caused by alkali-silica reaction instead of chloride-induced corrosion while the USACE simply asks if the cracking is "pattern" or "isolated." The crack geometry is described by its depth and width. While the Michigan DOT states that only cracks that extend to the depth of the rebar are of concern, assessing crack depth in the field is challenging and cannot be done visually. Crack width is more commonly measured and used as a criterion for selecting maintenance actions since it can be measured with a crack comparator, although the width of the crack varies along its length and its depth. The extent of cracking is described qualitatively as local or "widespread." The crack activity refers to changes in the crack width due to bridge movement and changes in temperature. Cracks that do not experience much activity are considered "dormant."
- **Repair Characteristics.** This category considers the practical requirements of the repair, such as the cost, service life, ease of application, cure time, and appearance. They allow constraints, such as the maximum cost, minimum required service life, and maximum traffic closure time, to be considered. Ease of application, repair material properties, and available labor skills and equipment can affect the installation quality and therefore repair performance.

2.4. Summary of Tool Outputs

The crack maintenance options, or tool outputs, considered in the state DOT manuals are listed in Table 2.7 along with the number of instances identified in the maintenance selection tools and methodologies of the state DOTs. For the general maintenance selection tools, only repairs suitable for bridge decks are included in Table 2.7, and non-relevant maintenance actions pertaining to other components of the bridge, such as the superstructure, substructure, bearings, and joints, or maintenance actions that do not address cracks are omitted. Crack repair matrices outside of bridge deck literature, identified in Section 2.2, *Crack Maintenance Decision Guides in Research Literature*, are also omitted from Table 2.7 due to limited relevance to bridge decks.

Some state DOTs comment on the general material to be used, such as epoxy or high-molecular weight methacrylate (HMWM), and others identify a specific application method, e.g., pressure-injection. To capture these details, the repair types listed in Table 2.7 are further subdivided based on materials and methods in Table 2.8, and the number of instances each combination is identified within the maintenance selection tools is provided.

Table 2.7. Number of instances in which each crack repair type listed was considered in a crack repair decision methodology by the state DOTs reviewed. [1]

Repair Type	No. of Instances in Crack-Focused Tools	No. of Instances in General Tools	No. of Instances in Comprehensive Tools for Crack Repairs	Total
Do Nothing	3	1	1	**5**
Clean and/or Wash Concrete Deck	1	2	0	**3**
Penetrating Sealers	4	2	1	**7**
Crack-Chasing Methods	4	0	2	**6**
Flood coat Methods	5	1	3	**9**
General Crack Sealing	5	4	0	**9**
Deck Sealing	0	1	0	**1**
Patching	0	5	0	**5**
Overlays[2]	2	10	1	**13**

Notes: [1]*Only crack repairs that are or can be applied to bridge decks are included.*
[2]*Number of instances overlays were cited (i.e. different types of overlays are counted independently).*

Table 2.8. Number of instances in which each crack repair method and material was considered in a crack repair decision methodology by the state DOTs reviewed. [1]

<table>
<tr><th>Repair Type</th><th>Repair Details</th><th>No. of Instances in Crack-Focused Tools</th><th>No. of Instances in General Tools</th><th>No. of Instances in Comprehensive Tools for Crack Repairs</th><th>Total</th></tr>
<tr><td colspan="2">Do Nothing</td><td>3</td><td>1</td><td>1</td><td>5</td></tr>
<tr><td colspan="2">Clean and/or Wash Concrete Deck</td><td>1</td><td>2</td><td>0</td><td>3</td></tr>
<tr><td rowspan="4">General Crack Sealing</td><td>No Method or Material Specified</td><td>2</td><td>4</td><td>0</td><td>6</td></tr>
<tr><td>HMWM;
No Method Specified</td><td>2</td><td>0</td><td>0</td><td>2</td></tr>
<tr><td>Epoxy;
No Method Specified</td><td>1</td><td>0</td><td>0</td><td>1</td></tr>
<tr><td>Subtotal</td><td>5</td><td>4</td><td>0</td><td>9</td></tr>
<tr><td colspan="2">Deck Sealing (No Material Specified)</td><td>0</td><td>1</td><td>0</td><td>1</td></tr>
<tr><td rowspan="5">Penetrating Sealers</td><td>No Material Specified</td><td>1</td><td>1</td><td>0</td><td>2</td></tr>
<tr><td>Silane</td><td>2</td><td>1</td><td>0</td><td>3</td></tr>
<tr><td>Silane or Siloxane</td><td>0</td><td>0</td><td>1</td><td>1</td></tr>
<tr><td>Reactive Silicate Solution</td><td>1</td><td>0</td><td>0</td><td>1</td></tr>
<tr><td>Subtotal</td><td>4</td><td>2</td><td>1</td><td>7</td></tr>
</table>

Repair Type	Repair Details	No. of Instances in Crack-Focused Tools	No. of Instances in General Tools	No. of Instances in Comprehensive Tools for Crack Repairs	Total
Crack-Chasing Methods	Reactive Silicate Solution	1	0	0	1
	Gravity-Fed Polymer	1	0	0	1
	HMWM	1	0	0	1
	Epoxy Injection	1	0	2	3
	Subtotal	**4**	**0**	**2**	**6**
Flood coat Methods	Gravity-Fed Polymer	2	1	0	3
	HMWM	1	0	1	2
	HMWM or Polyurethanes	0	0	1	1
	Epoxy	0	0	1	1
	Pavon® In-Deck	1	0	0	1
	Chip Seal	1	0	0	1
	Subtotal	**5**	**1**	**3**	**9**
Patching	Type Not Specified	0	3	0	3
	Wearing Surface	0	1	0	1
	Full-Depth	0	1	0	1
	Subtotal	**0**	**5**	**0**	**5**
Overlays	Thin Overlay (Material Not Specified)	0	1	0	1
	Thin Epoxy Overlay	2	2	1	5
	Polyester Polymer Concrete Overlay	0	1	0	1
	Rigid Overlay	0	3	0	3
	Flexible Overlay	0	1	0	1
	HMA Overlay with Waterproofing Membrane	0	2	0	2
	Subtotal	**2**	**10**	**1**	**13**

Notes: [1]*Only crack repairs that are or can be applied to bridge decks are included.*

The types of repairs or maintenance strategies listed in Table 2.7 and Table 2.8 include:

- **Do Nothing.** "Do nothing" consists of either deferring crack repairs to a later date, such as when the cracking severity or extent warrants action or when other maintenance is scheduled, or not conducting repairs at all. This action was identified as an option in four instances in the state DOT manuals reviewed. "Do nothing" was more commonly observed in crack-focused tools than in general maintenance selection tools.
- **Clean and/or Wash Concrete Deck.** This action may consist of sweeping the deck, blasting the deck with compressed air, or washing the deck. Cleaning or washing the deck is done to remove debris and

contaminants, thereby decreasing the potential for chloride ingress. However, this action is synonymous to "do nothing," as only very frequent washing on the order of once a day will prevent chloride ingress, which is not cost-effective or practical. When conducted annually or biennially, it is unlikely to have a significant effect (Soltesz 2005). Cleaning or washing the deck was identified as an option in three instances, two of which were in general maintenance selection tools.

- **Penetrating Sealers.** Penetrating sealers are applied as a deck seal and are most commonly silanes or siloxanes, which react with the concrete surface to form a hydrophobic surface that permits water vapor to pass but protects the concrete from moisture ingress.

  Several state DOTs, such as the Illinois and Indiana DOTs, consider penetrating sealers to be routine or scheduled preventative maintenance rather than a condition-based preventive maintenance strategy for addressing cracking. However, four crack-focused tools and the Florida DOT's comprehensive tool for crack repairs all identified penetrating sealers as a crack maintenance strategy.

- **Crack-Chasing Methods.** Crack-chasing methods involve applying the crack sealant or filler material only along the cracks instead of across the deck area. Crack-chasing may be done either by hand with bottles or by pressure injection. When completed by hand, a gravity-fed polymer, such as a HMWM or a low-viscosity epoxy, is most commonly used to fill the crack and inhibit moisture and chloride ingress. In some circumstances, routing the crack by widening the crack mouth with a saw prior to sealing may be desirable, but this is not typically done on bridge decks. When completed under pressure, epoxies are commonly used. Pressure injection is relatively labor-intensive and more sensitive to installation quality and contractor experience, and as a result is primarily done when restoration of structural capacity across the crack is required. Crack-chasing methods were identified in five instances, none of which were in general maintenance selection tools.

- **Flood coat Methods.** Flood coats are applied to the entire deck or cracked areas of deck rather than only along specific cracks. An alternative name is a "healer-sealer" as they "heal" cracks while also "sealing" the deck. A flood coat is generally understood to be a polymer that is broadcast with aggregates to provide adequate skid resistance for safe travel. However, the Missouri DOT sometimes prescribes an asphalt emulsion (Pavon® In-Deck) or chip seal, another bituminous repair, to address cracked concrete decks. Because these repairs heal cracks and seal decks like polymer flood coats, they are grouped with flood coats in this report. The state DOT tools reviewed identified flood coats as a feasible crack repair in eight instances, of which only one instance was in a general maintenance selection tool.

- **General Crack Sealing.** There are a variety of crack sealing methods and techniques and they generally may be classified as crack-chasing or flood coats, as discussed above. Some DOTs specifically call out the type of method, but if the method was not identified, then the instance was tallied as "General Crack Sealing." General crack sealing was identified in nine instances, five of which were in crack-focused tools and the remaining four of which were in general maintenance selection tools.

- **Deck Sealing.** The Wisconsin DOT recommends "deck sealing" as one preservation activity within its *Concrete Deck/Slab Eligibility Matrix* (2019), a general maintenance selection tool (Figure A.3). Based on the requirement that part of the deck area be in condition state CS3 or CS4 due to cracking, it is likely "deck sealing" refers to a flood coat in this case, but the Minnesota DOT generally considers "deck sealing" to refer to the application of a penetrating sealer. Due to the ambiguity of the term "deck sealing," this instance was tallied separately from "Flood coat Methods."

- **Patching.** Patching may refer to patching of the wearing surface or partial-depth or full-depth patching of the deck. This action consists of removing unsound concrete, such as delaminated concrete, and it is considered best practice to remove chloride-contaminated concrete from around any exposed rebar as well, even if the concrete is sound. A patch material is then applied and cured. Patch materials vary widely, from portland cement concretes or mortars to polymer mortars and concretes and mortars that use alternative cements.

  Patching was identified in five instances, all of which were in general maintenance selection tools. Patching is not typically considered a crack repair, as demonstrated by its absence in crack-focused tools.

- **Overlays.** There is a variety of overlay types, including polymer overlays, rigid overlays, and flexible overlays. Thin polymer overlays are 1.0 inch thick or less; thicker polymer overlays are generally premixed and made of polyester concrete although premixed epoxy concrete is an alternative. Rigid overlays are generally understood to be cementitious and include a variety of concrete types, including low slump concrete, high performance concrete, silica fume concrete, or latex-modified concrete, although latex-modified concrete is slightly less rigid due to its polymer additive. Flexible overlays are made of hot mix asphalt concrete and may be applied with a waterproofing membrane.

  Thin polymer overlays are most commonly considered a preventive maintenance action suitable for addressing a deck experiencing cracking; as presented in Table 2.8, two crack-focused tools and the Florida DOT's comprehensive tool for crack repair present a thin polymer overlay as a crack repair option while none of the other overlay types were identified as repair options for addressing cracking.

  Rigid overlays and polyester polymer concrete overlays are capable of addressing cracks in a bridge deck; however, they are relatively expensive, either in terms of agency costs or user costs. Therefore, state DOTs typically invest in these overlays when they are most beneficial, which is primarily when the deck is new and an overlay will slow down chloride ingress or when the deck is chloride-contaminated/distressed and a new wearing surface is warranted. Rigid overlays and polyester polymer concrete overlays are not typically considered when the primary objective of the repair is to address cracking.

  Hot mix asphalt (HMA) is assumed to be relatively permeable compared to concrete and as such, HMA overlays are not included in Table 2.7 or Table 2.8. However, an HMA overlay with a waterproofing membrane (HMAWM system) can effectively prevent moisture and chloride ingress and therefore can protect a cracked bridge deck. None of the crack-focused tools consider HMAWM systems, but VDOT does identify HMAWM systems as a potential option for cracked bridge decks in the footnotes to its deck decision matrix for concrete decks, a general maintenance selection tool.

Based on these findings, the following crack maintenance strategies were reviewed in greater depth for use in the guidance for remediating bridge deck cracking:

- Do Nothing,
- Apply a Penetrating Sealer,
- Apply a Gravity-Fed Polymer by Crack-Chasing,

- Rout and Seal,
- Pressure Inject with Epoxy,
- Apply a Flood Coat,
- Apply a Hot-Mix Asphalt Overlay with Waterproofing Membrane,
- Apply a Thin Polymer Overlay,
- Apply a Rigid Cementitious Overlay,
- Apply a Latex-Modified Concrete Overlay,
- Apply a Premixed Polymer Concrete Overlay, and
- Replace the Deck.

Detailed profiles discussing applicability and deck eligibility criteria, construction procedures and materials, costs, and service life for the repairs are provided in Appendix B.

CHAPTER 3. CAUSES, CHARACTERIZATION, AND INSPECTION OF BRIDGE DECK CRACKING

A wide variety of crack types may occur on a bridge deck. The type of cracking is often named after the cause of the cracks, such as plastic shrinkage cracks or settlement (subsidence) cracking. If the cause of cracking cannot be easily determined in the field, then the crack type may be identified based on the crack pattern or orientation instead, such as map cracking or transverse cracking. This chapter provides an overview of common causes of early age cracking and classification of different crack types based on their effect on the durability of bridge decks.

3.1. Causes of Bridge Deck Cracking

Bridge deck cracking may occur early or later in the life of the deck. Early-age cracking may occur due to a long list of interrelated factors concerning the material and structural design, construction, and environmental conditions during construction of the deck. These factors affect the tendency of the concrete to shrink or contract. Parameters of the structural design, such as the presence of girders and the span lengths; mix design parameters, such as aggregate size and volume; and environmental conditions that differ between the topside and underside of the deck, such as temperature or wind speed, determine the boundary conditions or restraint of the deck. Restraint prevents free shrinkage of the concrete and subsequently induces strain. A corresponding tensile stress develops in the concrete, the magnitude of which is affected by the concrete's modulus of elasticity, which is in turn controlled by the concrete mix design. If the tensile stress exceeds the tensile strength of the concrete, which is also governed by the mix design, then the concrete will crack. A substantial amount of early-age cracking is caused by the relationship between volumetric change of the deck concrete and restraint of the deck as described above. Specific situations that can cause early-age cracking include:

- **Autogenous Shrinkage.** Autogenous shrinkage occurs during cement chemical hydration when water from the capillary pores is consumed. If the amount of water is limited (i.e., the water-to-cementitious material ratio is less than approximately 0.40) then the water consumption and subsequent dessication of the cement paste causes a reduction in concrete volume.
- **Drying Shrinkage.** Once moist curing is complete and the concrete is exposed to the environment, it naturally dries out. Free water is lost first, which causes little change in the volume of the concrete. Then adsorbed water is lost to the environment until the concrete reaches equilibrium with its environment, during which the bulk concrete shrinks. The amount of shrinkage depends on the ambient relative humidity and the concrete mix design.
- **Differential Drying.** When the concrete dries, the exposed surfaces dry more quickly than the bulk concrete at the interior of the deck, and subsequently the surfaces contract more than the interior of the element, inducing stresses in the concrete. Decks are relatively susceptible to differential drying because they are long, thin plate elements with a high surface-area-to-volume ratio. Differential drying gradients commonly develop through the thickness of the deck within the first year and are affected by permeability within the concrete, ambient relative humidity, precipitation events, and evaporation rates from the top and bottom surfaces.
- **Plastic Shrinkage.** Water naturally bleeds to the surface of freshly-placed concrete due to settlement (subsidence) of the paste and aggregates due to gravity. The water at the concrete surface is also lost

to evaporation, and the rate of evaporation increases with increasing temperature, decreasing ambient relative humidity, and increasing wind speeds. Plastic shrinkage cracks form when evaporation rates at the concrete surface remove water faster than it can be replenished by the natural bleeding process. The rapid drying of the concrete surface causes local contraction of the surface, and the young concrete cracks (tears) in random patterns since it has not yet developed much strength.

- **Volumetric Change due to Thermal Effects.** Concrete expands and contracts in response to increases and decreases in temperature, respectively. At early ages, the heat of hydration given off by cement hydration temporarily heats the concrete and can induce very early-age stresses as the concrete first cools. Stresses may be minimized by controlling the maximum temperature reached and slowing the initial cooling rate. After the concrete has set, seasonal and daily changes in temperature cause volumetric change and induce stresses in concrete decks. The amount of volumetric change depends on the magnitude of seasonal and daily temperature changes and the coefficient of thermal expansion (CTE) of the deck concrete, which depends primarily on the type of aggregate used in the concrete. Decreasing the CTE decreases the strain and subsequent stresses experienced by the deck. Cracking due to thermal effects typically happens in the first year or two as the concrete adjusts to the environment and restraint conditions.
- **Settlement (Subsidence).** During concrete setting, the constituents naturally settle (subside) according to density, i.e., water and paste rise while aggregates settle. The presence of steel reinforcement blocks the constituents from rising or settling and bleed water collects underneath the rebar until it escapes as a channel rushing to the surface of the concrete. The channel becomes a weak plane with a high water and paste content that easily cracks after set, creating a path directly to the rebar. The propensity of subsidence and associated cracking increases with the use of high slump mixes, mixes with a poor combined aggregate gradation, large bars, low concrete cover, and/or deep placements. Although settlement cracks are not commonly observed on bridge decks, the remnant effects may be a secondary influence promoting cracking to either nucleate or orientate in line with deck reinforcing. These types of cracks can be characterized incorrectly as transverse cracks without appropriate investigation.

Other causes of early-age cracking might include formwork movement, deck bending, crazing due to over finishing with water, frost damage, and other materials issues; however, these factors are not primary causes of the cracking endemic to bridge decks.

Later-age cracking typically occurs due to material deterioration (such as corrosion of deck reinforcing) or structural loading:

- **Material Degradation.** The most common cause of degradation of bridge decks in northern states, such as Iowa, is corrosion of steel reinforcement. However, other types of concrete material degradation that can affect concrete elements are freeze-thaw and alkali-silica reaction (ASR).
  - **Steel Corrosion.** In northern states, chlorides from deicing chemicals applied during the winter eventually cause corrosion of the reinforcing steel. The rust products generated by the steel corrosion have a greater volume than the steel and, therefore, cause expansive stresses in the concrete and cracking that extends from the reinforcement. Cracking may extend horizontally and cause delaminations and/or vertically, creating wide, surface-breaking cracks that lead to faster corrosion of the reinforcement.

- **Freeze-Thaw Distress.** Freeze-thaw distress of concrete manifests as random cracking and scaling. Concrete deteriorates due to freeze-thaw cycles when it is critically saturated and the presence of salts and chlorides can exacerbate the degradation. Use of adequate air entrainment, low to moderately low water-to-cementitious material ratios, and durable aggregates in the concrete mix design can provide long-term protection from freeze-thaw degradation, and northern states have implemented these requirements in specifications. As a result, freeze-thaw distress on bridge decks is relatively uncommon.
- **ASR Distress.** Like freeze-thaw, ASR manifests as random cracking. ASR occurs when alkalis within the concrete react with reactive silica in the aggregates, generating a gel. Concrete deterioration does not occur until the gel is exposed to moisture and swells, causing expansive stresses and cracking. ASR is now relatively rare in bridge decks as the reactivity of the aggregates used is commonly assessed prior to construction, the alkali content of the cementitious materials is controlled, and decks are not typically exposed to external sources of alkalis, such as soils. However, ASR deterioration still occurs on bridge decks in select cases.

- **Structural Loading.** Bridge deck cracking may also occur due to flexural loads in the negative moment regions of continuous decks or unexpected movement of the structure (e.g., differential settlement between the piers and abutments). The structural restraint of the deck affects the magnitude of the stresses generated and must be considered by bridge designers when designing the structural system. Structural cracks may also be caused by overloading, e.g., by overweight trucks, or fatigue.

3.2. Describing Bridge Deck Cracking

A simple but sufficient characterization of bridge deck cracking is important for the general diagnosis of crack causes and selection of effective crack repairs. Therefore, a common understanding of how cracks are described is important. In this report, cracks are generally described based on the following list of characteristics and terminology:

- **Orientation.** Cracks are commonly identified based on orientation with respect to the bridge traffic. Transverse cracks, shown in Figure 3.1, are perpendicular to the length of the bridge deck while longitudinal cracks, shown in Figure 3.2, run parallel to the bridge deck length or traffic directions. Cracks may also be diagonal. Cracks described based on orientation are generally relatively straight and isolated.
- **Pattern.** Cracks may be identified as “isolated” or “discrete,” in which case they are better characterized by orientation, or as “pattern” cracking, alternatively called “map” or “craze” cracking (depending on cause). Figure 3.3 shows an example of pattern cracking on a bridge deck. Areas with pattern cracking typically have cracks that are closely spaced and intersect each other. “Plastic shrinkage cracks” are characterized by random orientation; however, they infrequently intersect and tend to have larger surface widths but short lengths. An example of plastic shrinkage cracking is shown in Figure 3.4.
- **Frequency.** Crack frequency may be represented by the crack spacing or crack density. Crack spacing characterizes the distance between cracks and is often used to describe regularly-spaced transverse cracks. Crack density is calculated by measuring the net length of cracks on the deck or studied area

and dividing by the surface area. Crack frequency is rarely used to describe pattern cracking, as it is understood that areas with pattern cracks have a relatively high crack density.

- **Geometry.** The crack geometry is described by crack shape, width, and depth. The width at the crack mouth is most commonly assessed since it can be easily measured, for example using a crack comparator gauge (Figure 3.5). Cracks extending through the entire deck thickness can often be identified by inspection of the deck soffit, as was shown in Figure 3.1. Through-depth cracks often have a constant width between reinforcing mats. Most cracks typically have a width that decreases with crack depth from the top or bottom deck surfaces, resulting in a V shape. Shape and depth can be estimated based on visual inspection and if the crack cause is known, but concrete cores are often required to fully assess crack geometry. Figure 3.6 shows a V-shaped crack in a concrete core from a bridge deck.
- **Location.** Crack location refers to the location relative to reinforcing steel and deck features, such as expansion joints, piers, and bridge ends, or deck distress, such as patches or delaminations. Information on the location of the crack is useful in the diagnosis of the cause of the crack.
- **Activity.** Cracks may be categorized as “active” or “dormant.” Active cracks are defined as cracks whose widths fluctuate cyclically with time due to changes in deck loads or concrete temperature. Dormant cracks are defined as cracks whose widths remain near constant. In practice, most cracks experience some level of movement and it is generally up to the engineer’s discretion if the amount of crack movement is significant enough to qualify the crack as active or not. Most early-age cracks occur within the first one or two years since construction. Except for cracks directly over piers in regions of negative moment, almost all early-age cracks are thought of as dormant or non-moving cracks for the purposes of repair. Additionally, some cracks consistently grow in size or length with time and while they do not classify as “active” because this change in crack width is not cyclic, identifying such cracks as “dormant” may be misleading. The potential for future crack growth should be noted when describing crack activity.

Figure 3.1. Photograph of underside of bridge deck with efflorescing, through-deck cracks. Transverse cracks are identified with pink arrows.

Figure 3.2. Photograph of topside of bridge deck with longitudinal cracking, identified with blue arrows.

Figure 3.3. Photograph of pattern cracking on a bridge deck.

Figure 3.4. Photograph of plastic shrinkage cracks, identified by orange arrows.

Figure 3.5. Photograph showing measurement of the width of a crack using a crack comparator.

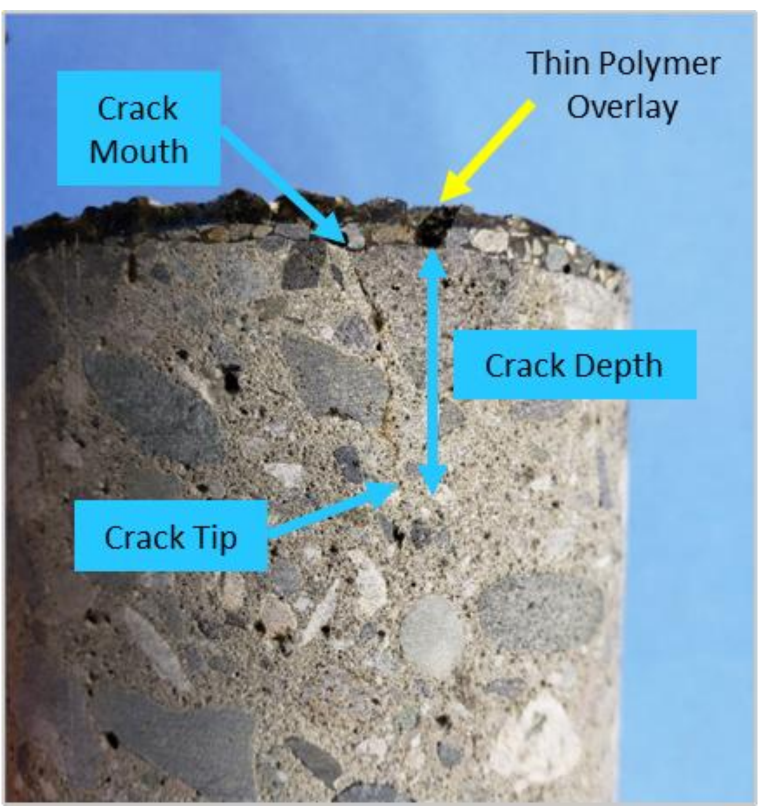

Figure 3.6. Photograph of a cracked concrete core from a bridge deck with a thin polymer overlay on top (identified by the yellow arrow). Key features of the crack are labeled (blue arrows).

3.3. Inspection of Deck Cracks

The purpose of crack inspection is to determine if the cracking warrants repair and which crack remediation options are suitable. Because crack width and depth affect how easily moisture and chloride can access the reinforcing steel, these crack characteristics should be reported for informed decision-making. Based on results in literature (Balakumaran et al. 2018; Krauss 1994; Hopper et al. 205; Xi et al. 2003), it is assumed that cracks with a width greater than 5 mils (0.005 inches), which is typically the width of cracks that can be seen and measured, will allow moisture and chloride ingress. Once cracks reach 10 mils (0.010 inches), it is assumed that the concrete no longer provides any protection at the crack location (Merrill et al. 2017). The depth of the crack will then determine if the chlorides and moisture have direct access to the deck reinforcement. When inspecting bridge deck cracking to identify repair needs and suitable crack remediation options, bridge deck cracks can be divided into three categories: shallow cracks, deep cracks that reach the reinforcement, and active cracks that reach the reinforcement. The sections below provide an overview of each of the different categories and how they can be classified based on the observed conditions. Note that identification of cracks length and width in the field is typically done using visual inspection. Emerging high resolution imaging methods can be used for automated crack identification. These methods include the use of high-resolution cameras mounted on vehicle or unmanned aerial system (UAS or drone) platforms and advanced post-processing image analysis algorithms that can be used to identify the length and width of cracks.

3.3.1. Shallow Cracks

Shallow cracks are defined as cracks with small width, generally less than or equal to 5 mils (0.005 inches), that do not reach the reinforcement. These cracks will allow for a more rapid ingress of moisture and chlorides through the cover concrete, but only for the top portion of the cover where the cracks extend. It is assumed for the purpose of the service life modeling presented in Chapter 4 that shallow cracks will only extend in the bridge deck to a depth of 1 inch. The following characteristics can be used to classify cracks as shallow:

- **Crack Pattern:** Shallow cracks typically manifest in a map cracking pattern.
- **Crack Width:** Shallow cracks tend to have a small width of 5 mils (0.005 inches) or less.
- **Activity:** Shallow cracks are considered “dormant” or non-active cracks. As such, variation in the crack width of shallow cracks tends to be very small and can be neglected.

In summary, bridge deck cracks with a small crack width (less than 5 mils) and a map cracking pattern can be considered shallow cracks.

3.3.2. Deep Cracks

Deep cracks are defined as cracks that reach the reinforcement bars and, as such, have a significant effect on the durability of the bridge deck. These cracks are mostly transverse cracks that form over the reinforcing bars and allow moisture and chlorides to have direct access to the steel, which may lead to more rapid corrosion initiation at cracked sections versus uncracked sections. As such, deep cracks tend to reduce the time for corrosion damage to manifest at cracked areas of the bridge deck. These cracks typically have a crack width of 5 mils (0.005 inches) or greater. The following characteristics can be used to classify cracks as deep:

- **Crack Orientation:** Due to the difficulty of confirming the depth of cracks without taking concrete cores, it is assumed that transverse cracks will reach the reinforcing bars. The same assumption can be made for other crack orientations and patterns other than map cracks (such as longitudinal cracks), unless a more detailed inspection is conducted to confirm that the cracks do not reach the reinforcement.
- **Crack Width:** Deep cracks tend to have a width of 5 mils (0.005 inches) or more. Typically early-age cracks resulting from shrinkage or thermal effects will have a width between 5 mils (0.005 inches) and 20 mils (0.020 inches), although in some cases these cracks may have a larger width. For this guide, the width of all observed transverse and longitudinal cracks will be assumed to be at least 10 mils (0.010 inches), the width at which it is assumed that the concrete no longer provides any protection at the crack location. The largest crack width that will be considered is 40 mils (0.040 inches). Cracks wider than 40 mils (0.040 inches) require additional investigation to determine the underlying cause of cracking.
- **Activity:** This section considers deep cracks that are "dormant" or non-active cracks. Note that these cracks, especially cracks with transverse orientation, tend to move with the thermal changes that are observed by the concrete deck. Generally, thermal changes will be small and can be neglected; however, wider cracks may have an adverse effect on the effectiveness of some of the considered repair strategies. Therefore, selection of crack remediation options will be dependent on the width of deep cracks.

In summary, transverse (and longitudinal) bridge deck cracks with a crack width between 10 mils (0.010 inches) and 40 mils (0.040 inches) are assumed to be deep cracks that reach the reinforcing steel.

3.3.3. Active Cracks

Active cracks, also known as working cracks, are defined as cracks with widths that fluctuate with time due to changes in deck loads or concrete temperature. If deep, these cracks will have a significant effect on the durability of the bridge deck as they allow moisture and chlorides to have direct access to the reinforcing steel.

For the purpose of this report, active cracks are assumed to include cracks of any width that are known to be active or wide cracks with a width of 40 mils (0.040 inches) or more. These cracks tend to have some structural significance, such as cracking at negative moment regions over piers for continuous bridge decks, and their width can change under the deck loads.

This type of cracking is out of the scope of this guide as it is typically limited to certain areas in the deck in addition to the need for a special repair to deal with active cracks. Remediation options for this type of cracking often include repairs that can allow crack movement without being compromised, such as rout and seal with flexible sealant, or repairs that restore the structural integrity of the cracked deck section, such as epoxy injection.

CHAPTER 4. EFFECTS OF CRACK REMEDIATION TREATMENTS ON DECK SERVICE LIFE

The primary objective of this project is to develop decision trees or matrices that identify the crack remediation treatment options with the greatest benefit-to-cost ratio for a specific deck. However, deck conditions may vary widely and there are many potential crack remediation treatments that may be applied. To quantify the expected impact of a range of crack conditions and support comparisons of various treatment alternatives for those conditions, service life modeling of the following scenarios was conducted:

- An uncracked bridge deck, which serves as a benchmark for the desired performance;
- Bridge decks with different severities and extents of cracking if no action is taken; and
- Cracked bridge decks with select remediation treatments.

This chapter presents the service life modeling methodology and results and is broken into four sections. The first section identifies the crack remediation treatments considered and to be included in the decision matrices in Chapter 5. The second section describes the methodology for service life modeling of cracked and uncracked Iowa bridge decks, and the third section describes how crack remediation treatments were modeled and how their impact on service life was considered. The fourth and final section summarizes and discusses the service life modeling results.

4.1. Crack Remediation Treatments Considered

Of the twelve crack repairs and remediation treatments identified in the literature review as potentially applicable, seven crack remediation treatments were deemed suitable for consideration in the decision matrices. The seven repairs and treatments are listed in Table 4.1. More information on these repairs and treatments may be found in the Crack Remediation Treatment Profiles in Appendix B.

Table 4.1. Crack remediation treatments considered in analysis.

Crack Remediation Treatments Modeled:
Do Nothing
Apply a Penetrating Sealer
Apply a Gravity-Fed Polymer by Crack-Chasing
Apply a Flood Coat
Apply a Hot-Mix Asphalt Overlay with Waterproofing Membrane
Apply a Thin Polymer Overlay
Apply a Premixed Polymer Concrete Overlay

The remaining five crack remediation treatments or alternative courses of action for addressing cracking that were identified in *Chapter 2 Literature Review* but were deemed unsuitable for inclusion in the decision matrices are:

- **Rout and Seal.** Routing and sealing is commonly done for pavements, but few state DOTs implement routing and sealing on bridge decks; of the 16 state DOTs whose specifications were reviewed, only the Virginia DOT considered routing and sealing to be a practical option for addressing bridge deck cracking, and only for discrete, linear cracks. Compared to filling cracks, i.e., applying a gravity-fed polymer by crack-chasing, routing and sealing is more costly and time-consuming due to the routing step. Based on the literature review, routing and sealing was estimated to cost approximately $40.6 per linear foot based on bid data from Texas while crack-chasing with a gravity-fed polymer was estimated to cost approximately $2.8 per linear foot based on bid data from Minnesota. Also, while routing theoretically would permit the crack to be cleaned more thoroughly and for sealants to perform better, the impact of routing on crack treatment service life has not been assessed quantitatively and it is likely that the service life benefit is not worth the substantially greater effort and cost. Because the Iowa DOT does not currently rout and seal cracks on bridge decks and because this crack remediation treatment is so rarely done in the other states, it was not considered suitable for inclusion in the decision matrices.

- **Pressure Inject with Epoxy.** Pressure injection with epoxy is an effective crack repair method that is not only good for restoring durability, but also for restoring strength. The Iowa DOT has a history of pressure injecting bridge deck delaminations, and local contractors can be expected to have experience and produce installations of good quality. However, pressure injection with epoxy is costly (estimated to be approximately $97.1/linear foot) and time-consuming and was assumed to be uneconomical unless the structural capacity of the deck needs to be restored. If the cracking is severe enough to cause structural capacity concerns, then it falls outside the scope of the decision matrices developed in this report and the repair approach should be selected to address the specific issues at that bridge deck. If the cracking is only a concern because it compromises durability, then applying a low-viscosity epoxy or other gravity-fed polymer by crack-chasing or as a flood coat is expected to be more economical. Therefore, pressure injection with epoxy was not included in the decision matrices.
- **Apply a Rigid Cementitious Overlay or Latex-Modified Concrete Overlay.** Application of a cementitious overlay is often a rehabilitation technique for deteriorating bridge decks as it essentially replaces the concrete cover over the top mat of reinforcing steel. This is logical for older bridge decks with chloride-contaminated cover, but is rarely appropriate on a new or young (less than 10-year-old) bridge deck. Cementitious overlays are relatively costly compared to other treatments (approximately $140 to $150 per square yard) and disruptive to traffic because they require days of curing. By comparison, polymer-based overlays can cure and be opened to traffic within hours. Some types of cementitious overlays are also difficult to construct and prone to cracking themselves. Therefore, application of a rigid cementitious overlay or LMC overlay was not considered for the decision matrices because: (a) it is not a common practice for new or young bridge decks within the scope of the decision matrices; and (b) of the practical disadvantages listed above.

  Even though overlays are rarely a favored option for new and young bridge decks, thin polymer overlays and premixed polymer concrete overlays were included in the analysis because they have relatively low permeability compared to cementitious overlays and are expected to have a comparatively large benefit to deck durability that may justify their cost. Application of polymer concrete overlays on new bridge decks is also currently a common practice in some states.
- **Replace the Deck.** Replacement of new or young decks is an extreme and costly action and can only be justified on a case-by-case basis. Therefore, deck replacement is considered outside the scope of the decision matrices.

4.2. Service Life Modeling of Iowa Bridge Decks

The service life of most concrete bridge decks in Iowa is anticipated to be controlled by chloride-induced corrosion due to the application of deicing chemicals during the winter. Chloride-induced corrosion of generic Iowa bridge decks was modeled using WJE CASLE™, a mechanistic service life modeling software developed by WJE, following the methodology presented in Appendix C. This section provides background on the chloride-induced corrosion deterioration mechanism and how it was modeled for Iowa bridge decks with and without cracks.

4.2.1. Chloride-Induced Corrosion of Bridge Decks

When a bridge deck is first built, the steel reinforcement embedded in concrete is generally protected from corrosion. If the steel reinforcement is uncoated, the concrete cover provides chemical protection of the steel through its highly alkaline pore solution (pH typically 12-14), which stabilizes a thin coating of iron oxide on the steel surface called a "passive film" or "passive layer." The passive film protects the steel from rapid corrosion as long as it remains intact. Alternatively, coated steel reinforcement such as galvanized rebar or epoxy-coated rebar may be used, in which case the coating provides a layer of protection against steel corrosion. In demanding circumstances, corrosion-resistant grades of steel reinforcement such as stainless steel may be used.

Chloride-induced corrosion of bridge decks occurs due to the direct application of chloride-containing deicing chemicals during winter. The chlorides build up on the riding surface of the concrete deck and over time diffuse through the concrete cover. In cases of external chloride sources, such as the deicing chemicals, chloride concentration typically decreases with depth and the chloride contamination of a bridge deck may be represented by a "chloride profile", that is the chloride concentration versus depth within the deck. The chloride concentration at the depth of the rebar is of the greatest concern. Once the chloride ions accumulate to a critical "threshold" chloride concentration, i.e. sufficient concentration to disrupt the passive film, at the depth of the rebar, corrosion may initiate on the steel, provided oxygen and water are available. The chloride threshold depends upon a number of factors, including the interfacial properties of the steel and concrete, the pH of the pore solution in the concrete, and the electrochemical potential of the steel (Bertolini et al. 2013). Because bridge decks are fully exposed to the atmosphere, oxygen and moisture required for the corrosion process are generally readily available.

During corrosion, a corrosion cell, shown schematically in Figure 4.1, is formed. The cell is essentially an electric circuit and consists of an anode and cathode and both an ionic connection and an electric connection between the anode and cathode. The anode is the location where the metal oxidizes, forming ions (Fe^{2+}) that react with available oxygen to form iron oxides, known as rust. The cathode is the location where the electrons released at the anode react with available oxygen and water to generate hydroxide ions (OH^-). For the electrons released at the anode to be consumed at the cathode, they must travel along the electrical connection. The anode and cathode may be on the same reinforcing bar, in which case the bar is the electrical connection, or on separate bars, in which case ties and stirrups may make up the electrical connection. The ionic connection permits OH^- ions generated at the cathode to travel to the anode, completing the electrical circuit. In reinforced concrete, the ionic connection is provided by concrete, which functions as an electrolyte. Oxygen must be present for the cathodic reaction to occur and water must be present to facilitate the cathodic reaction and cause the concrete to behave as an effective electrolyte.

The rust that forms has a greater volume than the steel and exerts an expansive stress on the concrete. Once corrosion has propagated to the point that a sufficient amount of rust and expansive stress has built up, the concrete cracks and delaminates. The delaminations eventually become spalls, which expose the rebar and require patching to restore the riding surface of the bridge deck.

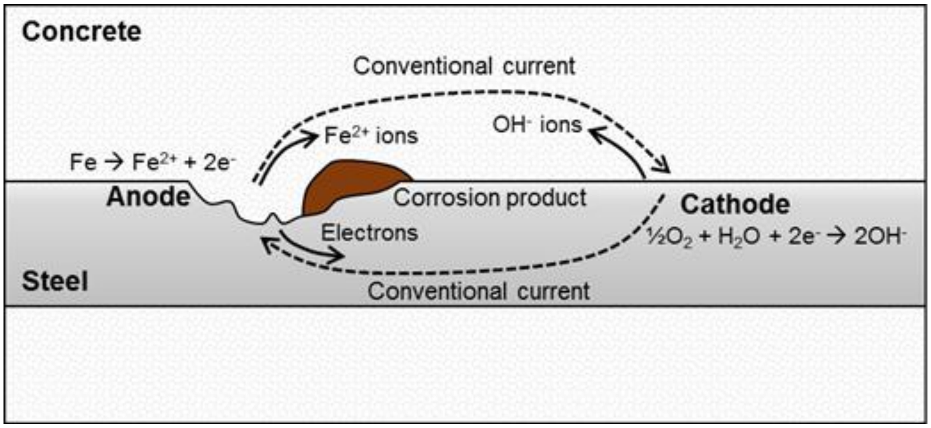

Figure 4.1. Schematic of a corrosion cell on an uncoated bar in saturated or partially-saturated concrete.

4.2.2. Service Life Modeling Methodology

Service life modeling was conducted in order to compare when distress due to chloride-induced corrosion might be expected to manifest on generic Iowa bridge decks with a range of cracking scenarios and remediation treatments. The modeling software WJE CASLE™ was used to perform the service life modeling, which was generally conducted following the full-probabilistic modeling approach presented in Appendix C. The probabilistic approach considers the variability of key corrosion-controlling parameters including exposure conditions, material properties, and as-built conditions, among other factors that affect service life. The probability of corrosion-related damage over time is determined by describing the key factors that govern corrosion as probabilistic variables with statistical distributions and performing a Monte Carlo analysis to estimate a statistical distribution for the probabilistic output, the "time-to-damage." The time-to-damage may be broken into two phases: (1) the initiation phase, or time required for corrosion to initiate; and (2) the propagation phase, or time required for distress to occur once corrosion has initiated. The initiation time and propagation time are added to calculate the time-to-damage. The time to corrosion initiation, t_i, was estimated using a full-probabilistic modeling approach while the propagation time, t_p, was assumed to be a fixed value.

For the purposes of this modeling, the "end of service life" was defined as the time at which the percentage of deck area expected to show corrosion-related damage reaches 20 percent. Note that in actual field applications partial- or full-depth repairs and rigid cementitious overlay may be performed at this damage limit, rather than replacing the deck as assumed herein.

The service life of a structure depends on a number of variables related to the exposure conditions, concrete properties, and reinforcing steel properties. The following discusses the input parameters considered by the model.

4.2.2.1. Input Parameters Related to Exposure Conditions

The input parameters that represent the exposure conditions include the following:

- **Temperature.** Temperature impacts the rate of chloride diffusion and the rate of corrosion. A mean annual temperature was used in the models.
- **Surface chloride concentration (C_s).** The surface chloride concentration is the chloride concentration at the top surface layer of the concrete deck due to the application of deicing chemicals each winter (or due to marine environments, which is not applicable in Iowa). Greater surface chloride concentrations correspond to more severe environments.
- **Build-up time.** The build-up time is the time required for the chloride concentration at the top surface of the deck to build up to the long-term value that the structure will see over its remaining life, i.e., the surface chloride concentration. The build-up time depends on how frequently the deicing chemicals are applied and the type and concentration.

4.2.2.2. Input Parameters Related to Concrete Properties

The input variables that represent the concrete properties include the following:

- **Apparent chloride diffusion coefficient (D_a).** The chloride diffusion coefficient of concrete describes how quickly chlorides can diffuse through the concrete cover. A greater diffusion coefficient indicates that chlorides can penetrate the concrete faster while a smaller diffusion coefficient indicates that chlorides will penetrate the concrete more slowly. The chloride diffusion coefficient input parameter describes this parameter at a concrete age of 28 days.
- **Aging factor (m).** The aging factor is used to model the improvement in chloride diffusion coefficient as the concrete ages past 28 days; the diffusion coefficient decreases because of continued hydration. This factor is affected by the percentage of supplementary cementitious materials in the concrete mix as described in Appendix C. If the concrete mixture contains supplementary cementitious materials such as fly ash and slag cement, then a greater reduction in the chloride diffusion coefficient is expected compared to cement only mixes, because these materials continue to hydrate and more effectively reduce concrete permeability over time.

4.2.2.3. Variables Related to Reinforcing Steel

The input variables related to the reinforcing steel include the following:

- **Concrete cover (a).** The concrete cover refers to the clear cover over the top mat of reinforcing steel in the bridge deck.
- **Chloride threshold (C_t).** The chloride threshold is the chloride concentration required to initiate corrosion. The chloride threshold depends on a variety of factors, including the type of reinforcing steel and the cementitious materials in the concrete mixture. Recognizing that the chloride threshold can vary across the deck, this parameter is modeled using a probability distribution.
- **Corrosion propagation time (t_p).** The corrosion propagation time is the number of years required, after corrosion initiation, for the corroding rebar to cause cracks, delaminations, or spalls.

4.2.2.4. Model Output

The model estimates the time required for corrosion to initiate and then propagate causing concrete cracking and delamination (damage). Due to the variation in the input parameters described by statistical distributions representing the range of conditions present in the modeled bridge deck, the model output "time-to-damage" is in turn a probabilistic variable. The cumulative density function (CDF) of the "time-to-damage" is used to describe the predicted quantity of damage with time. When the input parameters are defined based on field investigation and material testing to describe the conditions across the area of a bridge deck, the model output is the percentage of concrete surface area predicted to be affected by corrosion related damage with time. An example of the model output is shown in Figure 4.2. Applying the end of service life criterion, defined as 20 percent of the deck area affected by corrosion-related damage, the service life of the bridge deck can be estimated.

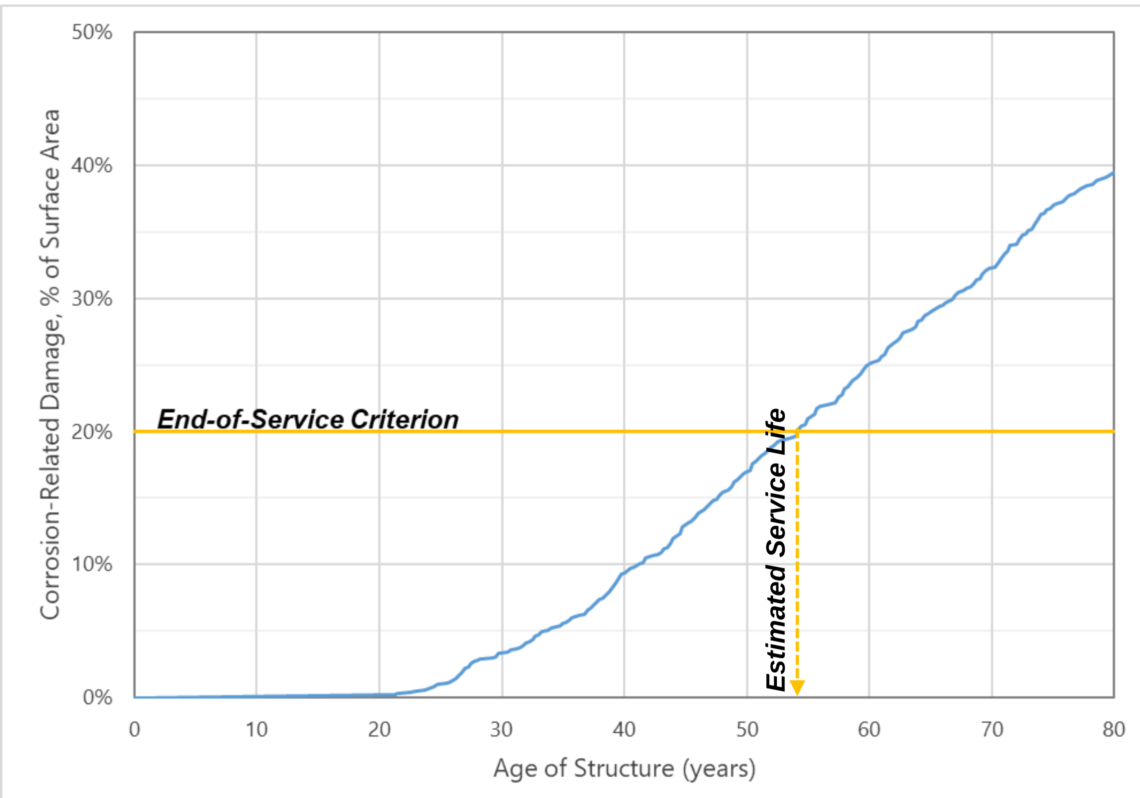

Figure 4.2. Example of service life model output.

4.2.3. Typical Iowa Bridge Deck Practice

To select appropriate model inputs for a generic Iowa bridge deck, the standard practices of the Iowa DOT for bridge deck design and maintenance were reviewed. The model inputs for a generic Iowa bridge deck and their justification are presented in this section.

4.2.3.1. Standard Specifications and Design Manual

Bridge deck design is specified by Section 5.2 of the Iowa DOT's LRFD Bridge Design Manual. The manual states that structural class C concrete with a 28-day strength of 4000 psi is to be used, unless otherwise specified. Typically, Class C-4WR or Class C-V47B concrete mixtures are used, the specified mix designs for which are shown in Table 4.2 and Table 4.3. The letters "WR" indicate a water-reducer is used and the letter "V" indicates a specific class of aggregate is used. Class C-V47B concrete mixtures use either fly ash or slag cement. Section 2412, Concrete Bridge Decks, of the Iowa DOT's Standard Specifications places maximum requirements on the supplementary cementitious materials allowed in bridge deck concrete, which are shown in Table 4.4. Alternatively, a high-performance concrete (HPC) mixture with lower permeability and greater compressive strength may be specified.

Concrete bridge decks are required to use epoxy-coated reinforcing steel, or reinforcing steel that has other corrosion protection. However, epoxy-coated rebar (ECR) is most typically used in Iowa. A concrete cover of 2.5 inches is specified for the top mat of reinforcing steel.

Table 4.2. Basic absolute volumes of materials per unit volume of concrete.

Constituent	Mix C-4WR	Mix C-V47B
Cement	0.112	0.113
Water	0.151	0.145
Air	0.060	0.060
Fine Aggregate	0.338	0.477
Coarse Aggregate	0.339	0.205

Source: Materials I.M. 529, Portland Cement (PC) Concrete Proportions (IowaDOT 2022).

Table 4.3. Requirements for water-to-cement (w/c) ratio for concrete mixture classes commonly used in Iowa bridge decks.

Parameter	Mix C-4WR	Mix C-V47B
Basic w/c	0.43	0.43
Max. w/c	0.488	0.488

Source: Materials I.M. 529, Portland Cement (PC) Concrete Proportions (IowaDOT 2022).

Table 4.4. Maximum allowable cement substitution rates according to Standard Specifications Section 2412.

Cement Type	Maximum Allowable Substitution[1]	Time Period
Type I, II	35% slag cement 20% fly ash	March 16 through October 15
Type IS, IP	0% slag cement 20% fly ash	March 16 through October 15
Type I, II, IS, IP	0% slag cement 0% fly ash	October 16 through March 15[2]

[1]*Maximum total mineral admixture substitution is 50%.*
[2]*Substitution of Type I/II cement with fly ash and slag cement is allowed between October 16 and March 15 when the maturity method is used to determine the time of opening.*

4.2.3.2. Model Inputs for Generic Uncracked Iowa Bridge Deck

The model inputs utilized for a generic uncracked Iowa bridge deck are summarized in Table 4.5 and discussed below.

Table 4.5. Summary of model inputs for a generic Iowa bridge deck with no cracking.

Parameter, Unit	Distribution	Generic Iowa Bridge Deck[1] (no cracking)
Exposure Conditions		
Mean annual temperature, °F	Constant	51
Surface chloride concentration, ppm	Normal	m: 5500; s: 1100
Build-up time, yr	Constant	5
Concrete Properties		
Apparent 28-day diffusion coefficient, in^2/yr	Normal	m: 0.32; s: 0.063
Aging factor	Constant	0.2
Background chloride concentration, ppm	Constant	0
Reinforcing Steel Properties		
Concrete cover, in.	Normal	m: 2.50; s: 0.31
Chloride threshold (epoxy-coated reinforcement), ppm	Normal	m: 1760; s: 536
Propagation time, yr	Constant	15

Notes: [1]m refers to mean and s refers to standard deviation.

4.2.3.2.1. Exposure Conditions for Generic Iowa Bridge Deck

The average annual temperature in Des Moines, Iowa[1] was considered in the models. The surface chlorides vary in concentration throughout the year, with the highest concentrations in the winter and the lowest concentration in the summer after rain. For the service life models, the surface chloride concentration (C_s) was modeled as a constant value over the year, with an average surface chloride concentration assumed based on values measured and estimated by WJE during previous evaluation of bridge decks in Iowa (Donnelly et al. 2011). The assumed average surface chloride concentration was 5500 ppm (0.55 percent by weight of concrete), with a coefficient of variation of 0.20. It was assumed that the chlorides built up to this level over a period of 5 years, consistent with WJE's typical procedure for reinforced concrete bridge decks subject to routine usage of de-icing salts.

4.2.3.2.2. Concrete Properties for Generic Iowa Bridge Deck

The apparent diffusion coefficient for the concrete mixture was estimated from measurements obtained by WJE during a previous evaluation of Iowa bridge decks (Donnelly et al. 2011). In the previous study, chloride concentration profiles were determined for a total of 44 cracked and uncracked cores taken from 8 bridge decks throughout Iowa. The bridge decks ranged in age from 17 to 32 years at the time of inspection. Assuming the mixtures contained no fly ash or slag, the average apparent diffusion coefficient for uncracked concrete at 28 days (D_{28}) was estimated from the data to be 0.32 in^2/yr. The model input parameter for the diffusion coefficient was assumed as normal distribution with an average diffusion coefficient of 0.32 in^2/yr and a coefficient of variation of 0.20. The model assumed that no supplementary

[1] https://weatherspark.com/y/11510/Average-Weather-in-Iowa-City-Iowa-United-States-Year-Round, accessed March, 2022

cementitious materials are used in the concrete mixture of the generic bridge deck; therefore an aging factor of 0.2 was used to describe the improvement in diffusion coefficient as the concrete matures.

4.2.3.2.3. Reinforcing Steel Properties for Generic Iowa Bridge Deck

Distribution of the reinforcement cover depth was assumed based on the minimum specified cover of 2.5 inches and an assumed standard deviation of 0.31 inch (8 mm), as recommended by the *fib Model Code for Service Life Design*. As described in Appendix C, the chloride threshold (C_t) for epoxy-coated steel was assumed to be normally distributed with a mean of 1.15 percent by weight of cement and a standard deviation of 0.35 percent by weight of cement. The chloride threshold for epoxy-coated reinforcement was determined based on a review of previous work performed by WJE for bridge decks and substructures in 13 states as discussed in Appendix C. For a typical C-4WR or C-V47B concrete mixture without SCMs, the cement is approximately 15.3 percent of the weight of the concrete; therefore, the chloride threshold for epoxy-coated steel is approximately 1760 ppm, with a standard deviation of 536 ppm. Propagation time is assumed to be 15 years for epoxy coated bars in exposed uncracked concrete.

4.2.4. Effect of Cracking on Iowa Bridge Decks

Cracks compromise the durability of bridge decks by facilitating the transport of moisture and chlorides that might cause degradation. The following discusses how cracks accelerate damage due to chloride-induced corrosion qualitatively and how cracking was modeled quantitatively. The model inputs for a generic Iowa bridge deck with different cracking scenarios and the justification are presented in this section.

4.2.4.1. Impact of Cracking on Chloride-Induced Corrosion

Cracks in the concrete bridge deck permit higher transport rates of oxygen, moisture, and chlorides than sound concrete, which shortens the time to corrosion initiation. Additionally, the increased availability of oxygen and water facilitates the corrosion reaction while the chloride reduces the concrete resistivity. Both of these processes increase the rate of corrosion thereby shortening the propagation time. Cracks also retain moisture and take longer to dry than the deck surface, which contributes to increased moisture availability.

The impact of cracking is limited to the local area around the crack. Therefore, the crack characteristics heavily influence how much the cracking impacts the service life of the bridge deck:

- **Crack Location with Respect to Reinforcement.** Cracks above reinforcing steel have a greater impact on service life than cracks away from reinforcing steel. For example, subsidence cracks that originate at reinforcing bars can provide a direct path for chlorides to reach the reinforcing steel. However, if a crack is located few inches away from the reinforcing steel, then the chlorides must still diffuse horizontally from the crack to reach the steel.
- **Crack Depth.** Deeper cracks that extend to the depth of the reinforcing steel shorten service life more than shallow cracks that are limited to only a portion of the concrete cover. In the latter case, the resistance of concrete to chloride ingress is only compromised over a segment of the concrete cover depth.

- **Crack Width.** As crack width increases, chloride diffusion increases, thus increasing chloride ingress and reducing service life. During previous investigations conducted by WJE on cracked concrete, it was observed that concrete mixtures exhibit approximately the same apparent diffusion once crack widths exceed approximately 10 mils (0.010 inches) (Merrill et al. 2017). From a practical standpoint, only cracks that are 5 mils (0.005 inches) in width and greater are typically identifiable during a bridge inspection.
- **Extent of Cracking.** The extent of cracking may be represented by the crack density (the total length of cracks per unit area). As the crack density increases, the percentage of the deck area that is affected by the cracks increases such that a larger area is expected to show distress caused by chloride-induced corrosion at an earlier time.

4.2.4.2. Modeling the Effects of Cracking

The impact of cracks on chloride transport could be represented by increasing the apparent chloride diffusion coefficient of the concrete to account for the increased chloride ion penetrability and faster chloride diffusion to the reinforcing steel in the local area around the crack. This is shown schematically in Figure 4.3.

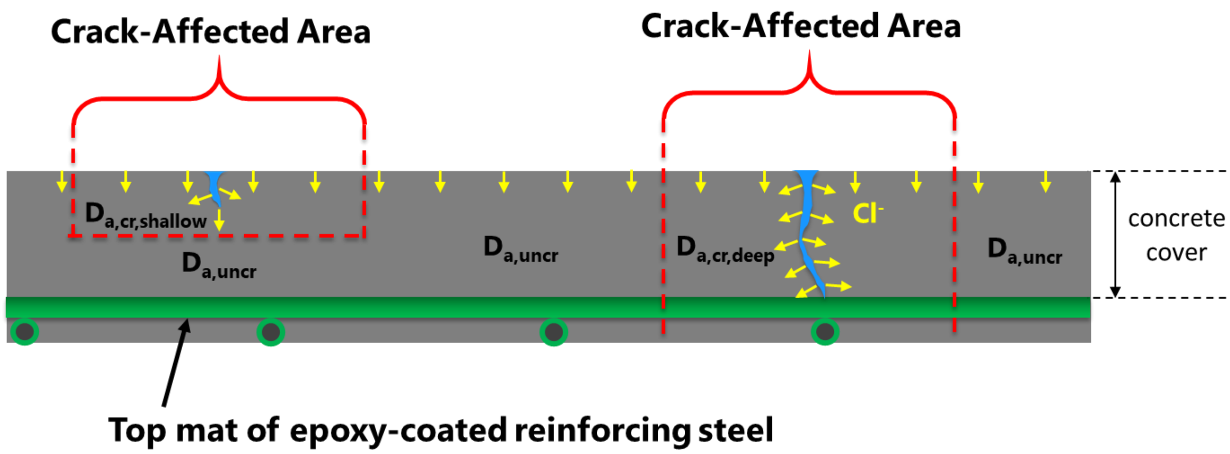

Figure 4.3. Schematic showing how cracks facilitate higher rates of chloride ion transport through the concrete cover. Uncracked concrete has a chloride diffusion coefficient of $D_{a,uncr}$ while concrete within the crack-affected areas has greater diffusion coefficients $D_{a,cr,shallow}$ if the crack is shallow and $D_{a,cr,deep}$ if the crack is deep. The yellow arrows show the direction of chloride ingress.

For the sake of modeling these bridge decks, a region approximately 2 inches on either side of a crack is assumed to have a higher apparent diffusion than the surrounding uncracked concrete. Thus, the crack-affected concrete surface area is defined as the crack density multiplied by the crack-affected width (4 inches). Note that the crack density is defined in this report as the summation of the length of all the visible cracks, assumed to be measuring 5 mils (0.005 inches) or greater, divided by the evaluated bridge deck area. Two separate crack densities should be calculated for shallow and deep cracks if possible, as each crack type has a different effect on the service life models. Table 4.6 shows the conversion between crack density and crack affected area. An average crack spacing is also presented assuming that all the cracks are transverse and extend the full width of the evaluated area of the deck. Note that the crack densities presented in the table can be divided into four categories for the extent of the bridge deck cracking based on a previous research effort by the project team as follows (Nelson et al. 2021):

- Mild Cracking: Crack density less than 0.10 ft/ft^2
- Moderate Cracking: Crack density between 0.10 and 0.22 ft/ft^2
- Severe Cracking: Crack density between 0.22 and 037 ft/ft^2
- Very Severe Cracking: Crack density more than 0.37 ft/ft^2

Service life modeling results from each crack density listed in Table 4.6 were compared to confirm that a similar behavior, in terms of service life, is expected within each crack density category. The results of the comparison are presented in the following sections. Examples for bridge decks with mild, moderate and severe cracking are provided in Figure 4.4, Figure 4.5, and Figure 4.6.

Table 4.6. Crack density versus crack affected area and crack spacing.

Crack Density (ft/ft^2)		Crack Affected Area (%)	Average Crack spacing (feet)
Mild Cracking	0.01	0.3%	100
	0.03	1.0%	30
	0.07	2.5%	14
Moderate Cracking	0.10	3.3%	10
	0.15	5.0%	6.5
	0.22	7.5%	4.5
Severe Cracking	0.30	10.0%	3.3
	0.37	12.5%	2.7
Very Severe Cracking	0.50	16.7%	2
	1.00	33.3%	1

The increase in diffusion coefficient for crack-affected areas is assumed to be linearly proportional to the crack width, where the diffusion coefficient input parameter (D_a) is assumed to be similar to uncracked concrete at crack widths of zero inches and increase linearly with the crack width for cracks up to 10 mils (0.010 inches) wide (Merrill et al. 2017). Concrete adjacent to cracks with widths of 10 mils (0.010 inches) or greater are assumed to have similar diffusion properties. For modeling purposes, shallow (map) cracks are assumed to have a crack width of 5 mils (0.005 inches) and extend to a depth of up to 1 inch through the concrete cover. Deep cracks are assumed to be at least 10 mils (0.010 inches) wide and extend to the depth of the reinforcement. Cracks discussed in this report generally refer to deep cracks that extend to the reinforcing steel, unless noted otherwise. The assumed statistical distributions of the apparent diffusion input parameter for shallow and deep cracks are defined in Table 4.7. No improvement of diffusion properties with time was considered for crack affected areas, which corresponds to a diffusion coefficient aging factor of 0.

The propagation time for crack affected areas is also anticipated to be shorter than that for uncracked concrete, due to the anticipated greater corrosion rates. Thus the propagation time was assumed to be 10 years for crack-affected areas, compared to 15 years for uncracked concrete. Crack-affected areas and uncracked areas were modeled separately and the overall damage of the modeled bridge deck at a given time is a weighted combination of the cracked and uncracked surface areas (based on the crack density).

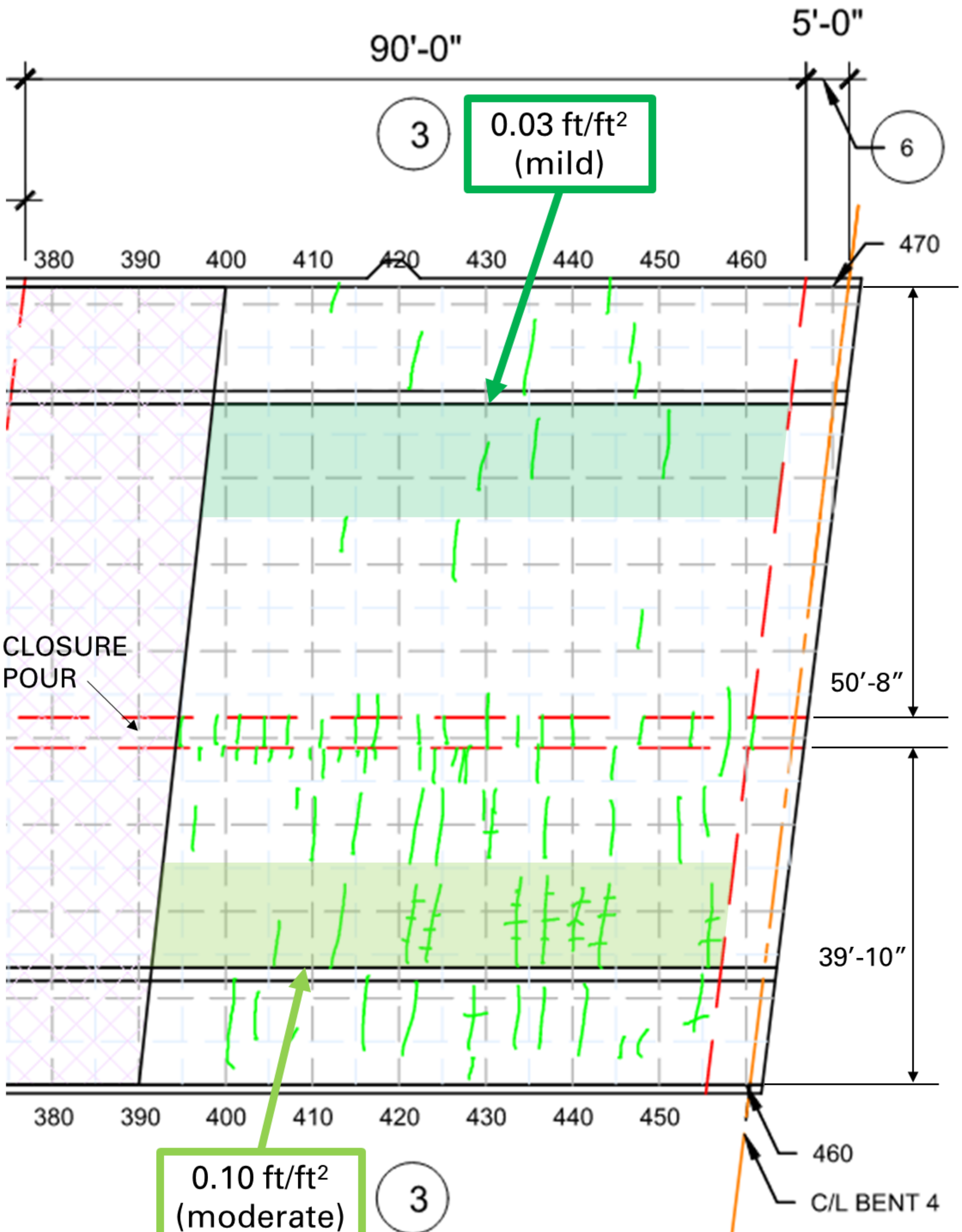

Figure 4.4. Examples of "Mild" and "Moderate" cracking based on the definitions in Table 4.6. The shaded areas identify the area used to calculate the crack density. Crack maps and data from Nelson et al. (2021).

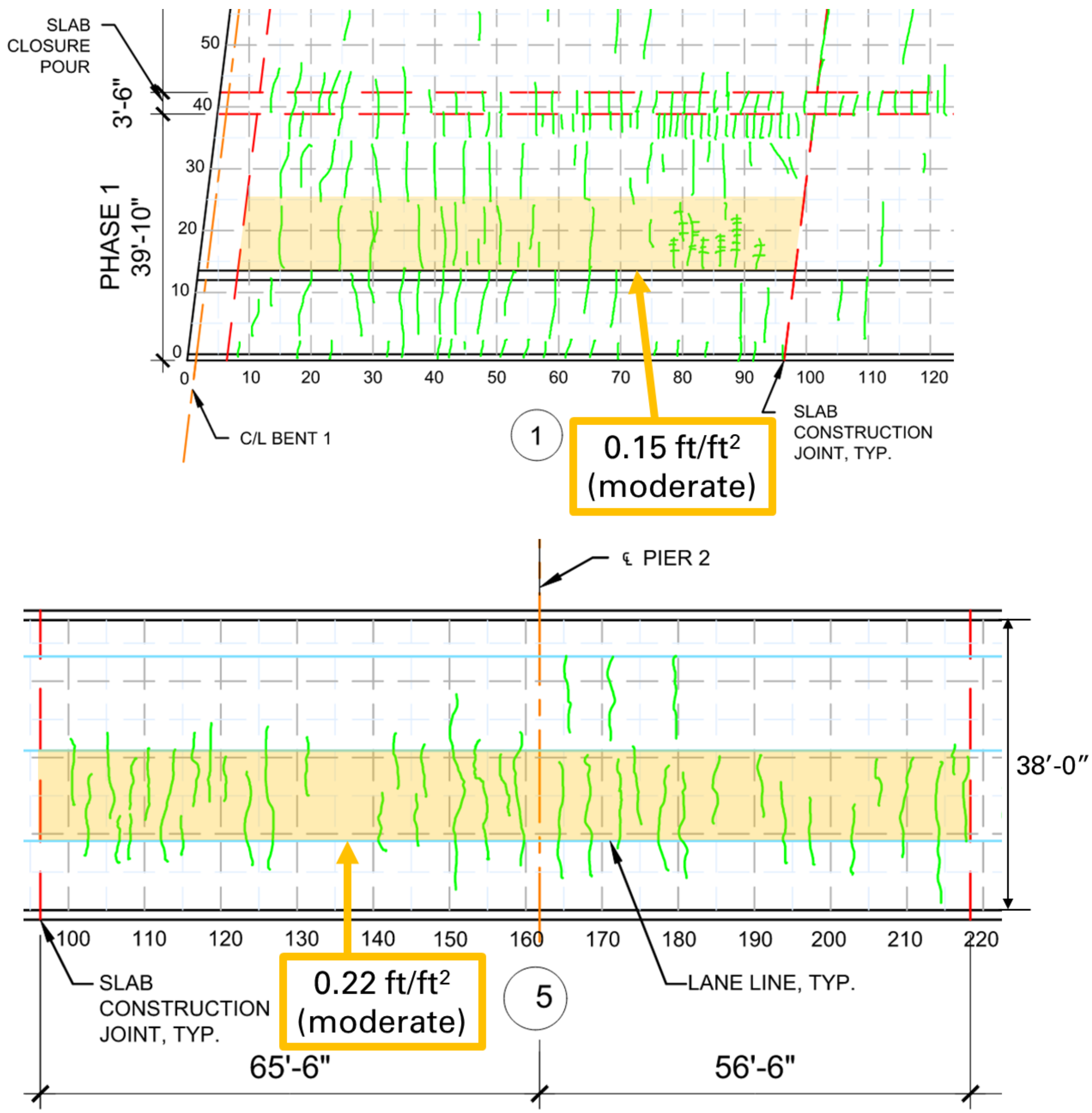

Figure 4.5. Examples of “Moderate” cracking based on the definitions in Table 4.6. The shaded areas identify the area used to calculate the crack density. Crack maps and data from Nelson et al. (2021).

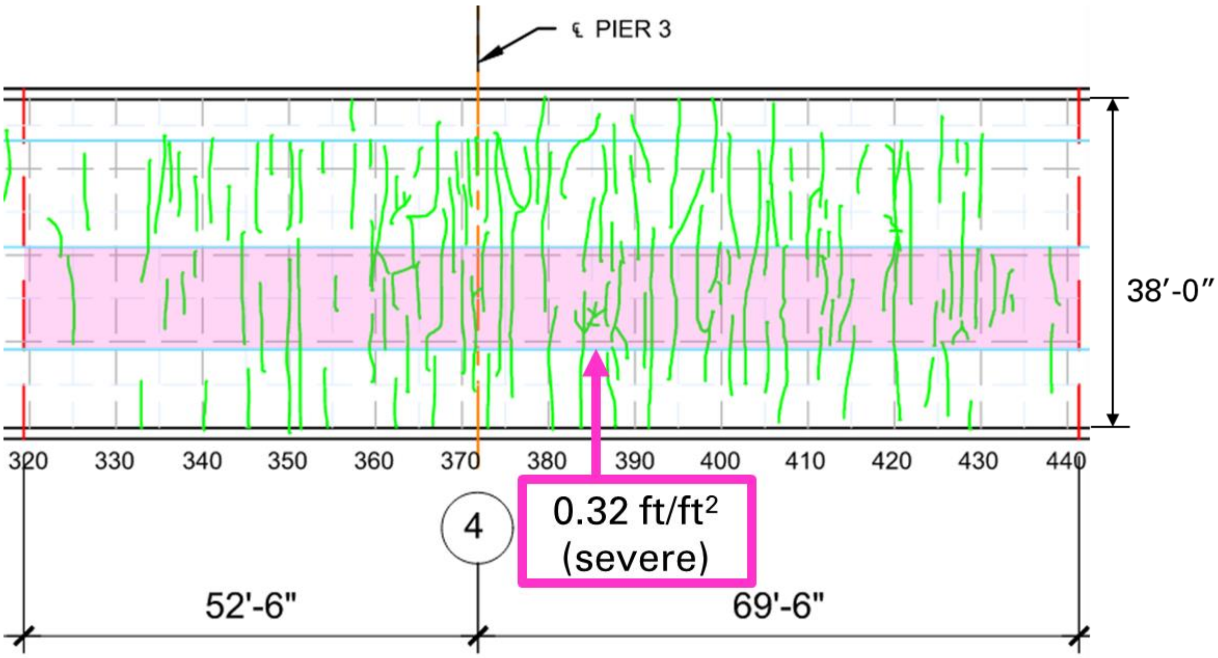

Figure 4.6. Example of "Severe" cracking based on the definitions in Table 4.6. The shaded areas identify the area used to calculate the crack density. Crack maps and data from Nelson et al. (2021).

4.2.4.3. Model Inputs for Generic Iowa Bridge Decks with Cracking

Crack-affected areas of a generic Iowa bridge deck with cracking were modeled to establish a baseline service life when no repairs or crack treatments are applied. A summary of the model input parameters for crack-affected areas is shown in Table 4.7 below. Values that were revised from the uncracked model inputs (Table 4.5) to account for cracked conditions are shown in bold font.

4.2.5. Baseline Model Results

Service life modeling was performed to predict the percentage of damaged area with time for the baseline cases (uncracked areas, crack-affected areas with shallow cracks, and crack-affected areas with deep cracks) assuming no crack treatments or repairs. The modeling results assuming the input parameters in Table 4.5 and Table 4.7 are shown in Figure 4.7. The baseline cases represent areas that are uncracked (green), areas that exhibit shallow (map) cracking (blue), and areas that exhibit deep cracking (orange). Based on the assumed inputs for the generic Iowa bridge deck, a deck with no cracking (i.e. a deck with full surface performing as an uncracked area) is predicted to reach the end of service life criterion of 20% of the surface area affected by corrosion-related damage at approximately 47 years of age. Areas affected by shallow cracking and deep cracking are predicted to reach 20% damage at approximately 25 and 17 years, respectively. For a bridge deck exhibiting cracking, the overall performance will be a weighted combination of the uncracked area and crack-affected area results depending on the crack density.

Table 4.7. Summary of model inputs for crack affected areas of a generic Iowa bridge deck.

Parameter, Unit	Distribution	Generic Iowa Bridge Deck[1] (shallow cracking)	Generic Iowa Bridge Deck[1] (deep cracking)
Exposure Conditions			
Mean annual temperature, °F	Constant	51	51
Surface chloride concentration, ppm	Normal	m: 5500; s: 1100	m: 5500; s: 1100
Build-up time, yr	Constant	5	5
Concrete Properties			
Apparent 28-day diffusion coefficient, in^2/yr	**Normal**	**m: 0.56 s: 0.17 (from 5-mil wide crack)**	**m: 0.8 s: 0.25 (from 10-mil wide crack)**
Aging factor	**Constant**	**0**	**0**
Reinforcing Steel Properties			
Concrete cover, in.	Normal	m: 2.50 s: 0.31	m: 2.50 s: 0.31
Chloride threshold (epoxy-coated reinforcement), ppm	Normal	m: 1760 s: 536	m: 1760 s: 536
Propagation time, yr	**Constant**	**10**	**10**

Notes: [1]m refers to mean and s refers to standard deviation.

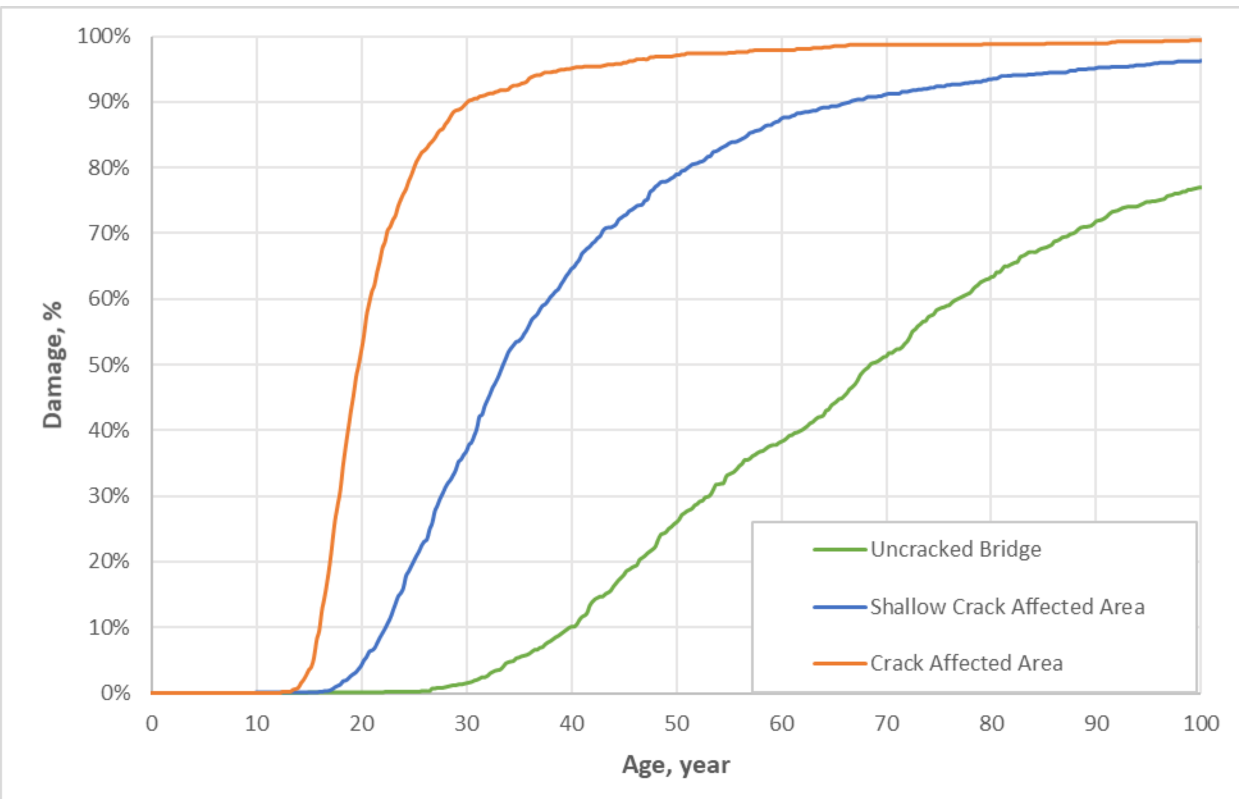

Figure 4.7. Service life predictions for baseline cases.

4.3. Crack Remediation Treatments Service Life Modeling

This section describes how the impact of the crack remediation treatments considered was implemented in the modeling.

4.3.1. Apply a Penetrating Sealer

When applied to a concrete surface, a penetrating sealer causes the surface to become water repellent. While moisture can still enter and exit the concrete, the penetrating sealer is an effective barrier to liquid solutions such as brine solutions and chloride-contaminated run-off and, therefore, slows the ingress of chlorides and other aggressive agents carried by the water. Penetrating sealers subsequently slow the rate of increase in the surface chloride concentration C_s and lengthen the build-up time. Penetrating sealers are also expected to extend the propagation time before damage occurs because they mitigate the corrosive environment by repelling water. However, penetrating sealers are often assumed to have a life of approximately 5 years before the sealed surface is fully abraded away by traffic. For more information on penetrating sealers, refer to the profile in Appendix B.

4.3.1.1. Model Assumptions

Surface sealers are considered to affect the rate of chloride build-up. In this method, the sealer is assumed to have an efficiency factor (e.g., reduction in build-up rate) of 90 percent initially; this efficiency factor then decreases linearly due to abrasion and weathering throughout the assumed lifespan of the sealer. A value of 90 percent was chosen to represent initial absorption reduction for a typical surface-sealer, such as a silane or siloxane. To account for aging and surface abrasion or erosion, surface-applied penetrating sealers are assumed to have a finite lifespan of 5 years. The effect of sealer was modeled similarly for uncracked and crack-affected areas.

4.3.1.2. Model Results

The results of modeling a generic Iowa bridge deck with various extents of cracking and penetrating sealer treatments versus bridge deck age at time of repair application are shown in Figure 4.8 through Figure 4.13. Figure 4.8 and Figure 4.9 show the impact of applying a penetrating sealer at 0 years of age on time-to-5% damage (i.e., 5% damage of the deck, which is assumed to be the limit where partial depth repairs are triggered) and time-to-replacement (i.e., assumed to be when 20% damage is reached), respectively. Note that at this damage level, other options such as placing a rigid cementitious overlay may be more appropriate than a full deck replacement but end of service life or replacement was assumed in this report for simplicity. Figure 4.10 and Figure 4.11 show the impact of first applying a penetrating sealer at 2 years of age, and Figure 4.12 and Figure 4.13 show the impact of first applying a penetrating sealer at 5 years of age. For each bar graph, the "Do Nothing" scenario is shown as a baseline and a one-time sealer application, three-time application at 4-year intervals, and three-time application at 6-year intervals are shown for comparison.

For easier comparison of the impact of applying penetrating sealers at different bridge deck ages instead of different application intervals, the model results are also shown in Figure 4.14 through Figure 4.19 for a one-time application (Figure 4.14 and Figure 4.15), three applications at 4-year intervals (Figure 4.16 and Figure 4.17), and three applications at 6-year intervals (Figure 4.18 and Figure 4.19). Each bar graph shows results for a time of first (or only) application at 0, 2, and 5 years.

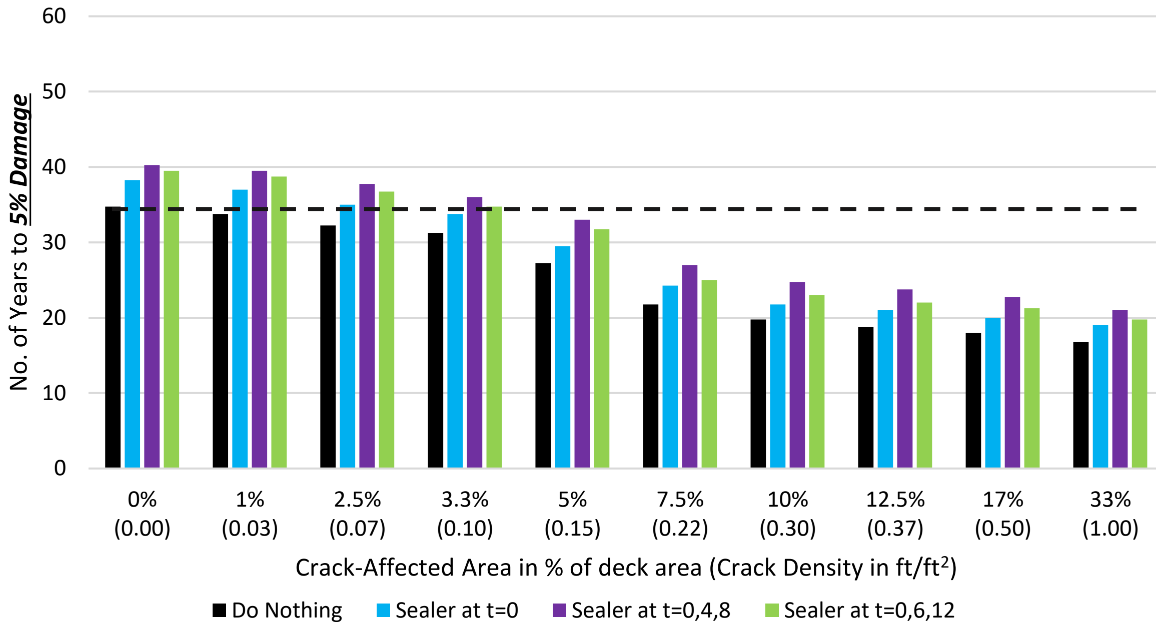

Figure 4.8. Time-to-5% damage for bridge decks treated with a penetrating sealer at 0 years of age. A one-time application, three applications at 4-year intervals, and three applications at 6-year intervals are shown.

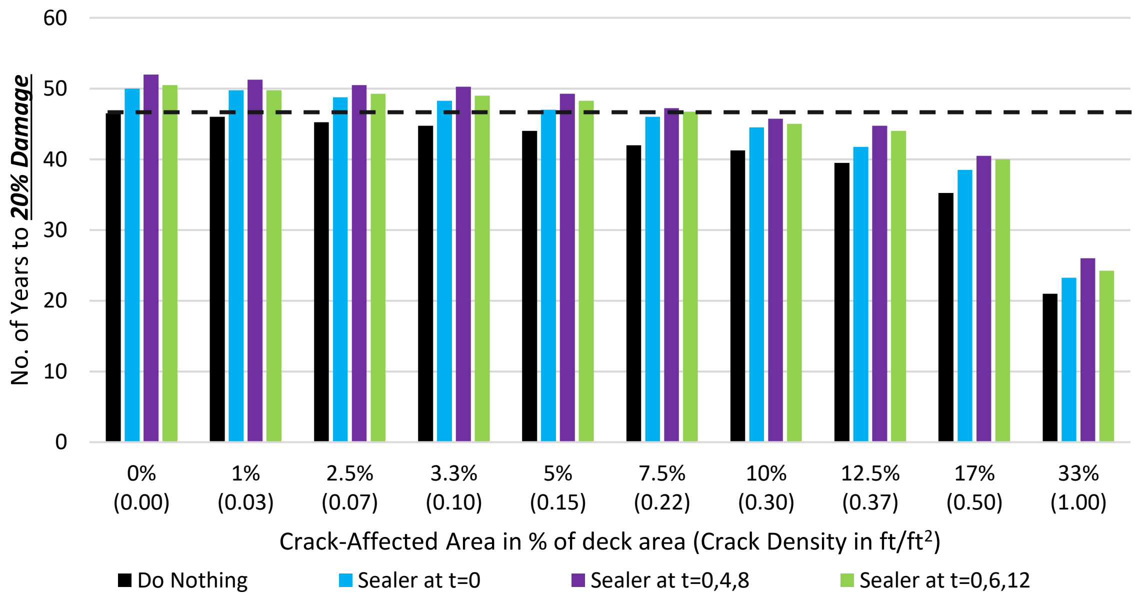

Figure 4.9. Time-to-replacement (i.e., 20% damage) for bridge decks treated with a penetrating sealer at 0 years of age. A one-time application, three applications at 4-year intervals, and three applications at 6-year intervals are shown.

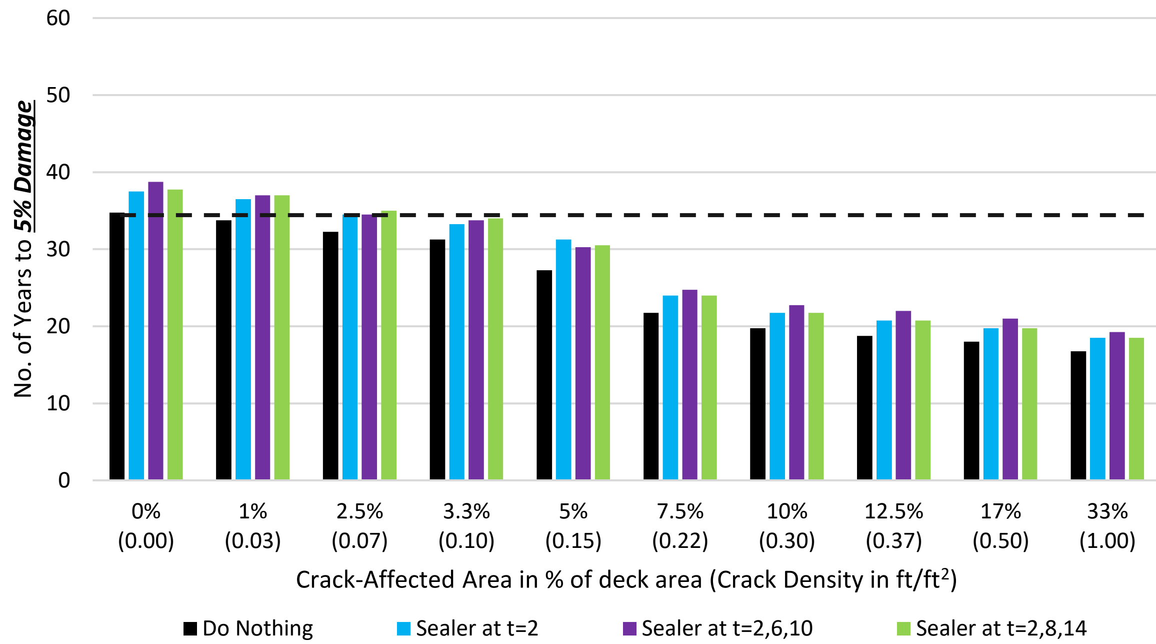

Figure 4.10. Time-to-5% damage for bridge decks treated with a penetrating sealer at 2 years of age. A one-time application, three applications at 4-year intervals, and three applications at 6-year intervals are shown.

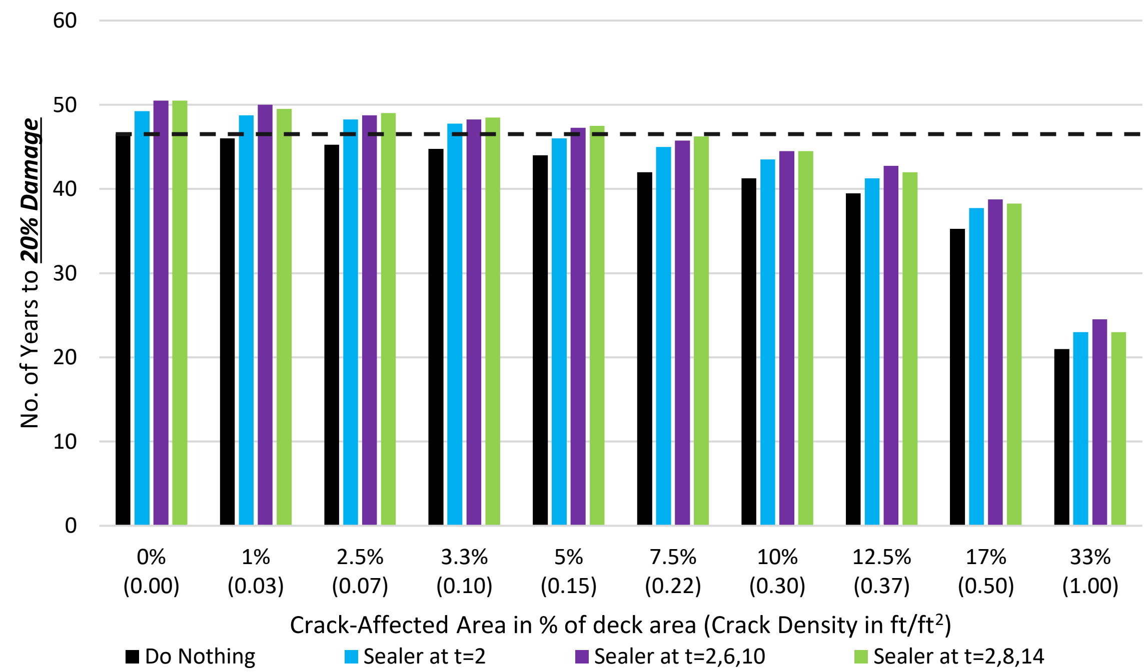

Figure 4.11. Time-to-replacement (i.e., 20% damage) for bridge decks treated with a penetrating sealer at 2 years of age. A one-time application, three applications at 4-year intervals, and three applications at 6-year intervals are shown.

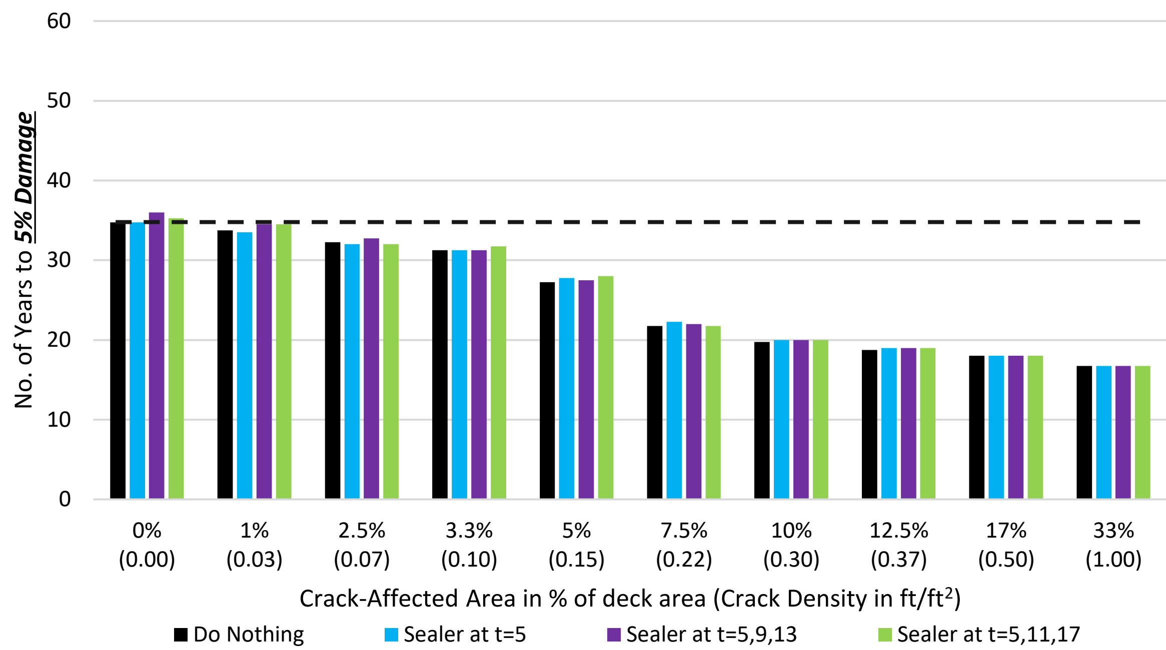

Figure 4.12. Time-to-5% damage for bridge decks treated with a penetrating sealer at 5 years of age. A one-time application, three applications at 4-year intervals, and three applications at 6-year intervals are shown.

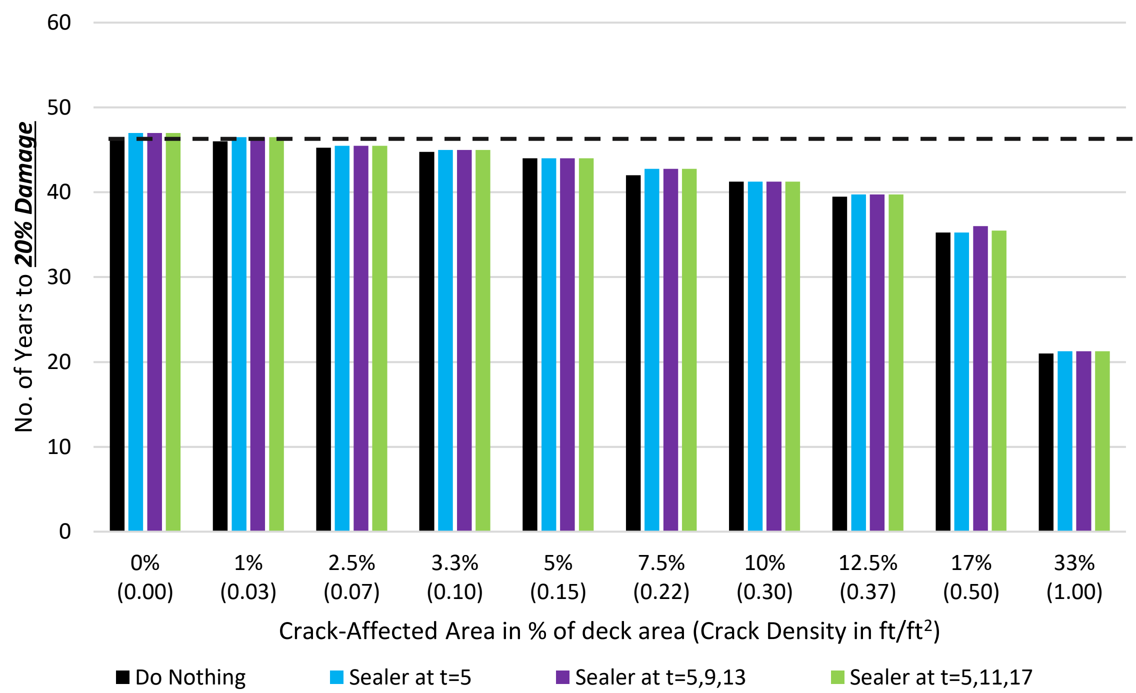

Figure 4.13. Time-to-replacement (i.e., 20% damage) for bridge decks treated with a penetrating sealer at 5 years of age. A one-time application, three applications at 4-year intervals, and three applications at 6-year intervals are shown.

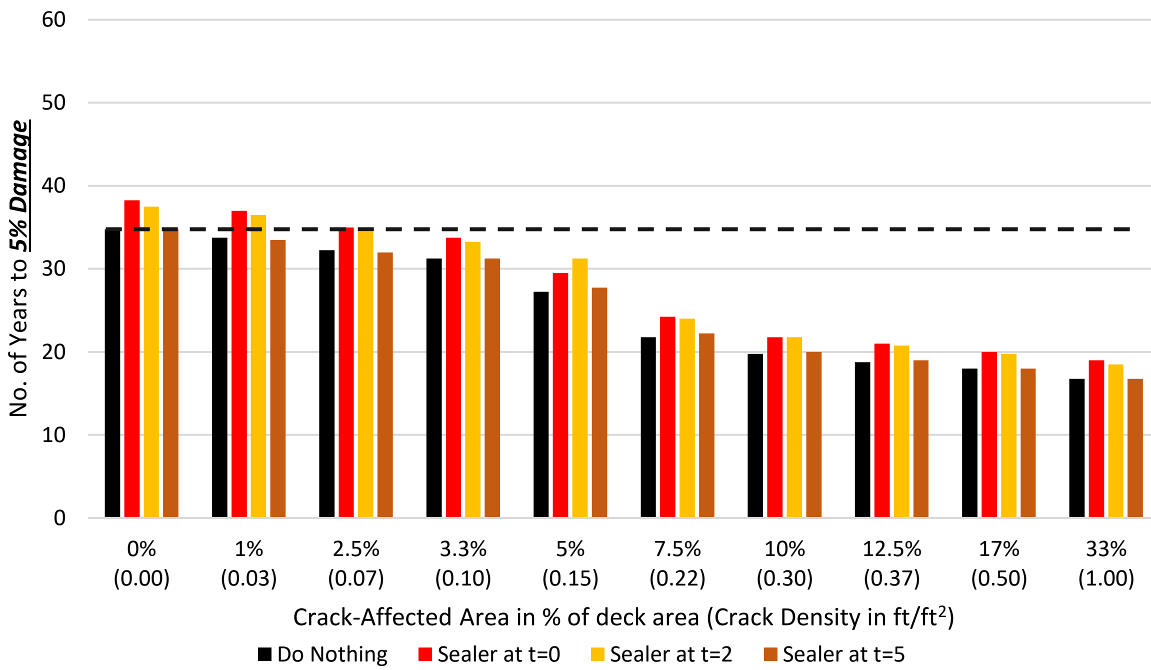

Figure 4.14. Time-to-5% damage for bridge decks scheduled for a one-time application of a penetrating sealer. One-time application at 0, 2, and 5 years of age is shown.

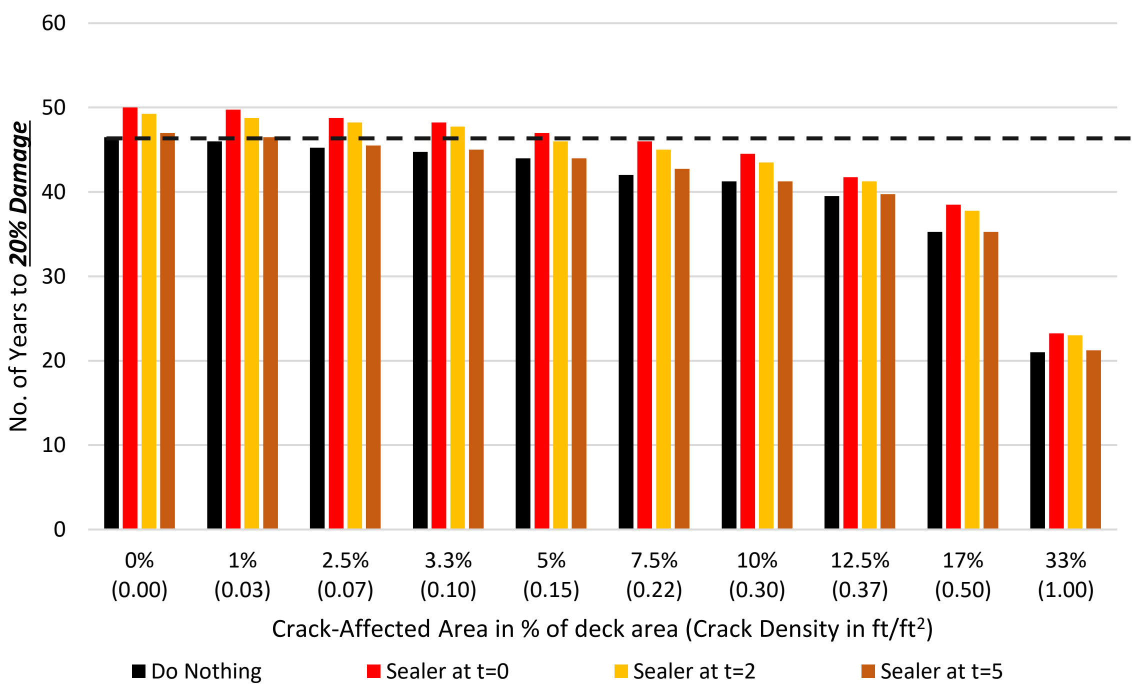

Figure 4.15. Time-to-replacement (i.e., 20% damage) for bridge decks scheduled for a one-time application of a penetrating sealer. One-time application at 0, 2, and 5 years of age is shown.

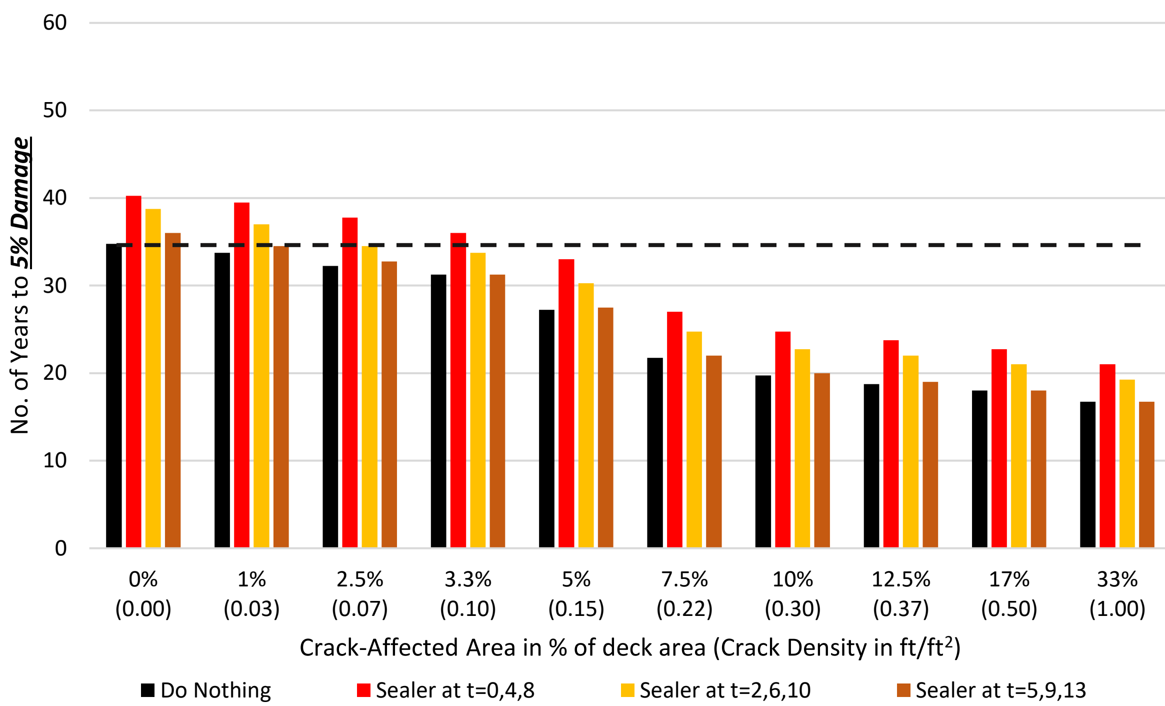

Figure 4.16. Time-to-5% damage for bridge decks scheduled for three applications of a penetrating sealer at 4-year intervals. First application at 0, 2, and 5 years of age is shown.

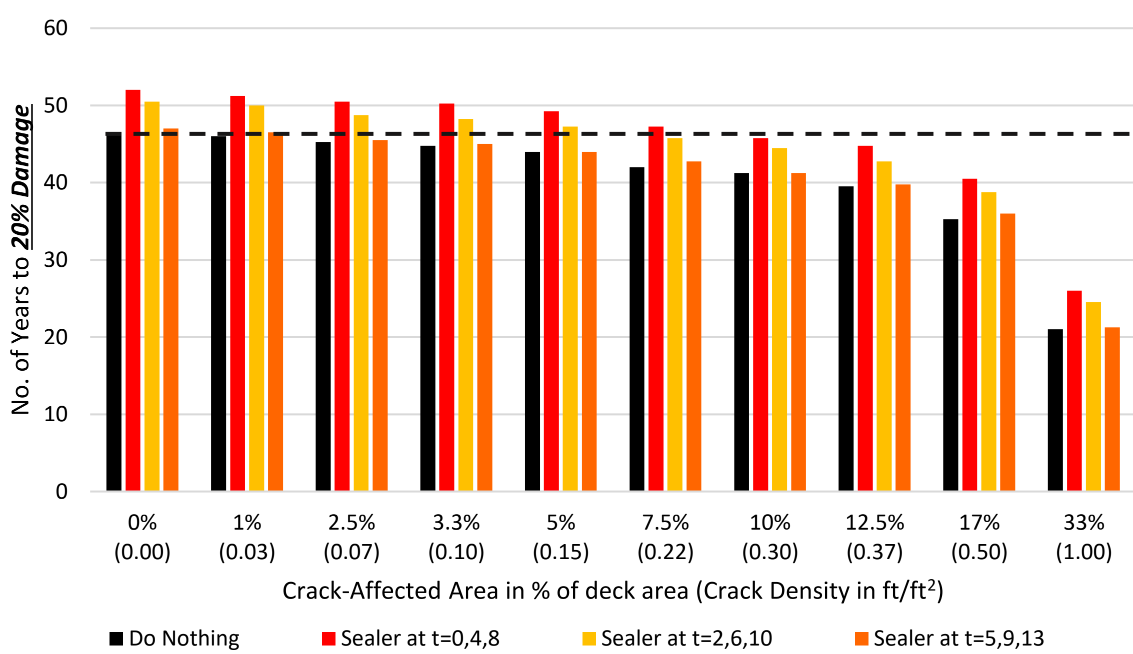

Figure 4.17. Time-to-replacement (i.e., 20% damage) for bridge decks scheduled for three applications of a penetrating sealer at 4-year intervals. First application at 0, 2, and 5 years of age is shown.

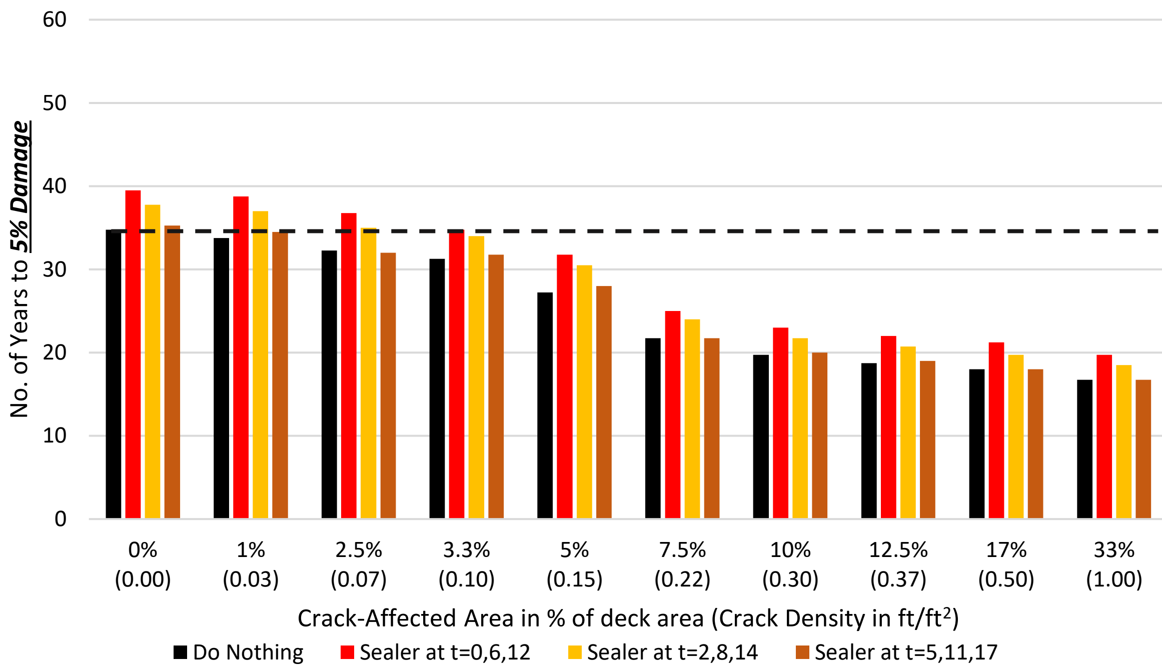

Figure 4.18. Time-to-5% damage for bridge decks scheduled for three applications of a penetrating sealer at 6-year intervals. First application at 0, 2, and 5 years of age is shown.

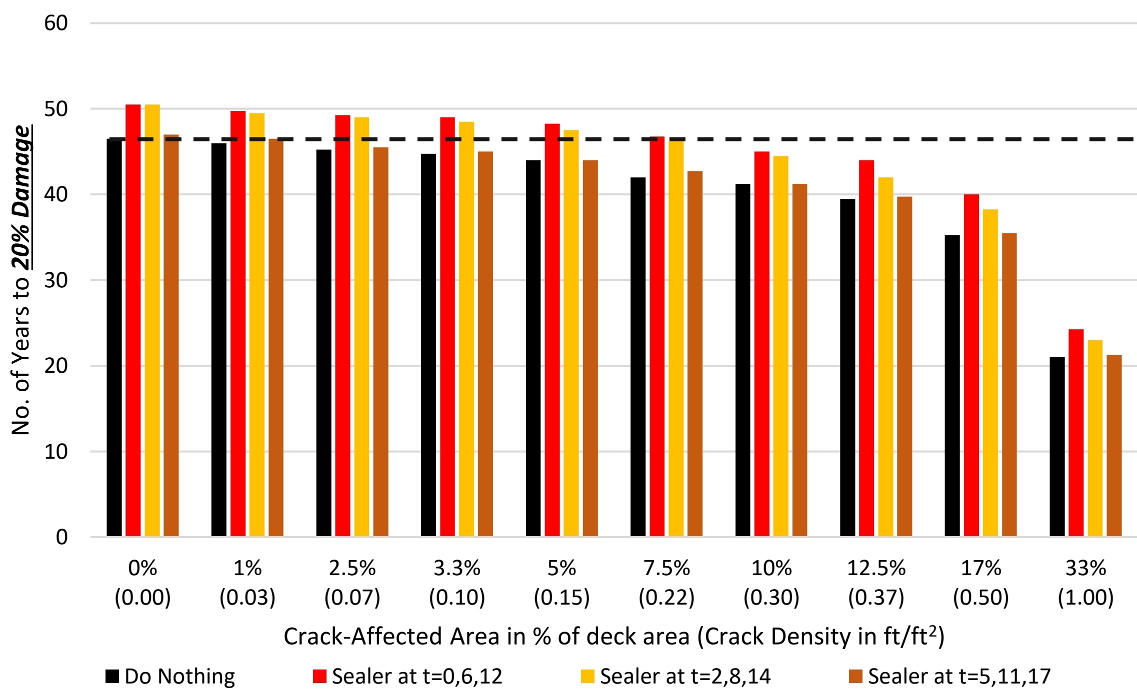

Figure 4.19. Time-to-replacement (i.e., 20% damage) for bridge decks scheduled for three applications of a penetrating sealer at 6-year intervals. First application at 0, 2, and 5 years of age is shown.

The application of penetrating sealers when the bridge was 0 to 2 years of age provided a clear benefit. When the first or only application was at 0 years, the time-to-5% damage (T_5) and time-to-replacement

(T_{20}) both increased by 2 to 6 years and when the first or only application was at 2 years of age, the T_5 and T_{20} both increased by 2 to 4 years. When the first or only application of the penetrating sealer was at 5 years of age, the benefit was negligible. At most, the T_5 or T_{20} increased by 1 year in the models.

Additionally, when the first or only application was at 0 years, multiple applications provided the greatest increase in T_5 and T_{20}, particularly at 4-year intervals. However, when the first or only application was at 2 years of age, a similar increase in T_5 and T_{20} was realized regardless of the number of applications or application interval; the increase differed by no more than 1 year between the treatment options.

The above results highlight the importance of the 5-year mark, which is the time at which crack-affected areas begin to have an increased likelihood of corroding. This can be determined from Figure 4.7, which shows that the percent damage for crack-affected areas with deep cracks begins to increase rapidly at approximately 15 years. By subtracting the propagation time, assumed to be 10 years for crack-affected areas, the time at which the percentage of the area experiencing corrosion initiation can be estimated at approximately 5 years. Because the primary benefit of the penetrating sealer is to slow chloride ingress and extend the initiation time, applying the penetrating sealer at or after 5 years did not provide much benefit in the models. This is why multiple applications at 4- and 6-year intervals had no to negligible benefit over one-time application when the first application was at 2 years of age, and why benefits were negligible for all of the scenarios in which the first or only application was at 5 years.

Overall, the increase in T_5 and T_{20} decreased with increasing crack density. Penetrating sealers provided the greatest improvement to bridge decks with crack densities between 0.00 and 0.15 ft/ft^2 (crack-affected areas between 0% and 5%).

4.3.2. Apply a Gravity-Fed Polymer by Crack-Chasing

Applying a gravity-fed polymer to seal cracks only along cracks (called "crack-chasing") is an effective method to restore the integrity of cracked areas. In essence, the applied polymer is used to fill and seal cracks, which restores the behavior of cracked areas and prevents the direct ingress of moisture and chlorides. Therefore, the only viable route for moisture and chlorides will be through diffusion, which is similar to the behavior of uncracked concrete.

If applied correctly, the effectiveness of crack-chasing is assumed to be more than 90% of the cracked area. Furthermore, it is assumed that this repair will seal cracks for the remaining service life of the deck. Due to the limited benefit that the uncracked areas of the deck have from crack-chasing, no service life modeling was completed for this repair. Alternatively, it was assumed that crack-chasing will provide a similar service life to an uncracked bridge deck. This technique is only feasible for bridge decks with low crack density.

4.3.3. Apply a Flood Coat

New flood coats provide a relatively impermeable barrier that prevents water (both liquid water and atmospheric moisture) and subsequently chlorides from entering or exiting the concrete. Like penetrating sealers, they slow the build-up of chlorides and lengthen the time required for the surface to reach the long-term surface chloride concentration (C_s). In the propagation phase, flood coats mitigate the corrosivity of the environment by preventing moisture ingress. In crack-affected areas, flood coats perform similarly to crack-chasing methods as both involve the application of a gravity-fed polymer. The polymer fills and thereby closes cracks, preventing water from penetrating cracks.

The effectiveness of a flood coat as a deck sealant is quickly compromised by wear and abrasion from traffic. The aggregates are pulled out or fractured by the traffic, leaving behind holes and cracks in the flood coat that will permit water and chloride ingress. Flood coats are typically assumed to have a life of 3 to 10 years, depending on traffic conditions and quality of installation. In contrast, the flood coat can remain an effective crack sealant for many more years since the polymer inside of the cracks is not subject to traffic and wear. Additionally, when the polymer sealing the crack fails, the deteriorated sealant is still beneficial because the new crack still has a smaller width than the original crack. Qualitatively, cracks with a smaller width are expected to permit less water intrusion than cracks with larger widths. For more information on flood coats, refer to the profile in Appendix B.

4.3.3.1. Model Assumptions

It is anticipated flooding the deck with a polymer material will result in filling a percentage of the cracks and inhibiting further chloride ingress through these cracks. Thus, a percentage of the crack-affected areas is assumed to have the same diffusion coefficient as uncracked areas for the remaining life of the bridge; this percentage is affected by the quality of the installation and the age of the cracks. For this analysis, it is assumed that the flood coat effectiveness of filling the cracks will range between 80% if applied at age of 0 or 2 years and down to 50% if applied at 10 years. Additionally, the flood coat is assumed to reduce the rate of chloride buildup in a similar manner as a penetrating sealer within an assumed life span of the coat of 5 years. The propagation time at crack-affected areas was assumed to be similar to the uncracked conditions (15 years) if the flood coat is applied at construction and decrease approaching the value for untreated cracks (10 years) if applied later. Application of a flood coat at an age of 5 years or later is assumed to provide no benefit in extending the propagation time.

4.3.3.2. Model Results

The results of modeling a generic Iowa bridge deck with various extents of cracking and treated with a flood coat at 0, 2, 5, and 10 years of age are shown in Figure 4.20 and Figure 4.21. Figure 4.20 shows the estimated time-to-5% damage and Figure 4.21 shows the estimated time-to-replacement (i.e., 20% damage).

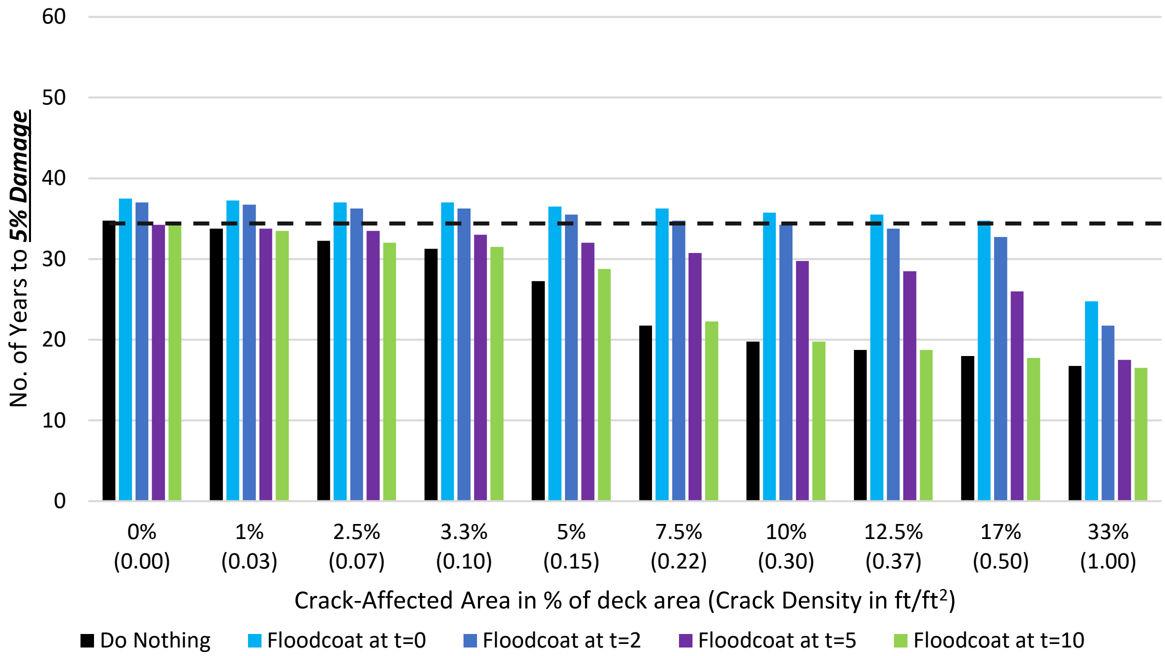

Figure 4.20. Time-to-5% damage for bridge decks treated with a flood coat at 0, 2, 5, and 10 years of age.

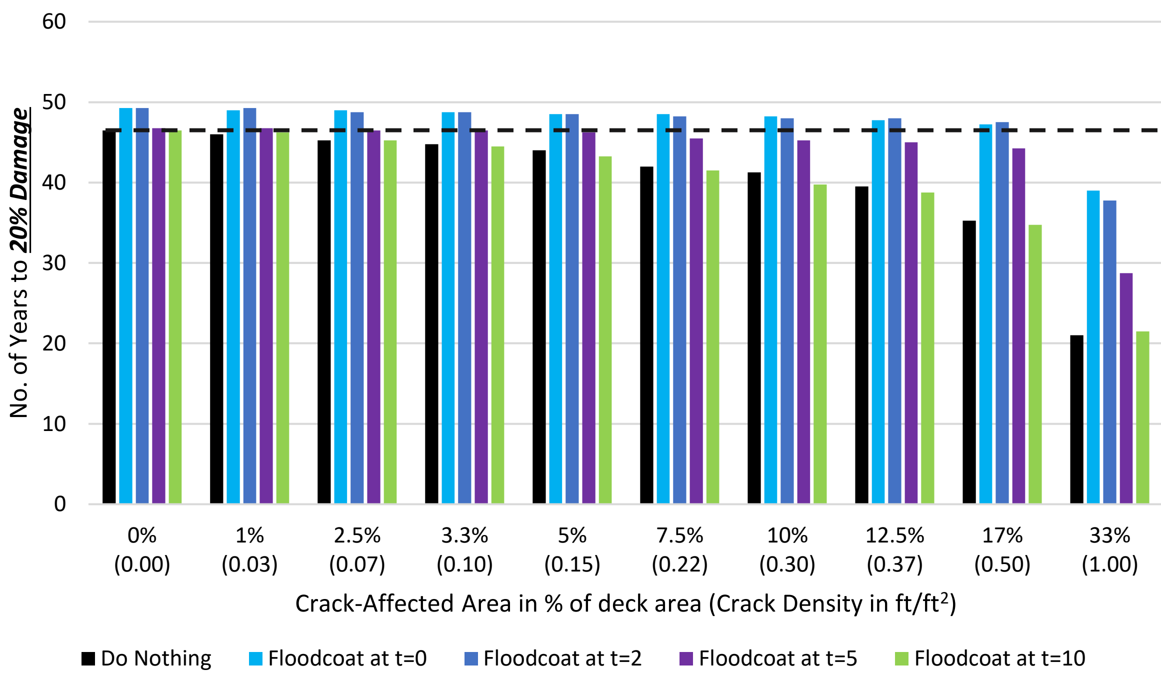

Figure 4.21. Time-to-replacement (i.e., 20% damage) for bridge decks treated with a flood coat at 0, 2, 5, and 10 years of age.

The model results show that flood coats are an effective tool for improving the durability of cracked bridge decks. When applied at early ages, i.e., 0 to 2 years, the time-to-5% damage (T_5) and time-to-replacement (T_{20}) of the flood coat-treated bridge decks were comparable to those of the uncracked and untreated bridge deck for crack densities up to 0.50 ft/ft^2 (crack-affected areas up to 17%).

With respect to the T_5, a flood coat treatment at 0 to 2 years was particularly beneficial at crack densities of 0.15 to 0.50 ft/ft^2 or crack-affected areas of 5 to 17%) as it greatly reduce the $T_{5:}$ with the exception of the greatest crack density modeled (1.00 ft/ft^2, or crack-affected area of 33%). Flood coat treatments also provided relatively little benefit to the T_5 at smaller crack densities of 0.00 to 0.07 ft/ft^2 (crack-affected areas of 0 to 2.5%), but that is because the cracks only have a small impact even if left untreated. The increase in the number of years to repair provided by a flood coat treatment applied at different ages is shown in Table 4.8. The trends observed occur because the flood coat significantly improves the resistance of crack-affected areas to chloride and moisture penetration and does not deteriorate quickly in the cracks while the flood coat on the deck surface deteriorates quickly due to traffic and thereby provides relatively little protection against chloride build-up and ingress. However, there is an upper limit beyond which the flood coat benefit begins to decrease. The upper limit is controlled by the construction quality, which was represented by assuming a certain percentage of the cracks would remain unsealed or the sealant would deteriorate too quickly to provide meaningful protection. For the construction quality assumed in these models, the flood coat began to be less effective at increasing the T_5 at crack densities exceeding 0.50 ft/ft^2 (crack-affected areas exceeding 17%), at which point the amount of unprotected crack-affected area offsets the benefit that could be realized by the flood coat treatment.

With respect to the T_{20}, a flood coat treatment at 0 to 2 years was particularly beneficial at the greatest crack densities modeled, 0.50 and 1.00 ft/ft^2 (crack-affected areas 17 and 33%), rather than the mid-range crack densities modeled. This is likely because the T_{20} was not severely impacted by cracking until greater crack densities of at least 0.37 ft/ft^2 (crack-affected areas of at least 12.5%) were reached, while cracking began severely increasing T_5 at a crack density of approximately 0.15 ft/ft^2 (crack-affected area of approximately 5%).

Both the magnitude of the benefit and the range of crack densities for which a flood coat is beneficial decreased as the flood coat was applied at later bridge deck ages. Based on the model results, flood coats provided the best benefit when applied at bridge deck ages of 0 to 2 years by increasing T_5 and T_{20} by up to 17 and 18 years respectively, depending on the crack density. The T_5 and T_{20} could still be increased by up to 10 years if the flood coat was applied at a bridge deck age of 5 years, again subject to the crack density as discussed above. When applied at 10 years of age, the flood coat was ineffective at increasing T_5 and T_{20}.

Table 4.8. Increase in time-to-5% damage and time-to-replacement with respect to untreated, cracked bridge deck when a flood coat is applied at different bridge deck ages

Crack-Affected Area in % (Crack Density in ft/ft^2)	Time-to-5% damage (yrs increase)				Time-to-Replacement (yrs increase)			
	0 yrs	2 yrs	5 yrs	10 yrs	0 yrs	2 yrs	5 yrs	10 yrs
0 (0.00)	3	2	0	0	3	3	0	0
1 (0.03)	4	3	0	0	3	3	1	0
2.5 (0.07)	5	4	1	0	4	4	1	0
3.3 (0.10)	6	5	2	0	4	4	2	0
5 (0.15)	9	8	5	2	5	5	2	0

Crack-Affected Area in % (Crack Density in ft/ft^2)	Time-to-5% damage (yrs increase)				Time-to-Replacement (yrs increase)			
	0 yrs	2 yrs	5 yrs	10 yrs	0 yrs	2 yrs	5 yrs	10 yrs
7.5 (0.22)	15	13	9	1	7	6	4	0
10 (0.30)	16	15	10	0	7	7	4	0
12.5 (0.37)	17	15	10	0	8	9	6	0
17 (0.50)	17	15	8	3	12	12	9	0
33 (1.00)	8	5	1	0	18	17	8	1

4.3.4. Apply a Hot-Mixed Asphalt Overlay with Waterproofing Membrane (HMAWM)

Hot-mixed asphalt with waterproofing membrane is an overlay technique for bridge deck rehabilitation efforts. Similar to sealers, the membrane will to slow down the chloride buildup and, as such, this technique can be for protection to bridge decks with and without cracks. The asphalt layer provides protection to the membrane, which allow this system to remain in service for up to 20 years. For more information on HMA Overlay with Waterproofing Membrane, refer to the profile in Appendix B.

4.3.4.1. Model Assumptions

The overlay with waterproofing membrane is assumed to reduce the rate of chloride buildup with an efficiency factor (e.g., reduction in build-up rate) of 90 percent initially; this efficiency factor then decreases linearly throughout an assumed lifespan of the membrane of 20 years. This assumes that maintenance of the HMA overlay will be performed at 10 years after application. The propagation time at crack-affected areas was assumed to be similar to the uncracked conditions (15 years) if the HMA is applied at construction and to decrease approaching the value for untreated cracks (10 years) if applied later. Application of HMA overlay with the membrane at age of 5 years or later is assumed to provide no benefit in extending the propagation time.

4.3.4.2. Model Results

The results of modeling a generic Iowa bridge deck with various extents of cracking and treated with a HMA overlay with a waterproofing membrane at 0, 2, 5, and 10 years of age are shown in Figure 4.22 and Figure 4.23. Figure 4.22 shows the estimated time-to-5% damage and Figure 4.23 shows the estimated time-to-replacement (i.e., 20% damage).

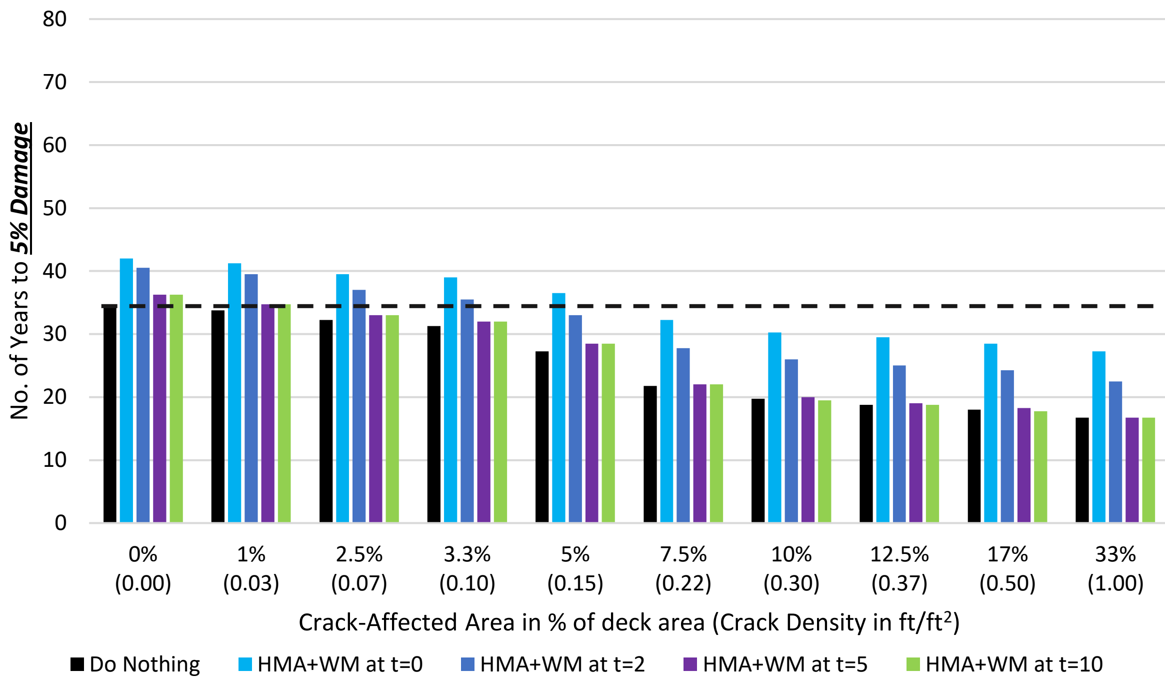

Figure 4.22. Time-to-5% damage for bridge decks treated with a HMA overlay with a waterproofing membrane (HMAWM) at 0, 2, 5, and 10 years of age.

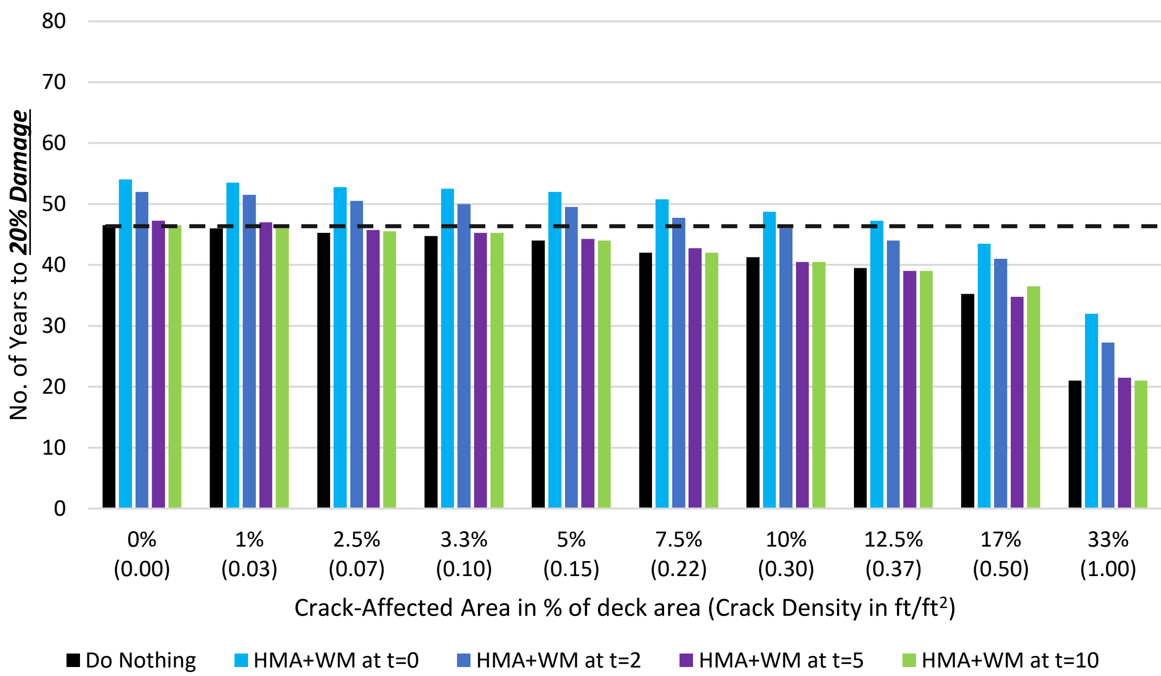

Figure 4.23. Time-to-replacement (i.e., 20% damage) for bridge decks treated with a HMA overlay with a waterproofing membrane (HMAWM) at 0, 2, 5, and 10 years of age.

The HMA overlay with a waterproofing membrane typically increased the time-to-5% damage (T_5) and time-to-replacement (T_{20}) by a consistent number of years regardless of crack density, as shown in Table 4.9. The exception was the impact of placing a HMA overlay with a waterproofing membrane on a bridge deck at an age of 0 years. The T_5 increased by 7 to 9 years for crack densities up to 0.15 ft/ft^2 (crack-affected areas up to 5%) and by approximately 11 years for the crack densities greater than 0.15 ft/ft^2 (crack-affected areas greater than 5%) in the models. Similarly, the T_{20} was increased by 8 or 9 years for all crack densities except the greatest, 1.00 ft/ft^2 (33% crack-affected area), for which the increase was 11 years. The crack density at which the benefit of the HMA overlay with the waterproofing membrane increased, when placed at a bridge deck age of 0 years, corresponded roughly to the crack density at which T_5 and T_{20} decreased at the greatest rate. However, as shown in Figure 4.22 and Figure 4.23, even though the HMA overlay with the waterproofing membrane was most effective when placed at 0 years of age for greater crack densities, it did not restore the T_5 nor the T_{20} to those of the baseline, uncracked, untreated bridge deck scenario.

The increase in T_5 and T_{20} was 4 to 6 years when the HMA overlay with the waterproofing membrane was placed on a bridge deck at 2 years of age, regardless of the crack density, and the increase in T5 and T20 was negligible (typically 0 or 1 year) when the HMA overlay with the waterproofing membrane was placed at 5 or 10 years of age.

Table 4.9. Increase in time-to-5% damage and time-to-replacement with respect to untreated, cracked bridge deck when a HMA overlay with a waterproofing membrane is applied at different bridge deck ages.

Crack-Affected Area in % (Crack Density in ft/ft^2)	Time-to-5% damage (yrs increase)				Time-to-Replacement (yrs increase)			
	0 yrs	2 yrs	5 yrs	10 yrs	0 yrs	2 yrs	5 yrs	10 yrs
0 (0.00)	7	6	2	2	8	6	1	0
1 (0.03)	8	6	1	1	8	6	1	0
2.5 (0.07)	7	5	1	1	8	5	1	0
3.3 (0.10)	8	4	1	1	8	5	1	1
5 (0.15)	9	6	1	1	8	6	0	0
7.5 (0.22)	11	6	0	0	9	6	1	0
10 (0.30)	11	6	0	0	8	5	0	0
12.5 (0.37)	11	6	0	0	8	5	0	0
17 (0.50)	11	6	0	0	8	6	0	1
33 (1.00)	11	6	0	0	11	6	1	0

4.3.5. Apply a Thin Polymer Overlay

Thin polymer overlays may be applied by several methods, but are most commonly applied in multiple layers of polymer into which an aggregate is broadcast, also known as multi-layer polymer overlays. Each layer is approximately 0.125-inches thick, and two to three layers are commonly placed, resulting in a typical total thickness of 0.25 to 0.375 inches. Thin polymer overlays are much less permeable than portland cement concrete overlays and offer excellent protection against chlorides and moisture once they have been placed. Because they are thicker than flood coats, thin polymer overlays are not as susceptible to aggregate pop-out and abrasion although these factors contribute to the decrease in their effectiveness with age. However, thin polymer overlays delaminate from the concrete substrate over time and are sensitive to the condition of the existing concrete deck substrate. If the deck is already corroding, any distress due to the corrosion or other deterioration mechanism will reflect through the thin polymer overlay. For more information regarding thin polymer overlays, refer to the crack repair profile "Apply a Thin Polymer Overlay" in Appendix B.

4.3.5.1. Model Assumptions

Polymer overlays are modeled as a discrete layer on top of the base concrete layer, with an independent diffusion coefficient to define the rate of transport of chlorides to the base concrete layer. A diffusion coefficient through the polymer overlays of 0.005 in^2/yr was utilized for modeling, based on the average ASTM C1202 test results reported by Sprinkel (2003) for polymer overlays, and based on WJE's experience with laboratory testing of concrete cores with polymer overlays. Note that this value is significantly less than the chloride diffusion coefficient measured for the mature base concrete.

Polymer overlays may delaminate from the concrete surface over time; however, with proper surface preparation, the total percentage of delaminations is expected to remain small. In this study, the thin polymer overlay was assumed to delaminate according to a Weibull distribution, which is commonly used in reliability analysis to model failure events. In the absence of sufficient information available in the literature, WJE selected a Weibull distribution based on our understanding of the likely rate of delaminations in polymeric deck overlays. A Weibull distribution with a scale parameter of 40 and a shape parameter of 2.2 (Figure 4.24), which resulted in a 5 percent probability of overlay delamination after 10 years and 10 percent probability of overlay delamination after 15 years. The life of the thin polymer overlay was limited to 20 years, after which the overlay is assumed to be fully delaminated. Note that these assumptions were developed for modeling purposes.

An overlay depth of 0.375 inch was assumed for this study; however, to account for anticipated abrasion of the overlay due to traffic and weathering, an effective depth of 0.30 inches was conservatively assumed to represent the level of protection provided for model purposes. No concrete milling was assumed at overlay application. The propagation time at crack-affected areas was assumed to be similar to the uncracked conditions (15 years) if the thin polymer overlay is applied at 0 or 2 years of age and decrease if applied later, approaching the value of untreated cracks (10 years) if applied at an age of 10 years or older.

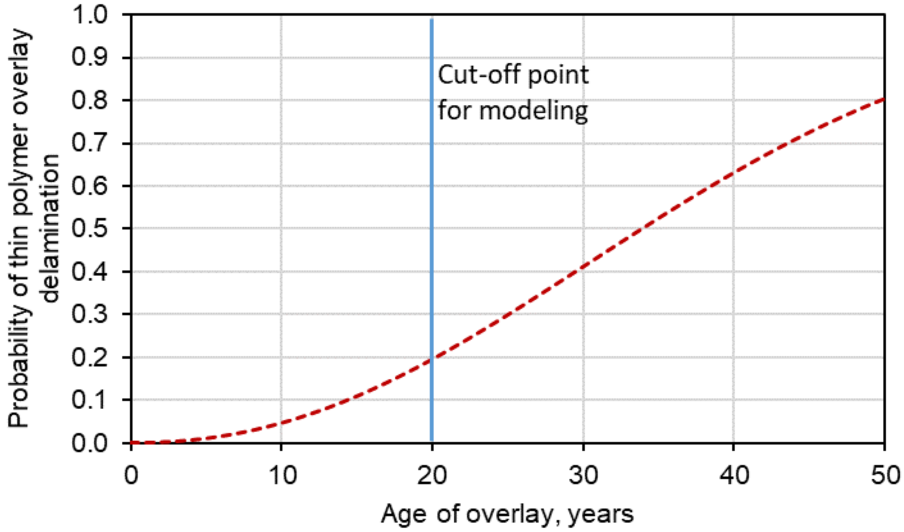

Figure 4.24. Probability distribution function assumed for thin polymer overlay delamination (Weibull distribution with scale parameter 40 and shape parameter 2.2)

4.3.5.2. Model Results

The results of modeling a generic Iowa bridge deck with various extents of cracking and treated with a thin polymer overlay at 0, 2, 5, and 10 years of age are shown in Figure 4.25 and Figure 4.26. Figure 4.25 shows the estimated time-to-5% damage and Figure 4.26 shows the estimated time-to-replacement (i.e., 20% damage).

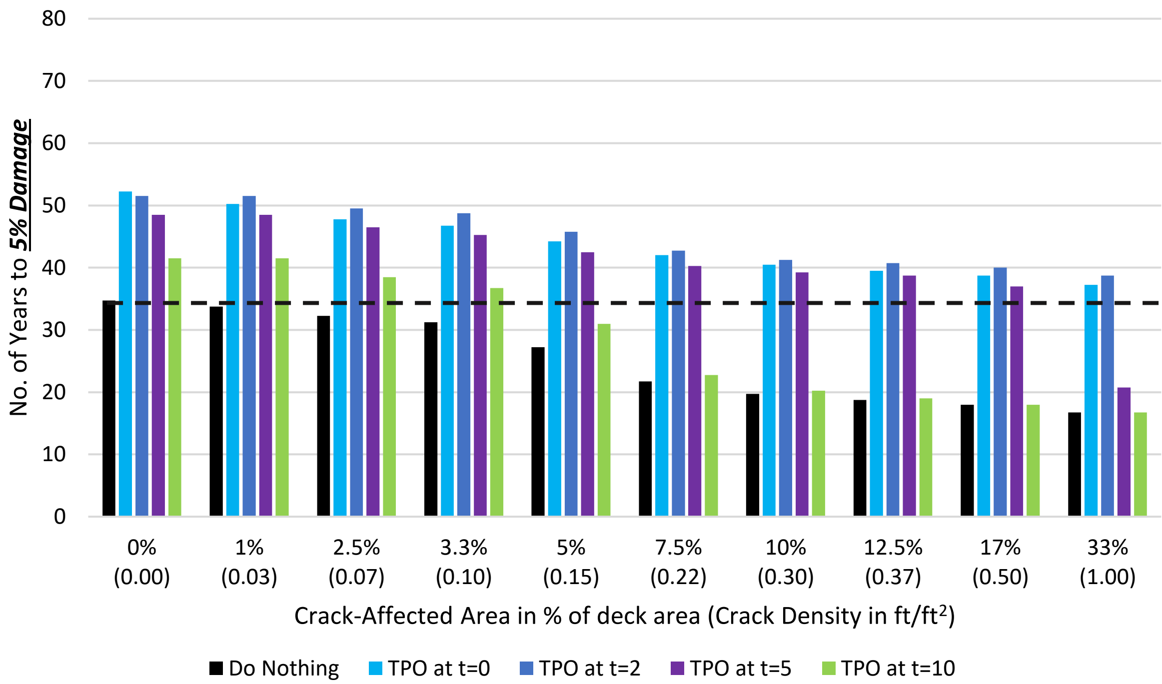

Figure 4.25. Time-to-5% damage for bridge decks treated with a thin polymer overlay (TPO) at 0, 2, 5, and 10 years of age.

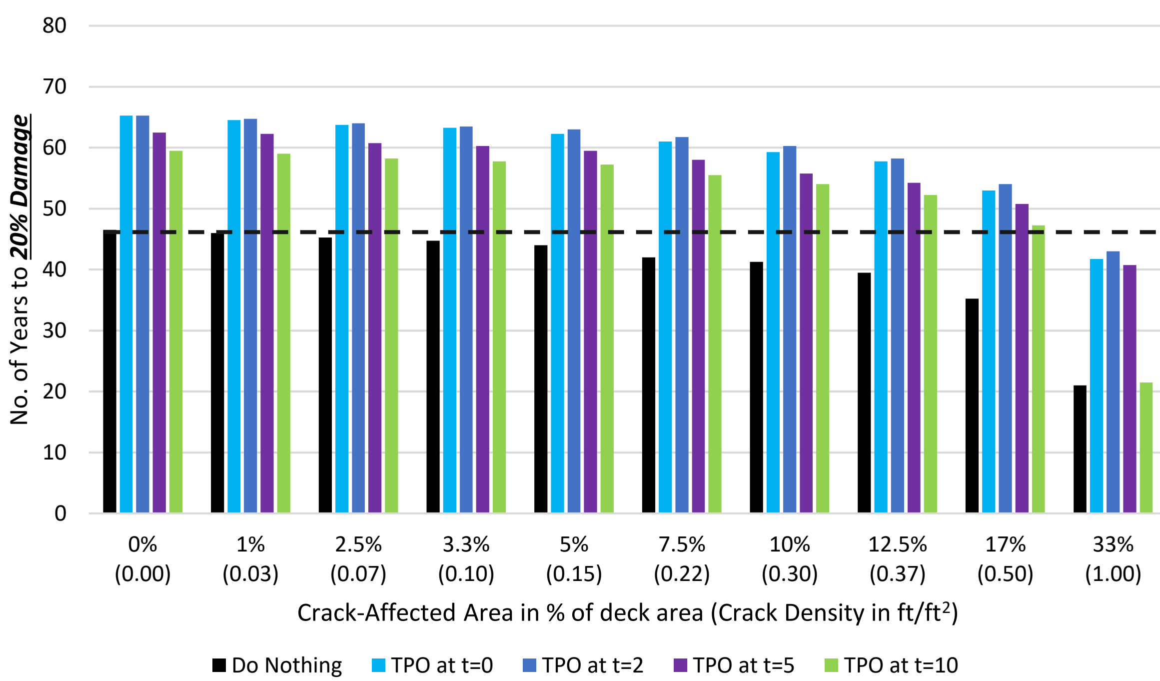

Figure 4.26. Time-to-replacement (i.e., 20% damage) for bridge decks treated with a thin polymer overlay (TPO) at 0, 2, 5, and 10 years of age.

The model results showed that applying a thin polymer overlay is typically an effective way to increase the time-to-5% damage (T_5) and time-to-replacement (T_{20}). For the uncracked bridge deck (crack density of 0.00 ft/ft^2 or crack-affected area of 0%), an increase of 7 to 18 years was estimated for T_5 and an increase of 13 to 19 years was estimated for T_{20} by the models depending on when the thin polymer overlay was applied. Overall, the results showed that applying a thin polymer overlay in the first 5 years can increase T_5 to that of an uncracked, untreated bridge deck for crack densities up to 0.50 ft/ft^2 (crack-affected areas up to 17%), and that applying a thin polymer overlay in the first 2 years can restore T_5 to that of an uncracked, untreated bridge deck for greater crack densities of 1.00 ft/ft^2 (crack-affected areas up to 33%). Applying a thin polymer overlay any time within the first 10 years was sufficient to restore T_{20} to that of an uncracked, untreated bridge deck for all of the crack densities considered with the exception of the most severe crack density considered of 1.00 ft/ft^2 (crack-affected area 33%), for which the thin polymer overlay was not able to restore T_{20} regardless of when it was applied.

Applying the thin polymer overlay at ages of 0 and 2 years provided a similar benefit; the increases in T_5 and T_{20} were between 16 and 22 years and, for a given crack density, only differed by 1 or 2 years between the two application ages. Waiting to apply the thin polymer overlay until an age of 5 years shortened the increase in T_5 and T_{20} by only 2 to 5 years, with the exception of T_5 in the most severe crack density scenario considered in the models, 1.00 ft/ft^2 (crack-affected area of 33%) as shown in Table 4.10. In the most severe crack density scenario, the benefit to T_5 decreased from 21 or 22 additional years before repair for an application age of 0 to 2 years to only 4 additional years for an application age of 5 years. Waiting to apply the thin polymer overlay until an age of 10 years shortened the benefit to T_5 dramatically but had less of an impact on T_{20}, again with the exception of the most severe cracking scenario. For a crack density of 1.00 ft/ft^2 (crack-affected area of 33%), the increase in T_{20} decreased from 20 years for an application age of 5 years to just 1 year for an application age of 10 years.

Overall, the benefit to T_5 and T_{20} decreases at very high crack densities and/or at later-age applications. This is because thin polymer overlays are a powerful tool for slowing corrosion initiation, but do not mitigate corrosion propagation well. While thin polymer overlays theoretically keep moisture and chlorides out, any existing water and chlorides in the concrete is trapped and the thin section of the polymer overlay makes it susceptible to reflective cracking and corrosion-related distress.

Table 4.10. Increase in time-to-5% damage and time-to-replacement with respect to untreated, cracked bridge deck when a thin polymer overlay is applied at different bridge deck ages.

Crack-Affected Area in % (Crack Density in ft/ft^2)	Time-to-5% damage (yrs increase)				Time-to-Replacement (yrs increase)			
	0 yrs	2 yrs	5 yrs	10 yrs	0 yrs	2 yrs	5 yrs	10 yrs
0 (0.00)	18	17	14	7	19	19	16	13
1 (0.03)	17	18	15	8	19	19	16	13
2.5 (0.07)	16	17	14	6	19	19	16	13
3.3 (0.10)	16	18	14	6	19	19	16	13
5 (0.15)	17	19	15	4	18	19	16	13
7.5 (0.22)	20	21	13	1	19	20	16	14
10 (0.30)	21	22	20	1	18	19	15	13
12.5 (0.37)	21	22	20	0	18	19	15	13

Crack-Affected Area in % (Crack Density in ft/ft^2)	Time-to-5% damage (yrs increase)				Time-to-Replacement (yrs increase)			
	0 yrs	2 yrs	5 yrs	10 yrs	0 yrs	2 yrs	5 yrs	10 yrs
17 (0.50)	21	22	19	0	18	19	16	12
33 (1.00)	21	22	4	0	21	22	20	1

4.3.6. Apply a Premixed Polymer Concrete Overlay

Premixed polymer concrete overlays are typically at least 1 inch thick and consist of a polymeric binder with aggregates. Polyester is most commonly used for this application, although some states have been investigating the use of epoxy in recent years. Unlike multi-layer thin polymer overlays, the resin and aggregates are premixed and then the polymer concrete is placed and screeded on the bridge deck. Aggregates are then broadcast on top of the overlay prior to cure to provide skid resistance. While polyester can fill cracks when the overlay is placed, a methacrylate primer is often used with polyester polymer concrete overlays to prime the deck and penetrate existing cracks. Premixed polymer concrete overlays delaminate over time. For more information regarding premixed polymer concrete overlays, refer to the crack repair profile "Apply a Premixed Polymer Concrete Overlay" in Appendix B.

4.3.6.1. Model Assumptions

Premixed polymer concrete overlays are modeled as a discrete layer on top of the base concrete layer with an assumed diffusion coefficient of 0.005 in^2/yr (similar to thin polymer overlays). Polymer overlays may delaminate from the concrete surface over time. In this study, the premixed polymer concrete was assumed to delaminate according to a Weibull distribution, with a scale parameter of 37 and a shape parameter of 3 (Figure 4.27), which resulted in a 2 percent probability of overlay delamination after 10 years, and 10 percent probability of delamination after 15 years. The life of the premixed polymer concrete overlay was limited to 35 years, after which the overlay is assumed to be fully delaminated. Note that these assumptions were developed for modeling purposes.

An overlay depth of 1.0 inch was assumed for this study. However, to account for anticipated abrasion of the overlay due to traffic and weathering, an effective depth of 0.80 inches was assumed to represent the level of protection provided for modeling purposes. The model also assumed that a depth of 0.50 inches will be milled before the overlay installation if the deck age is 5 years or older. Milling of the top layer, after years of deicing exposure, will remove chloride contaminated concrete and extend the life of the bridge. The propagation time at crack-affected areas was assumed to be similar to the uncracked conditions (15 years) if the overlay is applied at 0 or 2 years of age and decrease if applied later, approaching the value of untreated cracks (10 years) if applied at an age of 10 years or older.

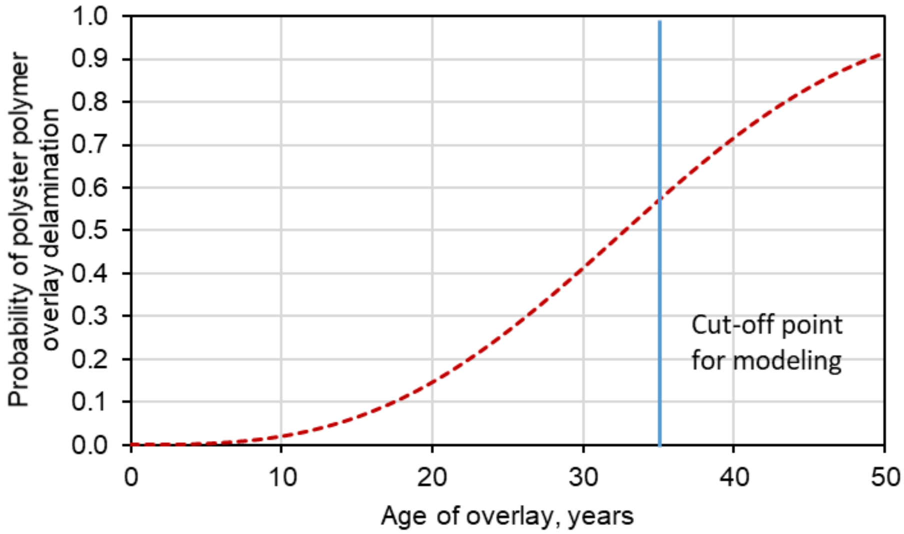

Figure 4.27. Probability distribution function assumed for premixed polymer concrete overlay delamination (Weibull distribution with scale parameter 37 and shape parameter 3)

4.3.6.2. Model Results

The results of modeling a generic Iowa bridge deck with various extents of cracking and treated with a premixed polymer concrete overlay at 0, 2, 5, and 10 years of age are shown in Figure 4.28 and Figure 4.29. Figure 4.28 shows the estimated time-to-5% damage and Figure 4.29 shows the estimated time-to-replacement (i.e., 20% damage).

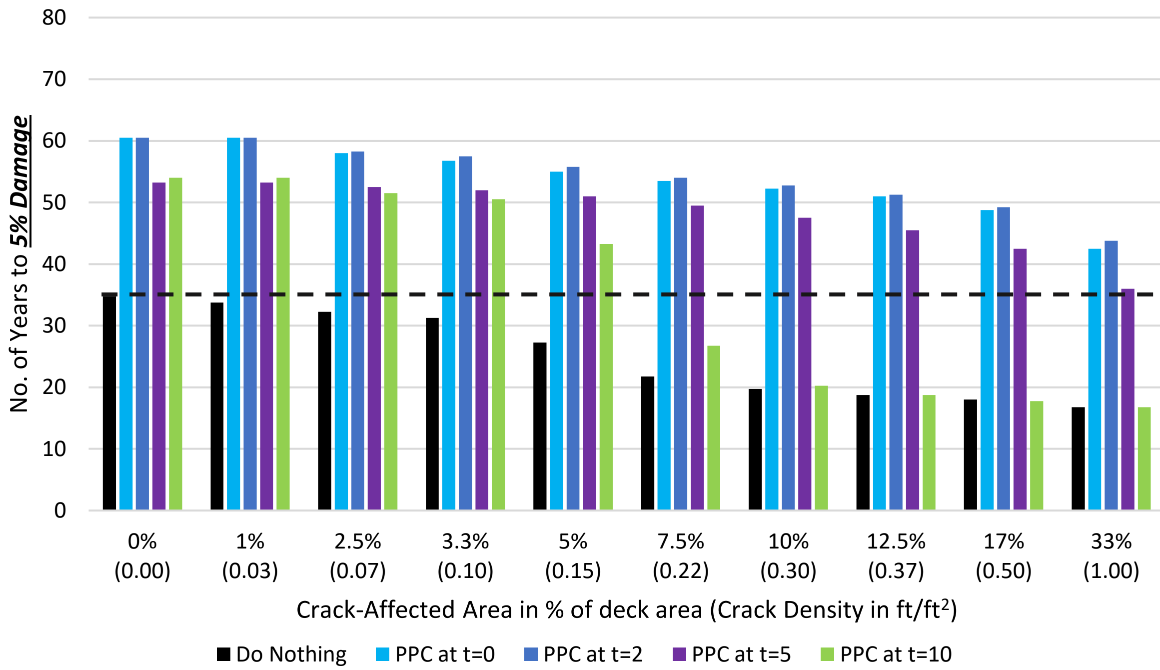

Figure 4.28. Time-to-5% damage for bridge decks treated with a premixed polymer concrete overlay (PPC) at 0, 2, 5, and 10 years of age.

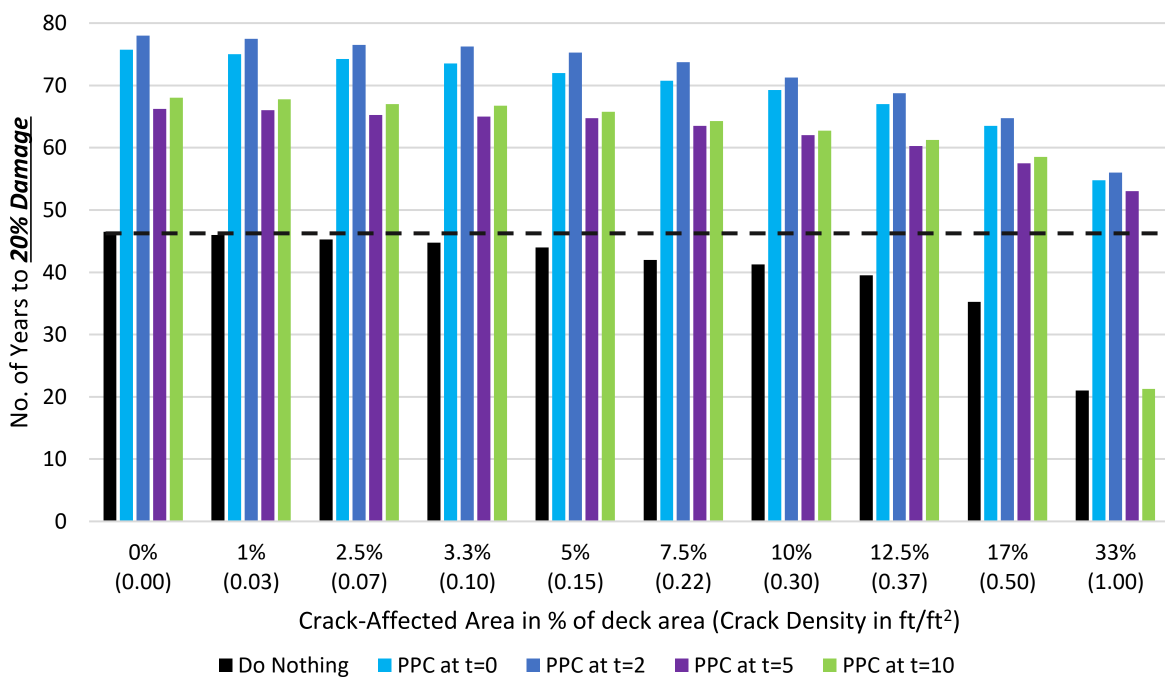

Figure 4.29. Time-to-replacement (i.e., 20% damage) for bridge decks treated with a premixed polymer concrete overlay (PPC) at 0, 2, 5, and 10 years of age.

A PPC overlay provided a substantial benefit for almost all of the crack densities and application ages modeled. Most of the scenarios increased the time-to-5% damage (T_5) to the T_5 of an uncracked, untreated bridge deck; the exceptions were application of a PPC overlay at 10 years and crack densities of 0.22 ft/ft^2 (crack-affected areas of 7.5%) and greater. All of the scenarios modeled increased the time-to-replacement (T_{20}) to the T_{20} of an uncracked, untreated bridge deck except application of a PPC overlay at 10 years and the most severe crack density of 1.00 ft/ft^2 (crack-affected area of 33%). The T_5 and T_{20} of the treated bridge decks was typically between 16 and 35 years greater than those of their untreated counterparts, as shown in Table 4.11, except in the exceptions identified above for which the increase in T_5 and T_{20} was only up to 5 years. For T_5, the largest benefits (30-year increase or greater) were observed when the PPC overlay was placed at 0 to 2 years and for crack densities of 0.22 to 0.50 ft/ft^2 (crack-affected areas of 7.5 to 17%). For T_{20}, the greatest benefits (30-year increase or greater) were observed when the PPC overlay was applied to bridge decks with the greatest crack density of 1.00 ft/ft^2 (crack-affected area of 33%) at ages up to 5 years, or for almost any crack density when the application age was 2 years.

The results reflect that PPC overlays are excellent at protecting crack-affected areas before corrosion is likely to have initiated. The likelihood that corrosion has initiated in a crack-affected area begins to increase dramatically at 5 years of age (Figure 4.7) and as a result, the PPC overlays dramatically lose their benefit when applied to bridge decks at later ages and with large enough crack densities that a sufficient amount of area had initiated corrosion before the PPC overlay was applied.

Table 4.11. Increase in time-to-5% damage and time-to-replacement with respect to untreated, cracked bridge deck when a PPC overlay is applied at different bridge deck ages.

Crack-Affected Area in % (Crack Density in ft/ft^2)	Time-to-5% damage (yrs increase)				Time-to-Replacement (yrs increase)			
	0 yrs	2 yrs	5 yrs	10 yrs	0 yrs	2 yrs	5 yrs	10 yrs
0 (0.00)	26	26	19	19	29	32	20	22
1 (0.03)	27	27	20	20	29	32	20	22
2.5 (0.07)	26	26	20	19	29	31	20	22
3.3 (0.10)	26	26	21	19	29	32	20	22
5 (0.15)	28	29	24	16	28	31	21	22
7.5 (0.22)	32	32	28	5	29	32	22	22
10 (0.30)	33	33	28	1	28	30	21	22
12.5 (0.37)	32	33	27	0	28	29	21	22
17 (0.50)	31	31	25	0	28	30	22	23
33 (1.00)	26	27	19	0	34	35	32	0

4.3.7. Combination of Flood Coats and Polymer Overlay

A potentially effective practice is to use a relatively inexpensive treatment, such as a penetrating sealer or flood coat, shortly after initial construction to preserve the bridge deck and delay corrosion initiation and then apply a more expensive treatment, such as an overlay, at a later date. In this study, the combination of a flood coat placed at initial construction (0 years of age) and either a thin polymer overlay or a premixed polymer overlay after 10 years was investigated.

4.3.7.1. Model Assumptions

The model utilized similar assumptions for flood coats and the thin polymer and premixed polymer overlays as those described in earlier sections of this chapter.

4.3.7.2. Model Results

The results of modeling a generic Iowa bridge deck with various extents of cracking and treated with a flood coat at 0 years of age and a thin polymer overlay or premixed polymer concrete overlay at 10 years of age are shown in Figure 4.30 and Figure 4.31. Figure 4.30 shows the estimated time-to-5% damage and Figure 4.31 shows the estimated time-to-replacement (i.e., 20% damage). The performance of the polymer overlays applied at 10 years without the initial flood coat treatment is shown in the bar graphs for reference.

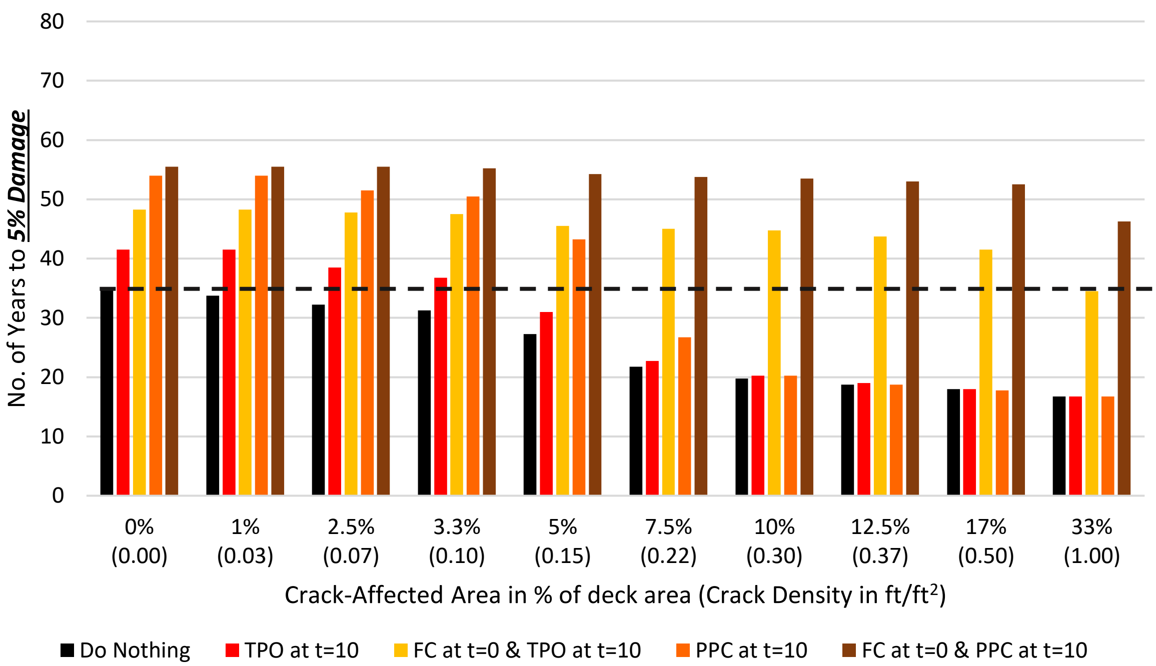

Figure 4.30. Time-to-5% damage for bridge decks treated with a flood coat (FC) at 0 years of age and a thin polymer overlay (TPO) or premixed polymer overlay (PPC) at 10 years of age.

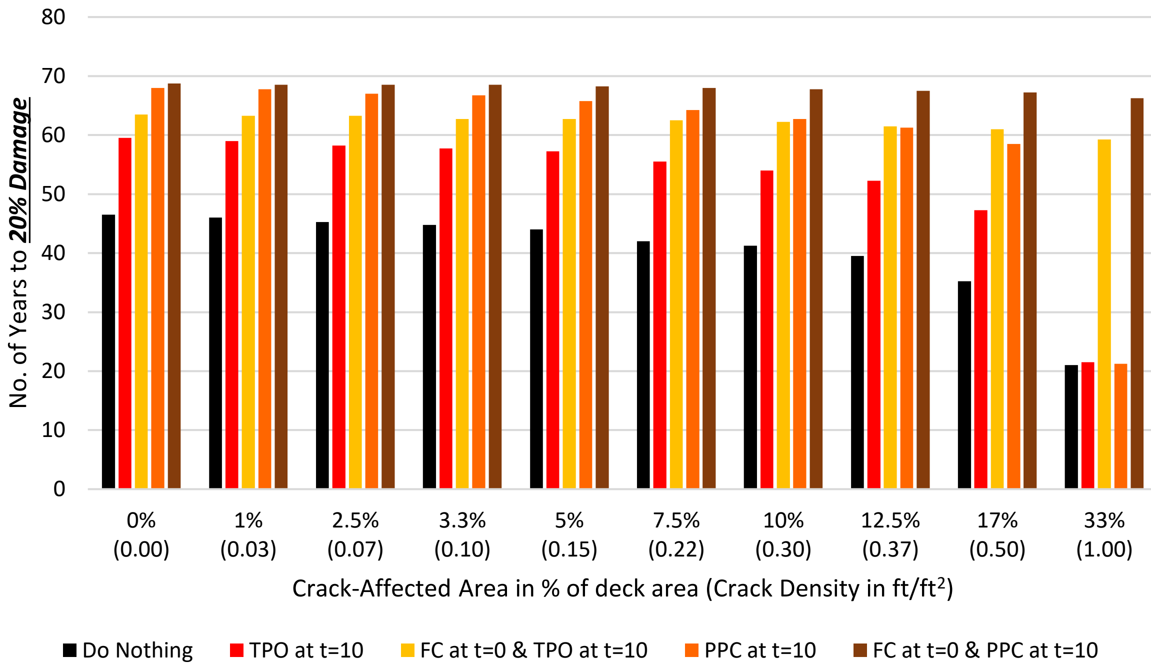

Figure 4.31. Time-to-replacement (i.e., 20% damage) for bridge decks treated with a flood coat (FC) at 0 years of age and a thin polymer overlay (TPO) or premixed polymer overlay (PPC) at 10 years of age.

The models showed that when applying a polymer overlay at 10 years, applying a flood coat immediately after initial construction can improve the benefit of the overlay substantially when the overlay would otherwise have provided little to no benefit due to corrosion initiation prior to its placement. The benefits to time-to-5% damage (T_5) and time-to-replacement (T_{20}) are compared in Table 4.12.

Thin polymer overlays provided relatively small benefits to T_5 of 0 to 8 years when applied at 10 years of age. However, when a flood coat was also applied at 0 years of age, the benefit to T_5 increased to 14 to 25 years. This jump in the benefit to T_5 was particularly prominent at greater crack densities. Where the thin polymer overlay would have had no impact on T_5 if applied at 10 years of age, the initial application of a flood coat permitted the thin polymer overlay to increase T_5 by 18 to 25 years despite the 10-year application age. A similar trend was observed for T_{20}. For crack densities up to 0.50 ft/ft^2 (crack-affected areas up to 17%), a thin polymer overlay with an application age of 10 years increased T_{20} by 12 to 14 years, but this benefit increased to 17 to 26 years when a flood coat was also applied at initial construction. For the most severe crack density modeled, 1.00 ft/ft^2 (crack-affected area 33%), where a thin polymer overlay with an application age of 10 years would have provided a negligible benefit of just 1 year to T_{20}, the use of a flood coat at initial construction increased the benefit of the thin polymer overlay applied at 10 years to a 38-year increase in T_{20}.

Applying a flood coat at initial construction had a similar impact on the benefit of applying a premixed polymer concrete overlay at an application age of 10 years. The impact was small or negligible (0 to 2 year increase in T_5 and T_{20}) at the lowest crack densities of 0.00 to 0.03 ft/ft^2 (crack-affected areas of 0 to 1%) but increased with increasing crack density and was especially pronounced at the greatest crack density modeled, 1.00 ft/ft^2 (crack-affected area 33%), as shown in Table 4.12.

Applying a flood coat at initial construction has a dramatic impact on the benefit of applying a polymer overlay at an age of 10 years due to the timing of the treatments relative to corrosion initiation. The effectiveness of the polymer overlays at extending the time of repair and replacement decreases quickly as the percentage of the deck that is in the corrosion propagation phase at the time of application increases. The flood coat applied at initial construction delays corrosion initiation, particularly in crack-affected areas, thereby lengthening the time over which a polymer overlay can be applied and effectively further delay corrosion initiation and eventual damage. The model results showed that for a generic Iowa bridge deck, a flood coat applied at initial construction can delay corrosion initiation to beyond 10 years in a significant amount of deck area such that polymer overlays, or other treatments that delay corrosion initiation, will remain effective when placed at 10 years. This delay is particularly pronounced for crack-affected areas, for which the model indicated that the likelihood of corrosion initiation began to dramatically increase at approximately 5 years and was approximately 50% at 10 years when left untreated.

Table 4.12. Increase in time-to-5% damage and time-to-replacement with respect to untreated, cracked bridge deck[1].

Crack-Affected Area in % (Crack Density in ft/ft^2)	Time-to-5% damage (yrs increase)				Time-to-Replacement (yrs increase)			
	TPO at 10 yrs	FC at 0 yrs & TPO at 10 yrs	PPC at 10 yrs	FC at 0 yrs & PPC at 10 yrs	TPO at 10 yrs	FC at 0 yrs & TPO at 10 yrs	PPC at 10 yrs	FC at 0 yrs & PPC at 10 yrs
0 (0.00)	7	14	19	21	13	17	22	22
1 (0.03)	8	15	20	22	13	17	22	23
2.5 (0.07)	6	16	19	23	13	18	22	23
3.3 (0.10)	6	16	19	24	13	18	22	24
5 (0.15)	4	18	16	27	13	19	22	24
7.5 (0.22)	1	23	5	32	14	21	22	26
10 (0.30)	1	25	1	34	13	21	22	27
12.5 (0.37)	0	25	0	34	13	22	22	28
17 (0.50)	0	24	0	35	12	26	23	32
33 (1.00)	0	18	0	30	1	38	0	45

[1]FC refers to flood coat, TPO to thin polymer overlay, and PPC to premixed polymer concrete overlay.

4.3.8. Apply a Penetrating Sealer or Flood Coat to Shallow Cracks

This section provides a summary for the modeling effort completed to understand the effect of deck sealers, including penetrating sealers and flood coats, on the service life of bridge decks with shallow cracks. Note that shallow cracks do not have a significant effect on the bridge deck service life as they only affect the top portion of the concrete cover.

4.3.8.1. Model Assumptions

The models utilized similar assumptions for penetrating sealers and flood coats as those described in earlier sections of this chapter.

4.3.8.2. Model Results

The results of modeling a generic Iowa bridge deck with various extents of shallow cracking and treated with a penetrating sealer or treated with a flood coat at 0 or 5 years are shown in Figure 4.32 and Figure 4.33. Figure 4.32 shows the estimated time-to-5% damage and Figure 4.33 shows the estimated time-to-replacement (i.e., 20% damage). As seen in the tables, the effect of shallow cracking on the service life of the deck is much smaller than that of deep cracks, which cause significant reduction in the service life at high crack densities. For shallow cracks, the bridge deck loses about 4 years of the time-to-5% damage and 3 years of the time-to-replacement at the highest crack density. The benefits to time-to-5% damage (T_5) and time-to-replacement (T_{20}) are compared in Table 4.13.

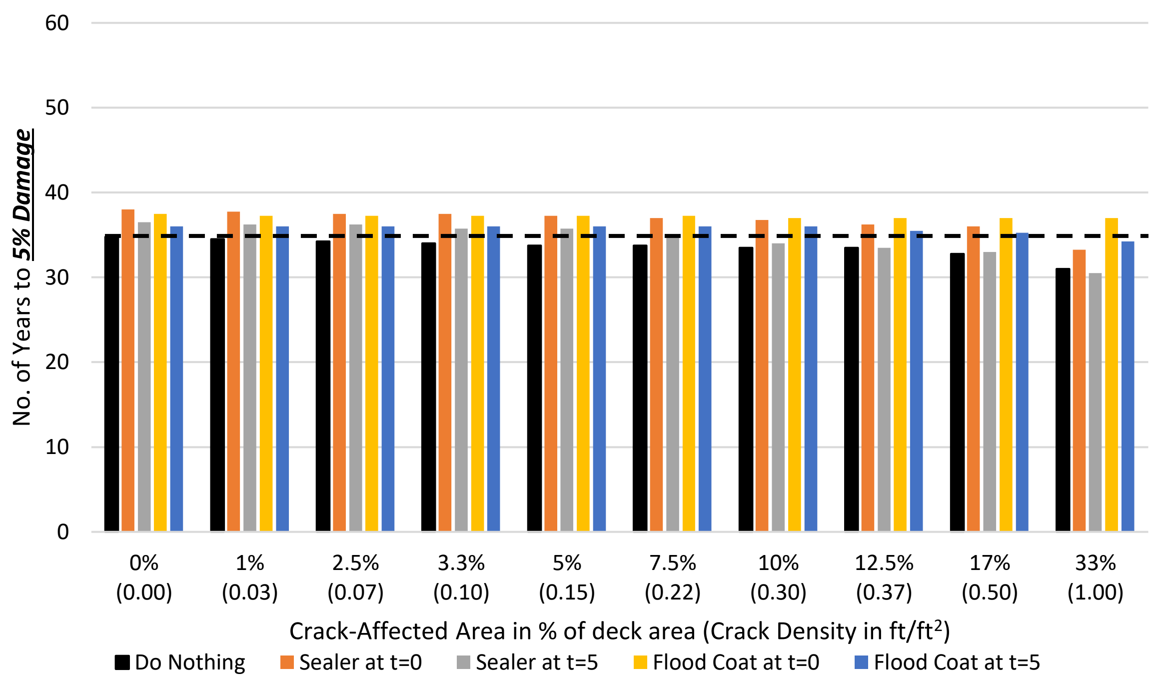

Figure 4.32. Time-to-5% damage for bridge decks treated with a penetrating sealer or flood coat applied on bridge decks with shallow cracks at deck age of 0 and 5 years.

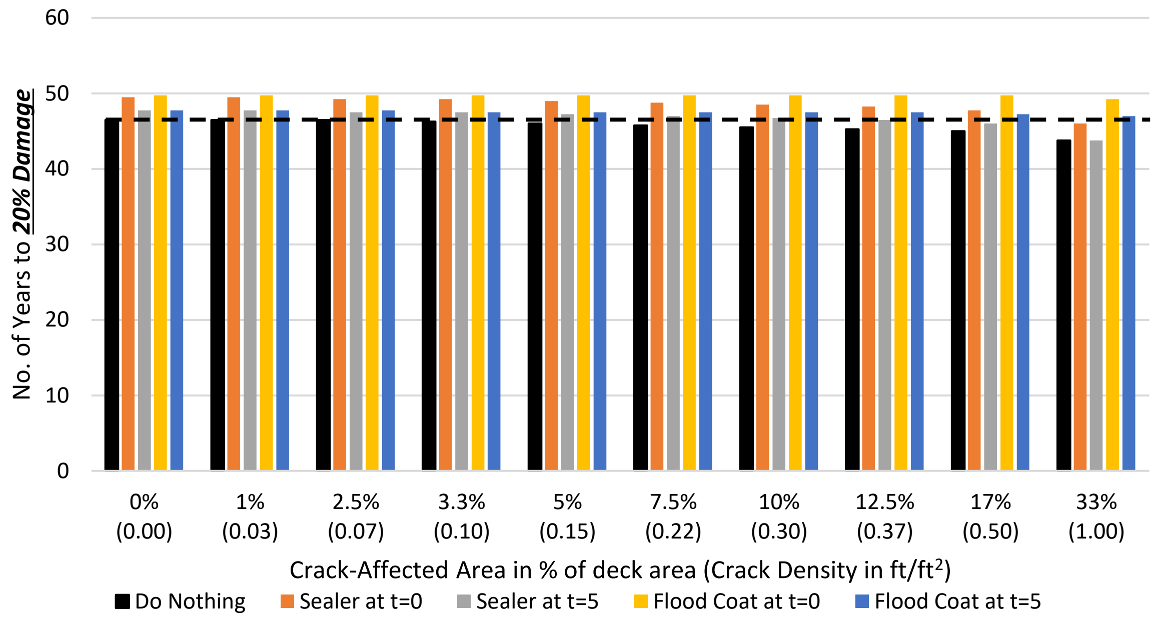

Figure 4.33. Time-to-replacement (i.e., 20% damage) for bridge decks treated with a penetrating sealer or flood coat applied on bridge decks with shallow cracks at deck age of 0 and 5 years.

Table 4.13. Increase in time-to-5% damage and time-to-replacement with respect to untreated, shallow cracked bridge deck when penetrating sealer or a flood coat are applied at different bridge deck ages.

Crack-Affected Area in % (Crack Density in ft/ft^2)	Time-to-5% damage (yrs increase)				Time-to-Replacement (yrs increase)			
	PS at 0 yrs	PS at 5 yrs	FC at 0 yrs	FC at 5 yrs	PS at 0 yrs	PS at 5 yrs	FC at 0 yrs	FC at 5 yrs
0 (0.00)	3	2	3	1	3	1	3	1
1 (0.03)	3	2	3	2	3	1	3	1
2.5 (0.07)	3	2	3	2	3	1	3	1
3.3 (0.10)	4	2	3	2	3	1	4	1
5 (0.15)	4	2	4	2	3	1	4	2
7.5 (0.22)	3	1	4	2	3	1	4	2
10 (0.30)	3	1	4	3	3	1	4	2
12.5 (0.37)	3	0	4	2	3	1	5	2
17 (0.50)	3	0	4	3	3	1	5	2
33 (1.00)	2	0	6	3	2	0	6	3

[1]PS refers to penetrating sealer and FC refers to flood coat

4.4. Results Summary and Discussion

Bar graphs comparing the benefits of each crack repair or treatment to the time-to-5% damage and time-to-replacement when applied at 0 years are shown in Figure 4.34 and Figure 4.35, respectively. Similar bar graphs for an application age of 5 years are shown in Figure 4.36 and Figure 4.37, and for an application age of 10 years are shown in Figure 4.38 and Figure 4.39. The findings from the service life modeling are summarized as follows:

- Penetrating sealers are good for extending the time-to-5% damage and time-to-replacement by 2 to 6 years. They are most beneficial when the crack density is low and must be applied at early ages before crack-affected areas have begun to corrode in order to be effective.
- Flood coats can extend the time-to-5% damage and time-to-replacement by up to 12 to 18 years. They provide the greatest benefit to time-to-5% damage at mid- to high crack densities (between 0.22 ft/ft^2 and 0.50 ft/ft^2; crack-affected areas between 7.5% and 17%), and the greatest benefit to time-to-replacement at more severe crack densities (0.50 ft/ft^2 and greater; crack-affected areas of 17% and greater). Flood coats are also best applied at early ages of 0 to 2 years, but can still provide more modest benefits of 5 to 10 years to time-to-5% damage or time-to-replacement when applied at a later age of 5 years for bridge decks for crack densities between 0.15 ft/ft^2 and 0.50 ft/ft^2 (crack-affected areas between 5% and 33%) and crack densities greater than 0.37 ft/ft^2 (crack-affected areas greater than 12.5%), respectively.
- HMA overlays with waterproofing membranes are good for extending the time-to-5% damage and time-to-replacement by approximately 5 to 10 years when applied at early ages of 0 to 2 years, and ineffective when placed at later ages of 5 or 10 years. Unlike sealers, which provide better benefits to bridge decks with little cracking, HMA with waterproofing membranes provide better benefits to bridge decks with larger crack densities (0.15 ft/ft^2 and greater, crack-affected areas of 5% and greater).
- Thin polymer overlays can increase the time-to-5% damage and time-to-replacement by approximately 17 to 22 years if applied at early ages of 0 to 2 years, regardless of crack density. They can still provide similar benefits to the time-to-5% damage when applied at 5 years for crack densities up to 0.50 ft/ft^2 (crack-affected areas up to 17%) and can still increase the time-to-replacement by 10 to 20 years when applied at 5 or 10 years regardless of crack density, with the exception of the greatest crack density assessed, 1.00 ft/ft^2 (crack-affected area of 33%). Their benefit decreases with application age, and they are ineffective when placed at later ages on bridge decks with more severe crack densities.
- Premixed polymer concrete overlays follow the same trends as thin polymer overlays; they are most-effective under the same conditions that thin polymer overlays are. However, because of their thicker nature, premixed polymer concrete overlays can increase the time-to-5% damage and time-to-replacement by a greater amount, up to 35 years.

The application ages and crack densities for which each crack repair or treatment is at its most effective, when the treatment is moderately effective, and when it is ineffective are identified in the heat maps shown in Figure 4.40. This was calculated based on comparing the benefits of each crack remediation option to the do nothing case. The key parameters that control when each crack repair or treatment is effective are the corrosion initiation time and the threshold damage percentages at which repair and replacement are triggered.

4.4.1. Corrosion Initiation Time

As shown in section 4.2.5, the baseline model results showed that corrosion initiation begins to increase steadily at approximately 5 years for cracked areas and 17 years for uncracked areas. The percentage of corrosion initiation reached 5% at 5 years and 20 years for crack-affected areas and uncracked areas, respectively, and 20% at 7 years and 32 years, respectively.

The corrosion initiation time of the crack-affected areas coincides with the application age above which flood coats and polymer overlays lose their effectiveness on crack-affected areas quickly. For example, for T_5 and at crack densities corresponding to crack-affected areas greater than the 5% repair threshold (with the exception of the greatest crack density considered), the benefit of a thin polymer overlay decreased from approximately 20 years at an application age of 5 years to 0 to 1 years at an application age of 10 years. For T_{20}, the abrupt decrease in effectiveness after 5 years occurred at the one crack density that corresponded to a crack-affected area greater than 20%.

The corrosion initiation time of the crack-affected areas also coincides with the application age at which penetrating sealers and HMA overlays with waterproofing membranes were no longer effective, 5 years, but this is because the build-up time assumed in the modeling was 5 years. The penetrating sealers and HMA overlays with waterproofing membranes were modeled by assuming they slowed the build-up of the surface chloride concentration, and therefore application after the maximum surface chloride concentration was assumed achieved in the model provided limited benefit to crack-affected or uncracked areas.

Only application ages of up to 10 years were considered since the scope of this work was focused on appropriate crack repairs and treatments for newly-constructed and young bridge decks. As a result, the impact of the corrosion initiation time of uncracked areas, approximately 20 years, on repair/treatment effectiveness was not observed.

To a certain extent, the correlation between corrosion initiation time and application age at which effectiveness decreases is due to the manner in which the crack repairs and treatments were modeled. Service life modeling typically models the corrosion initiation phase in great detail and simply assumes a constant value for the corrosion propagation phase. This is because once corrosion has initiated, damage is expected to follow quickly, i.e. the initiation phase is typically longer than the propagation phase. In this report, the completed service life models were based on assumptions that consider the effect of cracking and repair remediation options on both the initiation and propagation phases.

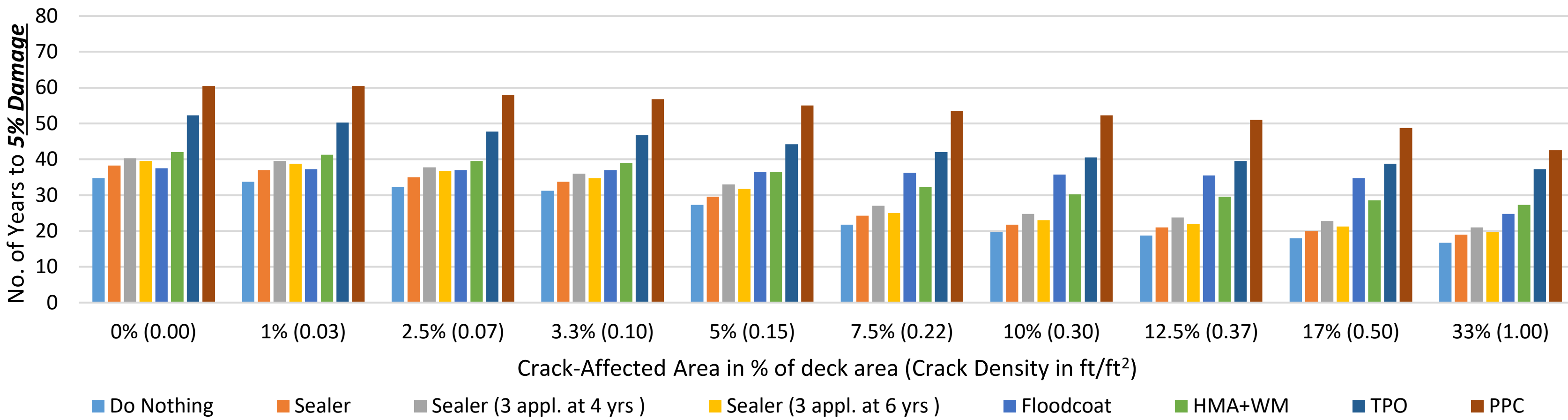

Figure 4.34. Time-to-5% damage (T_5) estimated for generic Iowa bridge decks with a range of crack densities and crack repairs or treatments applied at a bridge deck age of 0 years.

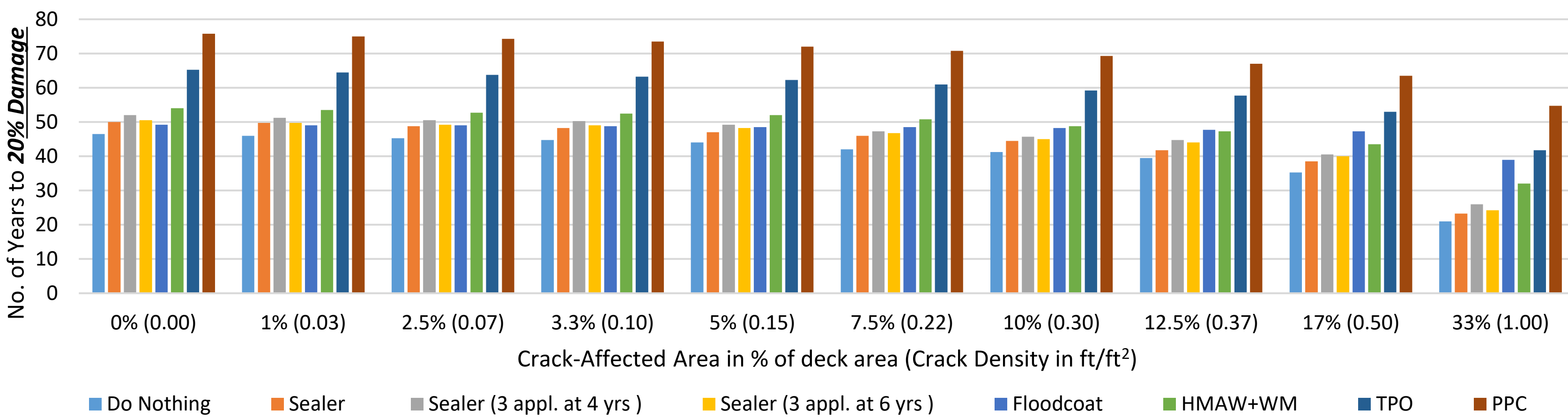

Figure 4.35. Time-to-replacement (T_{20}) estimated for generic Iowa bridge decks with a range of crack densities and crack repairs or treatments applied at a bridge deck age of 0 years.

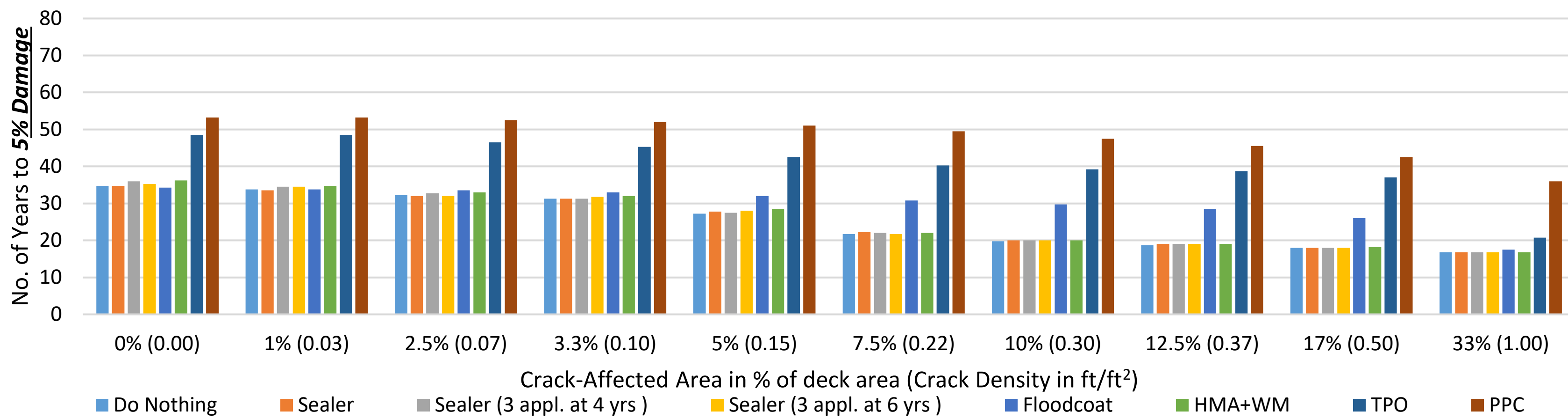

Figure 4.36. Time-to-5% damage (T_5) estimated for generic Iowa bridge decks with a range of crack densities and crack repairs or treatments applied at a bridge deck age of 5 years.

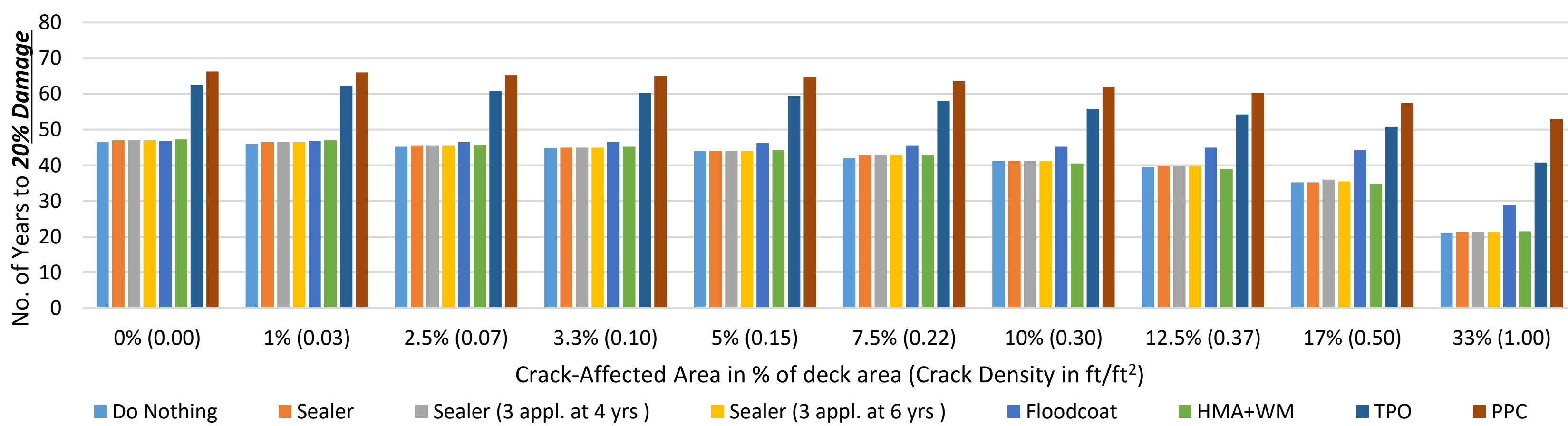

Figure 4.37. Time-to-replacement (T_{20}) estimated for generic Iowa bridge decks with a range of crack densities and crack repairs or treatments applied at a bridge deck age of 5 years.

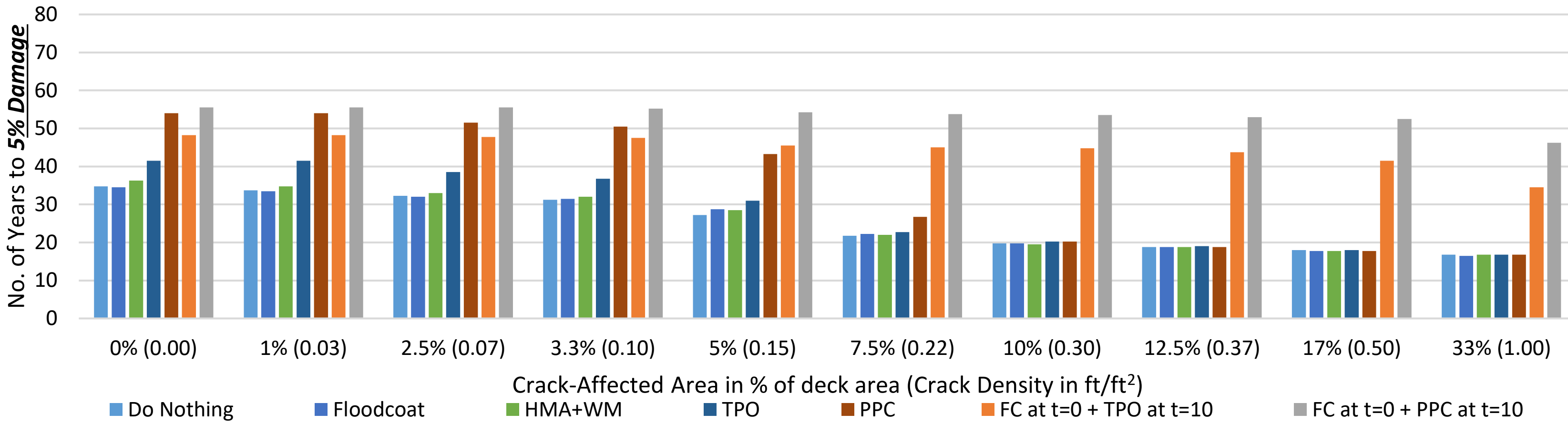

Figure 4.38. Time-to-5% damage (T_5) estimated for generic Iowa bridge decks with a range of crack densities and crack repairs or treatments applied at a bridge deck age of 10 years.

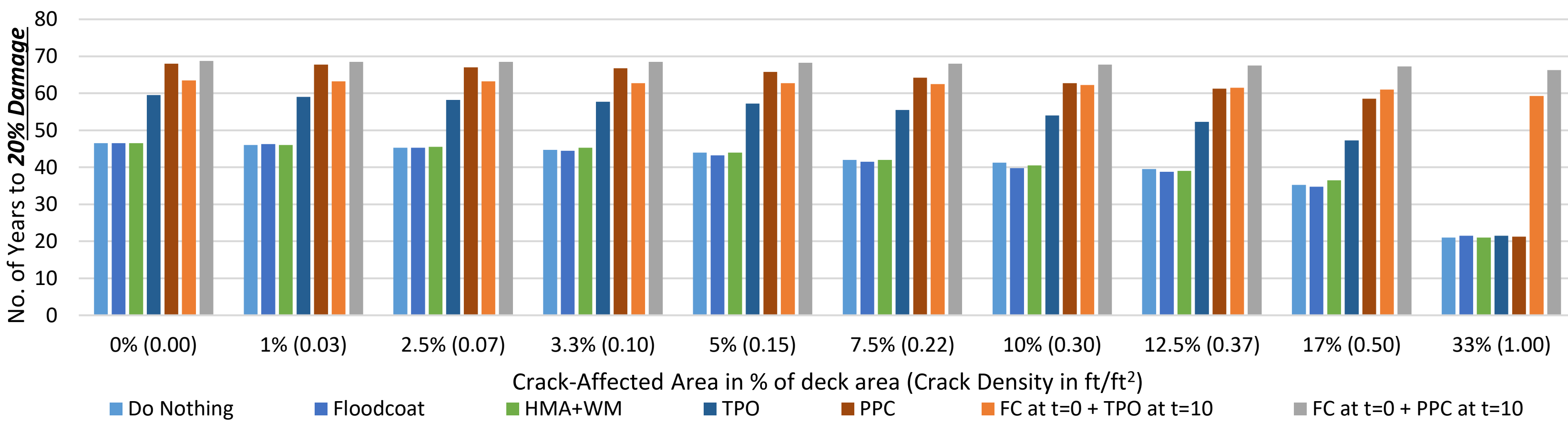

Figure 4.39. Time-to-replacement (T_{20}) estimated for generic Iowa bridge decks with a range of crack densities and crack repairs or treatments applied at a bridge deck age of 10 years.

4.4.2. Thresholds for Repair and Replacement

There are also clear correlations between the thresholds selected for bridge deck repair and replacement and the crack-affected area above which the crack remediation options were more or less effective. For example, flood coats, which primarily impacted crack-affected areas and provided little to negligible benefit to uncracked areas in the models, provided their best benefit to T_5 at crack densities corresponding to crack-affected areas of 7.5% to 17% and their best benefit to T_{20} at crack densities of 17% and 33% (when applied prior to corrosion initiation, as discussed above). This same trend was also observed for the polymer overlays, although only at later application ages. The difference is due to the fact that unlike flood coats, polymer overlays are robust enough to provide a substantial benefit to the life of uncracked bridge deck areas. As a result, they provide a similar benefit to uncracked and crack-affected areas when applied at early ages before corrosion initiation of the crack-affected areas.

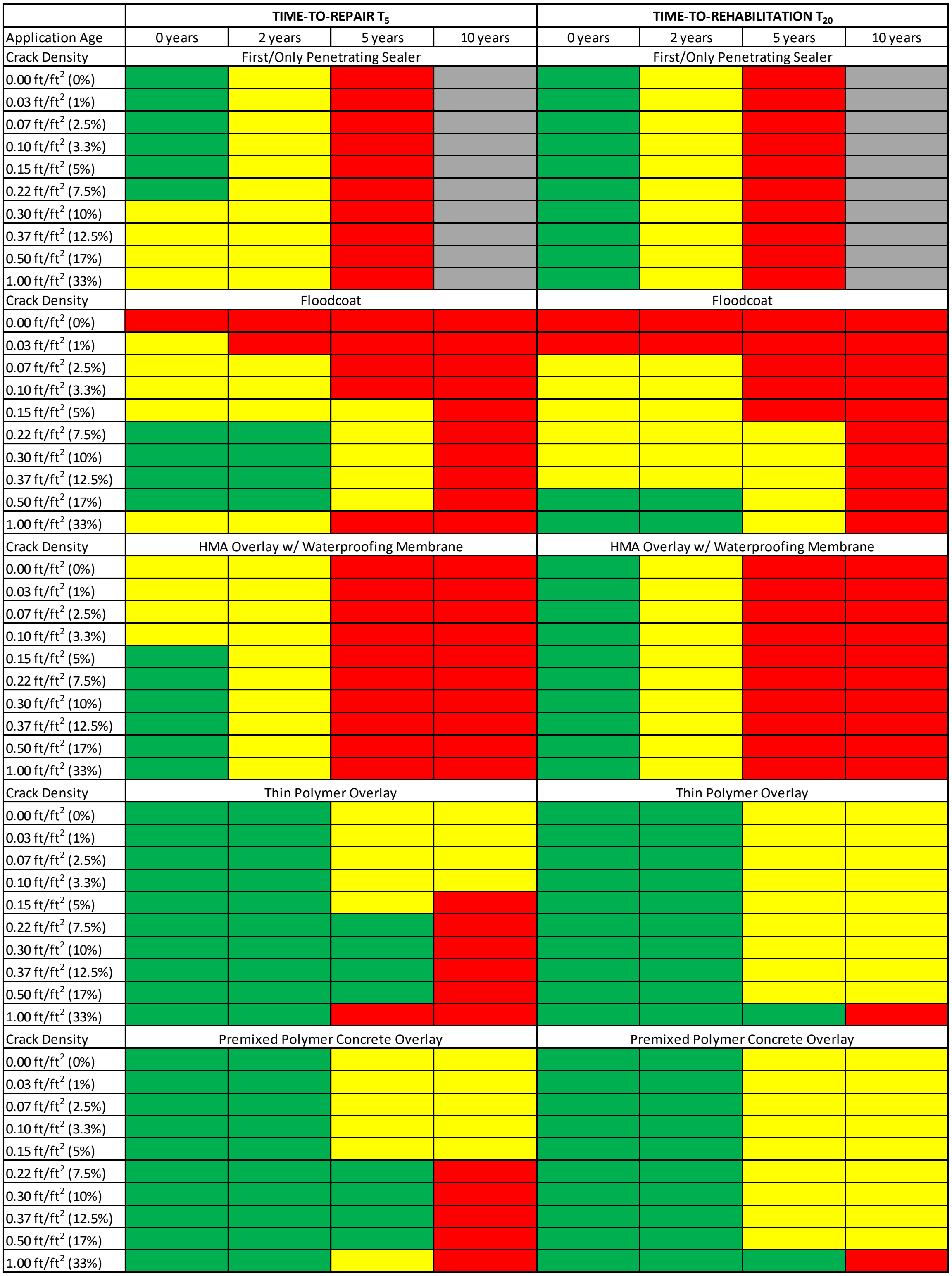

Figure 4.40. Heat map showing crack densities and application ages at which each treatment is at its most effective (green), moderately effective (yellow), and ineffective (red) at increasing time-to-5% damage T_5 or time-to-replacement T_{20}. All comparisons were made against the do nothing case. Grey indicates the scenario was not modeled.

CHAPTER 5. DATA-DRIVEN DECISION TREES

This chapter summarizes the development of data-driven decision trees to guide the selection of optimal crack remediation techniques for bridge decks. The methodology, assumptions and analyses completed to develop the decision trees are presented in the following sections.

5.1. Methodology

The main purpose of this project was to develop a comprehensive guide to remediate early-age cracks in bridge decks. An important step in this is to develop decision trees that utilize information related to deck condition, age, and crack characteristics to select the most appropriate and cost-effective crack remediation technique for the bridge's particular conditions. For the purpose of this guide, the following factors were considered in the decision trees' development. Figure 5.1 shows a schematic for how the different factors are used in the decision trees.

- **Deck Age:** The age of the deck is an important factor to consider when selecting crack remediation techniques. This is evident from the results reported in Chapter 4, which showed that the effectiveness of some remediation techniques decreases significantly with the increase in deck age when the repair is implemented. Age effects are primarily related to the amount of deicer salt that has been applied to the deck. Note that this guide only focuses on early-age cracking for decks with an age of 10 years or less.
- **Crack Classification:** As explained in Section 3.3, cracks are classified as either shallow cracks that do not reach the deck reinforcement (typically map cracks) or deep cracks that will allow chlorides and moisture to directly access the reinforcing steel in the deck. This classification will guide the user to different decision trees or crack remediation techniques that were developed for each case.
- **Crack Width:** Crack width information is mainly used to exclude some crack remediation options as appropriate treatments for bridge decks having wide cracks. This assumes that some options are not effective when used with cracks exceeding a certain width. Crack width in this chapter is provided in mils (where 1 mil = 0.001 inch).
- **Crack Density:** This factor is used to define the extent of cracking in a given bridge deck. As shown in Chapter 4, crack-affected area plays an important role in the service life of bridge decks. For the purpose of this guide, crack density is used as an input for the decision trees and can be calculated as the total length of cracks, within each crack classification, divided by total inspected area. It is noted that the area considered to calculate a deck crack density to guide repair selection has a significant effect on the calculated crack density. The relationship between crack density and crack-affected area is shown below, which assumes that each crack affects approximately 2 inches of concrete on each side of the crack.

$$Crack\ Affected\ Area\ (\%) = \frac{4}{12}(ft) \times Crack\ Density\ (ft/ft^2) \times 100$$

- **Crack Remediation Options:** This includes the different repair options considered for early-age cracking. Note that some crack remediation options were excluded based on the assumptions outlined in Chapter 4.

- **Initial Cost:** This factor provides an estimate for additional investment needed at the time of construction, or the selected application age (up to 10 years), to remediate cracking and increase the service life of the bridge deck. Additional details are provided in Section 5.2. This is one of the factors that can be considered when choosing between multiple crack remediation options for a cracking scenario.
- **Time-to-5% Damage (T_5):** This factor provides an estimate of the time it will take for the bridge deck to reach the damage threshold at which bridge deck repairs will be needed. Since the repair threshold will differ based on many variables, it was assumed that partial-depth repairs will be required when the amount of damage reaches approximately 5% of the deck area. This factor was determined using the service life analysis results presented in Chapter 4. This is one of the factors that can be considered when choosing between multiple crack remediation options for a cracking scenario.
- **Time-to-Replacement (T_{20}):** This factor provides an estimate for the end of service life of the bridge deck. It was assumed that bridge deck replacement will be required at a damage level of 20% of the deck area. This factor was determined using the service life analysis results presented in Chapter 4. This is one of the factors that can be considered when choosing between multiple crack remediation options. Note that in practice other options, such as rehabilitation with a rigid cementitious overlay, could be implemented instead of bridge deck replacement, which was assumed in this analysis for simplicity. End-of-life rehabilitation options are outside of the scope of this report.
- **Life-Cycle Cost:** This is the main factor for information regarding cost-benefit ratio of the different crack remediation options. Note that the life-cycle cost is highly dependent on the service life, i.e. time-to-replacement (T_{20}), of the deck as well as the extension achieved by different crack remediation factors. This is one of the factors that can be considered when choosing between multiple crack remediation options for a cracking scenario. Additional details are provided in Section 5.2.

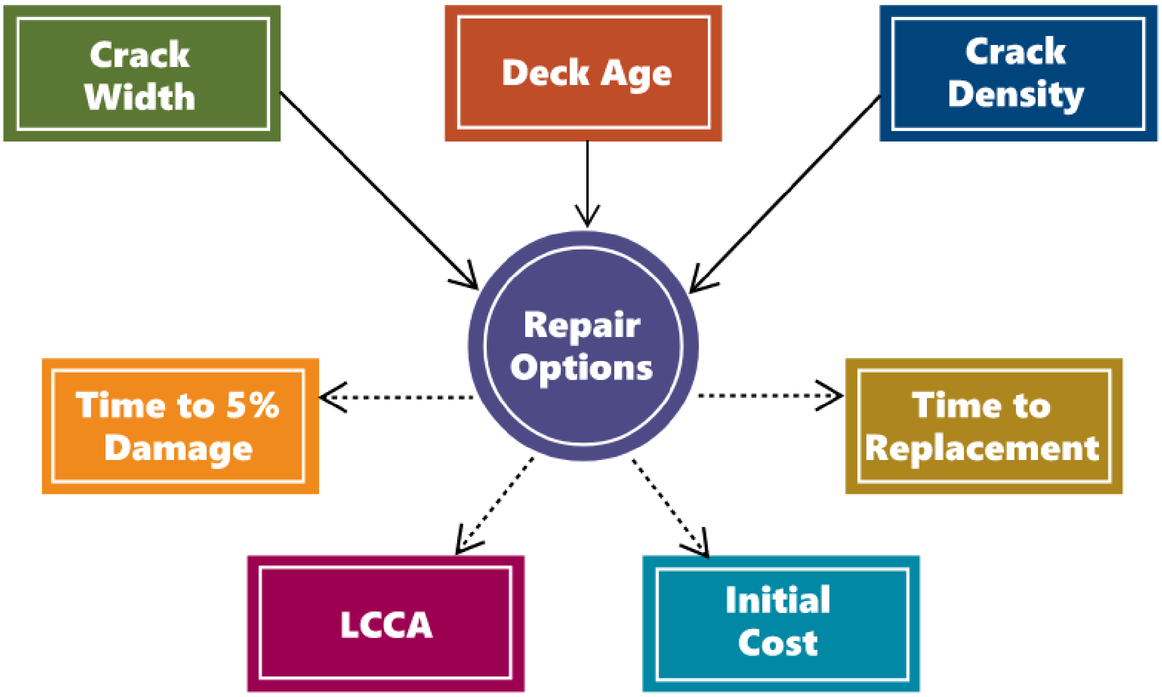

Figure 5.1. A schematic showing the different inputs and outputs considered in the decisions trees.

5.2. Cost Analysis

The selection of optimal early-age cracking remediation options is partially dependent on the cost-effectiveness of the repair, both in terms of initial investment and life-cycle cost. As such, initial investment and life-cycle cost information should be used to direct the decision-making process. Both initial cost and life-cycle cost are considered as shown in the following sections.

5.2.1. Initial Cost

A portion of the literature review effort was focused on compiling cost information for the different crack remediation options as shown in Appendix B. This information was mainly obtained from bid tabulations across a number of states with a focus on Iowa; information from other states was collected when not found within Iowa DOT letting data. Table 5.1 shows a summary of the average unit costs for the different crack remediation options considered for the decision trees. Note that the average value was used instead of a range for each option for simplicity. Also note that the cost for premixed polymer overlay is less than that shown in Appendix B as it is assumed that only a 3/4-inch overlay will be placed for preservation/crack remediation purposes instead of a 2-inch overlay, as was assumed for the cost shown in Appendix B.

Table 5.1. Summary of unit costs of different remediation options considered for the decision trees

Crack Remediation Option	Average Unit Cost	Source (State Letting Data)
Penetrating Sealer	$8.6 per SY	Illinois
Crack Chasing	$8.4 per LY	Minnesota
Flood Coat	$24.5 per SY	Minnesota
HMAWM	$82.7 per SY	Iowa, South Dakota, Michigan
Thin Polymer overlay	$66.4 per SY	Iowa, South Dakota
Premixed Polymer Overlay*	$135.9 per SY	Iowa, South Dakota, California

*Cost assumes an overlay thickness of 3/4 inch

5.2.2. Life-Cycle Cost Analysis

Life-cycle cost analysis (LCCA) was completed to compare the different crack remediation options and do nothing scenarios. Typically two types of costs can be considered in this analysis: agency costs and user costs. For the purpose of this study, only agency costs were considered. The time range for the analysis was selected to be 100 years, so the cost analysis considers the long-term benefits of the crack remediation options.

In order to conduct LCCA, both the cost of construction and maintenance were considered in conjunction with their respective service life. At the end of the service life, it was assumed that the bridge deck will be replaced with a new uncracked bridge deck, which is the base case for comparison. The cost for bridge deck replacement was obtained from Iowa DOT 2020 letting data, which was approximately $900 per square yard. This cost was also assumed for construction of a new bridge deck. At the end of the analysis period (100 years), the salvage value of the deck was calculated to represent its remaining worth. At the start of its life, the bridge deck was assumed to have an asset value equal to $900 per square yard times the deck area. At the end of its life, the deck was assumed to have a value of zero. The salvage value is used to compare options and was estimated by interpolation based on the remaining service life of the bridge deck (ElBatanouny et al. 2020).

It was assumed that the bridge deck will reach the end of its service, and be in need of replacement, when bridge deck damage reaches the 20% threshold (time-to-replacement, T_{20}). This information was obtained from the service life analysis results shown in Chapter 4. As an example, Figure 5.2 shows a graphical presentation of the different costs and service life considered for the base case, i.e., the uncracked bridge deck with no repairs, and the case where a penetrating sealer was used on a bridge deck with a crack density of 0.10 ft/ft^2 with three reapplications applied in increments of 6 years.

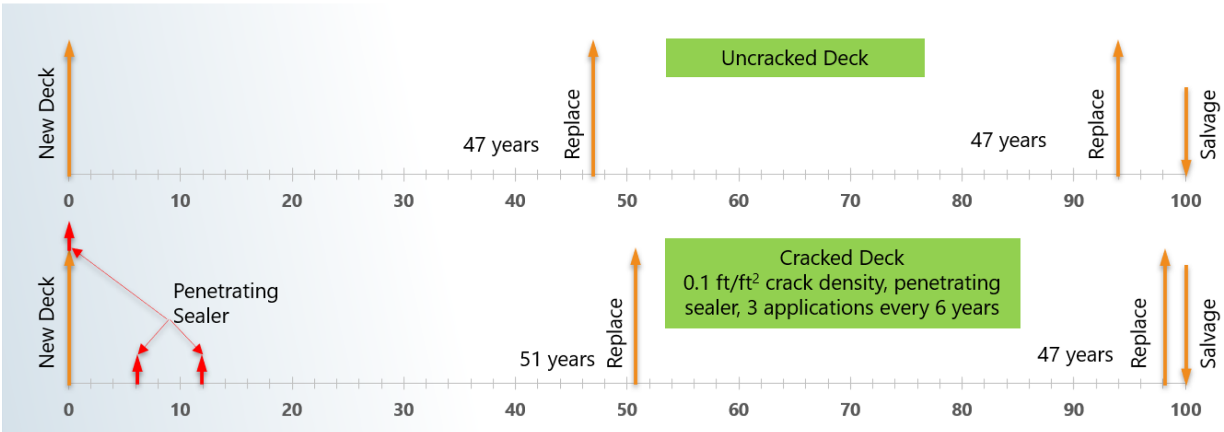

Figure 5.2. Graphical representation of two life-cycle cost analysis cases; base case with uncracked bridge deck and no repairs (top), and a case for a bridge deck with 0.10 ft/ft^2 crack density with three penetrating sealer surface applications at 6-year intervals starting at a deck age of 0 years (bottom). The latter scenario captured the added benefit of sealer applications to the entire deck surface, not just cracked areas.

To calculate the life-cycle cost, the present value was calculated for all the current and future costs. Future costs not incurred in the current year were discounted according the equation below.

$$PV = FV_n \frac{1}{(1+r)^n}$$

Where PV is the cost in the present (called the present value), FV_n is the cost n years from now (called the future value), and r is the discount rate. In accordance with common practice, the discount rate assumed was 4%. The present value was then used to compare the life-cycle cost of the remediated bridge decks, both uncracked and cracked, versus the base case of an untreated, uncracked bridge deck.

5.3. Data-Driven Decision Trees

This section summarizes the processes and analyses completed to create the decision trees to be used for selecting the most cost-effective crack remediation options based on bridge deck characteristics; namely deck age, crack width, and crack density. As noted in Chapter 4, the timing of the crack remediation application with respect to deck age has a significant effect on the rate of damage accumulation on the deck surface after applying the repair, i.e., the time-to-repair (T_5) and time-to-replacement (T_{20}). As such, three different decision trees were developed based on the deck age when the crack remediation options are applied as follows:

- Deck age between 0 and 2 years
- Deck age of approximately 5 years
- Deck age of approximately 10 years

Note that deck ages exceeding 10 years were excluded from the analysis as at this point sufficient deicer salts would have entered the deck, especially at cracked locations, such that a more robust remediation strategy beyond treating the cracks would be needed.

The main input that influences the impact of cracking on the service life of the deck is the crack density, as shown in Chapter 4. The four crack density ranges proposed in Chapter 4 were shown to provide similar service life expectancy for the different cases considered and, as such, were used to categorize crack density in the decision trees as shown below:

- Mild Cracking: Crack density less than 0.10 ft/ft^2
- Moderate Cracking: Crack density between 0.10 and 0.22 ft/ft^2
- Severe Cracking: Crack density between 0.22 and 037 ft/ft^2
- Very Severe Cracking: Crack density more than 0.37 ft/ft^2

Based on the deck age at the time of crack remediation application and the crack density, the time to reach the 5% damage threshold (time-to-5% damage, T_5) and the 20% damage threshold (time-to-replacement, T_{20}) was determined from Chapter 4. Then life-cycle cost for the different analysis cases was calculated as described in Section 5.2, Cost Analysis.

A summary of all the completed analyses is provided in three tables in Appendix D, where each table provides the results for applying the different crack remediation options at different deck ages of: between 0 and 2 years, at 5 years, and at 10 years. The tables include a summary of 87 analysis cases, which are considered a summary of the service life modeling cases completed and shown in Chapter 4. Based on the deck age in years and crack density in ft/ft^2, each table provides information for the different crack remediation options including initial cost of crack remediation in $ per unit area or length, time to reach the 5% damage threshold (T_5) in years, time to reach the 20% damage threshold (T_{20}) in years, and the life-cycle cost in $1,000. Crack width data is included as notes for each of the tables to limit the use of crack remediation options that would be ineffective or otherwise poor choices due to the crack width.

5.3.1. Basis for Decision Trees

To highlight the benefits of the different crack remediation options, a comparative analysis was completed by comparing the results of all the considered analysis cases in the tables shown in Appendix D to the cracked behavior at each assumed crack density as well as the base case of an uncracked bridge deck. This was done to highlight the benefits of applying crack remediation options in terms of service life characteristics, i.e., time-to-5% damage, time-to-replacement, and life-cycle cost. Note that the life-cycle cost for the crack remediation options is lower when compared to do nothing case for a bridge deck with the same crack density while it could be higher than the uncracked bridge deck case. Table 5.2 to Table 5.7 provide a summary of the comparative analysis completed at the three deck ages considered, where each deck age analysis includes two tables one comparing the crack remediation options to the do nothing scenario at the same crack density while the second compare all the options to a base case on uncracked, untreated bridge deck.. These six tables provide the basis and the source information for the decision trees presented in this chapter. Note that the following conditions apply to all the decision trees:

1. Crack densities exceeding 0.37 ft/ft^2 shall be investigated prior to implementation of repairs.
2. Crack widths between 30 mils and 40 mils with a crack density exceeding 0.10 ft/ft^2 shall be investigated prior to implementation of repairs.
3. The decision trees do not apply to crack densities exceeding 0.50 ft/ft^2 or crack widths exceeding 40 mils.

4. Crack width information is used to exclude crack remediation options from selection. For this guide, it will be assumed that if 25% of the deck cracks exceed the crack width limit for a given option, then that option should be excluded from viable options.

All the text in the tables is color coded where green text indicates a favorable condition compared to the do nothing or base case of uncracked concrete deck depending on the table (higher time-to-5% damage, higher time-to-replacement, or lower life-cycle cost) while the red text indicates an unfavorable comparison. Black text is used for neutral comparisons. Generally, the following nine crack remediation cases are considered in each table:

- Do Nothing
- Penetrating Sealer, 1 application
- Penetrating Sealer, 3 applications at 6-year intervals
- Penetrating Sealer, 3 applications at 4-year intervals
- Crack-Chasing with a Gravity-Fed Polymer
- Flood Coat
- Hot-Mixed Asphalt with Waterproofing Membrane (HMAWM)
- Thin Polymer Overlay
- Premixed Polymer Concrete Overlay

The data provided in Table 5.2 to Table 5.7 can be used for selection of the optimal crack remediation option by considering different inputs and outputs provided in the tables. However, because the tables are large and difficult to read, less detailed but more user-friendly tables were developed as described in the following sections.

5.3.2. Detailed Decision Trees

Three detailed decision trees for the selection of optimal crack remediation options for bridge decks 0 to 2 years in age, approximately 5 years in age, and approximately 10 years of age were developed and are shown in Table 5.8 to Table 5.10, respectively. The decision trees are a further simplification of the data provided in Appendix D and Table 5.2 to Table 5.7. The proposed decision trees can be used to select viable crack remediation options based on the crack density and crack width information in conjunction with analysis output including initial cost of crack remediation ($/SY), time to reach the 5% damage threshold (T_5) in years, time to reach the 20% damage threshold (T_{20}) in years, and the life-cycle cost in % as compared to the do nothing scenario at the same crack density or base case of uncracked, untreated bridge deck. These analyses highlight the advantages and disadvantages of each crack remediation option. Therefore, the provided decision trees can be utilized as a data-driven tool for selection of the optimal crack remediation options based on the specific conditions of the bridge deck of interest but should be used with proper judgement and experience.

As shown in previous decision trees in Appendix D and Table 5.2 to Table 5.7, the HMAWM option was considered. This option was excluded from the list of viable crack remediation options as it was always associated with a high life-cycle cost (even higher than the do nothing case for some crack densities) and low service life benefits compared to the other overlay options. As can be seen, at low crack densities and a deck age less than 2 years, penetrating sealers and flood coat options provide benefits in terms of service life extension at low initial cost and life-cycle cost. As the crack density increases to severe or very severe, the penetrating sealer options become essentially excluded and the polymer overlay options emerge as a suitable option to restore or extend service life of more severely cracked bridge decks. For a deck age of 5 years, a substantial reduction of the benefits of all the remediation options is observed, especially for the time to reach 5% damage threshold (T_5) as would be expected for decks receiving annual deicer applications. As crack repairs are delayed some of the remediation options, particularly the penetrating sealers and flood coats, provide a smaller service life compared to the uncracked, untreated bridge deck base case; however, flood coats still provide substantial benefits compared to the do nothing scenario. As such, the delay in repair application shifts the analysis to favor installation of a more robust preservation option (thin polymer overlay or premixed polymer concrete overlay) if the goal is to restore the service life to be equal to or exceed the service life of the base case. For a deck age of 10 years, penetrating sealer options are completely excluded from the decision tree while a significant reduction in the service life extension is observed for the remaining options, especially in the time to reach the 5% damage threshold.

Table 5.2. Summary of data analysis results showing time to 5% damage, service life, and life-cycle cost estimates as compared to the do nothing scenario at the same crack density for all the considered cases. Assumes remediation options are implemented at a bridge deck age between **0 and 2 years**. Green text indicates favorable comparison to base case while red text indicates unfavorable comparison.

Crack Density[1] (ft/ft^2)	Do Nothing			Penetrating Sealer[2] (IC = $8.6/SY)			Penetrating Sealer, 3 applications @ 6 years[2] (IC= $20.8/SY)[3]			Penetrating Sealer, 3 applications at 4 years[2] (IC= $22.3/SY)[3]			Crack Chasing (IC= $8.4/LY)			Flood Coat[4] (IC= $24.5/SY)		
	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)
< 0.10	0	0	0%	3	4	-2%	5	5	1%	6	5	0%	1	1	0%	3	3	1%
0.10 to 0.22	0	0	0%	3	3	-1%	5	4	-1%	6	5	-1%				10	5	-1%
0.22 to 0.37	0	0	0%	2	3	-2%	4	5	-2%	5	5	-2%				17	8	-3%
0.37 <	0	0	0%	3	3	-3%	4	4	-3%	5	5	-3%				13	15	-11%

Crack Density[1] (ft/ft^2)	Do Nothing			HMAWM (IC= $82.7/SY)			Thin Polymer Overlay (IC= $66.4/SY)			Premixed Polymer Concrete Overlay (IC= $135.9/SY)		
	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)
< 0.10	0	0	0%	7	8	1%	16	19	-4%	27	29	4%
0.10 to 0.22	0	0	0%	10	8	3%	17	18	-3%	28	28	1%
0.22 to 0.37	0	0	0%	11	8	2%	21	19	-5%	33	28	-1%
0.37 <	0	0	0%	11	10	-3%	21	19	-10%	29	31	-9%

IC: Initial cost of remediation option; T_5: Time-to-5% damage; T_{20}: Time-to- replacement or deck service life, assuming a damage threshold of 20%; LCC: Life-cycle cost assuming bridge deck replacement at the end of service life (T_{20}).

[1]Assumed crack density calculated as summation of crack length divided by inspected deck area. Crack densities exceeding 0.37 ft/ft^2 shall be investigated prior to implementation of repairs. Crack widths between 30 and 40 mils with a crack density exceeding 0.10 ft/ft^2 shall be investigated prior to implementation of repairs. The decision tree does not apply to crack densities exceeding 0.50 ft/ft^2 or crack widths exceeding 40 mils.

[2]Penetrating sealers are only considered for crack widths less than 15 mils.

[3]Initial cost is assumed to include all 3 applications. Future applications are calculated as present value.

[4]Flood coats are only considered for crack widths less than 30 mils.

Table 5.3. Summary of data analysis results showing time to 5% damage, service life, and life-cycle cost estimates as compared to base case (uncracked, untreated concrete deck) for all the considered cases. Assumes remediation options are implemented at a bridge deck age between **0 and 2 years**. Green text indicates favorable comparison to base case while red text indicates unfavorable comparison.

Crack Density[1] (ft/ft²)	Do Nothing			Penetrating Sealer[2] (IC = $8.6/SY)			Penetrating Sealer, 3 applications @ 6 years[2] (IC= $20.8/SY)[3]			Penetrating Sealer, 3 applications at 4 years[2] (IC= $22.3/SY)[3]			Crack Chasing (IC= $8.4/LY)			Flood Coat[4] (IC= $24.5/SY)		
	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)
< 0.10	-1	-1	1%	+2	+3	-1%	4	4	-0.4%	5	4	-0.3%	0	0	0.1%	2	2	1%
0.10 to 0.22	-8	-3	2%	-5	0	1%	-3	1	1%	-2	2	1%				2	2	1%
0.22 to 0.37	-16	-7	5%	-14	-4	4%	-12	-2	3%	-11	-2	3%				1	1	2%
0.37 <	-18	-19	18%	-15	-16	15%	-14	-15	15%	-13	-14	14%				-5	-4	5%

Crack Density[1] (ft/ft²)	Do Nothing			HMAWM (IC= $82.7/SY)			Thin Polymer Overlay (IC= $66.4/SY)			Premixed Polymer Concrete Overlay (IC= $135.9/SY)		
	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)
< 0.10	-1	-1	1%	6	7	2%	15	18	-2%	26	28	2%
0.10 to 0.22	-8	-3	2%	2	5	5%	9	15	-1%	20	25	3%
0.22 to 0.37	-16	-7	5%	-5	1	7%	5	12	0.4%	17	21	4%
0.37 <	-18	-19	18%	-7	-9	15%	3	0	6%	11	12	7%

IC: Initial cost of remediation option; T_5: Time-to-5% damage; T_{20}: Time-to- replacement or deck service life, assuming a damage threshold of 20%; LCC: Life-cycle cost assuming bridge deck replacement at the end of service life (T_{20}).

[1]Assumed crack density calculated as summation of crack length divided by inspected deck area. Crack densities exceeding 0.37 ft/ft² shall be investigated prior to implementation of repairs. Crack widths between 30 and 40 mils with a crack density exceeding 0.10 ft/ft² shall be investigated prior to implementation of repairs. The decision tree does not apply to crack densities exceeding 0.50 ft/ft² or crack widths exceeding 40 mils.

[2]Penetrating sealers are only considered for crack widths less than 15 mils.

[3]Initial cost is assumed to include all 3 applications. Future applications are calculated as present value.

[4]Flood coats are only considered for crack widths less than 30 mils.

Table 5.4. Summary of data analysis results showing time to 5% damage, service life, and life-cycle cost estimates as compared to the do nothing scenario at the same crack density for all the considered cases. Assumes remediation options are implemented at a bridge deck age of **5 years**. Green text indicates favorable comparison to base case while red text indicates unfavorable comparison.

Crack Density[1] (ft/ft^2)	Do Nothing			Penetrating Sealer[2] (IC = $7.1/SY)			Penetrating Sealer, 3 applications @ 6 years[2] (IC= $17.1/SY)[3]			Penetrating Sealer, 3 applications at 4 years[2] (IC= $18.3/SY)[3]			Crack Chasing (IC= $6.9/LY)			Flood Coat[4] (IC= $20.1/SY)		
	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)
< 0.10	0	0	0%	0	+1	0%	+1	+1	1%	+1	+1	1%	0	0	0%	0	+1	1%
0.10 to 0.22	0	0	0%	+1	0	1%	+1	0	2%	+1	0	2%				+5	+2	1%
0.22 to 0.37	0	0	0%	+1	+1	0%	+1	+1	1%	+1	+1	1%				+10	+5	-2%
0.37 <	0	0	0%	0	0	1%	0	0	1%	0	+1	0%				+5	+9	-7%

Crack Density[1] (ft/ft^2)	Do Nothing			HMAWM (IC= $68.0/SY)			Thin Polymer Overlay (IC= $54.5/SY)			Premixed Polymer Concrete Overlay (IC= $111.7/SY)		
	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)
< 0.10	0	0	0%	+1	+1	6%	+15	+16	-2%	+19	+20	2%
0.10 to 0.22	0	0	0%	+2	0	6%	+16	+16	-3%	+24	+21	1%
0.22 to 0.37	0	0	0%	+1	0	6%	+20	+15	-4%	+28	+21	-1%
0.37 <	0	0	0%	+1	0	6%	+12	+18	-10%	+22	+27	-10%

IC: Initial cost of remediation option calculated as present value since the repair is applied at a deck age of 5 years; T_5: Time-to-5% damage; T_{20}: Time-to-replacement or deck service life, assuming a damage threshold of 20%; LCC: Life-cycle cost assuming bridge deck replacement at T_{20}.

[1]Assumed crack density calculated as summation of crack length divided by inspected deck area. Crack densities exceeding 0.37 ft/ft^2 shall be investigated prior to implementation of repairs. Crack widths between 30 and 40 mils with a crack density exceeding 0.10 ft/ft^2 shall be investigated prior to implementation of repairs. The decision tree does not apply to crack densities exceeding 0.50 ft/ft^2 or crack widths exceeding 40 mils.

[2]Penetrating sealers are only considered for crack widths less than 15 mils.

[3]Initial cost is assumed to include all 3 applications. Future applications are calculated as present value.

[4]Flood coats are only considered for crack widths less than 30 mils.

Table 5.5. Summary of data analysis results showing time to 5% damage, service life, and life-cycle cost estimates as compared to base case (uncracked, untreated concrete deck) for all the considered cases. Assumes remediation options are implemented at a bridge deck age of **5 years**. Green text indicates favorable comparison to base case while red text indicates unfavorable comparison.

Crack Density[1] (ft/ft^2)	Do Nothing			Penetrating Sealer[2] (IC = $7.1/SY)			Penetrating Sealer, 3 applications @ 6 years[2] (IC= $17.1/SY)[3]			Penetrating Sealer, 3 applications at 4 years[2] (IC= $18.3/SY)[3]			Crack Chasing (IC= $6.9/LY)			Flood Coat[4] (IC= $20.1/SY)		
	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)
< 0.10	-1	-1	1%	-1	0	1%	0	0	1.7%	0	0	1.8%	-1	-1	1%	-1	0	2%
0.10 to 0.22	-8	-3	2%	-7	-3	3%	-7	-3	4%	-7	-3	4%				-3	-1	3%
0.22 to 0.37	-16	-7	5%	-15	-6	5%	-15	-6	6%	-15	-6	6%				-6	-2	3%
0.37 <	-18	-19	18%	-18	-19	19%	-18	-19	20%	-18	-18	19%				-13	-10	10%

Crack Density[1] (ft/ft^2)	Do Nothing			HMAWM (IC= $68.0/SY)			Thin Polymer Overlay (IC= $54.5/SY)			Premixed Polymer Concrete Overlay (IC= $111.7/SY)		
	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)
< 0.10	-1	-1	1%	0	0	7%	14	15	-2%	18	19	2%
0.10 to 0.22	-8	-3	2%	-6	-3	9%	8	13	-1%	16	18	3%
0.22 to 0.37	-16	-7	5%	-15	-7	12%	4	8	0.8%	12	14	4%
0.37 <	-18	-19	18%	-17	-19	25%	-6	-1	6%	4	8	6%

IC: Initial cost of remediation option calculated as present value since the repair is applied at a deck age of 5 years; T_5: Time-to-5% damage; T_{20}: Time-to-replacement or deck service life, assuming a damage threshold of 20%; LCC: Life-cycle cost assuming bridge deck replacement at T_{20}.

[1]Assumed crack density calculated as summation of crack length divided by inspected deck area. Crack densities exceeding 0.37 ft/ft^2 shall be investigated prior to implementation of repairs. Crack widths between 30 and 40 mils with a crack density exceeding 0.10 ft/ft^2 shall be investigated prior to implementation of repairs. The decision tree does not apply to crack densities exceeding 0.50 ft/ft^2 or crack widths exceeding 40 mils.

[2]Penetrating sealers are only considered for crack widths less than 15 mils.

[3]Initial cost is assumed to include all 3 applications. Future applications are calculated as present value.

[4]Flood coats are only considered for crack widths less than 30 mils.

Table 5.6. Summary of data analysis results showing time to 5% damage, service life, and life-cycle cost estimates as compared to the do nothing scenario at the same crack density for all the considered cases. Assumes remediation options are implemented at a bridge deck age of **10 years.** Green text indicates favorable comparison to base case while red text indicates unfavorable comparison.

Crack Density[1] (ft/ft^2)	Do Nothing			Penetrating Sealer			Penetrating Sealer, 3 applications @ 6 years			Penetrating Sealer, 3 applications at 4 years			Crack Chasing (IC= $5.7/LY)			Flood Coat[2] (IC= $16.5/SY)		
	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)
< 0.10	0	0	0%										0	0	0%	0	+1	1%
0.10 to 0.22	0	0	0%													+2	+1	1%
0.22 to 0.37	0	0	0%													0	+3	-1%
0.37 <	0	0	0%													0	+3	-2%

Crack Density[1] (ft/ft^2)	Do Nothing			HMAWM (IC= $55.9/SY)			Thin Polymer Overlay (IC= $44.8/SY)			Premixed Polymer Concrete Overlay (IC= $91.8/SY)		
	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)
< 0.10	0	0	0%	+1	0	5%	+8	+13	-2%	+20	+22	-1%
0.10 to 0.22	0	0	0%	+2	0	5%	+4	+13	-3%	+16	+22	-2%
0.22 to 0.37	0	0	0%	0	0	5%	+1	+13	-4%	+1	+22	-3%
0.37 <	0	0	0%	0	+1	3%	0	+6	-2%	0	+12	-3%

IC: Initial cost of remediation option calculated as present value since the repair is applied at deck age of 10 years; T_5: Time-to-5% damage; T_{20}: Time-to-replacement or deck service life, assuming a damage threshold of 20%; LCC: Life-cycle cost assuming bridge deck replacement at the end of service life (T_{20}).
[1]Assumed crack density calculated as summation of crack length divided by inspected deck area. Crack densities exceeding 0.37 ft/ft^2 shall be investigated prior to implementation of repairs. Crack widths between 30 and 40 mils with a crack density exceeding 0.10 ft/ft^2 shall be investigated prior to implementation of repairs. The decision tree does not apply to crack densities exceeding 0.50 ft/ft^2 or crack widths exceeding 40 mils.
[2]Flood coats are only considered for crack widths less than 30 mils.

Table 5.7. Summary of data analysis results showing time to 5% damage, service life, and life-cycle cost estimates as compared to base case (uncracked, untreated concrete deck) for all the considered cases. Assumes remediation options are implemented at a bridge deck age of **10 years.** Green text indicates favorable comparison to base case while red text indicates unfavorable comparison.

Crack Density[1] (ft/ft^2)	Do Nothing			Penetrating Sealer			Penetrating Sealer, 3 applications @ 6 years			Penetrating Sealer, 3 applications at 4 years			Crack Chasing (IC= $5.7/LY)			Flood Coat[2] (IC= $16.5/SY)		
	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)
< 0.10	-1	-1	1%										-1	-1	1%	-1	0	2%
0.10 to 0.22	-8	-3	2%													-6	-2	3%
0.22 to 0.37	-16	-7	5%													-16	-4	4%
0.37 <	-18	-19	18%													-18	-16	16%

Crack Density[1] (ft/ft^2)	Do Nothing			HMAWM (IC= $55.9/SY)			Thin Polymer Overlay (IC= $44.8/SY)			Premixed Polymer Concrete Overlay (IC= $91.8/SY)		
	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)
< 0.10	-1	-1	1%	0	-1	6%	7	12	-2%	19	21	0%
0.10 to 0.22	-8	-3	2%	-6	-3	7%	-4	10	-1%	8	19	1%
0.22 to 0.37	-16	-7	5%	-16	-7	11%	-15	6	1%	-15	15	2%
0.37 <	-18	-19	18%	-18	-18	22%	-18	-13	15%	-18	-7	14%

IC: Initial cost of remediation option calculated as present value since the repair is applied at deck age of 10 years; T_5: Time-to-5% damage; T_{20}: Time-to-replacement or deck service life, assuming a damage threshold of 20%; LCC: Life-cycle cost assuming bridge deck replacement at the end of service life (T_{20}).

[1]Assumed crack density calculated as summation of crack length divided by inspected deck area. Crack densities exceeding 0.37 ft/ft^2 shall be investigated prior to implementation of repairs. Crack widths between 30 and 40 mils with a crack density exceeding 0.10 ft/ft^2 shall be investigated prior to implementation of repairs. The decision tree does not apply to crack densities exceeding 0.50 ft/ft^2 or crack widths exceeding 40 mils.

[2]Flood coats are only considered for crack widths less than 30 mils.

Table 5.8. Data-driven decision tree for crack remediation implemented at bridge ages between **0 and 2 years**. Green text indicates favorable comparison to base case while red text indicates unfavorable comparison.

Crack Density (ft/ft^2)[1]	Remediation Options	Crack Width Limit[1]	Benefit Compared to Do Nothing at each Crack Density				Benefit Compared to Base Case (Uncracked, Untreated Deck)		
			IC ($/SY)	T_5 (yrs)	T_{20} (yrs)	LCC (%)	T_5 (yrs)	T_{20} (yrs)	LCC (%)
< 0.10	Do nothing (T5=34; T20 =46)	Up to 10 mils	$0	0	0	0%	-1	-1	1%
	Penetrating sealer	Up to 15 mils	$8.6	+3	+4	-2%	+2	+3	-1%
	Penetrating sealer + reapplication	Up to 15 mils	$22.3[2]	+6	+5	0%	+5	+4	-0.3%
	Crack chasing	Up to 40 mils	$0.8[3]	+1	+1	0%	0	0	0.1%
	Flood coat	Up to 30 mils	$24.5	+3	+3	1%	+2	+2	1%
	Thin polymer overlay	Up to 40 mils	$66.4	+16	+19	-4%	+15	+18	-2%
	Premixed polymer concrete overlay	Up to 40 mils	$135.9	+27	+29	4%	+26	+28	2%
0.10 to 0.22	Do nothing (T_5=27; T_{20}=44)	Up to 10 mils	$0	0	0	0%	-8	-3	2%
	Penetrating sealer	Up to 15 mils	$8.6	+3	+3	-1%	-5	0	1%
	Penetrating sealer + reapplication	Up to 15 mils	$22.3[2]	+6	+5	-1%	-2	+2	1%
	Flood coat	Up to 30 mils	$24.5	+10	+5	-1%	+2	+2	1%
	Thin polymer overlay	Up to 40 mils	$66.4	+17	+18	-3%	+9	+15	-1%
	Premixed polymer concrete overlay	Up to 40 mils	$135.9	+28	+28	1%	+20	+25	3%
0.22 to 0.37	Do nothing (T_5=19; T_{20}=40)	Up to 10 mils	$0	0	0	0%	-16	-7	5%
	Penetrating sealer	Up to 15 mils	$8.6	+2	+3	-2%	-14	-4	4%
	Penetrating sealer + reapplication	Up to 15 mils	$22.3[2]	+5	+5	-2%	-11	-2	3%
	Flood coat	Up to 30 mils	$24.5	+17	+8	-3%	+1	+1	2%
	Thin polymer overlay	Up to 40 mils	$66.4	+21	+19	-5%	+5	+12	0 %
	Premixed polymer concrete overlay	Up to 40 mils	$135.9	+33	+28	-1%	+17	+21	4%
0.37 <	Do nothing (T_5=17; T_{20}=28)	Up to 10 mils	$0	0	0	0%	-18	-19	18%
	Penetrating sealer	Up to 15 mils	$8.6	+3	+3	-3%	-15	-16	15%
	Penetrating sealer + reapplication	Up to 15 mils	$22.3[2]	+5	+5	-3%	-13	-14	14%
	Flood coat	Up to 30 mils	$24.5	+13	+15	-11%	-5	-4	5%
	Thin polymer overlay	Up to 40 mils	$66.4	+21	+19	-10%	+3	0	6%
	Premixed polymer concrete overlay	Up to 40 mils	$135.9	+29	+31	-9%	+11	+12	7%

[1] Crack densities exceeding 0.37 ft/ft^2 shall be investigated prior to implementation of repairs. Crack widths between 30 and 40 mils with a crack density exceeding 0.10 ft/ft^2 shall be investigated prior to implementation of repairs. The decision tree does not apply to crack densities exceeding 0.50 ft/ft^2 or crack widths exceeding 40 mils.
[2]Calculated assuming 3 reapplications, one every 4 years. Costs for future applications are added as present value.
[3]Price per square yard. Assuming a crack density of 0.10 ft/ft^2.

Table 5.9. Data-driven decision tree for crack remediation options implemented at bridge age of **5 years**. Green text indicates favorable comparison to base case while red text indicates unfavorable comparison.

Crack Density (ft/ft^2)[1]	Remediation Options	Crack Width Limit[1]	Benefit Compared to Do Nothing at each Crack Density				Benefit Compared to Base Case (Uncracked, Untreated Deck)		
			IC ($/SY)	T_5 (yrs)	T_{20} (yrs)	LCC (%)	T_5 (yrs)	T_{20} (yrs)	LCC (%)
< 0.10	Do nothing (T5=34; T20 =46)	Up to 10 mils	$0	0	0	0%	-1	-1	1%
	Penetrating sealer	Up to 15 mils	$7.1	0	+1	0%	-1	0	1%
	Penetrating sealer + reapplication	Up to 15 mils	$17.1[2]	+1	+1	1%	0	0	2%
	Crack chasing	Up to 40 mils	$0.7[3]	0	0	0%	-1	-1	1%
	Flood coat	Up to 30 mils	$20.1	0	+1	1%	-1	0	2%
	Thin polymer overlay	Up to 40 mils	$54.5	+15	+16	-2%	+14	+15	-2%
	Premixed polymer concrete overlay	Up to 40 mils	$111.7	+19	+20	2%	+18	+19	2%
0.10 to 0.22	Do nothing (T_5=27; T_{20}=44)	Up to 10 mils	$0	0	0	0%	-8	-3	2%
	Penetrating sealer	Up to 15 mils	$7.1	+1	0	1%	-7	-3	3%
	Penetrating sealer + reapplication	Up to 15 mils	$17.1[2]	+1	0	2%	-7	-3	4%
	Flood coat	Up to 30 mils	$20.1	+5	+2	1%	-3	-1	3%
	Thin polymer overlay	Up to 40 mils	$54.5	+16	+16	-3%	8	13	-1%
	Premixed polymer concrete overlay	Up to 40 mils	$111.7	+24	+21	1%	16	18	3%
0.22 to 0.37	Do nothing (T_5=19; T_{20}=40)	Up to 10 mils	$0	0	0	0%	-16	-7	5%
	Penetrating sealer	Up to 15 mils	$7.1	+1	+1	0%	-15	-6	5%
	Penetrating sealer + reapplication	Up to 15 mils	$17.1[2]	+1	+1	1%	-15	-6	6%
	Flood coat	Up to 30 mils	$20.1	+10	+5	-2%	-6	-2	3%
	Thin polymer overlay	Up to 40 mils	$54.5	+20	+15	-4%	+4	+8	0.8%
	Premixed polymer concrete overlay	Up to 40 mils	$111.7	+28	+21	-1%	+12	+14	4%
0.37 <	Do nothing (T_5=17; T_{20}=28)	Up to 10 mils	$0	0	0	0%	-18	-19	18%
	Penetrating sealer	Up to 15 mils	$7.1	0	0	1%	-18	-19	19%
	Penetrating sealer + reapplication	Up to 15 mils	$17.1[2]	0	+1	0%	-18	-18	19%
	Flood coat	Up to 30 mils	$20.1	+5	+9	-7%	-13	-10	10%
	Thin polymer overlay	Up to 40 mils	$54.5	+12	+18	-10%	-6	-1	6%
	Premixed polymer concrete overlay	Up to 40 mils	$111.7	+22	+27	-10%	+4	+8	6%

[1] Crack densities exceeding 0.37 ft/ft^2 shall be investigated prior to implementation of repairs. Crack widths between 30 and 40 mils with a crack density exceeding 0.10 ft/ft^2 shall be investigated prior to implementation of repairs. The decision tree does not apply to crack densities exceeding 0.50 ft/ft^2 or crack widths exceeding 40 mils.

[2] Calculated assuming 3 reapplications, one every 4 years. Costs for future applications are added as present value.

[3] Price per square yard. Assuming a crack density of 0.10 ft/ft^2.

[4] IC: Initial cost of remediation option calculated as present value since the repair is applied at deck age of 5 years.

Table 5.10. Data-driven decision tree for crack remediation options implemented at bridge age of **10 years**. Green text indicates favorable comparison to base case while red text indicates unfavorable comparison.

Crack Density (ft/ft²)[1]	Remediation Options	Crack Width Limit[1]	Benefit Compared to Do Nothing at each Crack Density				Benefit Compared to Base Case (Uncracked, Untreated Deck)		
			IC[3] ($/SY)	T_5 (yrs)	T_{20} (yrs)	LCC (%)	T_5 (yrs)	T_{20} (yrs)	LCC (%)
< 0.10	Do nothing (T5=34; T20 =46)	Up to 10 mils	$0	0	0	0%	-1	-1	1%
	Crack chasing	Up to 40 mils	$0.6[2]	0	0	0%	-1	-1	1%
	Flood coat	Up to 30 mils	$16.5	0	+1	1%	-1	0	2%
	Thin polymer overlay	Up to 40 mils	$44.8	+8	+13	-2%	+7	+12	-2%
	Premixed polymer concrete overlay	Up to 40 mils	$91.8	+20	+22	-1%	+19	+21	0%
0.10 to 0.22	Do nothing (T_5=27; T_{20}=44)	Up to 10 mils	$0	0	0	0%	-8	-3	2%
	Flood coat	Up to 30 mils	$16.5	+2	+1	1%	-6	-2	3%
	Thin polymer overlay	Up to 40 mils	$44.8	+4	+13	-3%	-4	+10	-1%
	Premixed polymer concrete overlay	Up to 40 mils	$91.8	+16	+22	-2%	+8	+19	1%
0.22 to 0.37	Do nothing (T_5=19; T_{20}=40)	Up to 10 mils	$0	0	0	0%	-16	-7	5%
	Flood coat	Up to 30 mils	$16.5	0	+3	-1%	-16	-4	4%
	Thin polymer overlay	Up to 40 mils	$44.8	+1	+13	-4%	-15	+6	1%
	Premixed polymer concrete overlay	Up to 40 mils	$91.8	+1	+22	-3%	-15	+15	2%
0.37 <	Do nothing (T_5=17; T_{20}=28)	Up to 10 mils	$0	0	0	0%	-18	-19	-18
	Flood coat	Up to 30 mils	$16.5	0	+3	-2%	-18	-16	16%
	Thin polymer overlay	Up to 40 mils	$44.8	0	+6	-2%	-18	-13	15%
	Premixed polymer concrete overlay	Up to 40 mils	$91.8	0	+12	-3%	-18	-7	14%

[1] Crack densities exceeding 0.37 ft/ft² shall be investigated prior to implementation of repairs. Crack widths between 30 and 40 mils with a crack density exceeding 0.10 ft/ft² shall be investigated prior to implementation of repairs. The decision tree does not apply to crack densities exceeding 0.50 ft/ft² or crack widths exceeding 40 mils.
[2] Price per square yard. Assuming a crack density of 0.10 ft/ft².
[3] IC: Initial cost of remediation option calculated as present value since the repair is applied at deck age of 10 years.

5.3.3. Decision Tree for Shallow Cracks

Service life modeling analysis results presented in Chapter 4 showed that shallow cracks (defined as cracks with small width, generally less than or equal to 5 mils (0.005 inches), that do not reach the reinforcement) have a limited effect on the service life of bridge decks. If left untreated, the analysis shows that shallow cracks at the highest crack severity will only reduce the time-to-5% damage and time-to-replacement by about 3 years as can be seen in Table 4.13.

Application of a penetrating sealer or a flood coat at bridge deck ages of 0 and 5 years was considered for the case of shallow cracks. A summary of the analysis results in terms of time-to-5% damage, time-to-replacement, and life-cycle cost estimates as compared to the do nothing scenario at the same crack density and base case (uncracked, untreated concrete deck) for all the considered cases is provided in Table 5.11 and Table 5.12. As shown in the tables, placing either repair option at a bridge deck age of 0 years provides a better service life and life-cycle cost for all the considered cases. Delaying the crack remediation treatment to a deck age of 5 years results in reduced benefits, especially for applying a penetrating sealer on a deck with a very severe crack density where the performance becomes very similar to the do nothing condition. Table 5.11 and Table 5.12 can be considered the detailed decision tree for the shallow crack remediation options.

Table 5.11. Data-driven decision tree for shallow cracks remediation options implemented at a bridge age between **0 and 2 years** or at **5 years** as compared to the do nothing scenario at the same crack density for all the considered cases. Green text indicates favorable comparison to base case while red text indicates unfavorable comparison.

Crack Density (ft/ft^2)	Remediation Options For Shallow Cracks	Benefit Compared to Base Case, Uncracked Concrete Deck							
		Bridge age of 0 years to 2 years				Bridge age of 5 years			
		IC ($/SY)	T_5 (yrs)	T_{20} (yrs)	LCC (%)	IC[1] ($/SY)	T_5 (yrs)	T_{20} (yrs)	LCC (%)
< 0.10	Do nothing (T_5 = 34; T_{20} = 47)	$0	0	0	0%	$0	0	0	0%
	Penetrating sealer	$8.6	+4	+3	-1%	$7.1	+2	+1	0%
	Flood coat	$24.5	+3	+3	0%	$20.1	+2	+1	1%
0.10 to 0.22	Do nothing (T_5 = 34; T_{20} = 46)	$0	0	0	0%	$0	0	0	0%
	Penetrating sealer	$8.6	+3	+3	-1%	$7.1	+2	+1	0%
	Flood coat	$24.5	+3	+4	0%	$20.1	+2	+2	1%
0.22 to 0.37	Do nothing (T_5 = 34; T_{20} = 45)	$0	0	0	0%	$0	0	0	0%
	Penetrating sealer	$8.6	+3	+3	-1%	$7.1	0	+2	-1%
	Flood coat	$24.5	+3	+5	-1%	$20.1	+2	+3	0%
0.37 <	Do nothing (T_5 = 32; T_{20} = 44)	$0	0	0	0%	$0	0	0	0%
	Penetrating sealer	$8.6	+3	+3	-1%	$7.1	0	+1	0%
	Flood coat	$24.5	+5	+6	-2%	$20.1	+3	+3	0%

IC: Initial cost of remediation option; T_5: Time-to-5% damage; T_{20}: Time-to- replacement or deck service life, assuming a damage threshold of 20%; LCC: Life-cycle cost assuming bridge deck replacement at the end of service life (T_{20}).
[1] IC: Initial cost of remediation option calculated as present value since the repair is applied at a deck age of 5 years.

Table 5.12. Data-driven decision tree for shallow cracks remediation options implemented at a bridge age between **0 and 2 years** or at **5 years** as compared to base case (uncracked, untreated concrete deck) for all the considered cases. Green text indicates favorable comparison to base case while red text indicates unfavorable comparison.

Crack Density (ft/ft^2)	Remediation Options For Shallow Cracks	Benefit Compared to Base Case, Uncracked Concrete Deck							
		Bridge age of 0 years to 2 years				Bridge age of 5 years			
		IC ($/SY)	T_5 (yrs)	T_{20} (yrs)	LCC (%)	IC[1] ($/SY)	T_5 (yrs)	T_{20} (yrs)	LCC (%)
< 0.10	Do nothing (T_5 = 34; T_{20} = 47)	$0	-1	0	0%	$0	-1	0	0%
	Penetrating sealer	$8.6	3	3	-1%	$7.1	1	1	0.1%
	Flood coat	$24.5	2	3	0.5%	$20.1	1	1	1%
0.10 to 0.22	Do nothing (T_5 = 34; T_{20} = 46)	$0	-1	-1	1%	$0	-1	-1	1%
	Penetrating sealer	$8.6	2	2	-0.4%	$7.1	1	0	1%
	Flood coat	$24.5	2	3	0.5%	$20.1	1	1	1%
0.22 to 0.37	Do nothing (T_5 = 34; T_{20} = 45)	$0	-1	-2	1%	$0	-1	-2	1%
	Penetrating sealer	$8.6	2	1	0.2%	$7.1	-1	0	1%
	Flood coat	$24.5	2	3	0.5%	$20.1	1	1	1%
0.37 <	Do nothing (T_5 = 32; T_{20} = 44)	$0	-3	-3	2%	$0	-3	-3	2%
	Penetrating sealer	$8.6	0	0	1%	$7.1	-3	-2	2%
	Flood coat	$24.5	2	3	0.5%	$20.1	0	0	2%

IC: Initial cost of remediation option; T_5: Time-to-5% damage; T_{20}: Time-to- replacement or deck service life, assuming a damage threshold of 20%; LCC: Life-cycle cost assuming bridge deck replacement at the end of service life (T_{20}).
[1] IC: Initial cost of remediation option calculated as present value since the repair is applied at a deck age of 5 years.

5.3.4. Crack Remediation Decision Trees

All the data presented in Chapter 4 and 5, combined with engineering selection, were used to develop three decision trees for optimal selection of crack remediation options based on deck age, type of cracks (shallow or deep), crack density, and crack width. The crack remediation options in each decision tree were color-coded to enable easy selection of maintenance actions, where green indicates the most suitable option, yellow indicates alternative suitable options, orange indicates the least suitable option, blue indicates an overlay (thin polymer overlay or premixed polymer concrete overlay) is the most suitable option, and pink indicates the need for additional investigation. The three decision tress are presented in Table 5.13 to Table 5.15. Note that detailed information regarding the effect of each crack remediation option on the initial cost, time-of-repair, time-of-replacement, and life-cycle cost was used to rank suitability and specifics can be obtained from previous sections.

Another consideration for selection of crack remediation options is the disturbance to traffic during application of the treatment. This is an important consideration as it is preferred to use treatments that can be easily applied especially within the first few years after construction. Assumptions for the expected traffic disturbance associated with the different crack remediation strategies are as follows:

- Sealers – minimal traffic disruption, can be applied in one day during lane closures
- Crack Chasing - minimal traffic disruption, can be applied in one day during lane closures

- Flood coats– minimal traffic disruption, can be applied in one day during lane closures
- Thin Polymer Overlays – somewhat minimal traffic disruption, can be completed and open to traffic in one to two days
- Premixed Polymer Overlays – moderate traffic disruption, require surface preparation but can open to traffic within hours after completion. More labor intensive compared to other options

A summary of the recommendations presented in the decision trees and the reasoning behind their selection is below.

- **Crack Remediation Decision Tree for Deck Ages between 0 and 2 Years**
  a. Shallow Cracks
     i. In addition to do nothing, the only crack remediation options considered for shallow cracks are penetrating sealers and flood coats. For mild, moderate and severe crack densities, the most suitable options are do nothing (as it has no initial cost and only limited reduction in service life) and penetrating sealers (as it has low initial cost but provides service life extension). Flood coats can be used for the case of severe crack density although they have higher initial cost than penetrating sealers. For very severe crack density, flood coats are the most suitable option.
  b. Mild Crack Density < 0.10 ft/ft^2 (Deep Cracks)
     i. Do nothing is a viable option as there is no initial cost involved and negligible impact on service life. This option is suitable for mild crack density and small crack width cases.
     ii. Penetrating sealers with and without reapplication have a low to moderate initial cost and results in a minor improvement of the service life of the deck. As such these options are preferred for this case, if appropriate depending on crack width.
     iii. Crack chasing comes at a very low initial cost, but has a little beneficial effect on the service life as it only restores the deck condition without offering additional protection. For mild crack densities, this is the preferred option for crack widths exceeding 15 mils.
     iv. Flood coats have a moderate cost and result in an improvement in the service life of the bridge deck. This repair can be used with wider cracks compared to applying a penetrating sealer.
     v. Thin polymer overlays are not a preferred option at mild crack densities as they have a very high initial cost. However, this option provides the lowest life cycle cost and a higher benefit for service life extension compared to the other options.
     vi. Premixed polymer concrete overlays are not a suitable option at mild crack densities as they have a high initial cost and the highest life cycle cost. They do, however, provide the highest benefit for service life extension compared to the other options.
  c. Moderate Crack Density 0.10 ft/ft^2 to 0.22 ft/ft^2 (Deep Cracks)
     i. Do nothing is excluded at this crack density due to the high service life reduction that is associated with this option; the time to reach the 5% damage threshold (T_5) is estimated to be 8 years less than the base case of uncracked, untreated concrete deck.
     ii. Penetrating sealers with and without reapplication have a low to moderate initial cost but provide low benefits in terms of service life compared to the do nothing scenario. As such these options can be used but are not the most suitable.

   iii. Crack chasing is not a practical option for moderate, severe, or very severe crack density.
   iv. Flood coats have a moderate cost and result in an improvement in the service life of the bridge deck. This repair option is the most suitable option for this crack density for crack widths up to 30 mils.
   v. Thin polymer overlays are not a preferred option at crack widths smaller than 30 mils, due to the presence of another, less costly option in terms of initial cost and traffic disruption. However, this option provides the lowest life cycle cost and a higher benefit for service life extension compared to the other options. Polymer overlays are the only option for crack widths exceeding 30 mils and up to the 40-mil limit of the decision trees.
   vi. Premixed polymer concrete overlays are not a preferred option at crack widths smaller than 30 mils, due to the presence of another, less costly option in terms of initial cost and traffic disruption. However, this option provides the highest benefit for service life extension compared to the other options. Polymer overlays are the only option for crack widths exceeding 30 mils and up to the 40-mil limit of the decision trees.

d. Severe Crack Density 0.22 ft/ft^2 to 0.37 ft/ft^2 (Deep Cracks)
   i. Do nothing is excluded at this crack density due to the high service life reduction that is associated with this option; the time to reach the 5% damage threshold (T_5) is estimated to be 16 years less than the base case.
   ii. Penetrating sealers with and without reapplication are excluded at this crack density due to the high service life reduction compared to the base case that is associated with these options, although they do provide benefits if compared to the do nothing scenario at the same crack density. The time to reach the 5% damage threshold (T_5) is estimated to be 14 years less than base case.
   iii. Crack chasing is not a practical option for moderate, severe, or very severe crack density.
   iv. Flood coat have a moderate cost and result in substantial improvement in the service life of the bridge deck compared to the do nothing scenario. This repair option is a suitable option for this crack density at crack widths up to 30 mils due to its low initial cost compared to other viable options.
   v. Thin polymer overlays are not a preferred option at crack widths smaller than 30 mils, due to the presence of another, less costly option in terms of initial cost and traffic disruption. However, this option provides the lowest life cycle cost and a higher benefit for service life extension compared to the other options. Polymer overlays are the only option for crack widths exceeding 30 mils and up to the 40-mil limit of the decision trees.
   vi. Premixed polymer concrete overlays are not a preferred option at crack widths smaller than 30 mils, due to the presence of another, less costly option in terms of initial cost and traffic disruption. However, this option provides the highest benefit for service life extension compared to the other options. Polymer overlays are the only option for crack widths exceeding 30 mils and up to the 40-mil limit of the decision trees.

e. Very Severe Crack Density > 0.37 ft/ft^2 (Deep Cracks)
   i. Do nothing is excluded at this crack density due to the high service life reduction that is associated with this option; the time to reach the 5% damage threshold (T_5) is estimated to be 18 years less than the base case.

ii. Penetrating sealers with and without reapplication are excluded at this crack density due to the high service life reduction compared to the base case that is associated with these options, although they do provide benefits if compared to the do nothing scenario at the same crack density. The time to reach the 5% damage threshold (T_5) is estimated to be 15 years less than base case.

iii. Crack chasing is not a practical option for moderate, severe, or very severe crack density.

iv. Flood coat have a moderate cost and result in substantial improvement in the service life of the bridge deck compared to the do nothing scenario. However, the total service life is less than of the base case of uncracked deck, which indicate that repairs will have to be done sooner. This repair option is somewhat suitable option for this crack density at crack widths up to 30 mils due to its low initial cost compared to other viable options.

v. Thin polymer overlays are not a preferred option at crack widths smaller than 30 mils, due to the presence of another, less costly option in terms of initial cost and traffic disruption. However, this option provides the lowest life cycle cost and a higher benefit for service life extension compared to the other options. Polymer overlays are the only option for crack widths exceeding 30 mils and up to the 40-mil limit of the decision trees.

vi. Premixed polymer concrete overlays are not a preferred option at crack widths smaller than 30 mils, due to the presence of another, less costly option in terms of initial cost and traffic disruption. However, this option provides the highest benefit for service life extension compared to the other options. Polymer overlays are the only option for crack widths exceeding 30 mils and up to the 40-mil limit of the decision trees.

- **Crack Remediation Decision Tree for Deck Age of 5 Years**

a. Shallow Cracks

i. Similar to the information provided for the decision tree for deck ages between 0 and 2 years. The only exception is that penetrating sealers are no longer a preferred option for the very severe crack density in this case.

b. Mild Crack Density < 0.10 ft/ft^2 (Deep Cracks)

i. Do nothing is a viable option as there is no initial cost involved and there is a negligible impact on service life. This option is suitable for mild crack density and small crack width cases.

ii. Penetrating sealers with and without reapplication have a low to moderate initial cost and results in a minor improvement of the service life of the deck. As such these options are preferred for this case, if appropriate depending on crack width.

iii. Crack chasing comes at a very low initial cost, but has a little beneficial effect on the service life as it only restores the deck condition without offering additional protection. For mild crack densities, this is the preferred option for crack widths exceeding 15 mils.

iv. Flood coats have a moderate cost and result in an improvement in the service life of the bridge deck. This repair can be used with wider cracks compared to applying a penetrating sealer, between 15 and 30 mils.

v. Thin polymer overlays are not a preferred option at mild crack densities as they have a very high initial cost. However, this option provides the lowest life cycle cost and a higher benefit for service life extension compared to the other options.

   vi. Premixed polymer concrete overlays are not a suitable option at mild crack densities as they have a high initial cost and the highest life cycle cost. They do, however, provide the highest benefit for service life extension compared to the other options.

c. Moderate Crack Density 0.10 ft/ft^2 to 0.22 ft/ft^2 (Deep Cracks)
   i. Similar to other decision trees, do nothing is excluded at this crack density.
   ii. Penetrating sealers with and without reapplication have a low to moderate initial cost but provide little benefits in terms of service life compared to the do nothing scenario. As such, these options are no longer preferred at this deck age.
   iii. Crack chasing is not a practical option for moderate, severe, or very severe crack density.
   iv. Flood coats have a moderate cost and result in an improvement in the service life of the bridge deck. This repair can be used with wider cracks compared to applying a penetrating sealer, between 15 and 30 mils.
   v. Thin polymer overlays are not a preferred option at crack widths smaller than 30 mils, due to the presence of another, less costly option in terms of initial cost and traffic disruption. However, this option provides the lowest life cycle cost and a higher benefit for service life extension compared to the other options. Polymer overlays are the only option for crack widths exceeding 30 mils and up to the 40-mil limit of the decision trees.
   vi. Premixed polymer concrete overlays are not a preferred option at crack widths smaller than 30 mils, due to the presence of another, less costly option in terms of initial cost and traffic disruption. However, this option provides the highest benefit for service life extension compared to the other viable options. Polymer overlays are the only option for crack widths exceeding 30 mils and up to the 40-mil limit of the decision trees.

d. Severe Crack Density 0.22 ft/ft^2 to 0.37 ft/ft^2 (Deep Cracks)
   i. Similar to other decision trees, do nothing is excluded at this crack density.
   ii. Penetrating sealers with and without reapplication are excluded at this crack density due to the high service life reduction compared to the base case of uncracked deck that is associated with these options, although they do provide benefits if compared to the do nothing scenario at the same crack density. The time to reach the 5% damage threshold (T_5) is estimated to be 15 years less than base case.
   iii. Crack chasing is not a practical option for moderate, severe, or very severe crack density.
   iv. Flood coat have a moderate cost and result in substantial improvement in the service life of the bridge deck compared to the do nothing scenario. This repair option is a suitable option for this crack density at crack widths up to 30 mils due to its low initial cost compared to other viable options.
   v. Thin polymer overlays are not a preferred option at crack widths smaller than 30 mils, due to the presence of another, less costly option in terms of initial cost and traffic disruption. However, this option provides the lowest life cycle cost and a higher benefit for service life extension compared to the other options. Polymer overlays are the only option for crack widths exceeding 30 mils and up to the 40-mil limit of the decision trees.
   vi. Premixed polymer concrete overlays are not a preferred option at crack widths smaller than 30 mils, due to the presence of another, less costly option in terms of initial cost and traffic disruption. However, this option provides the highest benefit for service life extension

compared to the other viable options. Polymer overlays are the only option for crack widths exceeding 30 mils and up to the 40-mil limit of the decision trees.

e. Very Severe Crack Density 0.37 ft/ft^2 (Deep Cracks)
   i. Flood coat have a moderate cost and result in an improvement in the service life of the bridge deck compared to the do nothing scenario. However, the total service life is significantly less than of the base case of uncracked deck, which indicate that repairs will have to be done sooner. This repair option is not a preferred option for this crack density.
   ii. Thin polymer overlays are a suitable option at this crack density. This option provides the lowest life-cycle cost and a higher benefit for service life extension compared to the other options.
   iii. Premixed polymer concrete overlays are a suitable option at this crack density. This option provides the lowest life-cycle cost highest benefit for service life extension compared to the other options, although it has the highest initial cost.

- **Crack Remediation Decision Tree for Deck Age of 10 Years**

a. Shallow Cracks
   i. Similar to the information provided for the decision tree for a deck age of 5 years.

b. Mild Crack Density < 0.10 ft/ft^2 (Deep Cracks)
   i. Do nothing is a viable option as there is no initial cost involved and a negligible impact in terms of service life. This option is suitable for low crack density and small crack width cases.
   ii. Penetrating sealers with and without reapplication are excluded at this deck age.
   iii. Crack chasing comes at a very low initial cost, but has a little beneficial effect on the service life as it only restores the deck condition without offering additional protection. For mild crack densities, this is the preferred option for crack widths exceeding 15 mils.
   iv. Flood coats have a moderate cost and result in an improvement in the service life of the bridge deck. This repair is the most suitable option for crack widths less than 30 mils.
   v. Thin polymer overlays are not a preferred option at mild crack densities as they have a very high initial cost. However, this option provides the lowest life cycle cost and a higher benefit for service life extension compared to the other options.
   vi. Premixed polymer concrete overlays are not a preferred option at mild crack densities as they have a high initial cost and the highest life cycle cost. They do, however, provide the highest benefit for service life extension compared to the other options.

c. Moderate Crack Density 0.10 ft/ft^2 to 0.22 ft/ft^2 (Deep Cracks)
   i. Similar to other decision trees, do nothing is excluded at this crack density.
   ii. Penetrating sealers with and without reapplication are excluded at this deck age.
   iii. Crack chasing is not a practical option for moderate, severe, or very severe crack density.
   iv. Flood coats have a moderate cost but result in a reduction in the service life of the bridge deck compared to the base case. This repair option is a suitable option for this crack density at crack widths up to 30 mils.
   v. Thin polymer overlays are a suitable option at crack widths smaller than 30 mils, since they can restore the service life to that of the base case, although at a high initial cost. This option provides the lowest life cycle cost. Polymer overlays are the only option for crack widths exceeding 30 mils and up to the 40-mil limit of the decision trees.

    vi. Premixed polymer concrete overlays are a suitable option at crack widths smaller than 30 mils, since they can restore the service life to that of the base case, although at the highest initial cost. This option provides the highest benefit for service life extension compared to the other viable options. Polymer overlays are the only option for crack widths exceeding 30 mils and up to the 40-mil limit of the decision trees.

d. Severe Crack Density 0.22 ft/ft^2 to 0.37 ft/ft^2 (Deep Cracks)
    i. Similar to other decision trees, do nothing is excluded at this crack density.
    ii. Penetrating sealers with and without reapplication are excluded at this deck age.
    iii. Crack chasing is not a practical option for moderate, severe, or very severe crack density.
    iv. Flood coats have a moderate cost but result in a reduction in the service life of the bridge deck compared to the base case. This repair option is not a preferred option for this crack density.
    v. Thin polymer overlays are a suitable option at crack widths smaller than 30 mils, since they can restore the service life to that of the base case, although at a high initial cost. This option provides the lowest life cycle cost. Polymer overlays are the only option for crack widths exceeding 30 mils and up to the 40-mil limit of the decision trees.
    vi. Premixed polymer concrete overlays are a suitable option at crack widths smaller than 30 mils, since they can restore the service life to that of the base case, although at the highest initial cost. This option provides the highest benefit for service life extension compared to the other viable options. Polymer overlays are the only option for crack widths exceeding 30 mils and up to the 40-mil limit of the decision trees.

e. Very Severe Crack Density > 0.37 ft/ft^2 (Deep Cracks)
    i. Thin polymer overlays and premixed polymer overlays are the only option for bridge decks with a very severe crack density at this deck age at any crack width, although they cannot restore the service life of the cracked bridge deck to that of the base case (uncracked bridge deck). The analysis case shown in Section 4.3.7 where a flood coat was applied at a deck age of 0 years followed by a polymer overlay at a deck age of 10 years highlights the importance of treating cracks at an early age.

Table 5.13. Summary decision tree for crack remediation options at different crack density and crack width combinations for remediation options implemented at a bridge deck age of between **0 and 2 years**. Green indicates most suitable option; Yellow indicates suitable option; Orange indicates least suitable option; Blue indicates a thin polymer overlay or a premixed concrete polymer overlay is the most suitable option; Pink indicates need for additional investigation.

Crack Width	Crack Density (ft/ft^2)			
	Mild **< 0.10**	**Moderate** **0.10 to 0.22**	**Severe** **0.22 to 0.37**	**Very Severe** **0.37 <**
Shallow cracks (Map cracks)	Do Nothing	Do Nothing	Do Nothing	Do Nothing
	Penetrating Sealer	Penetrating Sealer	Penetrating Sealer	Penetrating Sealer
	Flood Coat	Flood Coat	Flood Coat	Flood Coat
5 to 15 mils	Do Nothing	Penetrating Sealer +/- Reapplication	Flood Coat	Flood Coat
	Penetrating Sealer +/- Reapplication			
	Crack Chasing, Flood Coat	Flood Coat	Thin Polymer Overlay	Thin Polymer Overlay
	Thin Polymer Overlay	Thin Polymer Overlay		
		Premixed Polymer Overlay	Premixed Polymer Overlay	Premixed Polymer Overlay
15 to 30 mils	Crack Chasing, Flood Coat	Flood Coat	Flood Coat	Flood Coat
	Thin Polymer Overlay	Thin Polymer Overlay	Thin Polymer Overlay	Thin Polymer Overlay
		Premixed Polymer Overlay	Premixed Polymer Overlay	Premixed Polymer Overlay
30 to 40 mils	Crack Chasing	Thin Polymer Overlay	Thin Polymer Overlay	Thin Polymer Overlay
	Thin Polymer Overlay	Premixed Polymer Overlay	Premixed Polymer Overlay	Premixed Polymer Overlay
Greater than 40 mils	Investigate			

Notes:

1. Crack densities exceeding 0.37 ft/ft^2 shall be investigated prior to implementation of repairs.
2. Crack widths between 30 mils and 40 mils with a crack density exceeding 0.10 ft/ft^2 shall be investigated prior to implementation of repairs.
3. The decision tree does not apply to crack densities exceeding 0.50 ft/ft^2 or crack widths exceeding 40 mils.
4. Crack width information is used to exclude crack remediation options from selection. For this guide, it is assumed that if 25% of the deck cracks exceed the crack width limit for a given option, then that option should be excluded from viable options.
5. Refer to Table 5.8, Table 5.11 and Table 5.12 for more detailed information regarding initial cost, time-to-5% damage, time-to-replacement, and life-cycle cost for the crack remediation options.

Table 5.14. Summary decision tree for crack remediation options at different crack density and crack width combinations for remediation options implemented at a bridge deck age of **5 years**. Green indicates most suitable option; Yellow indicates suitable option; Orange indicates least suitable option; Blue indicates a thin polymer overlay or a premixed concrete polymer overlay is the most suitable option; Pink indicates need for investigation.

Crack Width	Crack Density (ft/ft^2)			
	Mild **< 0.10**	**Moderate** **0.10 to 0.22**	**Severe** **0.22 to 0.37**	**Very Severe** **0.37 <**
Shallow cracks (Map cracks)	Do Nothing Penetrating Sealer Flood Coat	Do Nothing Penetrating Sealer Flood Coat	Do Nothing Penetrating Sealer Flood Coat	Do Nothing Penetrating Sealer Flood Coat
5 to 15 mils	Do Nothing Penetrating Sealer Crack Chasing, Flood Coat Thin Polymer Overlay	Penetrating Sealer +/- Reapplication Flood Coat Thin Polymer Overlay Premixed Polymer Overlay	Flood Coat Thin Polymer Overlay Premixed Polymer Overlay	Flood Coat Thin Polymer Overlay Premixed Polymer Overlay
15 to 30 mils	Crack Chasing, Flood Coat Thin Polymer Overlay	Flood Coat Thin Polymer Overlay Premixed Polymer Overlay	Flood Coat Thin Polymer Overlay Premixed Polymer Overlay	Flood Coat Thin Polymer Overlay Premixed Polymer Overlay
30 to 40 mils	Crack Chasing Thin Polymer Overlay	Thin Polymer Overlay Premixed Polymer Overlay	Thin Polymer Overlay Premixed Polymer Overlay	Thin Polymer Overlay Premixed Polymer Overlay
Greater than 40 mils	Investigate			

Notes:

1. Crack densities exceeding 0.37 ft/ft^2 shall be investigated prior to implementation of repairs.
2. Crack widths between 30 mils and 40 mils with a crack density exceeding 0.10 ft/ft^2 shall be investigated prior to implementation of repairs.
3. The decision tree does not apply to crack densities exceeding 0.50 ft/ft^2 or crack widths exceeding 40 mils.
4. Crack width information is used to exclude crack remediation options from selection. For this guide, it is assumed that if 25% of the deck cracks exceed the crack width limit for a given option, then that option should be excluded from viable options.
5. Refer to Table 5.9, Table 5.11 and Table 5.12 for more detailed information regarding initial cost, time-to-5% damage, time-to-replacement, and life-cycle cost for the crack remediation options.

Table 5.15. Summary decision tree for crack remediation options at different crack density and crack width combinations for remediation options implemented at a bridge deck age of **10 years**. Green indicates most suitable option; Yellow indicates suitable option; Orange indicates least suitable option; Blue indicates a thin polymer overlay or a premixed concrete polymer overlay is the most suitable option; Pink indicates need for investigation.

Crack Width	Crack Density (ft/ft^2)			
	Mild **< 0.10**	**Moderate** **0.10 to 0.22**	**Severe** **0.22 to 0.37**	**Very Severe** **0.37 <**
Shallow cracks (Map cracks)	Do Nothing	Do Nothing	Do Nothing	Do Nothing
	Penetrating Sealer	Penetrating Sealer	Penetrating Sealer	Penetrating Sealer
	Flood Coat	Flood Coat	Flood Coat	Flood Coat
5 to 15 mils	Do Nothing[2]	Flood Coat	Flood Coat	Thin Polymer Overlay
	Crack Chasing, Flood Coat			
	Thin Polymer Overlay	Thin Polymer Overlay	Thin Polymer Overlay	Premixed Polymer Concrete
	Premixed Polymer Concrete	Premixed Polymer Concrete	Premixed Polymer Concrete	
15 to 30 mils	Crack Chasing, Flood Coat	Flood Coat	Flood Coat	Thin Polymer Overlay
	Thin Polymer Overlay	Thin Polymer Overlay	Thin Polymer Overlay	
	Premixed Polymer Concrete	Premixed Polymer Concrete	Premixed Polymer Concrete	Premixed Polymer Concrete
30 to 40 mils[1]	Crack Chasing	Thin Polymer Overlay	Thin Polymer Overlay	Thin Polymer Overlay
	Thin Polymer Overlay	Premixed Polymer Concrete	Premixed Polymer Concrete	Premixed Polymer Concrete
	Premixed Polymer Concrete			
Greater than 40 mils	Investigate			

Notes:

1. Crack densities exceeding 0.37 ft/ft^2 shall be investigated prior to implementation of repairs.
2. Crack widths between 30 mils and 40 mils with a crack density exceeding 0.10 ft/ft^2 shall be investigated prior to implementation of repairs.
3. The decision tree does not apply to crack densities exceeding 0.50 ft/ft^2 or crack widths exceeding 40 mils.
4. Crack width information is used to exclude crack remediation options from selection. For this guide, it is assumed that if 25% of the deck cracks exceed the crack width limit for a given option, then that option should be excluded from viable options.
5. Refer to Table 5.10, Table 5.11 and Table 5.12 for more detailed information regarding initial cost, time-to-5% damage, time-to-replacement, and life-cycle cost for the crack remediation options.

5.4. Example Iowa DOT Bridge

During the project, the project team had the opportunity to inspect a new bridge deck located on I-80 (Eastbound) at Grinnell exit to Highway 146. The bridge deck was cast on September 22, 2020. The inspection was completed on May 6, 2021 approximately 9 months after construction. The deck exhibited early-age cracks and, therefore, was included in the project as an example on how to apply the developed decision matrices.

Field inspection of the bridge deck included visual assessment and documentation of the cracks, collection of ground-penetrating radar data (GPR) to confirm reinforcement cover, and collection of cores for petrographic examination. The visual assessment indicated that the majority of the bridge deck cracks were transverse cracks concentrated in the southern portion of the deck as shown in Figure 5.3. The crack widths measured in the field were typically 10 mils. The GPR data indicated that the average concrete cover above the top steel reinforcement was approximately 3 inches, which exceeds the minimum cover requirements by the Iowa DOT. The petrographic examination was used to estimate the properties of the concrete mix design used for the deck, which confirmed that a typical Iowa DOT high-performance concrete (HPC) mixture was used. Note that the HPC mix includes supplementary cementitious material, namely fly ash and slag cement.

In order to use the decision trees, the following information is needed:

- Deck age: The age of the inspected bridge deck and anticipated time of treatment is between 0 and 2 years.
- Crack classification: The majority of the cracks observed were transverse cracks, which are classified as deep cracks that reach the reinforcement as indicated in Chapter 3.
- Crack width: Typical transverse crack widths measured were 10 mils.
- Crack density: Measured as the summation of the length of the cracks divided by the inspected area. As the crack density is highly dependent on the assumed inspected area, careful determination of this factor is required as discussed below.

Figure 5.4 shows the crack map of the inspected bridge deck. Calculated crack density information is also provided in the figure based on the three inspected areas below. Note that each of the calculated crack densities will result in recommending different remediation options based on the crack density classifications proposed in this report. Engineering judgment must be applied to determine which inspected area is most suitable for calculating the crack density to be input into the decision trees.

- Overall deck area: The overall deck area of this bridge is 15,000 ft^2 (based on the bridge width of 60 feet and length of 250 feet). The calculated crack density for this area in less than 0.02 ft/ft^2.
- Southern portion of the deck area: The area included in this assumption is a width of 10 feet multiplied by the bridge length of 250 feet, which translates to an area of 2500 ft^2. The calculated crack density for this area is 0.11 ft/ft^2.
- Select portion of the deck area at a heavily cracked location: The area included in this assumption is a width of 10 feet multiplied by a length of 40 feet where the majority of cracking is observed, which translates to an area of 400 ft^2. Calculated crack density for this area is 0.25 ft/ft^2.

The above calculations demonstrate the importance of selecting an appropriate area to be used for calculating the crack density. The Florida DOT specifies in Section 400-21, *Disposition of Cracked Concrete*, of its Standard Specifications for Road and Bridge Construction that an area not more than 400 square feet and not less than 100 square feet be used for determination of crack densities for bridge decks. This is a reasonable range of surface areas for calculating the crack densities and determining the most suitable repair for the surface areas based on the proposed decision trees.

Based on the inputs above, and using the decision tree provided in Table 5.13, the most suitable option for this particular bridge deck is to place a flood coat to remediate the effect of observed bridge deck cracks.

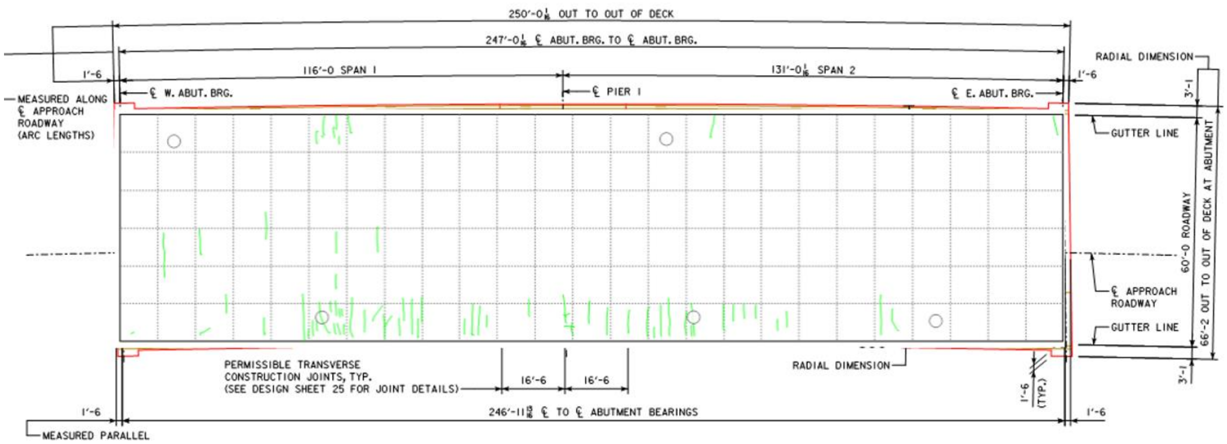

Figure 5.3. Observed early-age bridge deck cracks on a new bridge deck located on I-80 (Eastbound) at Grinnell exit to Highway 146.

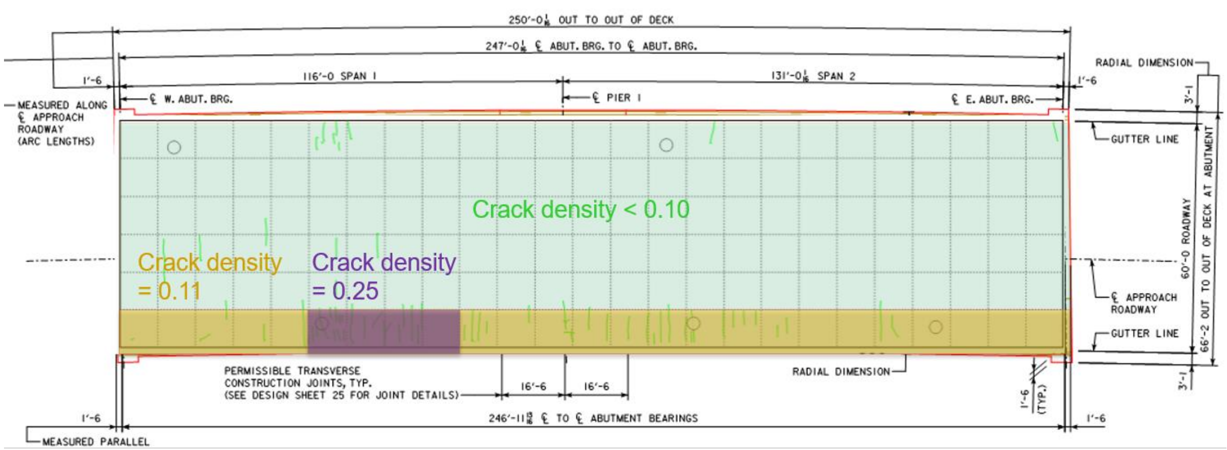

Figure 5.4. Crack densities calculated for different inspection areas.

CHAPTER 6. SUMMARY AND RECOMMENDATIONS

This report presents the work completed to develop a comprehensive guide to remediate cracks in bridge decks. This included developing data-driven decision trees that relied heavily on the results of an extensive service life modeling effort of a generic Iowa bridge deck with various extents of cracking in combination with various methods to remediate the effect of bridge deck cracking. All the models were analyzed using WJE CASLE™, a mechanistic service life modeling software developed by WJE, following the methodology presented in Appendix C.

6.1. Summary

A summary of the completed effort and major findings of this report is presented in this section.

- A comprehensive literature review of state DOTs practices to deal with bridge deck cracking issues was completed. In general, limited guidance was found in terms of decision trees that are focused on treating bridge deck cracks. The few available decision trees relied on very simplistic approaches by considering few inputs and remediation options. FDOT adopts a more sophisticated decision tree; however, that provides guidance without consideration of the age of bridge deck at the time of repair application, which was found to be a significant factor.
- A summary of causes, characterization, and inspection of cracks in the field was presented. This included providing a practical classification technique to categorize cracks in three categories: shallow, deep, and active cracks as indicated below. All the completed analyses are focused on shallow and deep cracks. Active cracks are considered out of the scope of this work as they require additional investigation and/or analysis.
  - Shallow cracks: Cracks that do not reach the depth of reinforcement. These cracks do have an effect on the durability of the bridge deck, but it is usually limited. These cracks are classified as map cracks with a crack width of approximately 5 mils (0.005 inches).
  - Deep cracks: Cracks that reach the depth of reinforcement. These are typically transverse cracks, but can also include longitudinal or diagonal cracks. The crack width associated with this type of cracking is generally between 10 and 40 mils (0.010 and 0.040 inches).
  - Active cracks: Cracks that are known to have a width that can fluctuate with time due to changes in deck loads or concrete temperature.
- Crack remediation options that can be used to repair bridge deck cracks were determined based on the literature review. Information regarding all identified crack remediation techniques can be found in Appendix B, while Appendix E include a summary of sections related to crack repair and inspections in the standard specifications and special provisions of the 16 state DOTs included in the literature review.
- Service life modeling was completed to compare the service life of a generic Iowa uncracked bridge deck to bridge decks with different extents of shallow and deep cracking. Multiple service life models were then analyzed with the application of different crack remediation options including do nothing, penetrating sealers, crack-chasing, flood coats, hot-mixed asphalt overlay with waterproofing membrane (HMAWM), thin polymer overlay (TPO), and premixed polymer overlay (PPC). A high level summary of the modeling results is below, all the results are for deep cracks unless noted otherwise:

- The time of application of crack remediation options have a significant effect on the service life extension benefits that can be achieved by the repair.
- Increase in crack density (or crack affected area) can lead to a significant reduction in the service life extension associated with the crack remediation options. Four different categories of crack density were proposed as shown below:
  - Mild Cracking: Crack density less than 0.10 ft/ft^2
  - Moderate Cracking: Crack density between 0.10 and 0.22 ft/ft^2
  - Severe Cracking: Crack density between 0.22 and 037 ft/ft^2
  - Very Severe Cracking: Crack density more than 0.37 ft/ft^2
- Penetrating sealers provide service life extension if applied on bridge decks with mild crack density at an age between 0 and 2 years. Re-application leads to an increase of service life extension. This option is not appropriate for bridge decks with severe or very severe crack densities. Service life extension benefits decrease when the time of application is delayed to a deck age of 5 years. Minimal benefits are expected in terms of remediation of bridge decks cracking effects when penetrating sealers are applied at later ages; based on the currently available literature.
- Crack-chasing with gravity fed polymer is a practical option for bridge decks with mild crack density only. This remediation option restores the performance of cracked areas to behave like uncracked areas. This option has the lowest initial cost of all remediation options considered.
- Flood coats provide service life extension for bridge decks with mild to severe crack densities when applied at bridge deck age between 0 and 2 years. The benefits associated with flood coats decrease when applied on older bridge decks. This option has a moderate initial cost; more expensive than penetrating sealers but cheaper than the overlay options.
- Hot-mixed asphalt overlays with waterproofing membrane (HMAWM) were predicted to provide higher service life extension compared to the sealers and flood coats options when applied on bridge decks of age between 0 and 2 years but comes at a much higher initial cost. The benefits of HMAWM decreases significantly when applied on older bridge decks. The increase in service life benefits from applying HMAWM does not compensate for their higher initial cost, especially when compared to the benefits of polymer overlay options for the considered exposure conditions.
- Thin polymer overlays (TPO) provide significant increase in service life benefits compared to other options, especially when applied on bridge decks with age between 0 and 2 years. Slight decrease in benefits is observed when applied at deck age of 5 years while significant decrease is observed when applied at 10 years. This option is appropriate for all crack densities; however, is not recommended on young deck with mild or moderate crack densities as there are other less expensive and less disruptive to traffic alternatives. At bridge decks of age of 5 years or more, this option becomes more economical especially for bridge decks with higher crack densities.
- Premixed polymer concrete overlays (PPC) were predicted to provide the greatest service life extension out of all considered options, but it also has the highest initial cost. This option is appropriate for similar conditions as thin polymer overlays. The decision between the two options should be based on the objective of the repair; whether to minimize costs (TPO is more appropriate) or maximize extension of service life (PPC is more appropriate).
- For shallow cracks, only penetrating sealers or flood coats are considered. Both options provide service life extension benefits when applied to bridge decks with mild to severe crack densities. Only flood coats were predicted to provide benefits when applied to bridge decks with very severe

crack density. When applied at a later age (5 years), flood coats provide higher benefits compared to penetrating sealers for bridge decks with moderate to very severe crack densities. Note that penetrating sealers initial cost is about one third of that for flood coats.

- Life-cycle cost analyses for all the considered options and crack densities were completed. The life-cycle costs were essential in the development of decision trees.
- Data-driven decision trees were developed based on the completed analyses described in this report. Inputs for the decision trees include bridge age, crack density and crack width. Outputs/factors used to make the decision include initial cost of the remediation option, time-to-5% damage (T_5), time-to-replacement or end of service life which is assumed to occur when 20% damage is reached (T_{20}), and life-cycle cost. Three decision trees were developed for different bridge deck ages at the time of application of crack remediation; between 0 and 2 years, at 5 years and at 10 years. In total, 87 analysis cases were included in the decision trees for deep cracks. Raw data results for the analysis cases is shown in Appendix D while processed data as compared to the do nothing scenario and the base case of uncracked bridge deck is shown in Table 5.2 to Table 5.7. Note that all the options provide service life extension benefits compared to the do nothing case.
- Three detailed decision trees were presented for the case of deep cracks that summarize the conditions where different crack remediation options are appropriate as shown in Table 5.8 to Table 5.10. For shallow cracks, decision trees are presented in Table 5.11 and Table 5.12.
- Three simplified, data-driven, color-coded decision trees were developed for optimal selection of crack remediation options for bridge decks with shallow or deep cracks at different crack densities. The Crack Remediation Decision Trees are presented in Table 5.13 to Table 5.15. A detailed summary for the basis of selection of the different options at different bridge deck characteristics is provided in section 5.3.4.
- An example bridge was inspected and analyzed. The example showed the importance of selecting appropriate representative deck areas for completing the crack inspections and calculating crack density to be used in the decision trees. Based on the example, it is recommended that the inspected deck area to be considered for calculating the bridge deck crack density shall not be more than 400 square feet or not less than 100 square feet.

6.2. Future Research Needs

The analyses completed in this report, particularly those related to the service life modeling effort using WJE CASLE™ (a mechanistic service life modeling software developed by WJE), are based on practical assumptions made by the research team through experience and previous similar work conducted on numerous bridge decks throughout the United States. Although a substantial service life modeling effort was completed, the research was focused on a generic Iowa bridge deck that does not include the use of supplementary cementitious materials, which are becoming more popular with the drive for low carbon dioxide emissions. As such, the following research needs are identified for future efforts:

- Completion of a similar effort that considers the use of supplementary cementitious materials, such as fly ash or slag. These materials are included in Iowa HPC mixes, which is the mix used for construction of the example bridge deck included in this report.

- Research to verify the effect of penetrating sealers when applied on bridge decks that have already been chloride contaminated. Penetrating sealers help reduce the ingress of chlorides and moisture. The effect of the latter should be of particular interest in future research.
- Evaluate the performance of bridge decks with older application of thin polymer and premixed polymer concrete overlays to characterize the overlay wear and delamination rates and validate the benefits related to the deck service life extension.
- Conduct a comparative study of actual field applications that can assess the benefits of application of the proposed remediation options versus a do-nothing scenario.

6.3. Implementation

The content of this report is intended to be used as general guidelines for Iowa DOT to choose optimal crack remediation options for bridge decks with different ages and different extents of cracking. Portions of this report can be included in Iowa DOT Bridge Maintenance Manual. In addition, the information provided regarding crack remediation options in Appendix B and Appendix E, which includes a summary of sections related to crack repair and inspections in the standard specifications and special provisions of the 16 state DOTs included in the literature review, can be used as reference to update or develop standard specification or special provisions for the crack remediation options considered in this report.

The findings of this report indicate that application of crack remediation options within the first 2 years after bridge deck construction is essential to achieve the maximum benefits of the repair. This is highlighted by improvement in service life extension and reduction in life-cycle cost, especially when compared to the do nothing scenario. Therefore, it is recommended that these preventive maintenance approaches be applied early in the life of new bridges.

A summary of the sections of this report that can be used to develop standard specifications for bridge deck crack remediation options is provided below.

- Crack inspections and classifications as detailed in section 3.3. It is recommended to include a requirement to conduct a visual assessment and crack mapping of newly constructed bridge decks.
- Requirements for deck inspection area to be used to calculate crack density. It is recommended that the inspected deck area to be considered for calculating the bridge deck crack density shall not be more than 400 square feet or not less than 100 square feet.
- Crack Remediation Decision Trees presented in section 5.3.4 (Table 5.13 to Table 5.15). It is recommended to include the detailed decision trees presented in Table 5.8 to Table 5.12 for deep and shallow cracks. All the notes and limitations for application of the decision trees presented in Chapter 5 should also be included.

CHAPTER 7. REFERENCES

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APPENDIX A. STATE DOT DECISION TOOLS FOR CRACK MAINTENANCE

This appendix presents the tables and matrices used by the sixteen state DOTs included in the literature review to select between crack maintenance strategies. Appendix A is organized by the types of tools provided, as categorized in the report: crack-focused maintenance selection tools (Section A.1) or general maintenance selection tools (Section A.2). The one comprehensive tool for crack repair found, which was by FDOT, was provided in 2.1, Established Practices According to State DOT Manuals as Table 2.1.

Section A.1 Crack-Focused Maintenance Selection Tools

ODOT, MDOT, MnDOT, MoDOT, NYSDOT, VDOT, and WisDOT were identified in Table 2.1 as providing crack-focused maintenance selection tools or guidance. Of these state DOTs, only MoDOT and NYSDOT provide tables, shown in Table A.1 and Table A.2, respectively. The remaining state DOTs discuss the specific crack widths, activities, and other characteristics for which limited repairs are appropriate in the text of their manuals.

Table A.1. Matrix for the selection of bridge deck preventive maintenance treatments, per MoDOT (2016).

Condition Description	Preventive Maintenance Treatment
New Decks and Decks with minimal cracking	EPG 771.16 Penetrating Concrete Sealer - Silane
Decks with hairline cracks < 1/128" (0.008 in.) wide	EPG 771.17 Concrete Crack Filler -Low Viscosity Polymer (LVP)
Decks with cracks >1/128" (0.008 in.) wide	EPG 771.18 In-Deck Bridge Deck Crack Filler
Decks with cracks >1/64" (0.016 in.) wide	EPG 771.19 Chip Seal to Entire Deck

Table A.2. Concrete crack treatments, per NYSDOT (2019).

Treatment	Working Cracks and/or Deicer Exposure (flatwork)	Nonworking Cracks
Do Nothing	< 0.004"	< 0.007"
Penetrating Sealer	< 0.007"	< 0.012"
High Molecular Weight Methacrylate (HMWM) Epoxy Injection	> 0.007"	> 0.012"

Section A.2 General Maintenance Selection Tools

InDOT, MDOT, VDOT, and WisDOT were identified in Table 2.1 as providing general maintenance selection tools. All of these state DOTs provide tables identifying criteria for the deck to be eligible for the maintenance actions considered:

- InDOT provides one table for condition-driven preventative maintenance and a second table for scheduled preventative maintenance. These tables are shown in Table A.3 and Table A.4, respectively. "CS" refers to "Condition State."
- MDOT provides two bridge deck preservation matrices, one for decks with uncoated rebar, shown in Figure A.1, and a second for decks with epoxy-coated rebar, shown in Figure A.2.

- VDOT provides a single deck decision matrix for repair, rehabilitation, or replacement of concrete decks, shown in Table A.5. The matrix contains extensive discussion of cracking and eligibility for crack repair in its notes.
- WisDOT provides a concrete deck/slab eligibility matrix, shown in Figure A.3.

Table A.3. Condition-Driven Preventative Maintenance Eligibility Criteria, per Figure 412-1A from INDOT (2013).

Treatments Type	Bridge Component (Item Code	Component Rating	Other Criteria [2]
Bridge Culvert Liners	Culverts (62)	2-5	N/A [3]
Deck Patching (partial/full depth)	Wearing Surface (58.01)	>4	D/SS >4 and Max. 10% Deck Patching
Approach Slab Repair/Replacement	Approach Slab (Misc. Asset Data) or Concrete approach slab Elements	<6, or >10% Element Level in CS2 or any % in CS3	WS/D/SS>4
Expansion Joint Repair/Replacement/Elimination	Transverse Joints (Misc. Asset Data - Joints) or Joint Elements	<6, or >10% Element Level in CS2 or any % in CS3	WS/D/SS>4
Mudwall Patching	Substructure Backwall (60)	<6, or >10% Element Level in CS2 or any % in CS3	WS/D/SS>4
Bridge Deck Overlays - Flexible	Wearing Surface (58.01)	>4	D/SS>4 and Max. 10% Deck Patching
Bridge Deck Overlays - Rigid	Wearing Surface (58.01)	>3	D/SS>4 and Max. 15% Deck Patching
Spot Coating/Bridge Painting	Condition of Paint (Misc. Asset Data - Paint Condition Steel Superstructure Corrosion Elements, and/or Steel Bearing Corrosion Elements	<7[4] or >10% Element Level in CS2 or any % in CS3	WS/D/SS>4
Substructure/Pile Patching/Sealing/Fiber Wrap	Substructure (60)	N/A	WS/D/SS>4
Superstructure Crack Mitigation Superstructure Patching / Fiber Wrap	Concrete Girders (59) or Concrete Beams (59)	N/A	WS/D/SS>4
Erosion Mitigation	Channel and Channel Protection (61)	<6	WS/D/SS>4
Debris Removal/Channel Cleaning	Channel and Channel Protection (61)	<6	WS/D/SS>4
Slopewall Repair/Replacement	Misc. Asset Data - Slopewall	<6	WS/D/SS>4

Treatments Type	Bridge Component (Item Code	Component Rating	Other Criteria [2]
Bearing Repair/Replacement	Bearings (Misc. Asset Data), or Bearing Element Items	<6, or any % Element Level in CS2 or CS3	WS/D/SS>4
Scour Mitigation	NBI Scour Evaluation Code (113)	2-4	Not Programmed for Bridge Replacement
Deck Crack Sealing	Wearing Surface (58.01)	>5	D/SS>5
Brush Cutting/Herbicide Application [1]	Deficiency Noted	N/A	WS/D/SS>4
Railing Repair [1]	Deficiency Noted	N/A	WS/D/SS>4
Relief/Terminal Joint Repair [1]	Deficiency Noted	N/A	WS/D/SS>4
Upgrading End Treatments, Guardrail, Railing, Attenuators [1,4]	N/A	N/A	WS/D/SS>4
Adding Reinforced Concrete Deck to an Adjacent Box Beam Bridge without a Deck [5]	Superstructure (59) and Substructure (60)	(59) >5 (60) >4	N/A

Notes: [1] *Items may only be included in a project incorporating other preventative maintenance treatments*

[2] *WS = Wearing Surface (58.01); D = Deck (58); SS = Superstructure (59) and Substructure (60)*

[3] *Treatments should raise the condition of the rating to 5 or higher*

[4] *When found to be cost-effective*

[5] *Treatment is applicable to LPA bridges only. The minimum allowable deck thickness is 5 in.*

Table A.4. Scheduled Preventative Maintenance Eligibility Criteria, per Figure 412-1B from INDOT (2013).

Treatment Type	Bridge Component (Item Code)	Component Rating	Cycle (years)
Cleaning/flushing bridge decks	Deck (58)	>4	1
Substructure/superstructure washing	Superstructure (59) & Substructure (60)	>4	1
Clean Deck Drains	Deck (58)	>4	1
Cleaning/lubricating bearings	Superstructure (59)	>4	1
Cleaning Joints	Misc. Asset Data - Joints	>4	1
Deck Sealing	Wearing Surface (58.01)	>5	5

BRIDGE DECK PRESERVATION MATRIX – DECKS WITH UNCOATED "BLACK" REBAR

DECK CONDITION STATE				REPAIR OPTIONS	POTENTIAL RESULT TO DECK BSIR		ANTICIPATED FIX LIFE
Top Surface		Bottom Surface			Top Surface BSIR #58a	Bottom Surface BSIR #58b	
BSIR #58a	Deficiencies % (a)	BSIR #58b	Deficiencies % (b)				
≥ 5	N/A	N/A	N/A	Hold (c) / Seal Cracks	No Change	No Change	N/A
				Silane			5 years
				Healer Sealer (d)			8 to 10 years
	≤ 10%	≥ 6	≤ 2%	Epoxy Overlay (f)	8, 9	No Change	15 to 20 years
	≤ 10%	≥ 4	≤ 25%	Deck Patch (e, j)	6, 7, 8	No Change	5 to 10 years
4 or 5	10% to 25%	≥ 5	≤ 10%	Deep Concrete Overlay (h, j)	8, 9	No Change	25 to 30 years
		4	10% to 25%	Shallow Concrete Overlay (h, i, j)	8, 9	No Change	20 to 25 years
				HMA Overlay with water-proofing membrane (f, i)	8, 9	No Change	8 to 10 years
		2 or 3	> 25%	HMA Cap (g, i)	8, 9	No Change	2 to 4 years
≤ 3	>25%	≥ 6	< 2%	Deep Concrete Overlay (h, j)	8, 9	No Change	20 to 25 years
		4 or 5	2% to 25%	Shallow Concrete Overlay (h, i, j)	8, 9	No Change	10 years
				HMA Overlay with water-proofing membrane (f, i)	8, 9	No Change	5 to 7 years
		2 or 3	>25%	HMA Cap (g, i)	8, 9	No Change	1 to 3 years
				Replacement with Epoxy Coated or Stainless Rebar Deck	9	9	60+ years

(a) Percent of deck surface area that is spalled, delaminated, or patched with temporary patch material. Top surface decision making based on concrete surface, not the condition of thin epoxy overlays or other wearing surfaces.
(b) Percent of deck underside area that is spalled, delaminated or map cracked.
(c) The "Hold" option implies that there is on-going maintenance to sustain current ratings.
(d) Seal cracks when cracks are easily visible and minimal map cracking. Apply healer sealer when crack density is too great to seal individually by hand. Sustains the current condition longer.
(e) Crack sealing must also be used to seal the perimeter of deck patches and joint replacements.
(f) Deck patching required prior to placement of epoxy overlay or waterproofing membrane.
(g) Hot Mix Asphalt cap without waterproofing membrane for ride quality improvement. Deck should be scheduled for replacement in the 5 year plan.
(h) If bridge crosses over traveled lanes and the deck contains slag aggregate, do deck replacement.
(i) When deck bottom surface is rated poor (or worse) and may have loose or delaminated concrete over traveled lanes, sidewalks or non-motorized paths, an in-depth inspection should be scheduled. Any loose or delaminated concrete should be scaled off and false decking should be placed over traveled lanes where there is potential for additional concrete to become loose.
(j) Some full depth repairs should be expected where top surface deficiencies align with bottom surface deficiencies.

Bridge Deck Preservation Matrix **July, 2017 Rev.**

Figure A.1. Bridge deck preservation matrix for decks with uncoated "black" rebar, per MDOT (2017).

BRIDGE DECK PRESERVATION MATRIX – DECKS WITH EPOXY COATED REBAR (ECR)

DECK CONDITION STATE				REPAIR OPTIONS	POTENTIAL RESULT TO DECK BSIR		ANTICIPATED FIX LIFE
Top Surface		Bottom Surface					
BSIR #58a	Deficiencies % (a)	BSIR #58b	Deficiencies % (b)		Top Surface BSIR #58a	Bottom Surface BSIR #58b	
≥ 5	N/A	N/A	N/A	Hold (c) / Seal Cracks	No Change	No Change	N/A
				Silane			5 years
				Healer Sealer (d)			8 to 10 years
	≤ 10%	≥ 6	≤ 2%	Epoxy Overlay (f)	8, 9	No Change	15 to 20 years
	≤ 10%	≥ 4(k)	≤ 25%(k)	Deck Patch (e, j)	6, 7, 8	No Change	5 to 10 years
4(k) or 5	10% to 25%(k)	4(k)	10% to 25%(k)	Shallow Concrete Overlay (h, i, j)	8, 9	No Change	20 to 25 years
				HMA Overlay with water-proofing membrane (f, i)	8, 9	No Change	8 to 10 years
		2 or 3(k)	> 25%(k)	HMA Cap (g, i)	8, 9	No Change	2 to 4 years
≤ 3(k)	>25%(k)	4(k) or 5	2% to 25%(k)	Shallow Concrete Overlay (h, i, j)	8, 9	No Change	10 years
				HMA Overlay with water-proofing membrane (f, i)	8, 9	No Change	5 to 7 years
		2 or 3(k)	>25%(k)	HMA Cap (g, i)	8, 9	No Change	1 to 3 years
				Replacement with Epoxy Coated or Stainless Rebar Deck	9	9	60+ years

(a) Percent of deck surface area that is spalled, delaminated, or patched with temporary patch material. Top surface decision making based on concrete surface, not the condition of thin epoxy overlays or other wearing surfaces.
(b) Percent of deck underside area that is spalled, delaminated or map cracked.
(c) The "Hold" option implies that there is on-going maintenance to sustain current ratings.
(d) Seal cracks when cracks are easily visible and minimal map cracking. Apply healer sealer when crack density is too great to seal individually by hand. Sustains the current condition longer.
(e) Crack sealing must also be used to seal the perimeter of deck patches and joint replacements.
(f) Deck patching required prior to placement of epoxy overlay or waterproofing membrane.
(g) Hot Mix Asphalt cap without waterproofing membrane for ride quality improvement. Deck should be scheduled for replacement in the 5 year plan.
(h) If bridge crosses over traveled lanes and the deck contains slag aggregate, do deck replacement.
(i) When deck bottom surface is rated poor (or worse) and may have loose or delaminated concrete over traveled lanes, sidewalks or non-motorized paths, an in-depth inspection should be scheduled. Any loose or delaminated concrete should be scaled off and false decking should be placed over traveled lanes where there is potential for additional concrete to become loose.
(j) Some full depth repairs should be expected where top surface deficiencies align with bottom surface deficiencies.
(k) Contact the Bridge Management section if a deck with epoxy coated rebar in poor condition is identified.

Bridge Deck Preservation Matrix **July, 2017 Rev.**

Figure A.2. Bridge deck preservation matrix for decks with epoxy coated rebar (ECR), per MDOT (2017).

Table A.5. The deck decision matrix for concrete deck repair, rehabilitation, or replacement provided by VDOT (2019).

Deck Decision Matrix: Concrete Decks[1, 9, 10]					
Worse of These		**Condition Category**	**Year Built**	**Evaluation Results**	**Minimum Required Action**
Deck GCR	**%CA[2]**				
7 - 9	≤ 5	Good	Prior to 2003	Recommended, but Not Required	Patch, Epoxy Overlay, Fill Cracks[3], Clean Drains and Sweep/Wash Annually
				Recommended, but Not Required	Patch, Fill Cracks[3], Clean Drains and Sweep/Wash Annually
6	≤ 10	Satisfactory[4]	2003 or later	CA < 5% & CF < 1″	Patch and Epoxy Overlay
				CA ≤ 10% & CF < 1″	Patch and Rigid Overlay on Rotomilled Substrate
				No Evaluation or CF[5] > 1.5″	Rigid Overlay on Shallow Hydromilled Substrate
5	≤ 15	Fair[4]	Any	CF[5] ≤ Average Cover Depth of Top Bar Mat[6]	Rigid Overlay over Shallow Hydromilled Substrate
				4″ > CF[5] ≥ Avg. Cover Depth of Top Bar Mat[6]	Rigid Overlay over Deep Hydromilled Substrate
≤4	≤ 20	Poor[4]	Any	CF[5] ≤ Average Cover Depth of Top Bar Mat[6]	Rigid Overlay over Shallow Hydromilled Substrate
				4″ > CF[5] ≥ Avg. Cover Depth of Top Bar Mat[6]	Rigid Overlay over Deep Hydromilled Substrate
Any	Any	Any	Any	CF[5] > 4″	Replace Deck[7,8]
Any	Any	Any	Any	Spalls - deck bottom >3%	Replace Deck[7]
Any	Any	Any	Any	Reactive Aggregates Present & CI > 0.02 in/yd	Replace Deck[7]
Any	Any	Any	Any	f_c' ≤2,400 psi (average)	Replace Deck[7]
Any	Any	Any	Any	Cost to Rehab or Repair > 65% of Replace Cost	Replace Deck[7]

Notes: *[1]If any deck exhibits signs of alkali-silica reaction based on a qualitative visual assessment, then petrographic analysis is required. If petrographic analysis establishes the presence of highly reactive aggregate, tehn measure the Cracking Index (CI) to analyze the severity of damage. If CI < 0.02 in/yd, provide a rigid overlay on a hydromilled surface. Establish depth of hydromilling to eliminate chloride front. CI is defined in FHWA's Report on the Diagnosis, Prognosis, and Mitigation of Alkali-Silica Reaction (ASR) in Transportation Structures. A link is provided in Reference 1 on File No. 32.03-13.*

[2]Compromised Area (CA) of Deck is expressed as a percentage of the total deck area (width is based on the out-to-out dimension of the bridge) and is determined by either of the methods below. IF nondestructive testing is used, CA will be the greater of the two.

- *The total area of deck in condition state 2 or greater, as defined in terms of the AASHTO element definitions. Determined by visual examination.*

OR

- *The deck area measured as delaminated, spalled or patched (Determined using and acceptable methodology) plus additional areas of deck in condition state 1 with half-cell potential readings more negative than -0.35mV.*

[3]Cracks wider than 0.20 mm allow the inflow of water and must be sealed or overlaid. An asphalt overlay with approved membrane is required for Good decks with active cracks. Active cracks are those with widths that vary with temperature and/or live load. The District Structure and Bridge Engineer shall determine whether active cracks are significant enough to require an overlay. Good decks with non-active cracks wider than 0.20 mm require an epoxy overlay if built prior to 2003 and gravity filled polymer sealing (Crack Repair Type C) or epoxy injection (Crack Repair Type B) if built in or after 2003. Overlays or crack seals are recommended for decks with an average of more than 0.2 linear feet of crack per square foot measured over the entire deck (e.g., 20 linear feet for 100 sf of deck).

[4]A deck evaluation is required for decks in Fair or Poor condition unless more than 3% of deck bottom exhibits spalls and recommended for decks in Satisfactory condition.

[5]Chloride Front (CF): The depth, measured from the top of the existing deck, at which the average chloride ion concentration in concrete exceeds the chloride threshold (defined below). The CF is determined by graphing the chloride profile (concentration of chloride ions versus depth) using the average readings from chloride ion tests taken from the bridge deck.

Chloride Threshold: Concentration of chloride ions required at the depth of the reinforcing steel to initiate corrosion. Value: 2.0 pounds per cubic yard.

[6]Average Cover Depth of Top Bar Mat: Measured from the top of the deck to the top of the top bar layer in the top mat. For structures with existing concrete overlays the top of the overlay is considered to be the top of the deck.

[7]If a deck replacement is indicated as the most appropriate action but funds are not currently available, the replacement may be delayed for a period of 3 to 5 years by patching the worst portions of the deck and placing a 2" by 2 ½" intermediate mix asphalt overlay over a low-cost membrane. This is only a stop-gap measure to provide time until funds can be provided. The bridge must be load rated for additional dead load.

[8]For concrete decks that are integral parts of concrete T-beam superstructures, a deep hydromill and rigid overlay is required as long as beams are suitable for preservation. Where beams require replacement, replacement of the entire superstructure is required.

[9]Evaluation of Existing Rigid Overlays: If an existing rigid overlay exhibits more than 5% spalling, the bond strength of the overlay should be evaluated and areas with low bond strength (≤100 psi) should be replaced by patching. If the area to be replaced exceeds 20% and is not confined to one lane, the entire overlay should be replaced. Evaluate the deck and base final intervention decision on the requirements of this section.

[10]Decks with corrosion resistant reinforcement (CRR): Minimal corrosion-induced damage is anticipated for decks with CR over the next decade. Decks with CRR that exhibit distress or damage should be evaluated individually to determine cause(s) of deterioration.

	NBI Item 58	Top Deck Element Distress Area (%)	Bottom Deck Element Distress Area (%)	Preservation Activity	Benefit to Deck from Action	Application Frequency (in years)
Concrete Deck/Slab	≥7	-	-	Deck Sweeping/Washing	Extend Service Life	1 to 2
		5% < 3220 < 25%	-	Crack Sealing	Extend Service Life	3 to 5
		3220 CS3 + CS4 > 0%	-	Deck Sealing	Service life extended	3 to 5
		-	1080 < 5%	Full Depth Deck Patching	Service life maintained	As needed
		3210 CS3 + CS4 < 5%	1080 < 5%	Wearing Surface Patching	Service life maintained	As needed
		>20% (3220 OR 8911 CS3 + CS4) OR	(1140 OR 1150) < 20% for timber deck	Polymer Modified Asphalt Overlay	Service life extended	10 to 15
		>15% 3210 (applied to bare deck)				
		>20% (3210 OR 8911 CS3 + CS4) OR	1080 < 5% for concrete deck			
		>50% 3220 (reapplication)				
		>20% (3220 OR 8911 CS3 + CS4) OR	(1140 OR 1150) < 20% for timber deck	HMA w/ membrane	Service life extended	5 to 15
		>15% 3210 (applied to bare deck)				
		>20% (3210 OR 8911 CS3 + CS4) OR	1080 < 5% for concrete deck			
		>50% 3220 (reapplication)				
		3210 < 5%	1080 < 1%	Polyester Polymer Concrete	Service life extended	20 to 30
		3210 < 2% (applied to bare deck)	1080 < 1%	Thin Polymer Overlay	Service life extended	7 to 15
		8513 CS3 + CS4 > 15% (reapplication)				
	6	-	-	Deck Sweeping/Washing	Extend Service Life	1 to 2
		5% < 3220 < 25%	-	Crack Sealing	Extend Service Life	3 to 5
		3220 CS3 + CS4 > 0%	-	Deck Sealing	Service life extended	3 to 5
		-	1080 < 5%	Full Depth Deck Patching	Service life maintained	As needed
		3210 CS3 + CS4 < 5%	1080 < 5%	Wearing Surface Patching	Service life maintained	As needed
		>20% (3220 OR 8911 CS3 + CS4) OR	(1140 OR 1150) < 20% for timber deck	Polymer Modified Asphalt Overlay	Improve NBI (58) ≥ 7	10 to 15
		>15% 3210 (applied to bare deck)				
		>20% (3210 OR 8911 CS3 + CS4) OR	1080 < 5% for concrete deck			
		>50% 3220 (reapplication)				
		>20% (3220 OR 8911 CS3 + CS4) OR	(1140 OR 1150) < 20% for timber deck	HMA w/ membrane	Improve NBI (58) ≥ 7	5 to 15
		>15% 3210 (applied to bare deck)				
		>20% (3210 OR 8911 CS3 + CS4) OR	1080 < 5% for concrete deck			
		>50% 3220 (reapplication)				
		8513 CS3 + CS4 > 15% (reapplication)	1080 < 1%	Thin Polymer Overlay	Service life extended	7 to 15
		>20% (3220 OR 8911 CS3 + CS4) OR	1080 < 5% OR 1130 CS3 + CS4 < 25%	Concrete Overlay	Improve NBI (58) ≥ 7	12 to 20
		>15% 3210 (applied to bare deck)				
		>20% (3210 OR 8911 CS3 + CS4) OR				
		>50% 3220 (reapplication)				
	5	5% < 3220 < 25%	-	Crack Sealing	Extend Service Life	3 to 5
		3220 CS3 + CS4 > 0%	-	Deck Sealing	Service life extended	3 to 5
		-	1080 < 5%	Full Depth Deck Patching	Service life maintained	As needed
		3210 CS3 + CS4 < 5%	1080 < 5%	Wearing Surface Patching	Service life maintained	As needed
		>20% (3220 OR 8911 CS3 + CS4) OR	1080 < 5% OR 1130 CS3 + CS4 < 25%	Concrete Overlay	Improve NBI (58) ≥ 7	12 to 20
		>15% 3210 (applied to bare deck)				
		>20% (3210 OR 8911 CS3 + CS4) OR				
		>50% 3220 (reapplication)				
	4	>20% (3220 OR 8911 CS3 + CS4) OR	1080 < 5% OR 1130 CS3 + CS4 < 25%	Concrete Overlay	Improve NBI (58) ≥ 7	12 to 20
		>15% 3210 (applied to bare deck)				
		>20% (3210 OR 8911 CS3 + CS4) OR				
		>50% 3220 (reapplication)				
	≤ 4	-	1080 > 15% OR 1130 CS3 + CS4 > 50%	Deck Replacement	Improve NBI (58) = 9	25 to 45

Table 42.5-2

Concrete Deck/Slab Eligibility Matrix

Figure A.3. Concrete deck/slab eligibility matrix for preservation actions provided by WisDOT (2019).

Section A.3 Comprehensive Tools for Crack Repairs

FDOT was identified in Table 2.1 as providing comprehensive tools for crack repairs. The crack sealer summary in the FDOT's Bridge Maintenance Reference Manual was shown in Table 2.3. The tables for the disposition of cracked concrete other than bridge decks and for bridge decks in the FDOT's Standard Specifications for Road and Bridge Construction are shown in Figure A.4 and Figure A.5, respectively. The footnotes and abbreviations in the tables are defined in a separate table in the standard specifications, which is shown in Figure A.6.

Table 400-3
DISPOSITION OF CRACKED CONCRETE OTHER THAN BRIDGE DECKS
[see separate Key of Abbreviations and Footnotes for Tables 400-3 and 400-4]

Elev. Range	Crack Width Range (inch) (2) x = crack width	Cracking Significance Range per LOT (1): Isolated Less than 0.005%			Occasional 0.005% to<0.017%			Moderate 0.017% to<0.029%			Severe 0.029% or gtr.		
	Environment Category	SA	MA	EA	SA	MA	EA	SA	MA	EA	SA	MA	EA
Elevation: 0 to 6 ft AMHW	x ≤ 0.004	NT	NT	PS (6)	NT	PS (6)	PS (6)	PS (6)	PS (6)				
	0.004< x ≤ 0.008	NT	PS (6)	EI (3)	PS (6)	EI (3)	EI (3)	PS (6)					
	0.008< x ≤ 0.012	NT	PS (6)	EI									
	0.012< x ≤ 0.016	PS (6)			Investigate to Determine Appropriate Repair (4, 5) or Rejection								
	0.016< x ≤ 0.020												
	0.020< x ≤ 0.024										Reject and Replace		
	0.024< x ≤ 0.028												
	x > 0.028												
Elev.: More Than 6 ft to 12 ft AMHW	Crack Width	SA	MA	EA	SA	MA	EA	SA	MA	EA	SA	MA	EA
	x ≤ 0.004	NT	NT	PS (6)	NT	PS (6)	PS (6)	PS (6)	PS (6)	PS (6)	PS (6)		
	0.004< x ≤ 0.008	NT	PS (6)	EI (3)	PS (6)	PS (6)	EI (3)	PS (6)	EI (3)				
	0.008< x ≤ 0.012	NT	PS (6)	EI	EI	EI							
	0.012< x ≤ 0.016	PS (6)	EI	EI	EI								
	0.016< x ≤ 0.020	EI											
	0.020< x ≤ 0.024				Investigate to Determine Appropriate Repair (4, 5) or Rejection						Reject and Replace		
	0.024< x ≤ 0.028												
	x > 0.028												
Elev.: Over Land or More Than	Crack Width	SA	MA	EA	SA	MA	EA	SA	MA	EA	SA	MA	EA
	x ≤ 0.004	NT	NT	NT	NT	PS (6)	PS (6)	PS (6)	PS (6)	PS (6)	PS (6)		
	0.004< x ≤ 0.008	NT	PS (6)	PS (6)	PS (6)	PS (6)	EI (3)	PS (6)	EI (3)	EI (3)	PS (6)		

	0.008< x ≤ 0.012	NT	PS (6)	EI	EI	EI	EI	EI	EI				
	0.012< x ≤ 0.016	PS (6)	EI	EI	EI	EI	EI						
	0.016< x ≤ 0.020	EI	EI	EI	EI								
	0.020< x ≤ 0.024	EI		Investigate to Determine Appropriate Repair (4, 5) or Rejection									
	0.024< x ≤ 0.028										Reject and Replace		
	x > 0.028												

Figure A.4. Decision matrix for treating cracked concrete other than bridge decks in the Florida DOT's Standard Specifications for Road and Bridge Construction (January 2022).

Table 400-4 DISPOSITION OF CRACKED CONCRETE BRIDGE DECKS [see separate Key of Abbreviations and Footnotes for Tables 400-3 and 400-4]													
Elev. Range	Crack Width Range (inch) [2] x = crack width	Cracking Significance Range per LOT [1]											
		Isolated less than 0.005%			Occasional 0.005% to<0.017%			Moderate 0.017% to<0.029%			Severe 0.029% or gtr.		
		Environment Category											
		SA	MA	EA	SA	MA	EA	SA	MA	EA	SA	MA	EA
Elevation: 12 feet or Less AMHW	$x \leq 0.004$	NT	NT	NT	NT	NT	NT	NT	NT	NT			
	$0.004 < x \leq 0.008$	NT	NT	EI/M	NT	NT	EI/M	EI/M	EI/M	EI/M			
	$0.008 < x \leq 0.012$	NT	NT	EI/M	NT	EI/M	EI/M	EI/M	EI/M				
	$0.012 < x \leq 0.016$	NT	NT	EI/M	NT	EI/M							
	$0.016 < x \leq 0.020$	EI/M	EI/M	EI	EI								
	$0.020 < x \leq 0.024$	EI/M	EI	EI				Investigate to Determine Appropriate Repair [4, 5] or Rejection			Reject and Replace		
	$0.024 < x \leq 0.028$	EI/M	EI										
	$x > 0.028$												
Elevation: Over Land or More Than 12 feet AMHW	Crack Width	SA	MA	EA	SA	MA	EA	SA	MA	EA	SA	MA	EA
	$x \leq 0.004$	NT	NT	NT	NT	NT	NT	NT	NT	NT			
	$0.004 < x \leq 0.008$	NT	NT	NT	NT	NT	EI/M	NT	EI/M	EI/M			
	$0.008 < x \leq 0.012$	NT	NT	EI/M	NT	NT	EI/M	EI/M	EI/M				
	$0.012 < x \leq 0.016$	NT	NT	EI/M	NT	EI/M							
	$0.016 < x \leq 0.020$	NT	EI/M	EI	EI/M			Investigate to Determine Appropriate Repair [4, 5] or Rejection					
	$0.020 < x \leq 0.024$	NT	EI/M	EI							Reject and Replace		
	$0.024 < x \leq 0.028$	NT	EI/M										
	$x > 0.028$												

Figure A.5. Decision matrix for treating cracked bridge decks in the Florida DOT's Standard Specifications for Road and Bridge Construction (January 2022).

Key of Abbreviations and Footnotes for Tables 400-3 and 400-4		
Type Abbreviation	Abbreviation	Definition
Repair Method	EI	Epoxy Injection
	M	Methacrylate
	NT	No Treatment Required
	PS	Penetrant Sealer
Environment Category	EA	Extremely Aggressive
	MA	Moderately Aggressive
	SA	Slightly Aggressive
Reference Elevation	AMHW	Above Mean High Water

Footnotes

(1) Cracking Significance Range is determined by computing the ratio of Total Cracked Surface Area (TCSA) to Total Surface Area (TSA) per LOT in percent [(TCSA/TSA) x 100] then by identifying the Cracking Significance Range in which that value falls. TCSA is the sum of the surface areas of the individual cracks in the LOT. The surface area of an individual crack is determined by taking width measurements of the crack at 3 representative locations and then computing their average which is then multiplied by the crack length.

(2) Crack Width Range is determined by computing the width of an individual crack as computed in (1) above and then identifying the range in which that individual crack width falls.

(3) When the Engineer determines that a crack in the 0.004 inch to 0.008 inch width range cannot be injected then for Table 400-3 use penetrant sealer unless the surface is horizontal, in which case, use methacrylate if the manufacturer's recommendations allow it to be used and if it can be applied effectively as determined by the Engineer.

(4) (a) Perform epoxy injection of cracks in accordance with Section 411. Seal cracks with penetrant sealer or methacrylate as per Section 413. (b) Use only methacrylate or penetrant sealer that is compatible, according to manufacturer's recommendations, with previously applied materials such as curing compound or paint or remove such materials prior to application.

(5) When possible, prior to final acceptance of the project, seal cracks only after it has been determined that no additional growth will occur.

(6) Methacrylate shall be used on horizontal surfaces in lieu of penetrant sealer if the manufacturer's recommendations allow it to be used and if it can be applied effectively as determined by the Engineer.

(7) Unless directed otherwise by the Engineer, repair cracks in bridge decks only after the grinding and grooving required by 400-15.2.5 is fully complete.

Figure A.6. Abbreviations and footnotes for Table 400-3 and Table 400-4 of the Florida DOT's Standard Specifications for Road and Bridge Construction (January 2022) (Figure A.4 and Figure A.5, respectively).

APPENDIX B. CRACK REMEDIATION TREATMENT PROFILES

Repair activities that can be used to address bridge deck cracking are described in the following profiles. The profiles are generally organized into the following six sections:

- **Objectives.** In this section, the repair objectives that the repair can and cannot meet are identified. The list of different crack repair objectives is from ACI 224.1R.
- **Applicability.** This section presents the conditions under which the repair is applicable and appropriate. It summarizes the NBI condition ratings, deck condition states, deck characteristics, and crack characteristics for which the repair is considered effective and efficient. The thresholds and limits identified in state DOT manuals and literature are the basis for this summary.
- **Construction.** This section provides a step-by-step repair procedure based on state DOT specifications and manuals. Construction challenges or practical limitations are also discussed.
- **Materials.** The repairs under consideration can be further refined based on the repair material used by the contractor. In this section, the specific repair materials are described and compared.
- **Repair Costs.** This section provides a bottom-top cost estimate for the repair method under consideration based on material and labor cost estimates from Iowa bid tabulations. If Iowa prices are not available, values from other Midwest states are used.
- **Service Life.** In this section, estimates for the life of the repair (distinct from the service life extension of the deck) are presented and the degradation mechanisms that the repair is susceptible to are discussed.

The repairs may be categorized as (a) Judicious Neglect; (b) Penetrating Sealers; (c) Crack-Chasing Methods; (d) Flood coat Methods; (e) Overlays; or (f) Replacement, as shown in Table B. below. Judicious Neglect only consists of the "Do Nothing" repair option. Penetrating Sealers also only consists of one repair option, "Apply a Penetrating Sealer," and the variety of penetrating sealer materials available are discussed in the Materials section of the profile. Flood coat Methods are grouped together under "Apply a Flood Coat" since the differences between applying a gravity-fed polymer (a.k.a. a healer-sealer) as a flood coat and applying a film-forming sealer are nuanced and these repairs are expected to perform similarly.

In comparison, the crack-chasing methods differ significantly from each other and separate profiles for applying gravity-fed polymers, routing and sealing, and pressure injecting epoxy are necessary due to the vastly different types of materials used, construction methods, and performance of the repairs.

Overlays are also divided by overlay type. A hot-mix asphalt (HMA) overlay with a waterproofing membrane is considered a feasible repair option. Other overlays considered include thin polymer overlays and premixed polymer concrete overlays, which are given separate profiles due to their significantly different costs and performance. Cementitious overlays, including portland cement concrete (PCC), high-performance concrete (HPC), low slump dense concrete (LSDC), and silica fume concrete (SFC), are grouped together into one repair profile despite their different materials since they have similar construction methods and function similarly with respect to crack remediation. Finally, latex-modified concrete (LMC) overlays are provided their own repair profile since they are distinguished from cementitious overlays in industry based on their different materials, construction methods and equipment, and performance.

HMA overlays without the waterproofing membrane are omitted since they cannot meet any crack repair objectives with the exception of improving functionality, i.e., the riding surface. However, if the cracking is severe enough to affect the rideability of the surface then it is assumed that the cracking is also affecting the structural capacity of the bridge and a strengthening repair is needed. Strengthening repairs are not considered in this guide as they should be assessed and developed on a case-by-case basis.

Table B.1. Categorization of Remediation Treatment Profiles

Category	Remediation Treatment Profiles
Judicious Neglect	Do Nothing
Penetrating Sealers	Apply a Penetrating Sealer
Crack-Chasing Methods	Apply a Gravity-Fed Polymer by Crack-Chasing
	Rout and Seal
	Pressure Inject with Epoxy
Flood Coat Methods	Apply a Flood Coat
Overlays	Apply a Hot-Mix Asphalt with Waterproofing Membrane System
	Apply a Thin Polymer Overlay
	Apply a Rigid Cementitious Overlay
	Apply a Latex-Modified Concrete Overlay
	Apply a Premixed Polymer Concrete Overlay
Replacement	Replace the Bridge Deck

Do Nothing

The "Do Nothing" option is a strategic choice to defer maintenance and repairs to a later date. In the absence of repair, the unaddressed cracks may or may not accelerate deterioration, depending on their location relative to reinforcing steel, the types of aggressive ions present, and the level of ease with which chlorides and other aggressive ions may penetrate the cracks. At the end of the deferred period when repairs are being considered again, the deck condition and crack characteristics must be re-evaluated and a new analysis conducted.

Objectives

This repair option does not meet any repair objectives. It is selected in order to meet the higher, long-term objective of minimizing the life cycle cost of the bridge deck.

Applicability

Cracks that do not compromise the serviceability or the durability of the structure do not need to be repaired. However, there is considerable debate regarding the threshold criteria that should be used to trigger concern and action.

Qualitatively, cracks that are very fine and/or shallow do not permit aggressive ions such as chlorides to penetrate into the concrete and therefore have a relatively small to negligible effect on durability. Crack widths are the most measurable of these properties both in the laboratory and in the field and subsequently there have been many studies relating crack width to moisture and chloride penetration and corrosion. Literature indicates that the critical crack width is between 0.002 and 0.008 inches (Balakumaran et al. 2018; Krauss 1994). Several studies have noted that leakage has been observed for cracks as small as 0.002 inches but cracks less than 0.002 inches in width do not affect diffusion (Krauss 1994; Balakumaran 3t al. 2018). Hopper et al. (2015) stated that the critical width below which cracks do not permit moisture ingress is between 0.002 and 0.004 inches and Xi et al. (2003) stated that this value is between 0.004 and 0.008 inches.

In practice, the ACI 224 committee has stated that cracks up to 0.007 inches in width are considered tolerable in environments with deicing chemicals. Similarly, the Michigan and Virginia DOTs only require crack sealing when cracks are at least 0.008 inches in width. At the lower end of the range, the New York State DOT only permits "do nothing" for dormant cracks less than 0.007 inches and active cracks less than 0.004 inches. Even more conservatively, the Missouri DOT recommends treating hairline cracks, defined as cracks less than 0.008 inches in width, with a gravity-fed polymer and applying a penetrating sealer to new decks or decks with even smaller cracks. In contrast, the Kansas DOT defines hairline cracks as cracks with widths no greater than 0.02 inches.

Alternatively, wide and deep cracks may not be a concern depending on the types of ions the deck is exposed to and crack location relative to the reinforcing steel. Cracks away from reinforcing steel do not provide access to the steel and subsequently sealing the crack to keep chlorides out is unnecessary. However, the cracks still give ions deeper access into the concrete and so sealing may still be warranted if magnesium-chloride based deicing salts are used (which cause concrete degradation) or the deck concrete is susceptible to freeze-thaw cycles.

Table B.2. Crack Characteristics for which “Do Nothing” is a Feasible Option.

Crack Type	Crack Width	Crack Depth	Crack Shape	Crack Activity	Crack Extent
Craze	Less than 0.008 inches	Shallow	n/a	n/a	n/a

References

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Apply a Penetrating Sealer

Penetrating sealers are thus named because they penetrate into the capillary pore structure of the concrete. There are two types of penetrating sealers: water repellents, which include silanes and siloxanes, and pore blockers, which include silicates. Water repellents react with the cement paste to form hydrophobic silica gel along the concrete (and crack) surfaces. In this way, liquid water is discouraged from entering the concrete, but the concrete maintains its ability to transmit water vapor. Pore blockers build up precipitates within the capillary pores, blocking both water and water vapor. By preventing moisture ingress, penetrating sealers generally prevent corrosive conditions and also protect concrete from chlorides transported by moisture.

Objectives

The repair objectives that penetrating sealers are capable of meeting are identified in Table B..

Table B.3. Applicable repair objectives of penetrating sealers.

	Repair Objectives
	Restore or increase strength
	Restore or increase stiffness
	Improve functional performance
	Provide watertightness
	Improve appearance of the concrete surface
✓	Improve durability
✓	Prevent development of a corrosive environment at reinforcement

Applicability

Penetrating sealers are generally considered applicable under the following conditions:

- *NBI Condition Ratings.*
  Penetrating sealers are recommended when the deck NBI condition rating is fair or better (Wells et al. 2017; IDOT; MDOT). IDOT permits penetrating sealers to be applied to decks with a condition rating of 4 at the discretion of the engineer, but prohibits penetrating sealers for decks with a condition rating of 3 or less. INDOT considers penetrating sealers to be a scheduled preventative maintenance activity, to be completed when the wearing surface has an NBI condition rating greater than 5.
- *Deck Condition State.*
  Decks that are candidates for penetrating sealers should have no cracks or a few sealed cracks (Hearn 2020). MoDOT and NYSDOT require penetrating sealers be used on decks with minimal or hairline cracking. IDOT does not permit penetrating sealer treatments on decks if any of their area is in CS3 or CS4.
- *Deck Characteristics.*
  Deck condition is generally more important than deck age or other deck characteristics when deciding whether or not a penetrating sealer is appropriate. However, some state DOTs speak to the features of the deck. For example, NYSDOT has found that penetrating sealers are uneconomical if the deck has epoxy-coated reinforcing steel and the concrete is uncracked. However, if the deck has uncoated

reinforcing steel, a concrete cover less than the current standard design cover, or hairline cracking, a penetrating sealer is recommended. In contrast, MDOT permits silane penetrating sealers to be used regardless of whether the deck is reinforced with uncoated or epoxy-coated rebar.

Additionally, while decks are not typically precluded from penetrating sealer treatments based on their age, there is a general emphasis on applying penetrating sealers to new or newly-rehabilitated decks (Wells et al. 2017). NYSDOT requires penetrating sealers be applied to new decks, concrete overlays, and repairs with a history of corrosion-related distress. MoDOT requires penetrating sealers be applied to new decks, and reapplied in the first 3 years if new cracks form.

- *Crack Characteristics.*
  Penetrating sealers are typically used for hairline or narrow cracks. NYSDOT recommends penetrating sealers be applied to decks with cracks up to 0.007 inches in width if the crack is active or the deck is exposed to deicing chemicals and to decks with dormant cracks up to 0.012 inches in width.

Construction

The procedures for applying a penetrating sealer are as follows:

- Clean and dry deck.
  MnDOT specifies the deck be swept with a wire bristle broom or blown with compressed air. Johnson et al. (2009) states that while penetrating sealers can penetrate through curing compounds, removing them will likely result in better penetration and NYSDOT requires the surface to be lightly sandblasted in order to remove curing compounds. Some amount of moisture is required in order for the sealer to react, but the deck is generally specified to be dry at application because moisture inhibits penetration (Wells et al. 2017).

Apply penetrating sealer.
MoDOT specifies a low pressure, high volume sprayer and recommends avoiding hand pump sprayers. MoDOT also recommends applying the sealer at a rate of 200 ft^2/gal while MnDOT recommends an application rate of 250 to 300 ft^2/gal. Higher application rates improve chloride ion resistance (Johnson et al. 2009). However, because the sealer does not always dry at such a high application rate, MnDOT has had to apply the sealer in two layer at 500 to 600 ft^2/gal. One PennDOT district also recommended applying penetrating sealers in two coats for small cracks (less than 0.007 inches) (Hopper et al. 2015). After application, the sealer is spread across the deck area with brooms or squeegees.

Penetrating sealer application is sensitive to moisture, wind, and temperatures. Temperatures between 40°F and 100°F are best for penetrating sealers (Johnson et al. 2009). The higher temperatures can cause premature evaporation, resulting in poor penetration, while lower temperatures extend drying time.

The QA/QC procedures used to evaluate the installation quality typically assess penetration depth by coring. Wells et al. (2017) recommends specifying a minimum penetration depth of 3 mm.

Materials

Penetrating sealers are categorized in several ways. They are commonly identified as water repellents, which include silanes, siloxanes, and siliconates, or pore blockers, which consist of silicates. Water repellents are further categorized as water-based or solvent-based.

Water repellents make the concrete substrate surface hydrophobic such that liquid water cannot pass through, but water vapor may be transmitted. Water repellents are more commonly used than pore blockers and high solids content silanes are commonly preferred because they can penetrate more deeply than the heavier siloxanes (MoDOT, MnDOT). For example, penetration depths between 0.06 in. and 0.15 in. have been reported for siloxanes while penetration depths of 0.10 in. to 0.25 in. have been reported for silanes (Wells et al. 2017). However, silanes evaporate relatively quickly compared to the heavier siloxanes and therefore are not recommended for hot, windy conditions (Johnson et al. 2009).

Water repellents may be carried by water (water-based) or a petroleum-based solvent, an alcohol, or mineral spirits (solvent-based). Because silane is a liquid at ambient temperature, 100% silane products are also available and generally preferred over products with lower percent solids due to the relatively high volatility of silane. Water-based penetrating sealers are not recommended for reapplication projects because the medium (water) is repelled by any previous water repellents that remain in the concrete, preventing penetration of the sealer.

Pore blockers penetrate capillary pores and react to form precipitates. Because the precipitates fill the pores, they block both liquid water and water vapor. Pore blockers are commonly sodium, potassium, or lithium silicates.

Repair Costs

The average unit cost for applying a penetrating sealer is $8.6 per square yard of deck area. The value is based on Illinois DOT letting data, and the pay items assumed are listed in Table B..

Table B.4. Unit Cost for Applying a Penetrating Sealer

State	State Pay Item No.	Item Description	Unit	Unit Cost
IL	X5870015	Penetrating Sealer	SY	$8.6

Source: Illinois DOT awarded unit prices from letting data from January 2020 to July 2020.

Service Life

State DOTs widely recognize that penetrating sealers should be regularly reapplied. The reapplication frequency varies from 3 years to 10 years as shown in Table B., but an interval of 5 years is generally considered reasonable.

Table B.5. Specified or Recommended Application Frequency for Penetrating Sealers

Source	Reapplication Frequency
IDOT	4 years
INDOT	5 years
MDOT	5 years
MnDOT	5 to 7 years
MoDOT	7 to 10 years[1]
NYSDOT	5 years[2]
ODOT	5 years[3]
WisDOT	3 to 5 years

Source	Reapplication Frequency
ElBatanouny et al. 2020	2 to 6 years
Rahim et al. 2006	3 years
Sprinkel et al. 1993	7 years
Wells et al. 2017	4 to 5 years

Notes: [1]*If further cracking develops after the first application, reapplication within 3 years is recommended.*
[2]*Provided installation is of good quality.*
[3]*Expectation for silanes and reactive silicate solutions.*

The primary mechanism that affects the degradation of penetrating sealer treatments is abrasion from traffic and Johnson et al. (2009) reported that higher chloride penetration is expected in the wheel paths of the deck. Weyers et al. (1995) determined that the rate of abrasion is approximately 0.0067 in. per year for a bridge deck with an AADT of 24,270 vehicles. Johnson et al. (2009) postulated that the service life could then be estimated based on the rate of abrasion and the penetration depth, but Morse (2009) showed that penetrating silanes and siloxanes are only effective in preventing chloride ion ingress for approximately 3 to 5 years in a field study. Morse (2009) also tested a penetrating silica, which only provided protection from chlorides for one year.

Ultraviolet radiation is a common degradation mechanism of the materials used for penetrating sealers. However, because the sealer is within the pore structure of the concrete, penetrating sealers are not considered susceptible to degradation by ultraviolet radiation.

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Apply a Gravity-Fed Polymer by Crack-Chasing

Cracks are commonly sealed with gravity-fed polymers, which rely on gravity and low viscosity to penetrate cracks. They then polymerize within the cracks, thereby sealing them from moisture and chloride ingress. Gravity-fed polymers are typically either high molecular weight methacrylates (HMWMs) or low-viscosity epoxies and may be applied in a flood coat (see "Apply a Flood Coat") or by crack chasing, as discussed in this profile.

Objectives

Gravity-fed polymers applied by the crack-chasing method are capable of meeting repair objectives as identified in Table B..

Table B.6. Applicable repair objectives of gravity-fed polymers applied by crack-chasing method.

	Repair Objectives
	Restore or increase strength
	Restore or increase stiffness
	Improve functional performance
✓	Provide watertightness
	Improve appearance of the concrete surface
✓	Improve durability
✓	Prevent development of a corrosive environment at reinforcement

Applicability

Gravity-fed polymers applied by the crack-chasing method are generally considered applicable under the following conditions:

- *NBI Condition Ratings.*
  INDOT, MDOT, VDOT, and WisDOT specify minimum NBI condition requirements for deck crack sealing actions. INDOT and WisDOT do not elaborate on the specific types of actions, but VDOT groups "crack filling" actions as crack sealing with a mesh crossing the crack, a polymer fill, a "V" groove, or epoxy injection. MDOT distinguishes between sealing cracks and applying a healer-sealer, which classifies as a flood coat, but MDOT's requirements for crack sealing and applying a healer-sealer are the same. Crack sealing is understood to be distinct from deck sealing with a penetrating sealer and from placing thin polymer or other types of overlays. Therefore, the criteria used by these states are assumed to apply to the following profiles: "Apply a Gravity-Fed Polymer by Crack-Chasing," "Rout and Seal," "Pressure Inject with Epoxy," and "Apply a Flood Coat."

  In INDOT, decks are eligible for crack sealing as long as the NBI ratings of all the major bridge components (deck, superstructure, and substructure) and the NBI rating of the wearing surface (if applicable) are at least 6. VDOT requires crack sealing as long as the deck has a NBI rating of at least 7 while MDOT and WisDOT permit crack sealing as long as the deck has a NBI rating of at least 5; none of these state DOTs discuss the NBI ratings of the other bridge components.
- *Deck Condition State.*
  In addition to the minimum NBI condition ratings, VDOT and WisDOT specify the amount of distress

the deck is permitted to have and Indiana provides correlations between the NBI condition rating and the deck overlay condition. These requirements are assumed to apply to the following profiles: "Apply a Gravity-Fed Polymer by Crack-Chasing," "Rout and Seal," "Pressure Inject with Epoxy," and "Apply a Flood Ccoat."

VDOT only allows crack filling if the deck deterioration area does not exceed 5 percent. The deck deterioration area is defined as either the percentage of the deck in CS2, CS3, and CS4 based on visual inspection, or, in the case of an in-depth investigation, the percentage of the deck that is delaminated, spalled, patched, and/or in CS1 with a half-cell potential reading less than -0.35 mV. WisDOT requires between 5 and 25 percent of the deck area to demonstrate Defect 3220, Cracking in order to be eligible for crack sealing actions. Note that Defect 3220 characterizes the wearing surface, regardless of whether it is a deck or overlay.

Per INDOT's definitions, a rigid portland cement overlay has an NBI condition rating of 6 or greater as long as no more than 5 percent of the deck is delaminated, cracks are not wider than 0.021 inches, and the crack spacing is at least 3 feet. Semi-rigid (epoxy or polyester) overlays are considered to have an NBI condition rating of 6 or greater as long as no more than 0.5 percent of the deck is delaminated, no to minor surface wearing is present, cracks are not wider than 0.016 inches, and the crack spacing is at least 10 feet. Therefore, crack sealing is considered an option only if the deck conditions, crack widths, and crack spacings meet these thresholds.

- *Deck Characteristics.*
  VDOT recommends crack filling with either a gravity-fill polymer or epoxy injection if the deck was constructed in 2003 or later.

- *Crack Characteristics.*
  The suitability of a gravity-fed polymer applied by the crack-chasing method depends on the crack width, activity, depth, spacing, and pattern. Gravity-fed polymers are capable of sealing cracks regardless of width according to MoDOT and Hopper et al. (2015) supports this by stating that gravity-fed polymers are best used for cracks 0.001 to 0.08 inches wide, which is a relatively wide range. However, crack width affects the type of polymer selected, as discussed later. Additionally, MDOT states that local cracks to be sealed must be at least 0.008 inches wide, such that they are easily visible. Gravity-fill polymers are particularly useful over other methods for sealing narrow cracks and as a result MoDOT requires deck sealing with a low-viscosity polymer if cracks less than 0.008 inches in width are present (i.e. hairline shrinkage cracks). In contrast, NYSDOT requires either HMWM sealing or epoxy injection for cracks with a width of at least 0.007 inches if the crack is active or subject to deicer exposure. HMWM sealing or epoxy injection is only required for dormant cracks with a width of at least 0.012 inches. VDOT recommends dormant cracks be filled with gravity-fill polymers or by epoxy injection.

  Crack width should be considered when choosing between crack-chasing with a gravity-fed polymer and applying the polymer as a flood coat. The success of a crack-chasing method relies heavily on the contractor's ability to adequately clean the crack since debris or dust will cause a poor bond between the polymer and the crack wall and a subsequent crack between the materials. In comparison, the flood coat still provides protection from above the crack if the polymer within the crack and the substrate debond. Therefore, if the crack is too narrow to be cleaned, a flood coat should be considered instead. Alternatively, the crack may be widened or routed such that the crack mouth can be adequately cleaned and achieve a strong bond to the polymer (see "Rout and Seal"). A crack width threshold representing this practical limitation is not available in literature.

MDOT was the only state DOT reviewed to discuss crack depth. In general, only cracks reaching the depth of the reinforcement are considered a concern and recommended for sealing. However, MDOT warned that full-depth cracks should not be sealed with gravity-fill polymers because the sealant would fully penetrate the deck and leak out the soffit.

VDOT notes that gravity fill polymers are suited to addressing linear cracking and recommends an overlay or crack seal be installed if the crack density exceeds 0.20 linear feet per square foot. MnDOT uses crack spacing to determine if crack-chasing with a gravity-fed polymer or a flood coat is more economical and notes that the crack chase method is more efficient if the crack spacing is at least 3 feet. In general. the crack-chasing method is not suitable when pattern cracking is present.

Construction

The procedures for applying a gravity-fed polymer by the crack-chasing method are as follows:

- Prepare surface and clean cracks.
  The purpose of surface preparation and crack cleaning is to clear contaminants and moisture. The surface may be prepared by sandblasting and then blasting with oil-free compressed air, or sandblasting may be omitted. MDOT requires the area to be lightly sandblasted, which not only removes contaminants but also helps expose the surface of the cracked area and enhances penetration and visibility. The cracks are then blown clean with compressed air. In comparison, MnDOT has found that air-blown repairs typically outperform shot- or sandblasted repairs in the field and therefore requires the cracks and the entire deck surface to be blasted with compressed air. IowaDOT permits contaminants to be removed by high-pressure water, compressed air, or vacuum. ACI RAP-2, *Crack Repair by Gravity Feed with Resin*, recommends cleaning the individual cracks with wire brushes or wheels and then blowing them clean with compressed air. Following the crack cleaning procedures, IowaDOT requires the crack to dry naturally before applying the sealer. ACI RAP-2 recommends allowing the repair area to dry for at least 24 hours prior to sealing operations.
  If the cracks are packed with dirt or debris, then ACI RAP-2 recommends routing the crack. This is discussed in the profile "Rout and Seal."

Fill cracks with gravity-fill polymer.
The polymer is applied either with an epoxy pump or a squeegee bottle. The crack should be filled until it no longer accepts the sealant and ACI RAP-2 notes that for very narrow cracks, it may be necessary to wait for the sealant to penetrate the crack some and then apply another round of sealant. MnDOT requires the sealant bead to be no wider than 0.5 inches and MDOT specifies that the overband be no wider than 1 inch. ACI RAP-2 recommends allowing at least 20 to 30 minutes for penetration and observing the filled cracks for signs of penetration, such as air bubbles from displacement of the air with the resin sealer. Excess resin should be removed prior to cure.

Gravity-fill polymers are sensitive to temperature and moisture during application. MnDOT recommends gravity-fed polymers be applied when ambient temperatures are between 50°F and 90°F and at the coolest time of day, although temperatures of at least 65°F are preferred. In comparison, MoDOT recommends applying gravity-fill polymers at temperatures below 75°F for better penetration. The presence of moisture in cracks prevents good penetration and as a result, MnDOT requires applicators to wait at least 48 hours after a rain event to apply gravity-fed polymers and does not permit placement if precipitation is expected within 12 hours of placement.

None of the state DOT documents reviewed contained quality procedures but ACI RAP-2 suggested several quality control tests. Sealant quality can be checked by measuring compressive strength of cured prisms of the sealant material. Low strengths indicate improper mixing and curing or a defective batch of material. Penetration depth may be assessed by taking cores and examining the penetration of the sealant.

Materials

Gravity-fill polymers are most commonly either high molecular weight methacrylates (HMWMs) or low-viscosity epoxies, but other types of methacrylates, including methyl methacrylates (MMAs), and polyurethanes have also been used (Johnson et al. 2009; Hopper et al. 2015; Balakumaran et al. 2018). Many studies have demonstrated that HMWMs penetrate more deeply than low-viscosity epoxies and are well-suited to relatively narrow cracks. However, epoxies are safer to handle than HMWMs, stronger than HMWMs, and known for high bond strengths with concrete substrates. Minnesota recommends using a HMWM or MMA for cracks less than 0.005 inches to 0.02 inches and epoxies for cracks between 0.02 and 0.05 inches.

Johnson et al. (2009) state that when selecting a material, the viscosity, volatility, initial shrinkage, tensile strength, and tensile elongation should be considered. The viscosity affects the penetration depth and the crack widths that can be penetrated, and lower viscosities are often preferred. ACI RAP-2 states that the viscosity should be no greater than 200 cP and that many epoxies with viscosities under 100 cP and HMWMs with viscosities less than 50 cP are available. Volatility affects the curing time and subsequently the penetration depth as well. MMAs have a high volatility and therefore are relatively unfavorable, although they are safer to apply than HMWMs. Similarly, polyurethanes have a fast curing time and are easy to apply, but may not achieve adequate penetration depths (Johnson et al. 2009). The shrinkage and tensile properties of the polymer affect the polymer's ability to effectively seal the crack throughout the life of the repair. Durability of the repair material may also need to be considered; for example, polyurethanes are known to have freeze-thaw issues (Johnson et al. 2009).

Repair Costs

The average unit cost for applying a gravity-fed polymer by crack-chasing is $2.8 per foot length of crack. The value is based on Minnesota DOT bid data, and the pay items assumed are listed in Table B..

Table B.7. Unit Cost for Applying a Gravity-Fed Polymer by Crack-Chasing

State	State Pay Item No.	Item Description	Unit	Unit Cost
MN	2433603/00440	Crack Chasing Sealer	LF	$2.8

Source: Minnesota DOT average bid prices for awarded contracts from January 2017 to December 2019.

Service Life

Gravity-fed polymers applied by the crack-chasing method provide protection by filling the cracks to limit moisture ingress and chloride intrusion and studies on their performance demonstrate that they provide substantial protection. For example, Whiting showed that sealed cracks had half the seepage rate of unsealed cracks in a 2006 field study and Meggers (1998) estimated based on a laboratory study that unsealed cracks would begin to show corrosion-related distress at 4 or 5 years of age while epoxy sealers and HMWM sealers could delay chloride-induced corrosion for 15 and 10 years, respectively (Johnson et al. 2009).

Polymer crack-chasing repairs lose effectiveness with age due to the formation of new cracks, either within the sealant, within the substrate, or at the interface between them at the crack wall. Oman (2014) monitored discrete crack repairs for three years and determined by visual inspection that 60 percent of the sealers were effective after one year, all the specimens had cracked after two years, and at three years, 25 percent were effective while the remaining 75 percent were ineffective. The longevity of the repair depends to some extent on the installation quality and pre-existing condition of the deck and age of its cracks. Contaminants can cause decreased initial bond strength and additionally a more rapid loss of bond between the sealer and the substrate according to field studies (Johnson et al. 2009). Discrete cracks sealed with a polymer are also susceptible to degradation due to freeze-thaw cycles, which can decrease the flexibility of the polymer and make it more prone to cracking (Johnson et al. 2009). The full effects of age and cyclic loading from traffic on the performance of sealers are not well-studied nor understood.

Table B. lists the expected service life and recommended or specified reapplication frequencies found in state DOT manuals and specifications as well as in research literature. Based on this information, a service life of approximately 5 years is an appropriate expectation.

Table B.8. Expected Service Lives and Reapplication Frequencies for Gravity-Fed Polymers

Source	Expected Service Life or Reapplication Frequency
MDOT	5 years
MnDOT	3 to 5 years
MoDOT	As needed[1]
ODOT	10 or 15 years[1,2]
WisDOT	3 to 5 years
ElBatanouny et al. 2020	3 to 10 years[3]
Oman 2014	3 years
Rahim et al. 2006	4 to 5 years[4]

Notes: [1]*This is recommended for flood coats; the same life is assumed to apply to gravity-fed polymers applied by crack chasing.*

[2]*HMWMs are expected to last 15 years while other gravity-fed resins are expected to last 10 years.*

[3]*A repair life of at least 5 years may be expected if the deck has an NBI condition rating of at least 7.*

[4]*While 4 to 5 years was recommended, in their review Rahim et al. (2006) noted a life of 5 to 15 years could be expected from acrylics, which includes HMWMs.*

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Rout and Seal

Routing and sealing a crack consists of widening the mouth of the crack to form a reservoir, cleaning the crack, and then filling the crack and the reservoir with a sealant. This repair is much more commonly used for pavements and garage slabs but can be used to address wide and/or active cracks on bridge decks. The reservoir is designed such that flexible sealants can elongate and accommodate the movement of the crack. However, dormant cracks on bridge decks may also be routed and sealed with a more rigid sealant. There are several variations in the construction procedures that can affect the robustness of the repair and its suitability for different types of cracks but routing and sealing is inherently a crack-chasing method.

Objectives

The rout-and-seal repair method is capable of meeting repair objectives as identified in Table B..

Table B.9. Applicable repair objectives of routing and sealing.

Repair Objectives	
	Restore or increase strength
	Restore or increase stiffness
	Improve functional performance
✓	Provide watertightness
	Improve appearance of the concrete surface
✓	Improve durability
✓	Prevent development of a corrosive environment at reinforcement

Applicability

While routing and sealing is common, there is relatively little discussion on its use on bridge decks compared to other crack-chasing repair methods. Of the state DOT documentation reviewed, only VDOT mentions routing and sealing cracks. Routing and sealing is considered suitable for linear cracks but not pattern cracks and should not be implemented on bridge decks under 6 months of age. Note VDOT makes a V-shaped notch and seals the crack with an epoxy, indicating the method is used for dormant cracks.

Routing and sealing may be considered applicable under the following conditions:

- *NBI Condition Ratings.*
  INDOT, MDOT, VDOT, and WisDOT specify minimum NBI condition requirements for deck crack sealing actions. INDOT and WisDOT do not elaborate on the specific types of actions, but VDOT groups "crack filling" actions as crack sealing with a mesh crossing the crack, a polymer fill, a "V" groove, or epoxy injection. MDOT distinguishes between sealing cracks and applying a healer-sealer, which classifies as a flood coat, but MDOT's requirements for crack sealing and applying a healer-sealer are the same. Crack sealing is understood to be distinct from deck sealing with a penetrating sealer and from placing thin polymer or other types of overlays. Therefore the criteria used by these states are assumed to apply to the following profiles: "Apply a Gravity-Fed Polymer by Crack-Chasing," "Rout and Seal," "Pressure Inject with Epoxy," and "Apply a Flood Coat."

In INDOT, decks are eligible for crack sealing as long as the NBI ratings of all the major bridge components (deck, superstructure, and substructure) and the NBI rating of the wearing surface (if applicable) are at least 6. VDOT requires crack sealing as long as the deck has a NBI rating of at least 7 while MDOT and WisDOT permit crack sealing as long as the deck has a NBI rating of at least 5; none of these state DOTs discuss the NBI ratings of the other bridge components.

- *Deck Condition State.*
  In addition to the minimum NBI condition ratings, VDOT and WisDOT specify the amount of distress the deck is permitted to have and INDOT provides correlations between the NBI condition rating and the deck overlay condition. These requirements are assumed to apply to the following profiles: "Apply a Gravity-Fed Polymer by Crack-Chasing," "Rout and Seal," "Pressure Inject with Epoxy," and "Apply a Flood Coat."

  VDOT only allows crack filling if the deck deterioration area does not exceed 5 percent. The deck deterioration area is defined as either the percentage of the deck in CS2, CS3, and CS4 based on visual inspection, or, in the case of an in-depth investigation, the percentage of the deck that is delaminated, spalled, patched, and/or in CS1 with a half-cell potential reading less than -0.35 mV. WisDOT requires between 5 and 25 percent of the deck area to demonstrate Defect 3220, Cracking in order to be eligible for crack sealing actions. Note that Defect 3220 characterizes the wearing surface, regardless of whether it is a deck or overlay.

  Per INDOT's definitions, a rigid portland cement overlay has an NBI condition rating of 6 or greater as long as no more than 5 percent of the deck is delaminated, cracks are not wider than 0.021 inches, and the crack spacing is at least 3 feet. Semi-rigid (epoxy or polyester) overlays are considered to have an NBI condition rating of 6 or greater as long as no more than 0.5 percent of the deck is delaminated, no to minor surface wearing is present, cracks are not wider than 0.016 inches, and the crack spacing is at least 10 feet. Therefore crack sealing is considered an option only if the deck conditions, crack widths, and crack spacings meet these thresholds.

Because of the wide variety of materials that can be used in routing and sealing and the large number of variations of the construction procedures, routing and sealing is widely applicable regardless of the deck or crack characteristics, as discussed below.

- *Deck Characteristics.*
  As stated previously, VDOT requires bridge decks be at least 6 months of age such that the cracks have minimal activity or growth after sealing is completed. However, VDOT uses an epoxy sealant which is rigid and cannot accommodate movement. This age requirement can be waived if a flexible sealant is used instead.
- *Crack Characteristics.*
  Routing and sealing is most commonly considered for wide, active cracks because it is one of the few methods capable of addressing active cracks. However, it can be applicable regardless of crack width, activity, or depth. While crack width would affect the sealant material selected, ACI 224.1R states that this repair method is suitable for narrow and wide cracks and therefore the crack width would not preclude this method from consideration. Similarly, routing and sealing can use either rigid materials such as epoxies or flexible materials such as bituminous sealants and therefore can be conducted regardless of crack activity.

As identified in "Apply a Gravity-Fed Polymer by Crack-Chasing," routing may be more appropriate if the cracks are packed with debris or other contaminants and difficult to clean. In these scenarios, routing is advantageous because it produces a wider surface opening, which makes the crack more accessible for cleaning operations and can result in better bond between the sealant and the substrate at the crack walls.

Because routing and sealing requires additional crack preparation prior to sealing, it is typically only used to address discrete linear cracks and considered impractical for pattern cracking (VDOT 2009). The minimum crack spacing for which routing and sealing is economical is not specifically identified by state DOTs; however, VDOT's general requirement for a minimum crack density of 0.20 linear feet per square foot of deck and MnDOT's minimum crack spacing of 3 feet based on a comparison between crack-chasing with a gravity-fed polymer and application of a flood coat are assumed to apply. A larger spacing threshold is likely more accurate for routing and sealing due to the additional expenses associated with routing and applying a bondbreaker.

Construction

The procedures for routing and sealing are as follows:

- Rout cracks.
  The cracks are first prepared by groove cutting with a saw, grinder, or chipping tools. The mouth of the crack is widened and if the crack is active, then a reservoir with a specified width and depth is prepared. ACI 224.1R recommends a minimum width of 0.25 inches and states widths may be up to 1 inch. For active cracks, a width-to-depth ratio of at least 2 is commonly required such that the sealant has sufficient extensibility to accommodate movement. For dormant cracks, a V-notch is used to widen the mouth of the crack (VDOT).
- Clean cracks.
  Cracks may be cleaned by airblasting, sandblasting, or waterblasting. If overbanding is intended (see Step 5), then 1 to 3 inches of the deck on either side of the crack are sandblasted as well. Once cleaning is complete, the crack should be dried.
- Apply a Bondbreaker.
  This is an optional step and is commonly used only for active cracks. The bondbreaker may be a delaminating sheet or a compressible foam backer rod and is installed at the bottom of the reservoir. The purpose of the bondbreaker is to prevent stress concentrations at the bottom of the crack and subsequent tearing and deterioration of the sealant.

Fill cracks with the selected joint sealant.
The widened crack or reservoir is filled with the sealant. A variety of sealant types are available for routing and sealing, as discussed in the following subsection.

Overbanding.
This step is optional and is often recommended to help provide water-tightness and prevent edge spalling. It consists of applying a coating approximately 0.04 to 0.08 inches thick and 2 to 6 inches wide over the length of the crack.

According to literature, the routing step is sometimes omitted and while industry may still refer to the method as "routing and sealing," more accurate descriptions include "cleaning and sealing" or "crack filling." If routing is not desirable, then the reader should refer to the "Apply a Gravity-Fed Polymer by Crack-Chasing" profile, which is essentially a cleaning and sealing method. Alternatively, if cleaning and sealing with a bituminous material is being considered, the reader should refer to this profile but be aware that the repair will not be suitable for active cracks, the cost will be lower than the estimated value provided in this profile, and the performance of the repair will be relatively poor compared to a true rout and seal method.

Compared to other methods such as epoxy injection, this repair method is advantageous because it is relatively simple and does not required particularly skilled labor or experienced contractors. Cores may be taken to assess penetration depth and if a polymer sealant is used, compressive strength of the sealant may be assessed, as identified in "Apply a Gravity-Fed Polymer by Crack-Chasing."

Materials

Routing and sealing may be conducted with epoxies, urethanes, silicones, polysulfides, asphaltic materials, or polymer mortars (ACI 224.1R-14). Epoxies and HMWMs are most commonly used by state DOTs on bridge decks although asphaltic or bituminous materials and urethanes are also used (Rahim et al. 2006).

Epoxies are rigid and stiff, and considered relatively resistant to debonding under traffic loads. Epoxies that classify as gravity-fed polymers may be used if deep penetration as close to the crack tip as possible is desired, but due to the routing operation, more viscous epoxies are also permissible. Low-viscosity epoxies may also be used to fill active cracks below the reservoir and bondbreaker, where crack movement is relatively small. Otherwise, epoxies should only be used to seal dormant cracks or when the cause of crack movement has been otherwise addressed.

Urethanes are more flexible than epoxies and both rigid and flexible urethanes are available, making them suitable for dormant or active cracks. While some report that urethanes perform similarly to epoxies (Rahim et al. 2006), it is generally accepted that they degrade more quickly and are relatively susceptible to any moisture left in the cracks during installation (ACI 224.1R-14). They are the cheapest polymer sealant available.

Repair Costs

The average unit cost for routing and sealing cracks is $40.6 per foot length of crack. The value is based on Texas DOT bid data, and the pay items assumed are listed in Table B..

Table B.10. Unit Cost for Routing and Sealing Cracks

State	State Pay Item No.	Item Description	Unit	Unit Cost
TX	07806004	Rout and Seal	LF	$40.6

Source: Texas DOT average low bid unit prices from November 2019 to November 2020.

Service Life

Because routing and sealing is viewed as a pavement crack repair method and very few state DOTs conduct routing and sealing on bridge decks, literature on the performance of routed and sealed bridge deck cracks is absent. However, because of its close similarities to crack-chasing with a gravity-fed polymer, a similar service life of approximately 5 years is a reasonable assumption.

In some instances, routing and sealing may provide a longer or shorter life than would be expected if the crack had simply been cleaned and sealed. For example, if cracks are old and contaminated such that cleaning will not sufficiently remove contaminants, routing in order to provide access to the crack for better cleaning may increase the bond strength between the sealant and substrate and prolong the life of the repair.

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Pressure Inject with Epoxy

Epoxy injection under pressure is a robust crack repair method for concrete structures that can restore load transfer across the crack but requires an experienced contractor in order to be successful. The general procedure is to clean and seal off the crack(s), install entry and venting ports through which the epoxy is injected, and then remove the seal from the cured epoxy. Epoxy injection is not only used to repair surface cracks on bridge decks but also delaminations.

Objectives

Epoxy injection under pressure is capable of meeting repair objectives as identified in Table B..

Table B.11. Applicable repair objectives of routing and sealing.

	Repair Objectives
✓	Restore or increase strength
✓	Restore or increase stiffness
	Improve functional performance
✓	Provide watertightness
	Improve appearance of the concrete surface
✓	Improve durability
✓	Prevent development of a corrosive environment at reinforcement

Applicability

Epoxy injection is generally considered applicable under the following conditions:

- *NBI Condition Ratings.*
  INDOT, MDOT, VDOT, and WisDOT specify minimum NBI condition requirements for deck crack sealing actions. INDOT and WisDOT do not elaborate on the specific types of actions, but VDOT groups "crack filling" actions as crack sealing with a mesh crossing the crack, a polymer fill, a "V" groove, or epoxy injection. MDOT distinguishes between sealing cracks and applying a healer-sealer, which classifies as a flood coat, but MDOT's requirements for crack sealing and applying a healer-sealer are the same. Crack sealing is understood to be distinct from deck sealing with a penetrating sealer and from placing thin polymer or other types of overlays. Therefore the criteria used by these states are assumed to apply to the following profiles: "Apply a Gravity-Fed Polymer by Crack-Chasing," "Rout and Seal," "Pressure Inject with Epoxy," and "Apply a Flood Coat."

  In INDOT, decks are eligible for crack sealing as long as the NBI ratings of all the major bridge components (deck, superstructure, and substructure) and the NBI rating of the wearing surface (if applicable) are at least 6. VDOT requires crack sealing as long as the deck has a NBI rating of at least 7 while MDOT and WisDOT permit crack sealing as long as the deck has a NBI rating of at least 5; none of these state DOTs discuss the NBI ratings of the other bridge components.
- *Deck Condition State.*
  In addition to the minimum NBI condition ratings, VDOT and WisDOT specify the amount of distress the deck is permitted to have and Indiana provides correlations between the NBI condition rating and the deck overlay condition. These requirements are assumed to apply to the following profiles: "Apply

a Gravity-Fed Polymer by Crack-Chasing," "Rout and Seal," "Pressure Inject with Epoxy," and "Apply a Flood Coat."

VDOT only allows crack filling if the deck deterioration area does not exceed 5 percent. The deck deterioration area is defined as either the percentage of the deck in CS2, CS3, and CS4 based on visual inspection, or, in the case of an in-depth investigation, the percentage of the deck that is delaminated, spalled, patched, and/or in CS1 with a half-cell potential reading less than -0.35 mV. WisDOT requires between 5 and 25 percent of the deck area to demonstrate Defect 3220, Cracking in order to be eligible for crack sealing actions. Note that Defect 3220 characterizes the wearing surface, regardless of whether it is a deck or overlay.

Per INDOT's definitions, a rigid portland cement overlay has an NBI condition rating of 6 or greater as long as no more than 5 percent of the deck is delaminated, cracks are not wider than 0.021 inches, and the crack spacing is at least 3 feet. Semi-rigid (epoxy or polyester) overlays are considered to have an NBI condition rating of 6 or greater as long as no more than 0.5 percent of the deck is delaminated, no to minor surface wearing is present, cracks are not wider than 0.016 inches, and the crack spacing is at least 10 feet. Therefore crack sealing is considered an option only if the deck conditions, crack widths, and crack spacings meet these thresholds.

- *Deck Characteristics.*
  In general, VDOT requires the deck to be at least 6 months of age prior to any crack sealing operations, including by epoxy injection. Epoxy injection is considered appropriate for decks that were built after 2003.
- *Crack Characteristics.*
  The suitability of epoxy injection depends on the crack pattern, activity, width, depth, and spacing. NYSDOT and VDOT use epoxy injection to address linear or singular cracks and not for craze or map cracking. VDOT uses epoxy injection for dormant cracks greater than 0.008 inches. NYSDOT considers dormant cracks greater than 0.012 inches, working cracks greater than 0.007 inches, and cracks exposed to deicers and greater than 0.007 inches in width to be candidates for treatment with a HMWM or by epoxy injection. MnDOT specifies that an epoxy is to be used for cracks with widths between 0.02 and 0.05 inches, regardless of application method (i.e. as a gravity-fed polymer, by pressure injection, or as a flood coat). NDOR states that epoxy injection is generally for deep cracks in concrete structures; however, a "deep" crack is not defined. Finally, VDOT recommends an overlay or crack seal treatment if the crack density is greater than 0.20 linear feet per square foot of deck.

  In general, epoxy injection is considered synonymous to crack-chasing with a gravity-fill polymer, specifically a low-viscosity epoxy that does not need pressure in order to penetrate the crack. Although the application procedure is very different, the methods are considered similar from a technical standpoint. Subsequently state DOTs typically group epoxy injection and application of a gravity-fed polymer together and do not have distinct criteria for selecting between these two choices.

Construction

The IowaDOT currently has a standard procedure for epoxy injection of delaminations on bridge decks. However, the procedures vary slightly for addressing vertical, surface-breaking cracks. The procedures for pressure injecting a crack with epoxy are:

- Clean the crack.

  Contaminants within the crack including oil, grease, dirty, and fine particles of concrete can compromise bond between the epoxy and the concrete or steel substrates. Cracks may therefore be cleaned either by airblasting, sandblasting, or shotblasting; MnDOT notes that field studies show that crack repairs wherein the crack was cleaned by airblowing perform better than repairs wherein the crack was cleaned by sandblasting or shotblasting. Similarly, ACI 224.1R recommends vacuuming or flushing the crack with water. Once cleaned, the crack should be dried by flushing out the water with air or permitting the crack to airdry. MnDOT specifies a minimum drying time of 48 hours and then requires the crack and surrounding surface to be airblown again immediately prior to sealing.

- Install entry and venting ports.

  Ports may be installed by several methods. Currently, IowaDOT mounts the fittings by drilling holes into delaminated areas to the depth of the void. For injecting cracks, the fittings are more commonly epoxied into place such that they are flush over the face of the crack. Fittings should be applied at regular intervals; the IowaDOT currently requires an 8 to 12 inch spacing when repairing delaminations smaller than 10 square feet. VDOT requires the ports be placed at intervals not less than the depth of the crack.

- Seal the cracked surface.

  Once the fittings are in place, the crack must be sealed at all locations where it breaks the surface; through-depth cracks subsequently require sealing at the deck topside and soffit. An epoxy or polyester may be used to provide the seal, but these materials may require sand to be broadcast on top prior to setting so that adequate surface friction is maintained. VDOT uses an epoxy sealant. Alternatively, a strippable plastic surface sealer may be used.

- Mix and inject the epoxy.

  The epoxy may be premixed prior to application or continuously mixed during application. Continuous mixing is preferred because it permits fast-setting epoxies to be used, as noted in ACI 224.1R and by MnDOT. The pressure should be carefully selected such that it is not high enough to cause the crack to propagate further. IowaDOT specifies a pressure of 30 psi to address delaminations, and does not permit the pressure to exceed 35 psi. When sealing cracks by pressure injection, NDOR requires adjacent delaminations or other unsound concrete to be repaired prior to crack sealing to prevent the delamination from popping out during the injection repair.

  ACI 224.1R states that epoxy should be injected by proceeding from one end of the crack to the other. This may need to be repeated several times to fully fill the crack. VDOT requires injection in each port until the epoxy exits through the adjacent port. A constant pressure indicates that the crack has been filled; if the pressure cannot be maintained, then the crack is either not completely filled, the crack is propagating, or the surface seal is leaking.

- Remove the surface seal.

  This step only applies if a strippable seal was used. Once the injection process is complete, the surface seal is removed.

Epoxy pressure injection generally requires highly skilled labor for quality installation. Contractors with greater levels of experience are better able to judge which pressures are appropriate and when the crack has been fully filled.

Another challenge associated with this method is crack cleaning. Since epoxy injection is often used to restore structural integrity across the crack, a strong bond to the substrate is critical. A trial may be required in order to verify that the crack can be adequately cleaned (ACI 224.1R).

Like the polymers used in gravity-fed methods, epoxy is sensitive to temperature and moisture during application and MnDOT's specified temperatures and crack drying times are generally applicable for all crack sealing methods using polymers ("Apply a Gravity-Fed Polymer by Crack-Chasing," "Pressure Inject with Epoxy," and "Apply a Flood Coat"). MnDOT recommends polymers be applied when ambient temperatures are between 50°F and 90°F and at the coolest time of day, although temperatures of at least 65°F are preferred. The presence of moisture in cracks prevents good penetration and as a result, MnDOT requires applicators to wait at least 48 hours after a rain event to apply polymers and does not permit placement if precipitation is expected within 12 hours of placement. To verify the crack is dry, testing per ASTM D4263, *Standard Test Method for Indicating Moisture in Concrete by the Plastic Sheet Method*, wherein a polyethylene sheet is placed over the crack and inspected for condensation after at least two hours.

Materials

The epoxies used for pressure injection are commonly governed by ASTM C881, *Standard Specification for Epoxy-Resin-Base Bonding Systems for Concrete*. ASTM C881 classifies epoxies into seven types of systems based on their physical characteristics and mechanical properties, including viscosity and gel time, bond, compressive, and tensile strengths, compressive modulus and elongation, and thermal compatibility and coefficient of shrinkage on cure. ACI 224.1R-14 recommends using a Type IV epoxy for structural repairs while NDOR permits Type I or IV epoxies to be used. Type IV epoxies are stronger, with minimum bond strengths of 1,000 psi at 2 days and a minimum compressive yield strength of 10,000 psi at 7 days. Type I epoxies have the same minimum bond strength requirement but the minimum compressive yield strength at 7 days is 8,000 psi.

ACI 224.1R-14, Caltrans, MnDOT, and NDO all caution that when selecting the specific epoxy, the compatibility between the epoxy and the equipment and/or application needs to be considered. For example, fast-setting epoxies typically need to be applied using equipment that can mix the components continuously and are not suitable if the epoxy is to be batched prior to application. Additionally, Caltrans recommends using epoxies with thixotropic agents such that the epoxy does not run before set.

Repair Costs

The average unit cost for crack repair by epoxy injection is $97.1 per foot length of crack. The value is based on Illinois DOT letting data, and the pay items assumed are listed in Table B.12..

Table B.12. Unit Cost for Epoxy Injection

State	State Pay Item No.	Item Description	Unit	Unit Cost
IL	59000200	Epoxy Injection	LF	$97.1

Source: Illinois DOT awarded unit prices from letting data from January 2020 to July 2020.

Service Life

While epoxy injection under pressure is a common method for addressing cracks, only a few state DOTs, including ADOT, NVDOT, and WVDOT, use it to address cracks specifically in bridge decks (Wipf et al. 2019). Additionally, only a few other DOTs, including IowaDOT, use epoxy pressure injection to address delaminations in bridge decks. As a result, epoxy pressure injection has not been as extensively studied as other methods, notably gravity-fed polymers, and only a few groups discuss the expected service life.

In a state-wide survey of practices within Pennsylvania, respondents identified epoxy injection as a crack repair method for short-term repairs expected to last 1 to 5 years (Hopper et al. 2015). In their state-wide survey of practices within Iowa, Wipf et al. (2019) found that the districts generally expected lives of 10 to 15 years. Respondents from several districts said that reinjection may be required after 5 to 10 years, while others stated that reinjection is rarely to never done. One respondent said it is typical to return to the deck in 3 to 5 years to inject new voids, indicating that further maintenance was required not due to poor performance of the previously injected voids, but due to further distress of the deck. Based on these surveys and the classification of epoxy pressure injection as a relatively expensive crack-chasing method, a service life of 5 to 10 years is considered appropriate.

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Apply a Flood Coat

Flood coat repairs are commonly used when the crack pattern or crack characteristics make crack chasing methods uneconomical and are often favorable because they help protect the entire crack-affected surface from moisture and chloride infiltration instead of providing localized protection at cracks. Flood coats may be thought of as very thin overlays. They consist of flooding the deck with a polymer or bituminous material to provide a protective coating and then broadcasting aggregate across the surface of the material to provide adequate friction for traffic. Applying gravity-fill polymers by a flood coat method, applying a film-forming sealer, or applying a chip seal are all captured by this repair profile.

Objectives

Flood coats are capable of meeting repair objectives as identified in Table B..

Table B.13. Applicable repair objectives of flood coat application.

Repair Objectives	
	Restore or increase strength
	Restore or increase stiffness
	Improve functional performance
✓	Provide watertightness
✓	Improve appearance of the concrete surface
✓	Improve durability
✓	Prevent development of a corrosive environment at reinforcement

Applicability

Flood coats are generally considered applicable under the following conditions:

- *NBI Condition Ratings.*
- INDOT, MDOT, VDOT, and WisDOT specify minimum NBI condition requirements for deck crack sealing actions. INDOT and WisDOT do not elaborate on the specific types of actions, but VDOT groups "crack filling" actions as crack sealing with a mesh crossing the crack, a polymer fill, a "V" groove, or epoxy injection. MDOT distinguishes between sealing cracks and applying a healer-sealer, which classifies as a flood coat, but MDOT's requirements for crack sealing and applying a healer-sealer are the same. Crack sealing is understood to be distinct from deck sealing with a penetrating sealer and from placing thin polymer or other types of overlays. Therefore the criteria used by these states are assumed to apply to the following profiles: "Apply a Gravity-Fed Polymer by Crack-Chasing," "Rout and Seal," "Pressure Inject with Epoxy," and "Apply a Flood Coat."

  In INDOT, decks are eligible for crack sealing as long as the NBI ratings of all the major bridge components (deck, superstructure, and substructure) and the NBI rating of the wearing surface (if applicable) are at least 6. VDOT requires crack sealing as long as the deck has a NBI rating of at least 7 while MDOT permits crack sealing or a healer-sealer and WisDOT permits crack or deck sealing as long as the deck has a NBI rating of at least 5; none of these state DOTs discuss the NBI ratings of the other bridge components.

- *Deck Condition State.*

  In addition to the minimum NBI condition ratings, VDOT and WisDOT specify the amount of distress the deck is permitted to have and Indiana provides correlations between the NBI condition rating and the deck overlay condition. These requirements are assumed to apply to the following profiles: "Apply a Gravity-Fed Polymer by Crack-Chasing," "Rout and Seal," "Pressure Inject with Epoxy," and "Apply a Flood Coat."

  VDOT only allows crack filling if the deck deterioration area does not exceed 5 percent. The deck deterioration area is defined as either the percentage of the deck in CS2, CS3, and CS4 based on visual inspection, or, in the case of an in-depth investigation, the percentage of the deck that is delaminated, spalled, patched, and/or in CS1 with a half-cell potential reading less than -0.35 mV. WisDOT requires between 5 and 25 percent of the deck area to demonstrate Defect 3220, Cracking in order to be eligible for crack sealing actions and if any area of the deck is in CS3 or CS4 due to Defect 3220, Cracking, then the deck is eligible for deck sealing actions, which is assumed to include flood coats but not crack-chasing methods. Note that Defect 3220 characterizes the wearing surface, regardless of whether it is a deck or overlay.

  Per INDOT's definitions, a rigid portland cement overlay has an NBI condition rating of 6 or greater as long as no more than 5 percent of the deck is delaminated, cracks are not wider than 0.021 inches, and the crack spacing is at least 3 feet. Semi-rigid (epoxy or polyester) overlays are considered to have an NBI condition rating of 6 or greater as long as no more than 0.5 percent of the deck is delaminated, no to minor surface wearing is present, cracks are not wider than 0.016 inches, and the crack spacing is at least 10 feet. Therefore crack sealing is considered an option only if the deck conditions, crack widths, and crack spacings meet these thresholds.

- *Deck Characteristics.*

  In general, VDOT requires the deck to be at least 6 months of age prior to any crack sealing operations. Flood coats are considered appropriate activities for decks that were built after 2003.

- *Crack Characteristics.*

  The decision to use a flood coat commonly depends on the type of cracking or crack spacing or density. VDOT recommends an overlay or crack seal treatment if the crack density is greater than 0.20 linear feet per square foot of deck and uses flood coats to address pattern cracking, and MnDOT states that flood coats are typically more economical if crack spacing is less than 3 feet.

  In addition to the type and spacing of the cracking, crack activity and depth can affect the decision to apply a flood coat. VDOT uses flood coats to address dormant cracks only. In Michigan, general crack sealing operations including application of a healer-sealer are only conducted to address cracks that are expected to go to the depth of the steel reinforcement.

  Crack width is more commonly used to select the material or choose between the different types of flood coats included in this profile than to preclude the use of flood coats. For example, MoDOT notes that a flood coat using a gravity-fill polymer is preferred for hairline cracks less than 0.008 inches in width but can be applied for cracks of any width. However, a bituminous material or chip seal is recommended for wider cracks, as discussed in the Materials section of this report. VDOT generally requires crack treatment actions such as flood coats when cracks are greater than 0.008 inches.

As shown above, flood coats are widely applicable and very common; however, select states do not use them. While NYSDOT uses penetrating sealers, the use of "surface" sealers (assumed to be film-forming sealers or healer-sealers) is prohibited. However, NYSDOT does use thin polymer overlays and may consider these multi-layer overlays to be a more economical option than a single-layer flood coat.

Construction

The procedures for applying a flood coat are:

- Clean and prepare deck.

  The deck must be clean and dry prior to installation of the sealant. If the sealant is a polymer, then MoDOT requires the deck be pressure washed at a pressure of at least 2500 psi while MDOT requires cleaning by shotblasting. The deck is permitted to dry for at least 48 hours per MnDOT and 3 days per MoDOT or at least 48 hours after precipitation (MoDOT; MnDOT). Of the state DOTs reviewed, MoDOT was the only one to reference use of a bituminous material, in which case the deck is cleaned by blowing loose particles off with compressed air. MoDOT further requires the deck to be dry, but does not specify a drying time.

  Any features that are not be sealed over, such as expansion devices, drainage, and other metal features, are covered. If deck repair or patching was conducted prior to the flood coat, the repair materials should be permitted to cure. MDOT specifies a minimum cure duration of at least 28 days.

  Note that in some cases, the flood coat may be extended beyond the deck. For example, MoDOT extends chip seals 30 feet beyond each bridge end.

- Apply coating material.

  The sealant is applied to the deck, spread uniformly with squeegees and brooms and worked into the cracks. Some materials may require premixing prior to application. For flood coats that rely on existing deck grooves for adequate skid resistance, MoDOT recommends brooming parallel to the grooves so texture is not lost due to ponding within the grooves. Areas may require rebrooming to prevent puddles. For bituminous sealants, MoDOT requires any excess oil or bleeding be blotted immediately with sand or cinders.

  The rate of application varies. MoDOT recommends a rate of 100 square feet per gallon for polymers and certain bituminous materials. For chip seals, application rates from 22.5 to 30 square feet per gallon are typical (MoDOT).

  MnDOT and MDOT state to apply the sealant per the manufacturer's recommendations.

- Broadcast aggregate.

  The aggregate is applied to the surface before the sealant has fully cured or dried. The aggregate is required to ensure the deck retains adequate skid resistance and applied to refusal or a "single coat thickness" to provide the best friction (MnDOT; MoDOT). MoDOT states that application rates between 1 and 2 pounds per square yard are common although VDOT states that 0.5 pounds per square yard is acceptable if the deck will be grooved after flood coat application. MnDOT and MDOT generally require the aggregate to be applied as recommended by the manufacturer.

- Remove excess aggregates.

Once the sealant has cured or dried sufficiently such that the aggregate cannot be brushed off, the excess aggregate and protective coverings over the steel features are removed. Excess and loose aggregates may need to be broomed off the deck again after one or two days (MoDOT).

Polymers are sensitive to temperature and moisture during application and as a result MnDOT recommends gravity-fed polymers used in crack-chasing and flood coat methods be applied when ambient temperatures are between 50°F and 90°F and at the coolest time of day, although temperatures of at least 65°F are preferred. In comparison, MoDOT recommends applying gravity-fill polymers at temperatures below 75°F for better penetration. If a bituminous seal coat is being applied, MoDOT requires the coat to be applied during summer months prior to September 1.

Because the performance of polymer flood coats is also heavily influenced by the general quality of installation including the deck preparation, MDOT requires a representative of the epoxy manufacturer to be on-site during the installation process.

Materials

Flood coats consist of a binder and aggregate. The binder is most often an epoxy or HMWM, and the discussion of these materials in "Apply a Gravity-Fed Polymer by Crack-Chasing" applies. Alternatively, MoDOT sometimes uses an emulsified asphalt (Pavon® InDeck) to seal cracked bridge decks or applies a chip seal. Chip seals differ from flood coats in that the binder is a liquid asphalt.

The aggregates are typically a fine aggregate or sand (MDOT, MnDOT, VDOT). MnDOT requires a commercial quality dry blast sand with 95 percent passing a No. 8 sieve and 98 percent retained on a No. 20 sieve. For chip seals, MoDOT requires Iron Mountain Trap Rock or Joplin chat coarse aggregate with 100 percent passing the 0.5-inch sieve, 95 to 100 percent passing the 0.375-inch sieve, 0 to 10 percent passing the No. 4 sieve, and 0 to 1 percent passing the No. 200 sieve.

Repair Costs

The average unit cost for applying a flood coat is $24.5 per square yard. The value is based on Minnesota DOT bid data, and the pay items assumed are listed in Table B..

Table B.14. Unit Cost for Applying a Flood Coat

State	State Pay Item No.	Item Description	Unit	Unit Cost
MN	2433603/00440	Flood Coat	SY	$24.5

Source: Minnesota DOT average bid prices for awarded contracts from January 2017 to December 2018.

Service Life

Because this flood coat profile includes both polymer and bituminous materials and practices, establishing a single service life is difficult. In their literature review, ElBatanouny et al. (2020) estimated that healer-sealers may be expected to have lives between 3 and 10 years, with a minimum life of 5 years if the deck has an NBI condition rating of at least 7, while some bituminous surface treatments such as fog seals may only have 3 years of life and others such as chip seals may be expected to have approximately 15 years of life. This is corroborated by MoDOT, which recommends a reapplication frequency of 3 to 5 years for their emulsified asphalt bridge deck treatment (MoDOT 2016). Since polymer flood coats are more commonly used on concrete bridge decks, more weight is given to the reported service lives of polymer flood coats.

Polymer flood coats tend to degrade due to traffic and freeze-thaw cycling (ElBatanouny et al. 2020). The protection they offer the deck is compromised by aggregate popout, which leaves behind cracks and holes in the polymer matrix through which moisture and chlorides can access the underlying deck. However, while the surface coating is worn away, the polymer within the cracks is not exposed to traffic and therefore continue to protect the cracks from moisture and chloride ingress. Krauss (2000) observed this in a study for the Montana DOT, in which the surface of the applied HMWM coating had worn away within 3 to 4 years due to weathering and abrasion but the HMWM within the cracks remained intact.

Table B. lists the expected service lives or recommended or specified reapplication frequencies for flood coats. The list is similar to those shown in Table B. for gravity-fed polymers applied by crack chasing as the state DOTs typically use gravity-fed polymers for both crack chasing and flood coating and subsequently expect similar performance.

Table B.15. Expected Service Lives and Reapplication Frequencies for Flood Coats

Source	Expected Service Life or Reapplication Frequency
MDOT	5 or 8 to 10 years[1]
MnDOT	3 to 5 years[2]
MoDOT	3 to 5 years or as needed[3]
ODOT	10 or 15 years[4]
WisDOT	3 to 5 years
ElBatanouny et al. 2020	3 to 10 years[5]
Hopper et al. 2015	5 to 10 years
Oman 2014	3 years
Rahim et al. 2006	4 to 5 years

Notes: [1]*Crack sealing is estimated to last 5 years while a healer-sealer is estimated to last 8 to 10 years.*

[2]*MnDOT recommends monitoring the treatment annually and applying more frequently if needed.*

[3]*No frequency is specified for gravity-fill polymers; reapplication is done on an as needed basis. A reapplication frequency of 3 to 5 years is recommended for the emulsified asphalt material used by MoDOT.*

[4]*HMWMs are expected to last 15 years while other gravity-fed resins are expected to last 10 years.*

[5]*A minimum service life of 5 years may be expected if the deck has an NBI condition rating of at least 7.*

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Apply a Hot-Mix Asphalt Overlay with Waterproofing Membrane System

HMA overlays with waterproofing membranes (HMAWM systems) are capable of protecting cracked concrete from further degradation, but would typically be applied only if the deck is nearing the end of its life since the system prevents inspection of the underlying deck and is difficult to reapply. The waterproofing membrane may be either preformed or sprayed onto the deck surface as a liquid and acts as an effective barrier against moisture and chloride infiltration, provided the installation is of good quality and no moisture or contaminants are trapped underneath it. The HMA overlay is necessary to provide a riding surface for traffic and protect the membrane; however, an HMA overlay does not offer protection from moisture and ion ingress.

Objectives

HMA overlays with waterproofing membranes are capable of meeting crack repair objectives as identified in Table B..

Table B.16. Applicable repair objectives of HMA overlays with waterproofing membranes.

Repair Objectives	
	Restore or increase strength
	Restore or increase stiffness
✓	Improve functional performance
✓	Provide watertightness
✓	Improve appearance of the concrete surface
✓	Improve durability
✓	Prevent development of a corrosive environment at reinforcement

Applicability

Because HMAWM systems can be challenging to install and perform poorly if their installation is of poor quality, few states have accepted HMAWM systems into their standard practice and therefore only a few state DOTs in this review (MDOT, VDOT and WisDOT) discuss their use. Furthermore, because HMAWM systems prevent inspection of the underlying deck and are difficult to remove and/or reapply, they are often applied to address ride quality or other issues aside from cracking. MDOT and WisDOT include HMAWM systems in their deck preservation decision matrices and Indiana generally refers to flexible bridge deck overlays in its condition-driven preventative maintenance eligibility table, which is assumed to include both regular HMA overlays and HMAWM systems. VDOT is the only state to discuss the use of HMAWM systems specifically to address bridge deck cracking.

HMAWM systems are generally considered applicable under the following conditions:

- *NBI Condition Ratings.*

  WisDOT considers HMAWM systems to be an option for decks with an NBI condition rating of at least 6 while INDOT considers flexible bridge deck overlays when all the bridge components (wearing surface, deck, superstructure, and substructure) have an NBI condition rating of at least 5. VDOT considers HMAWM systems as methods to address cracking on decks with NBI condition ratings of at least 7. In contrast, MDOT considers HMAWM systems when the deck has a condition rating of 4 or 5 and the soffit has a rating of 4, or when the deck has a rating of 3 or less and the soffit has a rating of 4 or 5.

- *Deck Condition State.*

  MDOT and WisDOT recommend HMAWM systems be used only if the wearing surface has considerable amounts of distress. If the top surface of the deck has an NBI rating of 4 or 5, MDOT suggests HMAWM systems as an option when the percent deck deterioration of both the top surface and the soffit of the deck is between 10 and 25 percent. If the top surface of the deck has an NBI rating of 3 or less, then the percent deck deterioration is expected to be greater than 25 percent on the topside and a HMAWM system is considered an option if the percent soffic deterioration is between 2 and 25 percent. In Wisconsin, HMAWM systems are suggested if at least 20 percent of the wearing surface area is in CS3 or CS4 pertaining to Defect 3210, Delamination/Spall/Patched Area/Pothole, or Defect 8911, Abrasion, Wear, Rutting, or Loss of Friction. Alternatively, if an HMAWM system is already present but over 50 percent of its area has cracked (Defect 3220, Crack) then the reapplication is considered. No more than 5 percent of the underside of the deck can be delaminated, spalled, or patched (Defect 1080, Delaminations/Spalls/Patch Areas).

  However, INDOT does not permit flexible overlays to be placed on bridge decks if more than 10 percent of the deck area has been patched and Krauss et al. (2009) state that decks that have accumulated little chloride contamination are good candidates for protective membrane systems. VDOT does not identify any criteria pertaining to deck condition states.

- *Deck Characteristics.*

  The suitability of an HMAWM system for a deck depends on its age and traffic conditions. HMAWM systems have better bond on new decks rather than existing decks and ODOT and MoDOT only permit waterproofing membranes on newly constructed bridge decks (Hunsucker et al. 2018; Russell 2012). According to NCHRP Synthesis 425, most Canadian provinces and many European countries require HMAWM systems on all new bridge decks (Russell 2012). However, HMAWM systems are more commonly used in rehabilitation projects in the United States and IDOT, SDDOT, NDOR, KDOT, MDOT, and VDOT use them exclusively on existing decks (Russell 2012). They can be more favorable for older decks with a limited remaining service life that are scheduled for replacement because HMAWM systems prevent inspection of the concrete deck and are relatively difficult to remove. According to the survey completed by Russell (2012), Caltrans and NYSDOT used HMAWM systems on new and existing decks while WisDOT, MnDOT, NDDOT, and INDOT did not use HMAWM systems at the time.

  HMAWM systems are not suitable for decks with a high average daily traffic (ADT) count and should not be used in deceleration zones due to the propensity of the membranes to shoving under these conditions (Krauss et al. 2009). Some states do not use HMAWM systems on bridges with an ADT greater than 10,000 vehicles or on interstate bridges while others require the ADT to be less than 1,000 vehicles (Russell 2012).

- *Crack Characteristics.*

  HMAWM systems are required by VDOT when a deck has significant active cracking. VDOT generally requires cracks wider than 0.008 inches or with a density greater than 0.2 linear feet per square feet of deck area to be addressed, but since the width of active cracks varies with temperature and/or live load, the need for a HMAWM system is left to the discretion of the Engineer.

One reported benefit of HMAWM systems is that they can bridge and prevent reflection of most moving cracks in concrete wearing surfaces due to their elastic nature (Sohanghpurwala 2006).

Construction

The procedures for applying an HMA overlay with a waterproofing membrane are:

- Repair unsound concrete.
  Prior to installation of the system, delaminations, spalls, and any other unsound concrete is repaired and the patches should be fully cured prior to installation of the membrane. Cracks are often addressed during deck preparation or immediately prior to membrane application.
- Prepare the deck.
  The deck is milled or scarified to the desired depth and then cleaned and dried. When applying HMAWM systems to new decks, typically only 0.25 or 0.50 inches are removed to improve bond. For older decks, the removal depth is on the order of an inch or two to remove chloride-contaminated concrete. It is common practice to remove the existing overlay if one is present and it may be necessary to raise expansion joint edges and drainage structures as well (Hearn 2020). The final surface should be free of protrusions, rough edges, and holes (Russell 2012).

  The deck is cleaned of contaminants using abrasive blasting and then with brooms, vacuum, or compressed air. Sandblasting is most common although other abrasive blast techniques are also used (Krauss et al. 2009). Techniques that require water are prohibited since the surface must be dry when installing the membrane (Hunsucker et al. 2018). Cracks are repaired or reinforced, which helps prevent reflective cracking through the HMAWM system.
- Install the waterproofing system.
  The waterproofing system is installed by applying a primer to the concrete substrate and then applying the waterproof membrane. The primer improves the bond between the substrate and the membrane. Reinforcement over cracks and cold joints may be installed once the primer is applied (Russell 2012).

  If the membrane is a preformed membrane, then it is placed starting at the lowest point of the deck and rolled onto the deck longitudinally in order to facilitate water drainage during construction (Hunsucker et al. 2018; Russell 2012). Adjacent strips of membrane are lapped 2 to 6 inches at longitudinal seams and transverse seams are commonly staggered (Russell 2012). VDOT and TDOT require strips to be sealed using a wide-tipped torch, mastic, or polyurethane adhesive sealer, or rollers (Hunsucker et al. 2018).

  If the membrane is a liquid membrane, it is heated if necessary and then sprayed on the primed substrate. If reinforced, then one layer of liquid is applied, the fabric is placed, and finally a second layer of liquid is sprayed. The membrane is worked in with squeegees to a uniform thickness. Any blisters or other defects in the membrane are repaired before the asphalt concrete overlay is placed.

  States typically specify minimum and/or maximum wait times between application of the membrane and installation of the overlay in order to allow the membrane to cure properly but minimize the time when the membrane is susceptible to damage. Specified durations vary from 1 to 5 days (Russell 2012) although VDOT requires the overlay to be placed within 24 hours of application of the membrane (Hunsucker et al. 2018).

To protect the overlay, traffic on the membrane is prohibited or minimized and only rubber-tired vehicles are permitted, if necessary. An optional step is to place protection boards over the membrane, but while this is common in Canada, it is rarely done in the United States. Only New Hampshire reported using protective boards in 2012 (Russell 2012). According to Hunsucker et al. (2018), VDOT requires a protective covering be placed immediately over the membrane in its specifications.

Install the asphalt concrete overlay.
The tack coat is applied once the membrane has fully cured and improves the bond between the membrane and the asphalt concrete. Finally, the asphalt concrete overlay is applied to protect the waterproofing membrane from traffic and provide an adequate wearing surface. Typical thicknesses are 2 to 3 inches although they may vary from 1.5 inches to 4 inches. VDOT requires the overlay to be at least 1.5 inches thick after compaction (Hunsucker et al. 2018). However, thicker overlays permit easier reapplication of the asphalt concrete without damaging the membrane (Krauss et al. 2009).

The performance of the HMAWM system is sensitive to the installation quality of the membrane and a common reason states do not use HMAWM systems is due to poor experiences with waterproofing membranes. Of the states that do use HMAWM systems, approximately half specify specific installation procedures while the other half require contractors to follow the procedures of the manufacturers (Russell 2012). A manufacturer's representative is generally required to be present and the work may be required to be performed by personnel certified by the manufacturer as well.

When installing waterproofing membranes, the deck and the weather should both be dry. The installation time for HMAWM systems is typically 3 or more days such that they are best applied when the bridge can be closed for a weekend or there are no closure time restrictions (Krauss et al. 2009). Minimum ambient or deck surface temperatures are commonly specified as well. AASHTO LRFD requires the deck surface to be at least 35°F, or as recommended by the manufacturer, and states specify minimum temperatures between 35°F and 50°F (Russell 2012). Russell (2012) also pointed out that one state requires the deck temperature to be at least 5°F above the dew point for heat-welded membranes. While membranes are generally prohibited from being applied in freezing conditions, they can be applied at lower temperatures than most polymer crack repairs.

Quality testing programs may include the following:

- Electrical resistance tests similar to ASTM D3633, *Standard Test Method for Electrical Resistivity of Membrane-Pavement Systems*. VDOT requires the electrical resistance between the top surface of the asphalt concrete and the top mat of reinforcement to be at least 500 kOhms (Hunsucker et al. 2018; Russell 2012).
- Adhesion bond testing of the membrane per ASTM D4541, *Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers*. IDOT and NHDOT require the bond between the membrane and the concrete substrate to be at least 100 psi while NYSDOT requires the bond to be at least 145 psi (Russell 2012).

- Holiday testing per ASTM D4787, *Standard Practice for Continuity Verification of Liquid or Sheet Linings Applied to Concrete Substrates*. IDOT and NHDOT always or sometimes require the membrane to be tested for holidays, respectively (Russell 2012).
- Leak testing, which consists of ponding water on the top surface of the asphalt concrete and observing the deck soffit for leaks (no standard procedure available). MoDOT relies on leak testing and commonly conducts these tests during rainstorms (Russell 2012).

Materials

The two primary materials of HMAWM systems are the waterproofing membrane and the asphalt concrete. Waterproofing membranes are proprietary products and may be classified as either preformed membranes or liquid (also known as constructed-in-place) membranes.

Preformed membranes may be asphalt-impregnated fabric, polymer, elastomer, or asphalt-laminated board systems while liquid membranes are bituminous or resinous liquid-sprayed systems (Russell 2012). Preformed membranes have a pressure-sensitive adhesive backing, but this does not preclude them from requiring primers. Liquid membranes may also include a layer of reinforcing fabric and resins used for liquid-sprayed systems include two-component polymers, polyurethanes, and methyl methacrylates. Both preformed and liquid membranes may be made of rubberized asphalt, which is preferred by the Canadian provinces (Russell 2012). Several states restrict the types of membranes that may be used, and the membranes permitted by select states, as reported by Hunsucker et al. (2018), are shown in Table B.. The type of membrane used may depend on the characteristics of the bridge deck; for example, liquid membranes are better suited for rougher surfaces than preformed membranes (Krauss et al. 2009; Russell 2012).

Table B.17. Waterproofing membranes used by select state DOTs, as reported by Hunsucker et al. (2018)

Organization	Types of Waterproofing Membranes
VDOT	▪ A primer and prefabricated membrane consisting of a laminate formed with suitable plasticized coal tar and reinforced with nonwoven synthetic fibers or glass fibers ▪ A primer, mastic, and prefabricated membrane consisting of a laminate formed of rubberized asphalt and reinforced with synthetic fibers or mesh ▪ A primer and prefabricated membrane consisting of a laminate formed with suitably plasticized asphalt, reinforced with open-weave fiber glass mesh, and having a thin polyester top surface film ▪ A hot-poured liquid elastomeric membrane with protective covering ▪ A surface conditioner and a hot-applied rubberized asphalt membrane with protective covering
IDOT	▪ A penetrating primer; a built-up coal tar pitch emulsion membrane with two plies of coated glass fabric; and a 0.5-inch thick asphalt sand seal protection layer
TDOT	▪ A membrane laminate formed with suitable plasticized coal tar and reinforced with non-woven synthetic fibers or glass fibers ▪ A laminate of rubberized asphalt reinforced with synthetic fibers or mesh

There is relatively little discussion regarding the types of asphalt concretes that are suitable for HMAWM systems. However, one respondent in the survey conducted by Krauss et al. (2009) recommended selecting aggregates that minimize the likelihood of puncturing the membrane.

Repair Costs

The average unit cost for applying an HMAWM system is $82.7 per square yard. The value is based on data from Iowa, South Dakota, and Michigan DOTs, and the pay items assumed are listed in Table B..

Table B.18. Unit Cost for a Applying an HMAWM system

State	State Pay Item No.	Item Description	Unit	Unit Cost
IA[1]	2510-6745640	Remove existing concrete	SY	$26.1
SD[2]	491E0110	Clean deck with abrasive blasting	SY	$3.6
MI[3]	N/A	HMA Overlay with WP membrane	SY	$53.0
Total			**SY**	**$82.7**

Sources: [1] Iowa DOT bid tabs (awarded and non-awarded unit prices) from January 2020 to December 2020.
[2] South Dakota DOT average low bid prices from January 2019 to December 2019.
[3] Michigan DOT Local Bridge Program (LAP) - Bridge Cost Estimate Worksheet 2020.

Service Life

HMAWM systems are relatively susceptible to traffic. While other overlays and surface treatments experience loss of skid resistance under high average daily traffic counts, HMAWM systems experience shoving of the membrane and failure of the bond between the membrane and the substrate (ElBatanouny et al. 2020). Their performance also depends strongly on their installation quality and ensuring that water and chlorides are not trapped underneath the membrane. Based on the service lives reported in literature and shown in Table B., a life of 10 to 15 years is a reasonable expectation, although shorter lives are expected if the existing deck is in poor condition.

Unlike other crack repair methods, HMAWM systems do not have a recommended or specified reapplication frequency. It is generally accepted that the maintenance of the HMAWM system entails milling and replacing the asphalt overlay once, likely within 10 years, and then removing the entire HMAWM system when the second asphalt overlay reaches the end of its life. Instances in which the full HMAWM system is reapplied are not identified in literature, in part because some state DOTs only apply HMAWM systems when the bridge deck is scheduled for replacement and reapplication is unnecessary.

Table B.19. Expected Service Life for HMAWM Systems

Source	Expected Service Life
MDOT	8 to 10 years
WisDOT	5 to 15 years
ElBatanouny et al. 2020	6 to 20 years[1]
Hopper et al. 2015	5 to 10 years

Notes: [1]A service life of at least 10 years may be expected if the deck NBI condition rating is at least 7.

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Apply a Thin Polymer Overlay

Thin polymer overlays are commonly 0.25 to 0.625 inches thick and placed in two or three layers. Each layer consists of a polymer binder and broadcast aggregate. Their construction methods and materials and the manner in which they protect a cracked bridge deck from deterioration are similar to those of polymer flood coats. However, thin polymer overlays are thicker than flood coats and therefore more costly but also provide protection from chloride intrusion and moisture ingress for a longer period of time. Unlike other overlays, thin polymer overlays are best suited for bridge decks that are not experiencing active corrosion and have very little distress.

Objectives

Thin polymer overlays are capable of meeting repair objectives as identified in Table B..

Table B.20. Applicable repair objectives of thin polymer overlays.

	Repair Objectives
	Restore or increase strength
	Restore or increase stiffness
	Improve functional performance
✓	Provide watertightness
✓	Improve appearance of the concrete surface
✓	Improve durability
✓	Prevent development of a corrosive environment at reinforcement

Applicability

Thin polymer overlays are generally considered applicable under the following conditions:

- *NBI Condition Ratings.*

  VDOT generally requires a deck NBI condition rating of at least 7, although thin polymer overlays may be applied to decks with a rating of 6 pending the results of an in-depth investigation, as discussed in the following point. WisDOT also generally permits thin polymer overlays to be installed if the deck has an NBI condition rating of at least 7 but recommends them for decks with ratings of 8 or 9. If the deck rating is 6, then an existing thin polymer overlay may be replaced but bare decks with NBI ratings below 7 are not eligible for thin polymer overlays.

  In contrast, MDOT uses thin polymer overlays when the deck NBI rating is at least 5 and the soffit NBI rating is at least 6, but does not recommend thin polymer overlays if the deck has an NBI rating of 8 or 9.

- *Deck Condition State.*

  MDOT, VDOT, and WisDOT give specific condition state criteria. MDOT only permits epoxy overlays when the percent deck deterioration is 10 percent or less and the percent soffit deterioration is 2 percent or less. VDOT does not place thin polymer overlays on decks with a compromised area greater than 5 percent wherein the compromised area is defined as either the percentage of the deck in CS2, CS3, and CS4 based on visual inspection, or, in the case of an in-depth investigation, the percentage of the deck that is delaminated, spalled, patched, and/or in CS1 with a half-cell potential reading less than -0.35 mV. If the deck has an NBI rating of 6, then the chloride front also cannot be greater than 1 inch. In Wisconsin, when a first-time application is being considered, no more than 2 percent of the topside deck area may be experiencing Defect 3210, Delamination/Spall/Patched Area/Pothole, and no more than 1 percent of its underside may be experiencing Defect 1080, Delaminations/Spalls/Patch Areas. When a reapplication is being considered, at least 15 percent of the area of the current thin polymer overlay must be in CS3 or CS4 (no defect specified) and no more than 1 percent of the deck underside may be experiencing Defect 1080.

MDOT generally states that thin epoxy overlays are suitable for decks with minor delamination and spalling and/or moderate cracking, but does not define limits for these conditions. Additionally, VDOT notes that an epoxy overlay may be necessary if other crack treatment methods, such as crack-chasing repairs, compromise the ride quality of the deck.

- *Deck Characteristics.*

  Of the deck characteristics, states most commonly consider deck age when determining if a thin polymer overlay should be applied. There is general agreement that the overlay should be placed on mature decks to prevent reflective cracking; VDOT requires epoxy overlays for decks in good condition that were built prior to 2003, WisDOT recommends placing thin polymer overlays at a deck age of 2 years, and KDOT acknowledges that thin polymer overlays are best placed once cracks have fully developed. However, KDOT also uses thin polymer overlays to protect new construction prior to full development of cracks. WisDOT does not recommend placing thin polymer overlays on decks older than 10 years, or older than 15 years if a rigorous deck washing and sealing program has been implemented. Thin polymer overlays are required on new, state-owned decks located in relatively dense metropolitan areas and recommended for locally-owned decks regardless of traffic volume.

- *Crack Characteristics.*

  As for other crack treatment methods, VDOT recommends addressing cracks greater than 0.008 inches in width and applying an overlay or other treatment if the crack density is greater than 0.2 linear feet per square foot of deck area. According to VDOT and WisDOT, thin polymer overlays cannot be used to address active cracks. WisDOT further does not recommend thin polymer overlays if widespread cracking is present or cracks are large with widths greater than 0.04 inches. KDOT commonly encounters longitudinal shrinkage cracking on its bridge decks, and uses thin polymer overlays to protect decks that experience this type of cracking.

It should be noted that thin polymer overlays are applied to decks for a wide variety of reasons aside from crack treatment. However, since this review is focused on addressing deck cracking, some of these more general criteria for NBI condition ratings and deck conditions may not be incorporated in the above discussion.

Construction

Thin polymer overlays may be constructed in three ways: (1) the broom-and-seed or multiple-layer method, (2) the slurry method, or (3) the premixed method. Multiple-layer overlays are most common, and as a result an overview of their construction procedure is provided below. KDOT uses multi-layer polymer overlays and WisDOT uses two-layer, two-component epoxy systems. Other reports, such as NCHRP

Synthesis 423, *Long-Term Performance of Polymer Concrete for Bridge Decks*, and IHRB TR-717, *Use of Polymer Overlays or Sealers on New Bridges*, provide further details.

The procedures for applying a thin polymer overlay by the broom-and-seed method are as follows:

- Prepare the surface.
  The deck surface is roughened and cleaned by shot blasting to remove contaminants and then blown with compressed air to clear dust and debris. The substrate should be sound, defined as having a minimum tensile strength of 150 psi, and large cracks greater than 0.04 inches in width should be repaired (Fowler and Whitney 2011). Frosch et al. (2010) also noted that epoxy overlays experienced reflective cracking under simulated traffic loads and concluded that a gravity-fed polymer should be applied to cracks prior to placing a thin polymer overlay. Any patches should be fully cured prior to installation of the overlay and WisDOT requires portland cement patches to be at least 28 days old, unless approved otherwise. WisDOT additionally comments that the patch and crack repair materials should be compatible with the overlay materials.
- Place a layer of polymer resin and broadcast aggregate.
  As soon as possible after deck cleaning is complete, the polymer resin is sprayed, squeegeed, and/or broomed on the surface and the aggregate is immediately broadcast on the uncured resin to excess. Typical application rates are approximately 2 lb/yd^2 and 10 lb/yd^2 for the resin and aggregate, respectively (Fowler and Whitney 2011). Once the resin has cured, the excess, loose aggregate is removed.
- Place additional layers of polymer and aggregate to desired thickness.
  Step 2 is repeated once or twice as specified by the contract. Each layer typically adds approximately 0.125 inches of thickness to the overlay and two-layer or three-layer systems are most common. WisDOT requires a minimum total thickness of 0.25 inches. Application rates for the second layer are approximately 4 lb/yd^2 and 14 lb/yd^2 for the resin and aggregate, respectively (Fowler and Whitney 2011).

Adequate surface preparation is important for successful polymer overlay performance since polymer overlays are sensitive to the presence of contaminants, dust, and moisture, which decrease bond. As a result, ASTM D4263, *Standard Test Method for Indicating Moisture in Concrete by the Plastic Sheet Method*, is used to check for the presence of moisture and bond strength testing per ASTM C1583, *Standard Test Method for Tensile Strength of Concrete Surfaces and the Bond Strength or Tensile Strength of Concrete Repair and Overlay Materials by Direct Tension (Pull-off Method),* is a common quality assurance test completed on trials prior to full overlay application (Fowler and Whitney 2011). Polymer overlays are also sensitive to ambient conditions during installation. State DOTs typically specify minimum ambient or deck surface temperatures of 50°F to 60°F for epoxy overlays and maximum temperatures may be specified as well (Fowler and Whitney 2011).

KDOT states that thin polymer overlays may be completed within a few days and the bridge is returned to service quickly. Thin polymer overlays have the additional benefit of easy and relatively quick reapplication as the original overlay does not need to be removed prior to reinstallation.

Thin polymer overlays are susceptible to snow plow damage at the entrances and exits of the bridge, and for this reason, MDOT sometimes extends thin polymer overlays approximately 10 feet onto the approaches to act as a sacrificial edge. However, WisDOT avoids placing thin polymer overlays on concrete approaches, stating that they may fail prematurely due to moisture issues.

Materials

Thin polymer overlays consist of polymers and aggregates, and multiple-layer overlays are approximately 25% polymer by weight (Fowler and Whitney 2011). Epoxies are the most common type of polymer used, especially for multiple-layer overlays, followed by polyesters, which are more commonly used for premixed thin polymer overlays. Methacrylates and urethanes are other available alternatives. The viscosity, gel time, tensile elongation, bond strength, and modulus of elasticity affect the performance of the polymer during installation and service.

Durable, hard aggregates that provide long-term skid resistance are desirable. Aggregate composition, gradation, and hardness are often specified. KDOT uses flint rock from Oklahoma and WisDOT recommends using calcined bauxite if especially high skid resistance is required. The aggregates are typically gap-graded (Fowler and Whitney 2011) and a Moh's hardness of at least 6 or 7 is commonly required. Like the bridge deck, aggregates should be clean and dry to promote good bond with the polymer.

Repair Costs

The average unit cost for applying a thin polymer overlay is $66.4 per square yard. The value is based on data from Iowa and South Dakota DOTs, and the pay items assumed are listed in Table B..

Table B.21. Unit Cost for Applying a Thin Polymer Overlay

State	State Pay Item No.	Item Description	Unit	Unit Cost
SD[1]	491E0110	Clean deck with abrasive blasting	SY	$3.7
IA[2]	2599-9999018	Thin Polymer Overlay	SY	$62.7
Total			**SY**	**$66.4**

Sources: [1] South Dakota DOT average low bid prices from January 2019 to December 2019.
[2] Iowa DOT bid tabs (awarded and non-awarded unit prices) from January 2020 to December 2020.

Service Life

The expected service life or recommended or specified reapplication frequency for thin polymer overlays reported in state DOT manuals, specifications, and research literature is shown in Table B.. Based on the reported values, a service life of 10 to 15 years is deemed reasonable.

Thin polymer overlays generally lose their protective qualities due to aggregate popout or reflective cracking. These mechanisms cause cracks or holes to form in the overlay, permitting moisture and chloride ingress. However, they additionally become debonded and lose their skid resistance and serviceability with time. Aside from installation quality and pre-existing condition, the ability of a thin polymer overlay to provide chloride penetration resistance and adequate skid resistance is typically controlled by the volume of traffic (ElBatanouny et al. 2020a). Maintenance commonly entails placing a fresh layer on the overlay to restore skid resistance and crack sealing or repair of delaminated areas may also be conducted. New layers are commonly applied after 10 years, although they may be required sooner depending on traffic volume.

Table B.22. Expected Service Life or Reapplication Frequency for Thin Polymer Overlays

Source	Expected Service Life or Reapplication Frequency
KDOT	10 years
MDOT	10 years; or 15 to 20 years[1]
WisDOT	7 to 15 years
ElBatanouny et al. 2020a	5 to 15 years[2]
ElBatanouny et al. 2020b	5 to 20 years
Hopper et al. 2015	10 or more years

Notes: [1]*The "Asset Management Guide for Local Agency Bridges in Michigan" estimates a 10 year life while MDOT's bridge deck preservation matrices for decks reinforced with black and epoxy-coated rebar anticipate a life of 15 to 20 years.*

[2]*A minimum service life of 7 years may be assumed if the deck NBI condition rating is at least 7.*

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Apply a Rigid Cementitious Overlay

Cementitious overlays may be applied early in the life of the deck as a preventive measure prior to significant chloride intrusion and corrosion initiation. Alternatively, they may also be applied after deck distress has appeared, in which case the cracked and otherwise unsound concrete is patched and the chloride-contaminated cover removed prior to overlay installation. A wide variety of concretes have been used for overlays, including regular portland cement concrete (PCC), low-slump dense concrete (LSDC), high performance concrete (HPC), and silica fume concrete (SFC). However, all of these materials are based on portland cement and do not contain any polymer additives in large quantities the way polymer-modified concretes do. Most cementitious overlays contain pozzolans, which increase the chloride penetration resistance of the overlay. The overlay thereby provides protection across the full area of the deck by providing extra concrete cover and increasing the amount of time required for chlorides to build up at the reinforcing steel.

Objectives

Rigid cementitious overlays are capable of meeting repair objectives as identified in Table B..

Table B.23. Applicable repair objectives of cementitious overlays.

	Repair Objectives
✓	Restore or increase strength
✓	Restore or increase stiffness
✓	Improve functional performance
	Provide watertightness
✓	Improve appearance of the concrete surface
✓	Improve durability
✓	Prevent development of a corrosive environment at reinforcement

Availability

Rigid cementitious overlays are generally considered applicable under the following conditions:

- *NBI Condition Ratings.*

  INDOT, VDOT, and WisDOT specify criteria for the bridge NBI conditions. INDOT permits rigid cementitious overlays only if the wearing surface has an NBI rating of at least 3 and the other bridge components (deck, superstructure, and substructure) have NBI ratings of at least 4. In contrast, VDOT recommends rigid overlays for decks with an NBI rating of 6 or less and WisDOT considers rigid overlays for decks with NBI ratings of 5 or 6. Under special circumstances, a rigid overlay may be required regardless of NBI condition due to risk of alkali-silica reaction in Virginia as described below.

- *Deck Condition State.*

  INDOT, VDOT, and WisDOT additionally specify criteria for deck conditions. Indiana only permits rigid cementitious overlays if no more than 15 percent of the deck area has been patched.

  For first-time applications, WisDOT considers decks with at least 20 percent of their area in CS3 or CS4 per Defect 3220, Crack, or Defect 8911, Abrasion, Wear, Rutting, or Loss of Friction, or at least 15 percent deteriorated per Defect 3210, Debonding/Spall/Patched Area/Pothole. Regarding reapplication, if at least 20 percent of the area of the existing rigid overlay is in CS3 or CS4 per Defect 3210, Debonding/Spall/Patched Area/Pothole, or at least 50 percent of the area is deteriorated per Defect 3220, Crack, then a new rigid overlay is considered. In both cases, no more than 5 percent of the underside of the deck may be deteriorated per Defect 1080, Delaminations/Spalls/Patch Areas and no more than 25 percent of the underside may be in CS3 or CS4 per Defect 1130, Cracking.

In Virginia, rigid overlays are considered for decks with a compromised area up to 20 percent although thin polymer overlays are typically applied if the compromised area does not exceed 5 percent as long as the chloride front does not exceed a depth of 1 inch. Compromised area is defined as either the percentage of the deck in CS2, CS3, and CS4 based on visual inspection, or, in the case of an in-depth investigation, the percentage of the deck that is delaminated, spalled, patched, and/or in CS1 with a half-cell potential reading less than -0.35 mV. If the chloride front exceeds 1 inch, then a rigid overlay is required.

The above discussion commonly pertains to chloride-induced corrosion. If the primary deterioration mechanism is alkali-silica reaction instead, as indicated by visible distress and confirmed by petrographic examination, then VDOT requires a rigid overlay if the cracking index (CI) is less than 0.02 inches per yard and deck replacement otherwise. The cracking index is a quantitative measurement of the extent of cracking determined by drawing 20-inch-by-20-inch reference grids in several representative areas on the deck and measuring and summing the width of each crack crossing the gridlines. The measurement method is presented in "Report on the Diagnosis, Prognosis, and Mitigation of ASR in Transportation Structures" published by the Federal Highway Administration" (Fournier et al. 2010).

Rigid cementitious overlays are not inherently precluded from consideration due to any deck or crack characteristics.

Because two-course construction has demonstrated increased cracking and poorer performance compared to single-course construction, KDOT does not use portland cement concrete overlays anymore. Decks are constructed with 3 inches of cover instead such that a protective cementitious overlay is not needed early in the life of the structure.

It should be noted that rigid cementitious overlays are applied to decks for a wide variety of reasons aside from crack treatment. However, since this review is focused on addressing deck cracking, some of these more general criteria for NBI condition ratings and deck conditions may not be incorporated in the above discussion.

Construction

The procedures for applying a rigid cementitious overlay are as follows:

- Prepare the surface.
  Surface preparation includes removing the existing wearing surface to the desired depth and repairing unsound concrete. Concrete removal may be done by hydrodemolition, scarification, milling, abrasive blasting, or a combination of these techniques. For relatively new decks that do not contain much chloride contamination, only about 0.25 or 0.5 inches may be removed while older decks expected to

have higher levels of chloride-contamination may have most of their cover removed and replaced by the overlay. If an existing overlay is present, it is removed. Any unsound concrete is removed and repaired. Finally, in preparation for the overlay the deck is wetted to bring it to saturated-surface dry condition, which aids in curing and bond.

- Install and cure the overlay.
  The overlay is placed, levelled off, consolidated, and cured using conventional techniques and equipment. Rigid cementitious overlays are typically 1.25 to 4.5 inches thick (VDOT; NDOR; WisDOT). Curing generally takes several days to a week.
- Apply a surface friction treatment, as necessary.
  Once the overlay has cured, the deck may be grooved to provide adequate skid resistance.

Cementitious overlays are advantageous because they do not require specialized skills and are relatively low cost, but they require long traffic closures due to their cure times. They are also relatively permeable compared to the other overlays available and prone to cracking, particularly under hot or windy conditions that favor higher rates of evaporation. WisDOT notes that cementitious overlays will likely require crack sealing treatments throughout their life, much like the original deck.

Further information on the construction of rigid cementitious overlays may be found in NCHRP Research Report 950, *Proposed AASHTO Guides for Bridge Preservation Actions* (Hearn 2020) and practices of the Midwest states are highlighted in Appendix A of IHRB TR-775, *Late Life Low Cost Deck Overlays* (ElBatanouny et al. 2020b).

Materials

A wide variety of concrete are used for rigid cementitious overlays, including portland cement concrete or high performance concrete (PCC or HPC), low slump dense concrete or superplasticized dense concrete (LSDC or SDC), microsilica concrete or silica fume concrete (MSC or SFC), and fiber-reinforced concrete (FRC). However, these mixtures are generally characterized by low water-to-cementitious material ratios and high paste contents to provide low permeability but sufficient workability (ElBatanouny et al. 2020a). Supplementary cementitious materials (SCMs) including fly ash, ground granulated blast furnace slag (GGBFS), and silica fume may be included to decrease the permeability. MSC overlays generally contain high amounts of silica fume at rates of approximately 7% to 11% by weight of cement (ElBatanouny et al. 2020b). FRC overlays use fibers to help arrest cracks, and synthetic fiber dosage rates are approximately 3 to 8 lb/yd^3 (ElBatanouny et al. 2020a).

The specific cementitious mixtures vary between the states. NDOR no longer permits the use of LSDC overlays on bridge decks and instead uses MSC overlays exclusively. In contrast, WisDOT generally uses LSDC overlays and rarely uses MSC overlays when applying a cementitious overlay.

Repair Costs

The average unit cost for applying a PCC or HPC overlay is $141.6 per square yard. The value is based on data from Iowa and South Dakota DOTs, and the pay items assumed are listed in Table B..

Table B.24. Unit Cost for Applying a PCC or HPC Overlay

State	State Pay Item No.	Item Description	Unit	Unit Cost
IA[1]	2510-6745640	Remove existing concrete	SY	$26.1
SD[2]	491E0110	Clean deck with abrasive blasting	SY	$3.6
IA[1]	Varies	Class-O or HPC-O Deck Overlay	SY	$105.0
IA[1]	2412-0000100	Longitudinal Grooving in Concrete	SY	$6.9
Total			**SY**	**$141.6**

Sources: [1] Iowa DOT bid tabs (awarded and non-awarded unit prices) from January 2020 to December 2020.
[2] South Dakota DOT average low bid prices from January 2019 to December 2019.

Service Life

Rigid cementitious overlays have been used since the 1960s and their service life is therefore well-established. Based on their literature review, ElBatanouny et al. (2020a) found that a life between 15 and 30 years is a reasonable assumption, although the service life may be as short as 7 years if the deck NBI condition rating is 5 or 6. WisDOT (2020) states that a service life of 15 to 20 years is expected; the lower maximum may be explained by their preservation policy, which only suggests using rigid cementitious overlays when the deck has an NBI condition rating of 5 or 6.

With respect to maintenance during the service life of the overlay, WisDOT comments that cementitious overlays are expected to crack and periodic crack sealing treatments may be required (WisDOT 2020). For this reason, KDOT prohibits applying a cementitious overlay on newly constructed bridge decks and instead requires bridge decks to be constructed with adequate cover in a single course, which reportedly decreases crack density and improves performance (KDOT 2016). Therefore the cracks in a cementitious overlay affect its service, and if a crack sealing treatment program is to be prescribed, it must be considered in their cost.

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Apply a Latex-Modified Concrete Overlay

Typical concrete mixtures contain chemical admixtures such as superplasticizers or air entrainers on the order of a hundred ounces per cubic yard. However, polymer-modified concretes contain a large amount of a polymer admixture on the order of several thousand ounces per cubic yard. The most common polymer modifier used is an organic admixture called styrene-butadiene-latex and some states specify an application rate of 24.5 gallons per cubic yard. The latex modifier increases the cost of the concrete but significantly decreases the permeability of the hardened concrete, preventing both chlorides and moisture from penetrating to the reinforcement. They play a similar role to cementitious overlays and may be applied prior to deck deterioration or after distress has manifested.

Objectives

LMC overlays are capable of meeting repair objectives as identified in Table B..

Table B.25. Applicable repair objectives of LMC overlays.

	Repair Objectives
✓	Restore or increase strength
✓	Restore or increase stiffness
✓	Improve functional performance
✓	Provide watertightness
✓	Improve appearance of the concrete surface
✓	Improve durability
✓	Prevent development of a corrosive environment at reinforcement

Applicability

LMC overlays are not typically distinguished from rigid cementitious overlays in state DOT decision matrices and design manuals. The selection or eligibility criteria are assumed to be the same and it is generally left up to the Engineer to choose the type of cementitious overlay to be applied. Therefore, the Applicability discussion from "Apply a Rigid Cementitious Overlay" applies:

- *NBI Condition Ratings.*

  INDOT, VDOT, and WisDOT specify criteria for the bridge NBI conditions. INDOT permits rigid cementitious overlays only if the wearing surface has an NBI rating of at least 3 and the other bridge components (deck, superstructure, and substructure) have NBI ratings of at least 4. In contrast, VDOT recommends rigid overlays for decks with an NBI rating of 6 or less and WisDOT considers rigid overlays for decks with NBI ratings of 5 or 6. Under special circumstances, a rigid overlay may be required regardless of NBI condition due to risk of alkali-silica reaction in Virginia as described below.

- *Deck Condition State.*

  INDOT, VDOT, and WisDOT additionally specify criteria for deck conditions. INDOT only permits rigid cementitious overlays if no more than 15 percent of the deck area has been patched.

  For first-time applications, WisDOT considers decks with at least 20 percent of their area in CS3 or CS4 per Defect 3220, Crack, or Defect 8911, Abrasion, Wear, Rutting, or Loss of Friction, or at least 15 percent deteriorated per Defect 3210, Debonding/Spall/Patched Area/Pothole. Regarding reapplication, if at least 20 percent of the area of the existing rigid overlay is in CS3 or CS4 per Defect 3210, Debonding/Spall/Patched Area/Pothole, or at least 50 percent of the area is deteriorated per Defect 3220, Crack, then a new rigid overlay is considered. In both cases, no more than 5 percent of the underside of the deck may be deteriorated per Defect 1080, Delaminations/Spalls/Patch Areas and no more than 25 percent of the underside may be in CS3 or CS4 per Defect 1130, Cracking.

In Virginia, rigid overlays are considered for decks with a compromised area up to 20 percent although thin polymer overlays are typically applied if the compromised area does not exceed 5 percent as long as the chloride front does not exceed a depth of 1 inch. Compromised area is defined as either the percentage of the deck in CS2, CS3, and CS4 based on visual inspection, or, in the case of an in-depth investigation, the percentage of the deck that is delaminated, spalled, patched, and/or in CS1 with a half-cell potential reading less than -0.35 mV. If the chloride front exceeds 1 inch, then a rigid overlay is required.

The above discussion commonly pertains to chloride-induced corrosion. If the primary deterioration mechanism is alkali-silica reaction instead, as indicated by visible distress and confirmed by petrographic examination, then VDOT requires a rigid overlay if the cracking index (CI) is less than 0.02 inches per yard and deck replacement otherwise. The cracking index is a quantitative measurement of the extent of cracking determined by drawing 20-inch-by-20-inch reference grids in several representative areas on the deck and measuring and summing the width of each crack crossing the gridlines. The measurement method is presented in "Report on the Diagnosis, Prognosis, and Mitigation of ASR in Transportation Structures" published by the Federal Highway Administration (Fournier et al. 2010).

LMC overlays are not inherently precluded from consideration due to any deck or crack characteristics.

It should be noted that LMC overlays are applied to decks for a wide variety of reasons aside from crack treatment. However, since this review is focused on addressing deck cracking, some of these more general criteria for NBI condition ratings and deck conditions may not be incorporated in the above discussion.

Construction

The procedures for applying a LMC overlay are the same as those used for rigid cementitious overlays:

- Prepare the surface.
  Surface preparation includes removing the existing wearing surface to the desired depth and repairing unsound concrete. Concrete removal may be done by hydrodemolition, scarification, milling, abrasive blasting, or a combination of these techniques. For relatively new decks that do not contain much chloride contamination, only about 0.25 or 0.5 inches may be removed while older decks expected to have higher levels of chloride-contamination may have most of their cover removed and replaced by the overlay. If an existing overlay is present, it is removed. Any unsound concrete is removed and repaired. Finally, in preparation for the overlay the deck is wetted to bring it to saturated-surface dry condition, which aids in curing and bond.
- Install and cure the overlay.
  The overlay is placed, levelled off, consolidated, and cured using conventional techniques and

equipment. Curing generally takes several days to a week unless a very-early strength LMC overlay is used, in which case installation and cure may be completed within a day.

- Apply a surface friction treatment, as necessary.
  Once the overlay has cured, the deck may be grooved to provide adequate skid resistance.

Unlike rigid cementitious overlays, LMC overlays require specialized equipment and are more sensitive to ambient conditions due to their polymer modifier. Further information on the state practices regarding the construction of LMC overlays may be found in Appendix A of IHRB TR-775, *Late Life Low Cost Deck Overlays* (ElBatanouny et al. 2020b) and KTC-18-06, *Longer Lasting Bridge Deck Overlays* (Hunsucker et al. 2018).

Materials

LMC overlays are a specific type of cementitious overlay wherein approximately 60% of the mixing water is replaced with styrene-butadiene-latex (ElBatanouny et al. 2020b). The latex modifier significantly decreases the permeability of the concrete compared to rigid cementitious overlays. If a significantly lower curing time is desired, then alternative cements may be used to quicken strength gain. For example, VDOT uses calcium sulfoaluminate cements in their very-early strength LMC overlays while MoDOT uses ASTM C1157 Type HE cements (ElBatanouny et al. 2020b). While the latex modifier increases the material unit cost, INDOT finds LMC overlays more economical than LSDC while other state DOTs have observed the reverse (ElBatanouny et al. 2020b).

Repair Costs

The average unit cost for applying an LMC overlay is $152.9 per square yard. The value is based on data from Iowa, South Dakota, and Illinois DOTs, and the pay items assumed are listed in Table B..

Table B.26. Unit Cost for Applying an LMC Overlay

State	State Pay Item No.	Item Description	Unit	Unit Cost
IA[1]	2510-6745640	Remove existing concrete	SY	$26.1
SD[2]	491E0110	Clean deck with abrasive blasting	SY	$3.6
IL[3]	Z0006014	LMC Overlay	SY	$116.3
IA[1]	2412-0000100	Longitudinal Grooving in Concrete	SY	$6.9
Total			**SY**	**$152.9**

Sources: [1] Iowa DOT bid tabs (awarded and non-awarded unit prices) from January 2020 to December 2020.
[2] South Dakota DOT average low bid prices from January 2019 to December 2019.
[3] Illinois DOT awarded unit prices from letting data from January 2020 to July 2020.

Service Life

Like rigid cementitious overlays, LMC overlays have a long history and have been used in the states since 1957 (ElBatanouny et al. 2020b). They are less permeable than rigid cementitious overlays due to their polymer component but expected to perform similarly; as for rigid cementitious overlays, ElBatanouny et al. (2020a) stated that an LMC overlay is expected to have a service life between 15 and 30 years, unless the deck NBI condition rating is 5 or 6, in which case lower service lives as short as 7 years may be expected. While very early strength LMC overlays generally have service life expectations similar to those of LMC overlays, their performance is less reliable since they are much more prone to early-age cracking than regular LMC overlays and achieving good construction quality is more challenging.

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Apply a Premixed Polymer Concrete Overlay

Premixed polymer concrete overlays are distinct from other polymer overlays in that they are relatively thick. While they may be classified as thin polymer overlays, they generally have a minimum thickness of 0.75 inches, making them thicker than multiple-layer and slurry thin polymer overlays, and can be on the order of 2 or 3 inches thick, in which case they classify as a polymer concrete overlay. Instead of being installed in multiple layers of polymer and broadcasted aggregates, the polymer and the aggregates are premixed and then placed to the desired thickness. These overlays are best applied prior to corrosion initiation (or initiation of another degradation mechanism) but can be applied after delaminations or spalling have occurred as well. They are typically the costliest type of overlay available but are relatively impermeable and provide protection from chloride penetration and moisture ingress for a longer period of time than the other repair methods.

Objectives

Premixed polymer overlays are capable of meeting repair objectives as identified in Table B..

Table B.27. Applicable repair objectives of polymer overlays.

	Repair Objectives
✓	Restore or increase strength
✓	Restore or increase stiffness
✓	Improve functional performance
✓	Provide watertightness
✓	Improve appearance of the concrete surface
✓	Improve durability
✓	Prevent development of a corrosive environment at reinforcement

Applicability

Of the state DOTs reviewed, WisDOT is the only one to discuss premixed polymer concrete overlays. Premixed polymer concrete overlays are considered applicable under the following conditions:

- *NBI Condition Ratings.*

  Premixed polymer concrete overlays are considered only when the deck NBI rating is 7 or greater.

- *Deck Condition State.*

  To be eligible for a premixed polymer concrete overlay, less than 5 percent of the wearing surface area can be deteriorated per Defect 3210, Debonding/Spall/Patched Area/Pothole, and less than 1 percent of the deck underside may be deteriorated per Defect 1080, Delaminations/Spalls/Patch Areas.

It should be noted that premixed polymer concrete overlays are applied to decks for a wide variety of reasons aside from crack treatment. However, since this review is focused on addressing deck cracking, some of these more general criteria for NBI condition ratings and deck conditions may not be incorporated in the above discussion.

Construction

Unlike thin polymer overlays, thicker polymer overlays are exclusively constructed using the premixed method, which can yield overlays as thin as 0.75 inches (classified as a thin polymer overlay) or up to 2 or 3 inches (classified as a thick polymer overlay). WisDOT commonly uses thicknesses between 0.75 and 1.5 inches as greater thicknesses are typically cost-prohibitive. The procedures are as follows:

- Prepare the surface.
  As for thin polymer overlays, the deck surface is roughened and cleaned by shot blasting to remove contaminants and then blown with compressed air to clear dust and debris. The substrate should be sound, defined as having a minimum tensile strength of 150 psi, and large cracks greater than 0.04 inches in width should be repaired (Fowler and Whitney 2011). Any patches should be fully cured prior to installation of the overlay and patch and crack repair materials should be compatible with the overlay materials.
- Apply a primer.
  A primer is applied to improve bond between the polymer concrete and the deck substrate. The primer additionally fills cracks. A typical application rate is approximately 0.75 lb/yd^2 (Fowler and Whitney 2011).
- Premix and install the polymer concrete.
  For premixed polymer overlays, the polymer resin and the aggregate are mixed prior to or continuously during installation. The polymer concrete is placed, struck off, and consolidated similar to conventional concrete.
- Provide adequate skid resistance.
  Skid resistance may be provided by broadcasting aggregates on the surface of the overlay prior to cure, as is done for thin polymer overlays, or the surface may be tined.

Polymer concrete overlays are sensitive to ambient conditions during installation and the presence of dust, contaminants, and moisture on the substrate. As for thin polymer overlays, quality testing typically includes ASTM D4263, *Standard Test Method for Indicating Moisture in Concrete by the Plastic Sheet Method*, and ASTM C1583, *Standard Test Method for Tensile Strength of Concrete Surfaces and the Bond Strength or Tensile Strength of Concrete Repair and Overlay Materials by Direct Tension (Pull-off Method)*.

Materials

Premixed polymer overlays are typically made of polyester concrete, although some state DOTs such as OregonDOT have begun investigating or using epoxy for premixed polymer overlays in recent years as well. Polyester binders require an initiator in order to cure. Well-graded coarse and fine aggregates are used within the premixed concrete, permitting a greater aggregate content than is present in thin polymer overlays. The polymer binder typically comprises about 12% of the concrete by weight, resulting in a lower material unit cost than multiple-layer polymer overlays (Fowler and Whitney 2011). If broadcast aggregates are used to provide skid resistance, then they are subject to the same requirements such as composition, Moh's hardness, and gradation as were listed in "Apply a Thin Polymer Overlay." These requirements are not applicable to the aggregates used within the polymer concrete, whose primary role is to act as a filler that reduces shrinkage, improves thermal compatibility between the polymer concrete and deck substrate, and reduces cost. However, all aggregates used should still be free of moisture and dust.

WisDOT uses a high molecular weight methacrylate (HMWM) as the primer.

Repair Costs

The average unit cost for applying a premixed polyester polymer concrete overlay is $301.4 per square yard. The value is based on data from Iowa, South Dakota, and California DOTs, and the pay items assumed are listed in Table B..

Table B.28. Unit Cost for Applying a Premixed Polyester Polymer Concrete Overlay

State	State Pay Item No.	Item Description	Unit	Unit Cost
IA[1]	2510-6745640	Remove existing concrete	SY	$26.1
SD[2]	491E0110	Clean deck with abrasive blasting	SY	$3.6
CA[3]	600041	Place Polyester Polymer Concrete Overlay	SY	$116.8
CA[3]	600043	Furnish Polyester Polymer Concrete Overlay, 2"	SY	$148.0 [4]
IA[1]	2412-0000100	Longitudinal Grooving in Concrete	SY	$6.9
Total			**SY**	**$301.4**

Sources: [1] Iowa DOT bid tabs (awarded and non-awarded unit prices) from January 2020 to December 2020.
[2] South Dakota DOT average low bid prices from January 2019 to December 2019.
[3] California DOT bid data (awarded and non-awarded unit prices) from January 2020 to December 2020.
[4] Calculated for a 2-inch thick overlay based on the original unit price of $98.65 per cubic foot.

Service Life

Premixed polymer overlays with thicknesses greater than 0.75 to 1.0 inches are relatively new and limited to the western states and as a result there is less literature on their performance and service life (ElBatanouny et al. 2020b). However, WisDOT (2020) states that a service life between 20 and 30 years may be expected. ElBatanouny et al. (2020a) concluded based on their literature review that a service life between 7 and 25 years may be expected, with a minimum service life of 15 years considered reasonable if the deck has an NBI deck condition rating of at least 7.

These thicker polymer overlays are subject to the same deterioration mechanisms as thin polymer overlays: aggregate popout, polishing, and debonding. However, their additional thickness helps them maintain their ability to prevent moisture and chloride ingress for a longer duration, at least with respect to cracks and holes from aggregate popout. Thick polymer overlays are also prone to reflective cracking, or cracking due to movement of the structure. While cracking is not considered a significant issue for polymer overlays, if cracks do form they are often sealed with a compatible polymer.

References

ASTM International. (2018). ASTM D4263 Standard Test Method for Indicating Moisture in Concrete by the Plastic Sheet Method. West Conshohocken, Pennsylvania: American Society of Testing and Materials.

ASTM International. (2020). ASTM C1583/C1583M Standard Test Method for Tensile Strength of Concrete Surfaces and the Bond Strength or Tensile Strength of Concrete Repair and Overlay Materials by Direct Tension (Pull-off Method). West Conshohocken, Pennsylvania: American Society of Testing and Materials.

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Replace the Deck

Replacing the bridge deck is the most extreme action that can be taken in response to deck cracking and is usually done when the deck has a compromised capacity or limited service life. With respect to cracking, deck replacement would primarily be considered only under the two following scenarios:

- **Extensive Deck Distress.** When the deck has such extensive distress that rehabilitation with a cementitious overlay is comparable in cost to deck replacement due to partial-depth or full-depth repair needs, the deck is often scheduled for replacement. At this point, the deck typically has an NBI condition rating of 4 or less and a large area of delaminations and spalls requiring repair, and crack remediation is no longer a primary objective of the work. For example, WisDOT recommends deck replacement when the deck has an NBI condition rating of 4 or less and more than 15 percent of the soffit shows Defect 1080, Delaminations/Spalls/Patch Areas, or over 50 percent of the soffit is in CS3 or CS4 for Defect 1130, Cracking (2019).
- **ASR Degradation.** Decks are also often scheduled for replacement if the deck cracking is caused by alkali-silica reaction (ASR). Deterioration due to ASR can be slowed by sealing the deck and decreasing moisture ingress. However, ASR cannot be repaired and no treatments can fully prevent moisture ingress. Deterioration and strength loss will continue throughout the affected element until it is replaced.

According to the IowaDOT Transportation Asset Management Plan (2019), the cost of replacing a bridge deck is typically $75 per square foot.

References

IowaDOT. (2019). *2019 - 2028 Transportation Asset Management Plan.* Ames, IA: Iowa Department of Transportation.

WisDOT. (2019). Chapter 42 - Bridge Preservation. In *WisDOT Bridge Manual.* Wisconsin Department of Transportation.

APPENDIX C. WJE CASLE™ (CORROSION ASSESSMENT AND SERVICE LIFE EVALUATION) SERVICE LIFE MODELING METHODOLOGY

WJE

WJE CASLE™ SERVICE LIFE MODELING METHODOLOGY

(Corrosion Assessment and Service Life Evaluation)

Rev. 4.0 – March 2022

1. CORROSION IN REINFORCED CONCRETE STRUCTURES

Corrosion of reinforcement in concrete, initiated by carbonation and chloride ion contamination, is a common cause of structure degradation. As a background to the WJE CASLE™ Service Life Modeling Methodology, this section provides a general description of the nature of corrosion of reinforcing steel in concrete and the role of carbonation and chlorides in this process.

Corrosion of reinforcing steel in new concrete typically does not occur, because cement hydration products are highly alkaline (pH of 12.5 to 13.5) by nature, and this quickly produces a stable, thin oxide film (or passive film) on the surface of reinforcing bars embedded in concrete. This passive film impedes corrosion. However, there are two primary mechanisms that can develop as the structure ages, resulting in the destruction of the passive film (depassivation) and causing corrosion of reinforcing steel: carbonation and chloride ion contamination.

When these two processes, singularly or in combination, are coupled with moisture and oxygen, corrosion of the reinforcing bars in the concrete will proceed. Where the depassivation occurs first, the steel becomes anodic (corroding) and supports the reaction that, in the presence of water, produces red rust (hydrated ferric oxide) and other corrosion products. Adjacent areas of the steel become cathodic (non-corroding), where oxygen and water react. Both anodic and cathodic reactions, in combination with an electronic current path (the steel) and an ionic current path (the concrete) are needed to complete the corrosion cell. Once the corrosion cell develops, the corrosion products (rust) that result occupy a much larger volume than the steel from which they were formed. This increased volume leads to expansive pressures inside the concrete that result in cracking, delamination, and ultimately spalling of the cover concrete.

The rate at which corrosion proceeds is controlled by many factors, such as dissolved oxygen availability, moisture content, resistivity of concrete, and temperature. Because concrete acts as an impediment to flow of water, chloride ions, carbonation and oxygen, the depth of cover over the bars, cracks, and permeability of concrete influence the rate that corrosion will occur. It is a rule of thumb that corrosion rates of steel in concrete typically double for a temperature increase of 18°F (10°C) (Tuutti, 1982), though it has been suggested that the rate may increase by as much as a factor of five for that temperature increase (Broomfield, 2007). The ratio of the anodic area to cathodic area can also control the corrosion rate; the condition where small anodes are surrounded by large cathodes produces the most rapid corrosion.

1.1. Carbonation-Induced Corrosion

Carbonation of concrete occurs when carbon dioxide present in the air reacts with moisture and cement hydration products within the concrete. Carbonation is a result of the diffusion of carbon dioxide through air-filled pores in the concrete. The main reaction is calcium hydroxide within the paste reacting with carbon dioxide in the air to form calcium carbonate. Carbonation of portland cement paste has two distinct effects, one chemical and one physical. The chemical effect is to lower the pH of the pore solution from approximately 13 to about 9 or less. The protective passive film on the bar starts to break down at a pH of 10 to 11, permitting active corrosion to develop (Broomfield, 2007). The physical effects of carbonation are irreversible shrinkage and a moderate increase in density of the carbonated layer. Carbonation also can free chloride ions that were chemically bound in the aluminate phases of the cement paste, further aggravating corrosion of embedded steel.

The rate at which carbonation occurs is determined by concrete quality (porosity), cement chemistry, and exposure conditions, such as temperature and humidity (Broomfield, 2007). The carbonation process is normally slow because of the relatively low levels of carbon dioxide in the air (in non-urban areas, about 0.04 percent by volume) and the low permeability of concrete to carbon dioxide. Carbonation rates are very dependent on atmospheric moisture, being nearly zero at the extremes of 0 or 100 percent relative humidity and highest when relative humidity is between 40 and 80 percent (Parrott, 1987; Bertolini, Elsener, Pedeferri, & Polder, 2004; Bentur, Diamond, & Berke, 1997). This is illustrated schematically in Figure 1. High temperatures will also accelerate the carbonation process (Bentur, Diamond, & Berke, 1997). The rate of carbonation into concrete typically slows with depth of penetration as the penetration of carbon dioxide to the reaction site is hampered; however, carbonation can occur quickly where the concrete has cracked or the cover is otherwise compromised by local imperfections in the concrete.

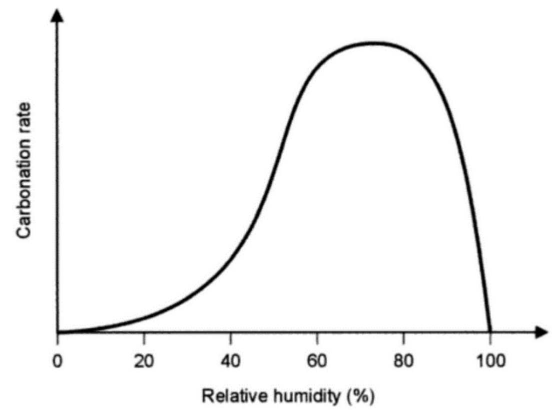


Figure 1. Schematic showing the effective of relative humidity on carbonation rate (from Bertolini, Elsener, Pedeferri, & Polder, 2004).

Once depassivation has occurred and sufficient oxygen is available, the corrosion rate in concrete is strongly influenced by the resistivity of the concrete (Alonso, Andrade, & Gonzalez, 1988). This is because the concrete forms the ionic current path, and a more resistive concrete will slow current. The resistivity of concrete is strongly influenced by moisture in the concrete; this can be quantified in relation to the relative humidity within the concrete (Enevoldsen, Hansson, & Hope, 1994). A number of studies of the relationship between corrosion rate and relative humidity have been reported in the literature, and it was found that this relationship is different depending on whether the corrosion is prompted by carbonation or chloride contamination (Broomfield, 2007). The range of experimentally measured carbonation rates in carbonated concrete given in the literature are plotted versus relative humidity inFigure 2. Generally, corrosion rates increase significantly as relative humidity within the concrete increases beyond 75 percent. The rates reach a peak at 95 to 97 percent, above which the additional moisture in the slab impedes the ingress of the oxygen necessary to support the cathodic reaction.

Carbonation and chloride contamination exhibit a synergistic effect, promoting corrosion when both occur in concrete beyond what would be expected by one mechanism alone. If the concrete is carbonated, with a pH less than approximately 10, the presence of even low levels of chloride will encourage corrosion of mild steel. In addition, chloride is hygroscopic and tends to keep moisture within the concrete. Furthermore, the presence of chloride lowers the resistivity of concrete, supporting more rapid corrosion rates (Enevoldsen, Hansson, & Hope, 1994).

1.2. Chloride-Induced Corrosion

In the absence of carbonation, chloride ions must accumulate to a critical concentration for corrosion to initiate on reinforcing steel that is embedded in sound concrete. In most modern construction, the onset of corrosion is governed by the time required for chloride in the environment to penetrate through the concrete cover over the steel and build up at the bar depth to the chloride threshold value. Chloride ions can also be present in the concrete from initial construction in the form of admixtures used to accelerate strength gain or in contaminated aggregate, such as sea sand.

Chloride threshold (C_t) can be expressed in a variety of ways: 1) chloride mass relative to weight of cement (% by wt. cem.); 2) chloride mass relative to weight of concrete (% by wt. conc., ppm, or lb/cu. yd.); or, 3) chloride ion to hydroxyl ion ratio [Cl^-]:[OH^-]. For WJE CASLE™, the basis for chloride threshold is set first by mass relative to weight of cement, and then converted to a mass relative to weight of concrete based on anticipated or estimated mix proportions. This is because laboratory testing of concrete measures chloride concentrations as a mass relative to the weight of concrete.

Because supplementary cementitious materials (SCMs) can bind hydroxyl ions (OH^-), the chloride corrosion threshold for reinforcement used in concrete containing SCMs may be reduced compared to concrete mixtures without SCMs.

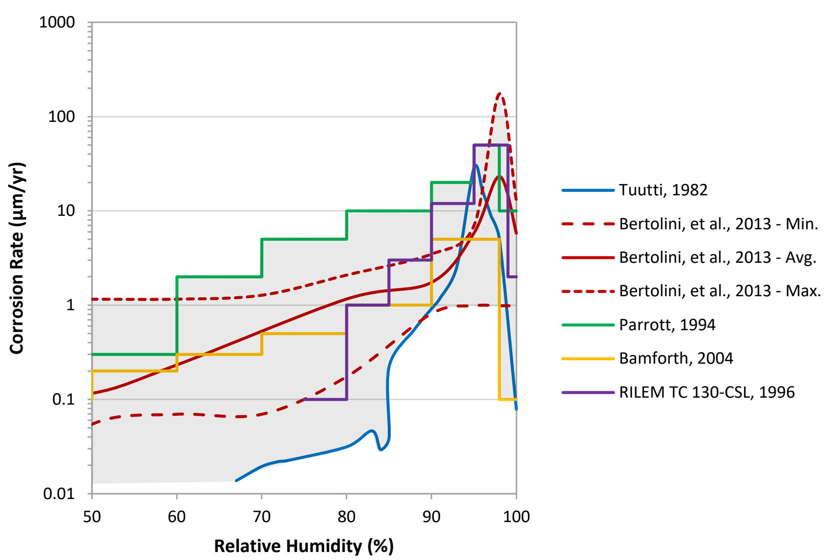


Figure 2. Corrosion rates in carbonated concrete versus relative humidity.

The effect of SCMs on the chloride threshold is therefore adjusted based on their percentage relative to the total amount of binder. For concrete containing fly ash, slag, or silica fume, this adjustment is based on the relationship published in the Concrete Society Technical Report No. 61, as shown in Equation 1 (Bamforth, 2004). This relationship is similar to data referenced by others (Ann & Song, 2007). For fly ash contents of less than 10 percent or slag cement contents of less than 20 percent, the threshold value is the same as ordinary portland cement.

It is important to recognize that corrosion is not certain at any particular chloride concentration, since multiple factors (including concrete mixture, cement content and chemistry, moisture conditions, temperature, bar type, and corrosion condition of surrounding bars) affect the influence of chloride concentration on corrosion. The likelihood, severity, and rate of corrosion for a particular bar type increase as chloride concentrations increase, as illustrated in Figure 3.

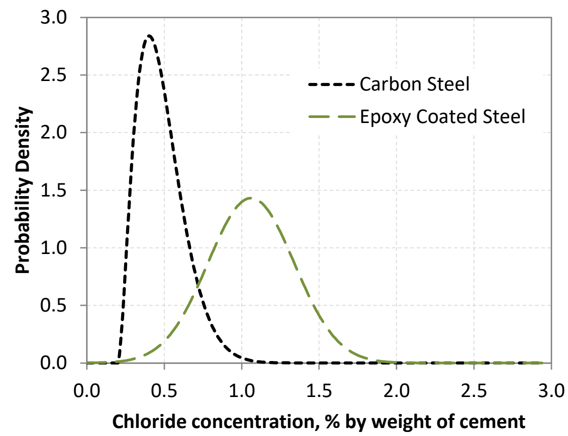


Figure 3. Probability distributions for critical chloride concentration of carbon steel and epoxy-coated steel in concrete; the x-axis shows chloride concentration as a percent by weight of cement.

In addition to the factors relative to chloride threshold outlined above, chloride ions can also be chemically or physically bound to the cement paste as they ingress into the material. This chloride is typically referred to as "bound" chloride; in contrast, chloride remaining dissolved in the pore solution is referred to as "free" chloride. Because the chloride binding is reversible, depending on both chloride concentration and pore solution pH, the "total" chloride content (bound plus free chloride) is used as the basis for modeling corrosion thresholds, unless noted otherwise. Acid-soluble chloride testing is commonly used by WJE to determine the total chloride content of concrete; the concentrations obtained by this method provide a conservative upper bound of the chloride content available for corrosion.

1.2.1. Uncoated (Black) Reinforcement

A lower bound of critical chloride concentration for initiation of corrosion of embedded mild steel is often approximated as 0.2 percent by weight of cement in non-carbonated concrete (Broomfield, 2007). This is equivalent to about 0.030 percent chloride ion by weight of concrete (or 1.1 lbs. chloride per cubic yard) for typical concrete mixtures. Many researchers have evaluated this threshold in more detail and found that critical chloride contents may range between 0.1 to 2.2 percent by weight of cement

$$Cement_{eqv} := CM \cdot [1 - max[0.010(\%FA - 10), 0] - max[0.005 \cdot (\%SG - 20), 0] - 0.025 \cdot \%SF]$$

Where: *Equation 1*

CM = weight of total cementitious
%FA = proportion of fly ash (applicable for up to 50%)
%SG = proportion of slag cement (applicable for up to 80%)
%SF = proportion of silica fume (applicable for up to 20%)

(Breit, 1997). Data from those studies formed the basis of the statistical distribution for chloride threshold adopted by the DuraCrete project (DuraCrete, 2000), a European Union-funded effort to develop service life modeling approaches for reinforced concrete. That distribution is a beta distribution with a mean of 0.48, a standard deviation of 0.15, a lower bound of 0.20, and an upper bound of 2.0 percent by weight of cement.

1.2.2. Epoxy-Coated Reinforcement

The chloride threshold for epoxy-coated reinforcement (ECR) was determined based on a review of previous work performed by WJE for bridge decks and substructures in 13 states (Lawler J. S., Kurth, Garrett, & Krauss, 2021). In these studies, 45 structures were evaluated and more than 400 ECR samples were extracted and analyzed (Cui, Krauss, & Lawler, 2007; Donnelly, Krauss, & Lawler, 2011; Krauss & Lawler, 2009; Krauss & Lee, 2003; Rogers & McGormley, 2011). During these investigations, the corrosion condition and chloride concentration in the surrounding concrete of all the bars sampled were characterized. Figure 4 illustrates representative corrosion conditions of extracted bars, and provides an associated rating of the corrosion activity used in this characterization. A histogram of the number of sampled epoxy-coated bars judged to be active or inactive versus chloride concentration is given in Figure 5.

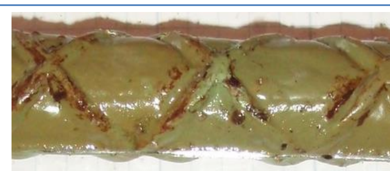
Value	Description	Representative photographs Epoxy-coated	
1	No evidence of corrosion		Not Active
2	A number of small, countable corrosion spots		
3	Corrosion area less than 20% of total surface area		
4	Corrosion area between 20% to 60% of total surface area		Active
5	Corrosion area greater than 60% of total surface area		

Figure 4. Figure of typical reference photos for categorizing active and non-active epoxy-coated bar corrosion.

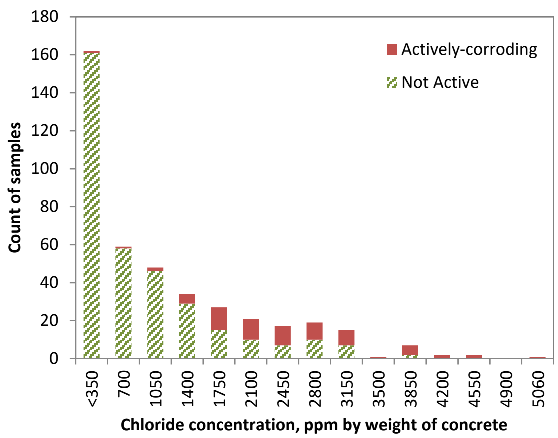


Figure 5. Histogram of actively-corroding versus non-active extracted ECR samples from evaluated bridge decks and substructures. Actively corroding bars are red and non-active bars are in green.

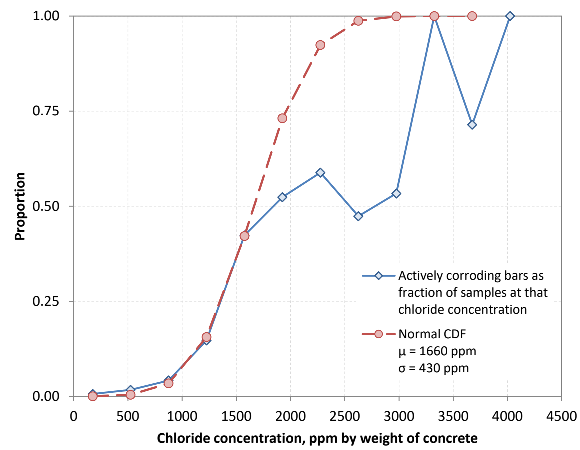


Figure 6. Plot of actively corroding bars as fraction of samples at that chloride concentration - an estimate of cumulative distribution of chloride threshold for epoxy coated reinforcing bars - versus chloride concentration at the bar depth.

The studies indicated that corrosion in ECR tends to occur initially at defects. Defects in the coating are not uniformly distributed, and vary depending on the epoxy film thickness, overall quality control of coating fabrication, and bar handling and placement methods. Additionally, greater amounts of chloride in the surrounding concrete increase the aggressiveness of corrosion, rendering smaller defects more susceptible to corrosion damage. Likely as a result of both of these effects, the chloride concentration associated with corrosion initiation was observed to be distributed over a range of values.

Corrosion initiated on a very limited number of bars at chloride concentrations similar to thresholds typically assumed uncoated steel; however, the barrier provided by the epoxy coating provided effective protection to many of the bars, shifting the overall distribution to higher chloride concentrations. Figure 6 shows the cumulative distribution of actively-corroding extracted ECR samples from the studies referenced above. Since relatively few bars were obtained in concrete with chloride concentrations above 2000 ppm, the shape of the cumulative distribution beyond this level is erratic. However, up to this level, the collected data approximates a normal distribution, and a normal distribution fitted to this data is also given in Figure 6. Many of these samples were taken with express purpose of finding corroding bars, so use of this distribution in modeling is conservative.

Based on this review of data, the chloride threshold for ECR is considered to be a normally-distributed variable. The referenced studies reported chloride concentrations as a portion of the total weight of concrete; these values were assumed to be representative of 6.5-sack concrete mixture, as might be used in bridge construction between approximately 1970 and 1990. With this assumption, the chloride threshold distribution was converted to an equivalent percentage by weight of cement. When adapting this threshold to other concretes, this distribution is adjusted relative to the weight of cement in the mix (Lawler J. S., Kurth, Garrett, & Krauss, 2021).

1.2.3. Galvanized Reinforcement

Zinc galvanizing provides protection to the underlying carbon steel of the reinforcing by providing an initial passive coating of zinc material that will act as a barrier to chlorides and as an anode that corrodes preferentially to the steel (i.e., zinc is anodic or more electrochemically active compared to steel). Galvanizing provides extended service life for the concrete because the zinc surface remains non-corroding at greater levels of chloride concentration than bare steel and because any corrosion products of the zinc layer are less expansive than the corrosion products of iron, which extends the time before cracking and spalling of the concrete occurs.

Reinforcing bars for concrete structures are typically galvanized through a hot-dip process that produces a multi-layer covering of zinc and zinc-iron alloys. When exposed to freshly placed concrete, the outer layer of zinc reacts to form a passive layer of calcium hydroxyzincate. This layer provides resistance to both chloride- and carbonation-induced corrosion. This layer is stable as long as the pH is less than about 13.3 and greater than about 6, as typically occurs in concrete. The characteristics of this layer are strongly influenced by the pH within this range, and as a result, the protection provided by galvanizing is dependent on the composition of the concrete, especially by the type and alkali content of the cement (Bertolini, Elsener, Pedeferri, & Polder, 2004). This passive layer protects the underlying zinc and may also slow the chemical reactions that occur at the cathode sites where oxygen reacts to balance the corrosion reaction.

As with other types of reinforcing, the concept of chloride threshold is used to predict the level of chloride contamination expected to break down the passive layer and promote corrosion initiation. However, the concept of chloride threshold may oversimplify the protection provided to reinforcing bars by galvanization, since that concept allows for two corrosion states: non-corroding and corroding. For galvanizing bars, there is likely a prolonged intermediate stage before corrosion of the steel occurs, during which the zinc is consumed. During this intermediate phase, the zinc surface layer corrodes, forming a white corrosion by-product. Since this by-product is less expansive than the rust formed by mild steel corrosion, the corrosion of the reinforcing steel is the corrosion state of primary interest when determining concrete damage. The transition from zinc to steel corrosion is only partially captured in the chloride threshold concept. Nevertheless, some quantification of the corrosion resistance of galvanized bars is needed for modeling and this concept is adopted for that purpose.

Published laboratory and field studies suggest that the chloride threshold for galvanized steel is approximately 1.5 to 2.5 times that of carbon steel, but published values for chloride threshold vary considerably (Ann & Song, 2007; Bamforth, 2004; Darwin, Browning, O'Reilly, Xing, & Ji, 2009; Maldonado, 2009; Sanchez & Sagues, 2014).

For modeling purposes, a probabilistic distribution of the chloride threshold of galvanized steel is based on the distribution of chloride threshold values for uncoated carbon reinforcing steel. This assumed distribution is the same as the distribution for black bar reinforcing steel, but shifted upwards by 0.2% by weight of cement to double the lower bound limit compared to uncoated mild steel. Although published data by others suggest that the distribution of the chloride threshold may be broader than that of carbon steel (Bamforth, 2004; Sanchez & Sagues, 2014), the standard deviation was conservatively assumed to be equal to that of carbon steel (i.e., 0.15% by weight of cement). Propagation time is also conservatively assumed to be equal to that of the carbon steel, although prior WJE experience with galvanized reinforcing bar indicates that the propagation time is longer for galvanized bar than for carbon steel.

1.2.4. Stainless Steel Reinforcement

Stainless steel is a steel alloy that contains at least 10.5 percent chromium, not more than 1.2 percent carbon, and exhibits a high resistance to atmospheric corrosion. Stainless steel's high corrosion resistance arises from a dense chromium-rich oxide layer that forms on its surface, providing protection in both chloride-rich and moderate pH environments. While this layer is more protective than the passive layer that forms on uncoated carbon steel reinforcement, localized or widespread breakdown of this passive layer can occur under highly corrosive environments, leading to corrosion of the stainless steel. The chloride corrosion threshold of stainless steel bars is a function of the specific type and composition of the alloy.

There are four general types of stainless steel alloy: austenitic; ferritic; martensitic; and duplex, which combines austenitic and ferritic steels in roughly equal proportions. These steels differ in their microstructure and alloying elements, and consequently have different mechanical and electrochemical properties. Among the various types of stainless steel alloys, only austenitic and duplex stainless steels are commonly used as reinforcement for concrete. Common grades of austenitic stainless steels include types 304 and 316, and common grades of duplex stainless steels include types 2101, 2205, and 2304.

The corrosion resistance of stainless steel is greater than that of uncoated carbon steel, but the specific threshold value varies depending on

Table 1. Chloride Threshold Statistical Distributions used for Modeling

Reinforcement Type	Distribution	Parameters (% by wt. cement)	
Uncoated	Beta	lower bound:	0.20
		upper bound:	2.00
		mean:	0.48
		std. deviation:	0.15
Epoxy-coated	Normal	mean:	1.06
		std. deviation:	0.28
Galvanized	Beta	lower bound:	0.40
		upper bound:	2.20
		mean:	0.68
		std. deviation:	0.15
Stainless[1]	Normal	mean:	3.0
		std. deviation:	0.9

[1] *Value shown for generic grade of austenitic or duplex stainless steel bar. Different values may be used if a specific grade or alloy is selected.*

the type of the alloy and the surface characteristics of the product. A summary of literature values for chloride threshold reports that the threshold is generally greater than 3% by weight of cement for a wide range of austenitic and duplex alloys, and can range between 5 and 10 times the critical chloride concentration for carbon steel bars (Poursaee, 2016, pp. 69-74; Ehlen, Thomas, & Bentz, 2009; Bamforth, 2004). The threshold is typically greatest for alloys containing higher chromium and nickel contents.

1.2.5. Summary of Chloride Thresholds

For modeling purposes, the chloride threshold is described by the statistical distribution for each type of the reinforcement material, as outlined in Table 1. This threshold is adjusted from weight of cement to weight of concrete based on assumed or estimated mix proportions, adjusting for supplementary cementitious materials content, as applicable.

2. MODEL DESCRIPTION

2.1. Approach

Service life in a given setting must be defined based on requirements unique to that structure in terms of performance and occupancy needs. The end of service life for a given element may be defined by a design criterion (i.e., initiation of corrosion within an element), a serviceability criterion (i.e., acceptable amount of spalls on a deck), or a structural criterion (i.e., percentage of delaminated area allowed before reducing the capacity of the element). The specific service life criteria that can be tolerated may also vary by element.

For new structures, the service life is often defined as either the time to corrosion initiation or corrosion-related surface damage (i.e., time until initiation plus time for propagation). Probabilistic service life modeling is conducted to predict the probability that corrosion will have initiated or propagated within the element at a specified design service life. The purpose of modeling for new structures is to determine the reliability (i.e., the level of confidence) that the design service life will be achieved. The models consider anticipated variations in the as-built conditions of the element based on the specified design criteria, construction tolerances, and the types of materials to be used in construction (e.g., concrete mix design and reinforcement type).

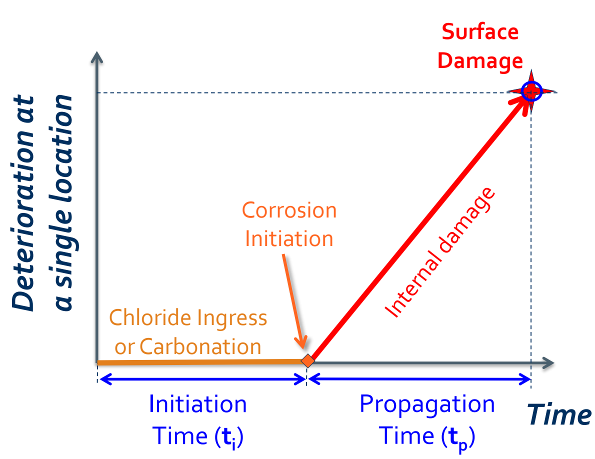


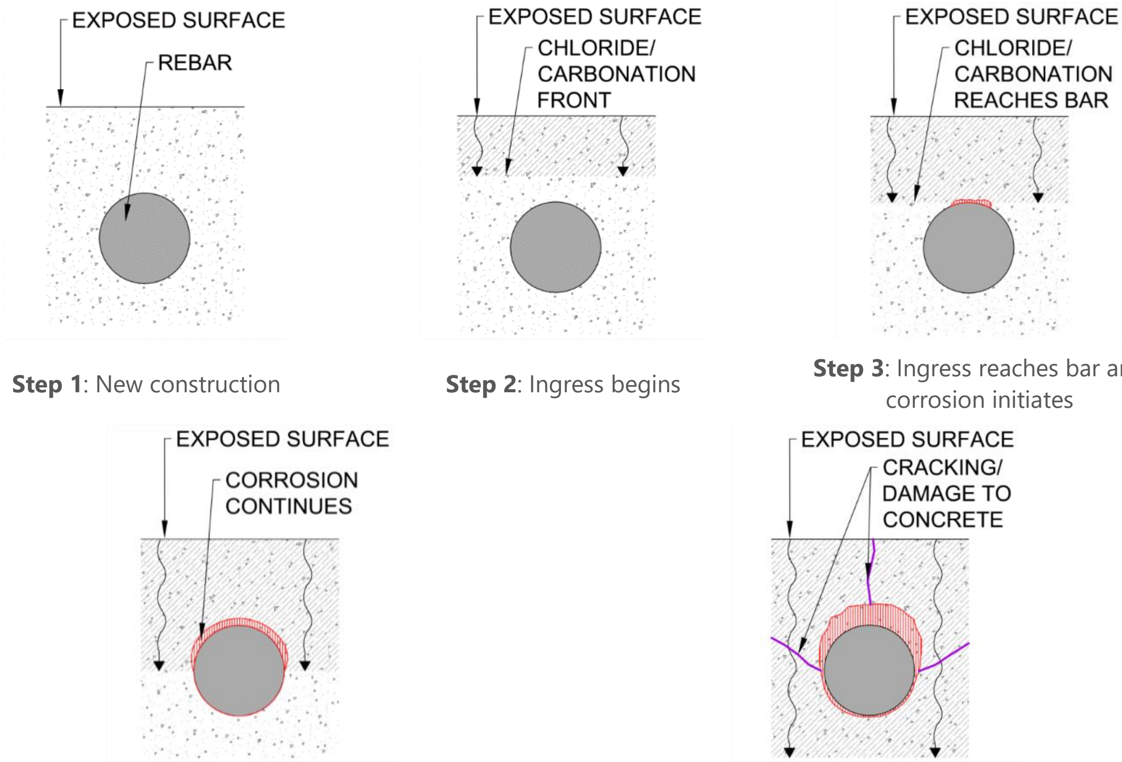
Figure 7. Corrosion sequence (from Tuutti 1982).

For existing structures, probabilistic service life modeling is conducted to predict the progression of corrosion-related concrete distress (i.e., delamination and spalls) over the life of the structure. The predicted damage is compared to the assumed end-of-service-life criteria to estimate the time remaining before the end of life is reached; end-of-service-life criteria is project specific, and defined based on input from the Owner or agency operating the structure or facility. The purpose of this modeling is to assist in identification of appropriate repair approaches and to determine if corrosion mitigation strategies are warranted. These models generally consider the representative conditions that are present, but do not consider the effect of atypical or localized features, e.g., drains, leaking piping, etc., that may be promoting deterioration.

2.2. Basis for Corrosion Modeling

Corrosion-related damage to concrete can be conceptualized in two stages: 1) initiation time (t_i), the time elapsed for corrosion to begin; and 2) propagation time (t_p), the time elapsed when corrosion begins and build-up of corrosion product occurs. Build-up continues until a limit where the volume of corrosion product exceeds the threshold needed to damage (i.e., crack or spall) the concrete. This concept is illustrated in Figure 7 and is well-suited for determining expected performance in both new and existing structures related to serviceability concerns, such as cracking, delaminations and spalls.

For a single bar location undergoing environmentally-induced corrosion, the sequence that leads to the progression of delamination and spalling includes the following steps, as illustrated in Figure 8.



Step 1: New construction

Step 2: Ingress begins

Step 3: Ingress reaches bar and corrosion initiates

Step 4: Corrosion continues and causes internal damage

Step 5: Corrosion continues and causes surface damage

Figure 8. Illustration of corrosion sequence.

1. Initially after construction, the bar is embedded in fresh concrete and is passivated against corrosion.
2. The concrete surface is exposed to a chloride source (e.g., brackish water) and chloride transport through the concrete begins. Concrete carbonation also proceeds from the exterior surface.
3. After some time has passed, the chloride reaches the bar and begins to accumulate. The passivation of the bar is lost when the chloride concentration at the bar exceeds an assumed value called the chloride threshold. Alternately, the carbonation front reaches the bar and changes the pH at the bar surface. In either case, corrosion initiates at the surface of the bar closest to the exposed face of the concrete element.
4. Chlorides accumulate to levels above threshold or carbonation proceeds deeper into the concrete and corrosion propagates around the bar.
5. Corrosion products on the bar have built up to a sufficient level to cause cracking, delaminations, or spalls in the concrete that become detectable from the surface.

Two established probabilistic modeling approaches, one outlined in fib Bulletin 34, *Model Code for Service Life Design* (fib, 2006), and the other developed by Sagüés (2003), were adapted and are the basis for the WJE CASLE™ service life model.

For new structures, the *fib 34* approach was adapted to determine the probability of corrosion initiation or propagation in an element over its design service life, based on statistical distributions of key parameters considered to govern corrosion in reinforced concrete structures. The model recognizes that our understanding of these factors will be incomplete during the design phase and estimates the likely final as-bult condition of the structure to support predictions of the time to corrosion initiation or propagation before construction commences.

For existing structures, the approach by Sagüés was adapted to determine the amount of surface area of the structural element that is affected by corrosion based on statistical distributions of the same key parameters considered to govern corrosion initiation. This model recognizes the fact that corrosion is a local process that develops at multiple locations over time depending on the local propensity for corrosion, and uses statistical distributions to describe the spatial variation of these parameters over an element's surface. For example, corrosion can be expected to initiate more readily at locations where cover is low, where the ability of the concrete to resist chloride ingress or carbonation is low, and where the chloride exposure is high. Corrosion will then advance over time to areas where the concrete element is progressively less susceptible to corrosion. The probabilistic approach considers this progression in damage development.

Time-to-corrosion initiation is considered in both models as a probabilistic variable influenced by combinations of independent random variables. This process can be described mathematically as follows (Bastidas-Arteaga, Chateauneuf, Sanchez-Silva, Bressolette, & Schoefs, 2011):

1. Corrosion initiation time is governed by a joint probability distribution, which is a function dependent on the properties of the modeled element, where *x* represents the vector of random variables, and *f(x)* represents a function of their joint probability distribution for chloride-related corrosion (Equation 2) and carbonation-related corrosion (Equation 3).
2. Corrosion initiates when the given deterioration mechanism reaches a particular bar depth. The initiation time at a given location is then defined by a limit state function (Equation 4), where *d(x, t)* is the depth of the deterioration mechanism at a given time *t,* and d_{crit} represents the depth of cover. Combining the two statements, the probability that the reinforcing steel in the modeled element has started to corrode is calculated by integrating over the failure domain (Equation 5).
3. For existing structures, the probability of failure (i.e., probability of initiation) with respect to a single location can be abstracted to the performance of the structural element as a whole. If the structural element is of sufficient size for multiple, independent locations of corrosion-related damage to develop, it can be discretized into a large number of segments with properties defined by statistical distributions that are measured or assumed. The cumulative probability of the structural element exhibiting damage

$$\boldsymbol{f(\underline{x}) = f(chloride\ exposure, transport\ rates, corrosion\ threshold)} \quad \text{Equation 2}$$

$$f(\underline{x}) = f(carbonation\ rate, cover) \quad \text{Equation 3}$$

$$g(\underline{x},t) = d_{crit} - d(\underline{x},t) \text{ where } \begin{cases} g(\underline{x},t) \leq 0, & corrosion\ initiation \\ g(\underline{x},t) > 0, & no\ corrosion \end{cases} \quad \text{Equation 4}$$

$$p_f = \int_{g(\underline{x},t)\leq 0} f(\underline{x})d\underline{x} \quad \text{Equation 5}$$

$$t_{damage} = t_i + t_p \quad \text{Equation 6}$$

through a given time then can be used to determine the percent area of the structural element where corrosion has initiated versus time. (Note, this abstraction is only applied to models of existing structures.)

4. After corrosion initiates, corrosion product builds up until a crack propagates to the concrete surface, or a delamination or spall is caused in the surrounding concrete. The total time to damage is then given as a combination of initiation time t_i and the propagation time t_p (Equation 6). In actual structures, the propagation time is dependent on cover depth, properties of the concrete and of the steel-concrete interface, type of corrosion products, size of reinforcing, and corrosion rate. For modeling purposes, the propagation time can be chosen as a constant based on experience for that type of construction or estimated based on the specific conditions in the structure, if known.

Because of the complexity of the probabilistic analysis used for both modeling approaches, a Monte Carlo simulation is used to account for the interaction between the considered variables. Latin Hypercube Sampling is also used to reduce the number of segments required for model convergence (Wyss & Jorgenson, 1998).

The processes by which initiation and propagation are modeled differ for carbonation- and chloride-related corrosion. The processes for each are outlined in the following sections.

2.3. Modeling Carbonation-Related Corrosion

2.3.1. Carbonation Rate

Carbonation rates are ultimately dependent on a wide range of factors, which include variations in concrete relative humidity, carbon dioxide concentration of the air, cement paste properties, and surface finishes. Because the time history and appropriate values for many of these properties are generally unknown, a simple model for carbonation rates has been selected.

$$carbonation\ depth(t) = A\sqrt{t} \qquad \text{Equation 7}$$

where *A* is a constant described as the "carbonation rate constant", and *t* is the time since construction. This is the most common model for quantifying carbonation (Parrott, 1987). For existing structures, *A* can be determined directly based on field or laboratory depth measurements from the structure, while for new structures, *A* is predicted using established models such as those presented in *fib Bulletin 34* (fib, 2006) and in Concrete Society Technical Report No. 61 (Bamforth, 2004) that consider the composition of the concrete and the environmental exposure conditions present. Typically, either a normal distribution or a lognormal distribution is considered to appropriately model the carbonation rate constant.

2.3.2. Corrosion Rate

As described earlier and depicted in Figure 2, the corrosion rate in carbonated concrete is strongly correlated to the relative humidity of the concrete. Where relative humidity data is unknown, a distribution for the rate of corrosion is assumed using the curve shown in Figure 9. These values are gathered from data reported in the literature, assuming that the concrete had a relative humidity of 90 percent, and are generally conservative for most conditions. A Weibull distribution was chosen as most appropriate distribution for this input, as Weibull distributions are often used for modeling processes related to time to failure and are also only defined for values greater than zero (Montgomery & Runger, 2007).

2.3.3. Propagation Time

Propagation time will be influenced by the rate of corrosion, cover, and physical properties of the concrete and reinforcing bar. Since carbonation-related corrosion typically proceeds more slowly than chloride-related corrosion, an approach considering concrete strength, bar size and cover depth based on the model presented in Concrete Society Technical Report No. 61 (Bamforth, 2004) can be used in the absence of better information to estimate critical section loss. The propagation time is the ratio of critical section loss to corrosion rate. Since critical section loss is a function of cover (a stochastic variable), the critical section loss is also a stochastic variable, as represented by the plot in Figure 10.

The relationship for critical section loss, given in U.S. customary units, is:

$$X_c = 3.30 \times 10^{-3} + 2.91 \times 10^{-4}\left(\frac{c}{\varphi}\right) - 6.14 \times 10^{-6} f_{st} \qquad \textit{Equation 8}$$

where:
X_c: critical loss of steel in inches
c: depth of cover in inches
φ: bar diameter in inches, and
f_{st}: concrete splitting tensile strength in psi

If tensile strength is not known, it is calculated based on ACI 318-20 Eq. 19.2.3.1 using an estimate of compressive strength (one standard deviation lower than the average measured compressive strength).

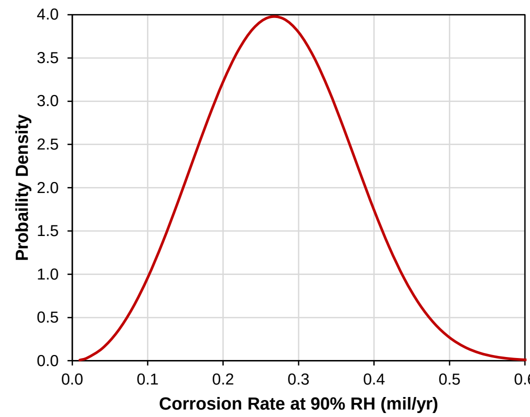


Figure 9. Probability density of corrosion rate at 90% relative humidity using an assumed Weibull fit; the x-axis shows corrosion rate in mils/year (1 mil = 0.001 inch).

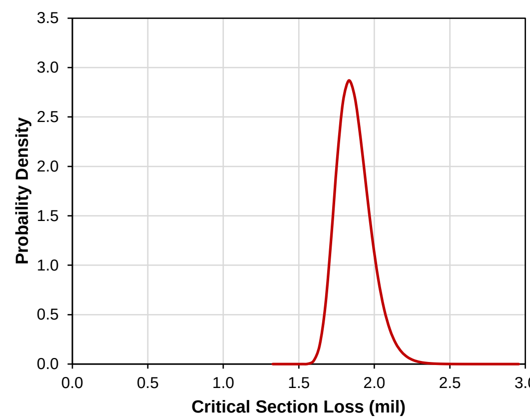


Figure 10. Example of probability density of critical section loss based on carbonation for a deck slab underside; the x-axis shows critical section loss in mils (1 mil = 0.001 inch).

2.4. Modeling Chloride-Related Corrosion

2.4.1. Chloride Transport

Chloride-related corrosion initiation is governed by the rate at which chloride ions move through the concrete and accumulate at the bar surface. This is determined by the chloride exposure, the resistance of the concrete to chloride ingress, and the concrete cover over the bars. Chloride ion transport in concrete is complex and may occur through diffusion (caused by chloride ion concentration gradient), capillary absorption (wetting and drying), and permeation (driven by pressure gradients) (Stanish, Hooton, & Thomas, 1997). Chloride transport may also be slowed by chemical binding of the chlorides with aluminate phases in the cement, or by physical absorption or trapping of chloride ions in the cement paste microstructure. Despite the potential complexity of the chloride penetration process in concrete, it is commonly assumed that diffusion plays the largest role. Therefore, describing chloride transport by using a mathematical representation of diffusion, quantified based on an "apparent" diffusion coefficient calculated from chloride concentration profiles measured in actual structures is judged to be a reasonable representation of this process accounting for other influences (Sohanghpurwala, 2006). In concrete that is cyclically wet and dry in service, this approach may be coupled with the use of a "transfer function", which defines a depth over the near-surface region of the element where chloride ingress is assumed to be more rapid as the result of rapid capillary suction than might be expected for diffusion alone (fib, 2006); see Section 2.4.4 and Figure 11.

The driving force behind the diffusion process is the chloride exposure, or the amount of chloride applied to the concrete surface. This is quantified in terms of the effective surface chloride concentration, C_s. Chloride diffusion in concrete, driven by a concentration gradient, can be described by Fick's Second Law of Diffusion:

$$\frac{\partial C}{\partial t} = D_a \frac{\partial^2 C}{\partial x^2} \qquad \textit{Equation 9}$$

where C is the chloride concentration at a depth of x from the concrete surface at time t, and D_a is the chloride diffusion coefficient.

If the surface chloride concentration C_s and D_a are assumed to be constants, then the concentration $C(x, t)$ through a uniform medium at depth of x and time t is given by the following solution:

$$C(x,t) = C_s - (C_s - C_0) \times erf\left(\frac{x}{2\sqrt{D_a t}}\right) \qquad \textit{Equation 10}$$

where erf() is the Gaussian error function, and C_0 is the background or original chloride concentration.

The closed-form solution above is not readily adaptable for modeling variations of exposure or material properties with time. Consequently, a finite difference solution for determining chloride concentration with depth over time is used. This solution is based on a Crank-Nicholson discretization of Equation 9, for which the general form is provided in Equation 11 (Chapra & Canale, 2002).

2.4.2. Apparent Diffusion Coefficient

The apparent diffusion coefficient is a time-dependent property of concrete that is affected by a number of factors; one of the most important is the age of the concrete. WJE CASLE™ considers the influences of concrete age (maturity) relative to the apparent diffusion coefficient at 28 days (D_{28}), with decreases in diffusion coefficient considered through 25 years as illustrated in Equation 12. Beyond 25 years, the apparent diffusion coefficient is assumed to be constant at the 25-year value.

$$\boldsymbol{D(t,m) = D_{28}\left(\frac{28\ days}{t}\right)^{m}} \qquad \textit{Equation 12}$$

where:
D_{28}: diffusion coefficient at reference age of 28 days
t: age of concrete considered
m: ageing constant for diffusion

$$\boldsymbol{D_a[V_{i+1} - 2(D_a + K)V_i] + D_a V_{i-1} = -D_a U_{i+1} + 2(D_a - K)U_i - D_a U_{i-1}} \qquad \textit{Equation 11}$$

Where:
i = current slice
D_a = apparent diffusion coefficient
U = concentration at timestep j
V = concentration at timestep j+1
$K = \frac{(\Delta X)^2}{\Delta T}$, where X = depth and T = time

The coefficient m controls the rate of decrease in apparent diffusion coefficient as the concrete ages and is dependent on the type and amounts of cement and supplementary cementitious materials used in the concrete mixture. For modeling, m is calculated as shown in Equation 13, based on the proportion of fly ash or slag (Thomas & Bentz, 2000). If no fly ash or slag is present, the coefficient m is 0.2.

$$\boldsymbol{m = 0.2 + 0.4\left(\frac{\%FA}{50} + \frac{\%SG}{70}\right)} \qquad \textit{Equation 13}$$

where:
m: ageing factor based on mixture proportions
%FA: percentage of fly ash
%SG: percent of slag cement

2.4.3. Surface Chloride Concentration

Surface chloride concentration (C_s) is considered a “load” in the service life model and is typically quantified by mass per weight of concrete. Values of C_s are strongly influenced by the exposure conditions (e.g., severity of deicing salt application or height of element relative to the waterline). Based on studies of bridge decks in northern states conducted by WJE, C_s can range from greater than 8000 ppm in New York to 1500 ppm in Virginia (Krauss & Lee, 2003). Exposure conditions may be characterized as follows based on C_s (Krauss, Lawler, & Steiner, 2009):

- mild: up to 2500 ppm
- moderate: 2500 to 4500 ppm
- severe: 4500 ppm or higher

For existing structures, surface chloride concentration is best characterized by extracting cores, measuring chloride contents, and fitting curves to the chloride profiles.

Surface chloride concentrations caused by cyclic exposure, such as deicing salt application or a marine splash zone, have a delayed build-up time. The build-up of chloride for deicing exposure is assumed to be bi-linear, such that the surface concentrations were equal to zero in the first year and increased to a level that was constant after a number of years. The total number of years may vary, but generally ranges between 5 and 30 years, depending on the severity of exposure.

2.4.4. Capillary Suction

When cyclic exposures to moisture are present, the ingress of chloride ions into the concrete will be more rapid near the surface because of capillary suction. Capillary suction is considered in the WJE CASLE™ service life models for new and existing structures through a “transfer function”, which defines the depth over which capillary suction is the governing chloride transport mechanism. Chloride transport in this capillary suction zone represented by the transfer function is modeled as essentially instantaneous, so that the surface chloride concentration is applied at some distance, Δx, inward from the concrete surface.

The transfer function is defined in *fib Bulletin 34* for both new and existing structures for a variety of chloride exposure conditions (fib, 2006). The transfer function typically ranges between 0 and 0.5 inches from the surface, but may be larger depending on the exposure conditions, internal relative humidity, porosity, and chloride binding capacity of the concrete.

2.4.5. Exposure Zones

The parameters that govern chloride transport (surface chloride concentration C_s, the transfer function Δx, and the apparent diffusion coefficient D_a) are anticipated to vary for each exposure zone on a structure. Statistical distributions for C_s, D_a, and Δx can be determined based on chloride profiles measured in core samples taken from these zones. For each chloride profile, a fitting process based on the

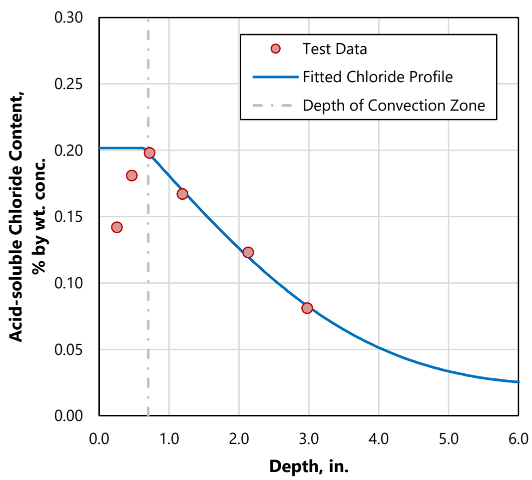


Figure 11. Chloride profile (blue line) defined in terms of the surface chloride concentration C_s, transfer function Δx (i.e., "depth of convection zone"), and apparent diffusion coefficient D_a, as fit to measured chloride profile.

finite difference solution described above for calculating chloride concentration with depth over time is applied to determine values for C_s D_a, and Δ*x* that coincide with the observed conditions. An example of a chloride profile and the resulting fit is shown in Figure 11.

The results of the fits, i.e., the C_s, D_a, and Δ*x* for each profile, for any given element type or exposure zone are examined together and used to estimate the distribution of these properties in the respective structural element. Where chloride profile data is not available for fitting (including for new construction), estimates of chloride exposures, diffusion coefficients, and transfer functions are instead based on WJE's prior testing of cores in similar exposure environments (C_s) and on laboratory testing of trial batches typically performed at 28 days of age (D_a at 28 days = D_{28}). If testing is performed at an age other than 28 days, corrections to the 28-day diffusion coefficient may be obtained using the aging factor described in Section 2.4.2.

In general, based on the available data, a normal distribution is used to describe C_s and D_a for the various zones and structural elements, while a beta distribution is used for the transfer function Δ*x*. During the Monte Carlo analysis, where the use of a normal distribution results in consideration of either a negative apparent diffusion or a negative surface chloride concentration, it is assumed that these values are zero, resulting in no chloride diffusion; the beta distribution for the transfer function is restricted to only values greater than 0.

2.4.6. Propagation Time

Propagation time is influenced by the rate and form of corrosion products that develop after corrosion initiation. In contrast to carbonation-related corrosion, typical propagation times for chloride-induced corrosion of uncoated carbon steel in environments where oxygen is readily available are on the order of 5 years. Since this time is short relative to the time to initiation, a simple approximation is made that propagation time will generally be a constant 5 years. However, where the concrete is saturated with moisture and oxygen is limited, corrosion may proceed more slowly and the form of corrosion product that develops may be less expansive than common "red" rust. As a result, cracking and spalling (damage) may develop more slowly. Consequently, propagation time for fully-submerged or oxygen-starved areas may be assumed to be 20 years or more. This value is based on experience with previous projects.

2.4.7. Surface Sealers

The benefit of sealers or coatings to concrete may be included in service life modeling. Sealers and coatings may be used to address local defects (such as voids or cracking) or provide a general wide-area beneficial effect.

For wide-area effects, surface sealers are considered to affect the rate of chloride build-up. In this method, the sealer is assumed to have an efficiency factor (e.g., reduction in build-up rate) of 90 percent initially; this efficiency factor then decreases linearly due to abrasion and weathering throughout the assumed lifespan of the sealer. A value of 90 percent was chosen to represent initial absorption reduction for a typical surface-sealer, such as a silane or siloxane. This reflects a minimum of 90 percent reduction in chloride ion intrusion when the sealer tested similarly to NCHRP 244 Series II testing. Unless otherwise noted, sealer effectiveness is based on a uniform application of 40 percent solids organofunctional silane, such as alkyl-alkoxy silane. These materials penetrate the pore structure of the concrete paste and react with silica, resulting in a near-permanent bond.

To account for aging effects and surface abrasion or erosion, surface-applied penetrating sealers are assumed to have a finite lifespan, typically 5 years.

2.5. Modeling Concrete Cover

For existing structures where available, the distribution for concrete cover is modeled based on the depths measured by non-destructive testing (e.g. GPR scans) on the structural elements. The data is aggregated for similar elements and analyzed to develop descriptive statistics. Generally, lognormal distributions are used, because this type of distribution is only defined for values greater than zero and, in WJE's experience, is well-suited for typical distributions of cover depths. For carbonation modeling, the data is treated slightly differently: to account for the time elapsed between when the carbonation front passes from the edge to the center of the bar, an equivalent cover is defined, using the centroid of the semi-circular arc for the shallower half of the bar.

For new structures or where cover data is not available, the mean cover depths is assumed to be equal to the project-specified cover. *Fib Bulletin 34* indicates that typical standard deviations for concrete cover range from 0.24 to 0.40 inch (6 to 10 mm), dependent on the expected quality control. This standard deviation is assumed to be independent of the magnitude of the cover depth.

2.6. Effect of Cracking

Correlation is often observed in concrete elements between cracking and deterioration because cracks permit a higher transport rate for chlorides, moisture, oxygen, and carbon dioxide than sound concrete.

Cracking is treated in the WJE CASLE™ service life models in one of two ways:

1. Crack exclusion: Crack-free concrete is assumed for modeling chloride diffusion. This assumption is justified if cracks that might permit chloride ingress are presumed to be sealed by crack filling materials, such as high-molecular-weight methacrylates or low-viscosity epoxy.
2. Explicit crack modeling: Cracked concrete is assumed to affect a percentage of the element's surface area. Diffusion rates of chloride through these cracked areas are increased. The overall service life of the element modeled is a weighted combination of the cracked and uncracked surface areas.

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APPENDIX D. SUMMARY OF SOURCE DATA FOR DECISION TREES

Table D.1. Summary of data analysis results showing time to repair, time to replacement, and life-cycle cost estimates for all the considered cases. Assumes remediation options are implemented at bridge age between **0 and 2 years**.

Crack Density[1] (ft/ft^2)	Do Nothing			Penetrating Sealer[2] (IC = $8.6/SY)			Penetrating Sealer, 3 applications @ 6 years[2] (IC= $20.8/SY)[3]			Penetrating Sealer, 3 applications at 4 years[2] (IC= $22.3/SY)[3]			Crack Chasing (IC= $8.4/LY)			Flood Coat[4] (IC= $24.5/SY)		
	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)
< 0.10	34	46	$1,056	37	50	1,038	39	51	1,044	40	51	1,046	35	47.0	1,050	37	49	1,060
0.10 to 0.22	27	44	$1,071	30	47	1,058	32	48	1,063	33	49	1,058				37	49	1,060
0.22 to 0.37	19	40	$1,104	21	43	1,087	23	45	1,084	24	45	1,086				36	48	1,067
0.37 <	17	28	$1,239	20	31	1,208	21	32	1,208	22	33	1,198				30	43	1,103

Crack Density[1] (ft/ft^2)	Do Nothing			HMAWM (IC= $82.7/SY)			Thin Polymer Overlay (IC= $66.4/SY)			Premixed Polymer Overlay (IC= $135.9/SY)		
	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)
< 0.10	34	46	$1,056	41	54	1,072	50	65	1,032	61	75	1,075
0.10 to 0.22	27	44	$1,071	37	52	1,100	44	62	1,042	55	72	1,082
0.22 to 0.37	19	40	$1,104	30	48	1,125	40	59	1,053	52	68	1,093
0.37 <	17	28	$1,239	28	38	1,205	38	47	1,116	46	59	1,123

IC: Initial cost of remediation option; T_5: Time-to-5% damage, assuming a damage threshold of 5%; T_{20}: Time-to- replacement or deck service life, assuming a damage threshold of 20%; LCC: Life-cycle cost assuming bridge deck replacement at the end of service life (T_{20}).

[1]Assumed crack density calculated as summation of crack length divided by inspected deck area. Crack densities exceeding 0.37 shall be investigated prior to implementation of repairs. Crack widths between 30 and 40 with a crack density exceeding 0.10 shall be investigated prior to implementation of repairs. The decision tree does not apply to crack densities exceeding 0.50 or crack widths exceeding 40 mils.

[2]Sealers are only considered for crack width less than 15 mils.

[3]Inistial cost is assumed to include all 3 applications. Future applications are calculated as present value.

[4]Flood coats are only considered for crack width less than 30 mils.

Table D.2. Summary of data analysis results showing time to repair, service life, and life-cycle cost estimates for all the considered cases. Assumes remediation options are implemented at bridge age of **5 years**.

Crack Density[1] (ft/ft²)	Do Nothing			Penetrating Sealer[2] (IC = $7.1/SY)			Penetrating Sealer, 3 applications @ 6 years[2] (IC= $17.1/SY)[3]			Penetrating Sealer, 3 applications at 4 years[2] (IC= $18.3/SY)[3]			Crack Chasing (IC= $6.9/LY)			Flood Coat[4] (IC= $20.1/SY)		
	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)
< 0.10	34	46	$1,056	34	47	$1,057	35	47	$1,067	35	47	$1,068	34	46	$1,057	34	47	$1,070
0.10 to 0.22	27	44	$1,071	28	44	$1,078	28	44	$1,088	28	44	$1,090				32	46	$1,077
0.22 to 0.37	19	40	$1,104	20	41	$1,103	20	41	$1,113	20	41	$1,114				29	45	$1,084
0.37 <	17	28	$1,239	17	28	$1,247	17	28	$1,257	17	29	$1,244				22	37	$1,153

Crack Density[1] (ft/ft²)	Do Nothing			HMAWM (IC= $68.0/SY)			Thin Polymer Overlay (IC= $54.5/SY)			Premixed Polymer Overlay (IC= $111.7/SY)		
	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)
< 0.10	34	46	$1,056	35	47	$1,117	49	62	$1,030	53	66	$1,074
0.10 to 0.22	27	44	$1,071	29	44	$1,139	43	60	$1,037	51	65	$1,077
0.22 to 0.37	19	40	$1,104	20	40	$1,172	39	55	$1,058	47	61	$1,091
0.37 <	17	28	$1,239	18	28	$1,307	29	46	$1,111	39	55	$1,115

IC: Initial cost of remediation option calculated as present value since the repair is applied at deck age of 5 years; T_5: Time-to-5% damage, assuming a damage threshold of 5%; T_{20}: Time-to- replacement or deck service life, assuming a damage threshold of 20%; LCC: Life-cycle cost assuming bridge deck replacement at the end of service life (T_{20}).

[1]Assumed crack density calculated as summation of crack length divided by inspected deck area. Crack densities exceeding 0.37 shall be investigated prior to implementation of repairs. Crack widths between 30 and 40 with a crack density exceeding 0.10 shall be investigated prior to implementation of repairs. The decision tree does not apply to crack densities exceeding 0.50 or crack widths exceeding 40 mils.

[2]Sealers are only considered for crack width less than 15 mils.

[3]Inistial cost is assumed to include all 3 applications. Future applications are calculated as present value.

[4]Flood coats are only considered for crack width less than 30 mils.

Table D.3. Summary of data analysis results showing time to repair, service life, and life-cycle cost estimates for all the considered cases. Assumes remediation options are implemented at bridge age of **10 years**.

Crack Density[1] (ft/ft^2)	Do Nothing			Penetrating Sealer[2]			Penetrating Sealer, 3 applications @ 6 years[2]			Penetrating Sealer, 3 applications at 4 years[2]			Crack Chasing (IC= $5.7/LY)			Flood Coat[3] (IC= $16.5/SY)		
	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)
< 0.10	34	46	$1,056										34	46	$1,057	34	47	$1,066
0.10 to 0.22	27	44	$1,071													29	45	$1,080
0.22 to 0.37	19	40	$1,104													19	43	$1,096
0.37 <	17	28	$1,239													17	31	$1,216

Crack Density[1] (ft/ft^2)	Do Nothing			HMAWM (IC= $55.9/SY)			Thin Polymer Overlay (IC= $44.8/SY)			Premixed Polymer Overlay (IC= $91.8/SY)		
	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)	T_5 (yrs)	T_{20} (yrs)	LCC ($1,000)
< 0.10	34	46	$1,056	35	46	$1,112	42	59	$1,031	54	68	$1,049
0.10 to 0.22	27	44	$1,071	29	44	$1,127	31	57	$1,039	43	66	$1,054
0.22 to 0.37	19	40	$1,104	19	40	$1,160	20	53	$1,057	20	62	$1,067
0.37 <	17	28	$1,239	17	29	$1,282	17	34	$1,209	17	40	$1,196

IC: Initial cost of remediation option calculated as present value since the repair is applied at deck age of 10 years; T_5: Time-to-5% damage, assuming a damage threshold of 5%; T_{20}: Time-to- replacement or deck service life, assuming a damage threshold of 20%; LCC: Life-cycle cost assuming bridge deck replacement at the end of service life (T_{20}).

[1]Assumed crack density calculated as summation of crack length divided by inspected deck area. Crack densities exceeding 0.37 shall be investigated prior to implementation of repairs. Crack widths between 30 and 40 with a crack density exceeding 0.10 shall be investigated prior to implementation of repairs. The decision tree does not apply to crack densities exceeding 0.50 or crack widths exceeding 40 mils.

[2]Sealers are only considered for crack width less than 15 mils.

[3]Flood coats are only considered for crack width less than 30 mils.

APPENDIX E. SPECIFICATIONS FOR BRIDGE DECK CRACK INSPECTION AND REPAIR

Specifications pertinent to the inspection and repair of cracks on bridge decks were collected from the standard specifications and special provisions of the 16 state DOTs included in the literature review with the exception of the Iowa DOT. Table E. on the next page identifies the specifications and sections found for each state that provide guidance on the execution of the crack repairs listed in Appendix B, with the exception of 'Do Nothing' and 'Replace the Deck.' The specifications and excerpted sections are provided after the table. They are organized by state. Brief commentary on the context of their use is provided for clarity as needed.

Table E.1. Summary of Standard Specification Sections and Special Provisions Regarding Execution of Bridge Deck Crack Repairs[1]

State	Penetrating Sealer	GFP by Crack-Chasing	Rout and Seal	Epoxy Pressure Injection	Flood Coat	HMA with Waterproofing Membrane	Thin Polymer Overlay	Rigid Cementitious Overlay	Latex-Modified Concrete Overlay	Premixed Polymer Concrete Overlay
CA				SS 60-3.05C	SS 60-3.03B	SS 54-5				SS 60-3.04B
FL	SS 413-2			SS 411	SS 413-3		DevS 403			
IL	SS 587			SS 590		SS 581 SS 582	SP 45	SP 29 SP 31 SP 72	SP 30	
IN	SS 709			SS 727			SP 738-B-297	SS 722	SS 722	
KS				SS 730			SP 15-07020 SP 15-07021	SS 717		
MI	SS 706.03S			SS 712.03U		SS 710.03C	SP 20RC712 (A615)	SS 712	SS 712	
MN	SP SB2020-2433.4-S40 SP SB2020-2433.4-S100	SS 2433.3C.3			SS 2433.3C.5		SP SB2020-2407.2 SP SB2020-2407.3	SS 2404		
MO	SS 703.3.8 JSP 07-08B				SS 704.4.3.3 JSP LL	JSP MM	SS 623.30 SS 623.50			NJSP-19-04
NE	SP G-30-1015			SP G-22-1015		SP G-39-1016	SP G-19-0316	SS 711 SP G-27-1015		SP G-41-1015
NY	SS 559 SpS 559.1696-25	SpS 557.2500NN16		SpS 555.80010001	SpS 557.2600NN16	SpS 595.50000018 SpS 595.60000018 SpS 595.98200018	SpS 584.50010018	SS 578 SS 584 SpS 584.21010001 SpS 584.310Xnn18	SpS 584.330X0002	SpS 584.40000005 SpS 584.40000009
ND	SS 602.04J					SS 602.04K		SS 650		
OH	SS 512.03			SS 512.07	SS 512.04 SS 512.06	SS 512.08 SuppS 856	SuppS 858	SuppS 847 SuppS 848	SuppS 847 SuppS 848	

State	Penetrating Sealer	GFP by Crack-Chasing	Rout and Seal	Epoxy Pressure Injection	Flood Coat	HMA with Waterproofing Membrane	Thin Polymer Overlay	Rigid Cementitious Overlay	Latex-Modified Concrete Overlay	Premixed Polymer Concrete Overlay
SD							SS 491	SS 550	SS 550	
VA	SS 428	SS 412.03(b)5 SP404-000120-00	SS 412.03(b)5	SS 412.03(b)5	SS 412.03(b)5 SP404-000110-00	SS 429	SS 431	SS 425	SS 425	
WI	SS 502.3.13.2	SS 502.3.13.1			SS 502.3.13.1			SS 509 SPV.0035.xx		SPV.0180.xx

Notes: [1]*SS denotes that the section is in the Standard Specifications for road or bridge construction for the state. SP indicates a special provision, JSP indicates a job special provision, NJSP indicates a non-standard job special provision, DevS indicates a developmental specification, SpS indicates a special specification, and SuppS indicates a supplemental specification.*

California

The following specifications and excerpts used by the California DOT were identified as relevant to bridge deck crack inspection and repair:

- **Standard Specifications Section 51-1.01D(3)(b)(iv) Crack Intensity.** This excerpt is from Section 51 Concrete Structures. It specifies when bridge deck crack repair with a methacrylate resin is required during new bridge deck construction.
- **Standard Specifications Section 54-5 Deck Seal.** This excerpt specifies the application of preformed membrane seal systems on bridge decks. Specifications for applying a HMA overlay over the system are not included in the section and were not extracted because HMA placement is a common activity.
- **Standard Specifications Section 60-3.03B Methacrylate Resin Bridge Deck Treatment.**
- **Standard Specifications Section 60-3.04B Polyester Concrete Overlays.**
- **Standard Specifications Section 60-3.05C Epoxy Crack Injection.**
- **Standard Specifications Section 95 Epoxy.** Section 60-3.05C Epoxy Crack Injection specifically refers to Section 95-1.02H Epoxy Resin Adhesive for Pressure Injection Grouting of Concrete Pavement for epoxy material requirements. However, the full Section 95 Epoxy is provided because it contains additional general requirements for epoxy materials.

Florida

The following specifications and excerpts used by the Florida DOT were identified as relevant to bridge deck crack inspection and repair:

- **Standard Specifications Section 400-21 Disposition of Cracked Concrete.** This section is from Section 400 Concrete Structures. It describes when and how cracks in new concrete construction (including bridge decks) are to be inspected, documented, and monitored and which crack repair to execute based on the crack width and density and bridge exposure.
- **Standard Specifications Section 411 Epoxy Injection of Cracks in Concrete Structures.**
- **Standard Specifications Section 413 Sealing Cracks and Concrete Structure Surfaces.** This section includes Section 413-2 Penetrant Sealers and Section 413-3 High Molecular Weight Methacrylate (HMWM).
- **Standard Specifications Section 926 Epoxy Compounds.** Section 411 Epoxy Injection of Cracks in Concrete Structures requires that the epoxy material meet the requirements of a Type E compound epoxy as defined in Section 926 Epoxy Compounds. The relevant sections within Section 926 Epoxy Compounds are excerpted here.
- **Developmental Specification 403 Epoxy Overlay for Sealing and High Friction Surface Treatment on Concrete Bridge Decks.**

Illinois

The following specifications and sections used by the Illinois DOT were identified as relevant to bridge deck crack inspection and repair:

- **Standard Specifications Section 581 Waterproofing Membrane System.** This section specifies the application of waterproofing membrane systems on bridge decks.
- **Standard Specifications Section 582 Hot-Mix Asphalt Surfacing on Bridge Decks.**
- **Standard Specifications Section 587 Concrete Sealer.** This section specifies the application of applying concrete sealers defined in Section 1026 Concrete Sealer.
- **Standard Specifications Section 590 Epoxy Crack Injection.**
- **Standard Specifications Section 1025 Epoxy Concrete Materials.** This section is referenced by Section 590 Epoxy Crack Injection and defines the material requirements for the "epoxy bonding compound."
- **Standard Specifications Section 1026 Concrete Sealer.** This section defines the material requirements for concrete sealers, which includes but is not limited to penetrating sealers.
- **Standard Specifications Section 1061 Waterproofing Membrane System.** This section is referenced by Section 581 Waterproofing Membrane System and defines the material requirements for waterproofing membrane systems.
- **Guide Bridge Special Provision 29 Bridge Deck Microsilica Overlay.**
- **Guide Bridge Special Provision 30 Bridge Deck Latex Concrete Overlay.**
- **Guide Bridge Special Provision 31 Bridge Deck High-Reactivity Metakaolin (HRM) Concrete Overlay.**
- **Guide Bridge Special Provision 45 Bridge Deck Thin Polymer Overlay.**
- **Guide Bridge Special Provision 72 Bridge Deck Fly Ash or Ground Granulated Blast-Furnace Slag Concrete Overlay.**

Indiana

The following specifications and excerpts used by the Indiana DOT were identified as relevant to bridge deck crack inspection and repair:

- **Standard Specifications Section 709 Portland Cement Concrete Sealers.** This section specifies the application of concrete sealers meeting the requirements of Section 909.10 Non-Epoxy PCC Sealers.
- **Standard Specifications Section 722 Concrete Bridge Deck Overlays.** This section provides guidance for silica fume modified concrete overlays, latex-modified overlays, and very early strength latex-modified overlays.
- **Standard Specifications Section 727 Structural Concrete Repair by Epoxy Injection.**
- **Standard Specifications Section 901.06 PCC Sealer/Healers.** Section 722 Concrete Bridge Deck Overlays references Section 901.06 PCC Sealer/Healers for repair of cracks in newly-placed overlays.
- **Standard Specifications Section 909.10 Non-Epoxy PCC Sealers.** This section provides the material requirements for non-epoxy PCC sealers referenced in Section 709 Portland Cement Concrete Sealers. While not explicitly called out as penetrating sealers, they are required to be silane-based.
- **Standard Specifications Section 909.12 Epoxy Resin Additives for Injection into Concrete.** This excerpt is referenced by Section 727 Structural Concrete Repair by Epoxy Injection and provides material requirements for the epoxy resin.
- **Recurring Special Provision 738-B-297 Warranted Polymer Overlay System for Bridge Deck Surfaces and Polymer Overlay System for Other Concrete Surfaces.** This special provision specifies the construction of a multi-layer polymer overlay.

Kansas

The following specifications and excerpts used by the Kansas DOT were identified as relevant to bridge deck crack inspection and repair:

- **Standard Specifications Section 717 Bridge Overlays.** This section specifies the application of portland cement concrete, i.e., rigid cementitious, overlays.
- **Standard Specifications Section 730 Epoxy Resin Crack Repair.** This section specifies epoxy injection of cracks using epoxy that meets the requirements of Section 1705 Epoxy-Resin-Base Bonding Systems for Concrete for Type IV, Grade 3 epoxy materials.
- **Standard Specifications Section 1705 Epoxy-Resin-Base Bonding Systems for Concrete.** This section provides the material requirements for the epoxy material referenced by Section 730 Epoxy Resin Crack Repair.
- **Standard Specifications Section 1730 Polymer Resins for Polymer Concrete Overlay Systems.** This section specifies the material requirements for the epoxy, polyester, and methyl methacrylate materials used in Special Provision 15-07020 Multi-Layer Polymer Concrete Overlay and Special Provision 15-07021 Slurry Polymer Concrete Overlay.
- **Special Provision 15-07020 Multi-Layer Polymer Concrete Overlay.** This special provision replaces Section 729 Multi-Layer Polymer Concrete Overlay of the standard specifications.
- **Special Provision 15-07021 Slurry Polymer Concrete Overlay.** This special provision replaces Section 739 Slurry Polymer Concrete Overlay of the standard specifications. It specifies the application of slurry polymer concrete overlays that may consist of epoxy, polyester, or methyl methacrylate as defined in Section 1730 Polymer Resins for Polymer Concrete Overlay Systems. A thickness is not given, but slurry polymer concrete overlays typically classify as a thin polymer overlay.

Michigan

The following specifications and excerpts used by the Michigan DOT were identified as relevant to bridge deck crack inspection and repair:

- **Standard Specification Section 706.03S Penetrating Water Repellant Treatment.** This excerpt is from Section 706 Structural Concrete Construction and specifies the application of a "penetrating water repellant," understood to be a penetrating sealer, to new concrete construction.
- **Standard Specification Section 710.03C Deck Waterproofing - Preformed.** This excerpt is from Section 710 Waterproofing and Protective Covers.
- **Standard Specification Section 712 Bridge Rehabilitation - Concrete.** This section includes specifications for silica fume modified concrete overlays, latex-modified concrete overlays, and pressure injection of cracks (712.03U) as well as water repellant treatment (712.03V) for which the user is referred to Section 706.03S Penetrating Water Repellant Treatment.
- **Standard Specification Section 914.06 Epoxy Resin Adhesive.** Although not referenced by Section 712 Bridge Rehabilitation - Concrete, this excerpt provides the material requirements for epoxy resins used in pressure injection of cracks.
- **Standard Specification Section 1006 Patching, Repair, and Overlay Mixtures.** This section specifies the material requirements for silica fume modified concrete mixtures and latex modified concrete mixtures for bridge deck overlays.
- **Special Provision 20RC712(A615) for Performance Warranty, High Friction Thin Epoxy Polymer Bridge Deck Overlay.**

Minnesota

The following specifications and excerpts used by the Minnesota DOT were identified as relevant to bridge deck crack inspection and repair:

- **Standard Specification Section 2404 Concrete Wearing Course for Bridges.** This section provides the requirements for a low-slump concrete overlay. An overlay thickness of at least 2 inches is specified.
- **Standard Specification Section 2433.3C Concrete Construction.** This excerpt is from Section 2433 Structure Renovation. It provides an overview of the crack sealing process (2433.3C.1 Bridge Deck Crack Sealing Process) and defines how to inspect cracks (2433.3C.2 Deck Cleaning and Mapping Cracks). It also includes Seal Cracks with Epoxy by Chase Method (2433.3C.3) and Methyl Methacrylate (MMA) Flood Seal (2433.3C.5).
- **Bridge Office Special Provision SB2020-2401.2C Structural Concrete - High Performance Concrete Bridge Decks.** This special provision provides an amendment to 2401.3I.2 Crack Sealing and provides a new table of crack sealing requirements for new concrete bridge decks.
- **Bridge Office Special Provision SB2020-2404.2 Concrete Wearing Course 3U17A.** This special provision provides amendments to Section 2404 Concrete Wearing Course for Bridges, including specification of a 3-inch minimum depth for the low-slump concrete wearing surface.
- **Bridge Office Special Provision SB2020-2404.3E Concrete Wearing Course Pneumatically Applied Wet Blanket Curing.** This special provision provides further amendments to Section 2404 Concrete Wearing Course for Bridges and is included for completion.
- **Bridge Office Special Provision SB2020-2407.1 Crack Pretreatment for Chip Seal Wearing Course.** This special provision specifies a flood application to treat cracks prior to placement of a polymer chip seal.
- **Bridge Office Special Provision SB2020-2407.2 Polymer Wearing Course Type Epoxy.** This special provision provides the requirements for a multi-layer, epoxy polymer overlay.
- **Bridge Office Special Provision SB2020-2407.3 Polymer Wearing Course Type Epoxy-Urethane.** This special provision provides the requirements for a multi-layer, epoxy-urethane polymer overlay.
- **Bridge Office Special Provision SB2020-2433.4-S40 Bridge Penetrating Sealer (Silane 40%).**
- **Bridge Office Special Provision SB2020-2433.4-S100 Bridge Penetrating Sealer (Silane 100%).**
- **Bridge Office Special Provision SB2020-2433.5 Chase Seal Cracks by Chase Method with Epoxy.** This special provision provides an amendment to the method of measurement for crack-chasing with epoxy and is included for completion.

Missouri

The following specifications and excerpts used by the Missouri DOT were identified as relevant to bridge deck crack inspection and repair:

- **Standard Specification Section 623.30 Epoxy Polymer Wearing Surface.** This section provides the requirements for a multi-layer epoxy polymer overlay.
- **Standard Specification Section 623.40 Polymer Concrete.** This section specifies the placement of polymer concrete; it is unclear if this is polymer concrete for repair or a polymer concrete overlay although the language indicates the section is likely intended to apply for polymer concrete overlays.
- **Standard Specification Section 623.50 Methyl Methacrylate Polymer Slurry Wearing Surface.** This section provides the requirements for a slurry polymer overlay. Section 623.50.4.2.5 Reflective Cracks addresses pretreatment of cracks prior to placement of the overlay.
- **Standard Specification Section 703.3.8 Surface Sealing for Concrete.** This excerpt is from Section 703 Concrete Masonry Construction and specifies the application of a penetrating concrete sealer for new concrete construction and new concrete overlays. The excerpt references Section 1053 Concrete Sealer and Concrete Crack Filler for the material requirements of the penetrating concrete sealer.
- **Standard Specification Section 704 Concrete Masonry Repair.** This section describes the variety of concrete repairs used by the Missouri DOT and specifies the application of concrete crack fillers defined in Section 1053 Concrete Sealer and Concrete Crack Filler.
- **Standard Specification Section 1039.20 Type III Epoxy.** This section provides the material requirements for epoxies used to grout dry cracks.
- **Standard Specification Section 1039.60 Epoxy Polymer Wearing Surface.** This section is referenced by Section 623.30 Epoxy Polymer Wearing Surface and provides material requirements.
- **Standard Specification Section 1039.80 Methyl Methacrylate (MMA) Polymer Slurry Wearing Surface.** This section is referenced by Section 623.50 Methyl Methacrylate Polymer Slurry Wearing Surface and provides material requirements.
- **Standard Specification Section 1039.90 Polyester Polymer Wearing Surface.** This section provides the material requirements for polyester polymer wearing surfaces.
- **Standard Specification Section 1053 Concrete Sealer and Concrete Crack Filler.** This section provides the material requirements for penetrating concrete sealers (1053.10) and concrete crack fillers (1053.20).
- **Job Special Provision JSP 07-08B Protective Surface Treatment for Concrete - Penetrating Sealers.**
- **Job Special Provision LL. Concrete Crack Filler - High Molecular Weight Methacrylate.** This special provision specifies the application of a methacrylate. It is unclear if the methacrylate is applied as a flood coat or using crack-chasing although based on the language, a flood coat appears more likely.
- **Job Special Provision MM. Seal Coat for Bridge Decks Prior to Asphalt Overlay.** This special provision specifies the placement of a polymer-modified liquid asphalt emulsion with cover

aggregate, i.e., the seal coat. While not expected to be as effective as a waterproofing membrane, it provides a similar function.

- **Non-Standard Job Special Provision NJSP-19-04 Polyester Polymer Concrete Overlay.**

Nebraska

The following specifications and excerpts used by the Nebraska DOT were identified as relevant to bridge deck crack inspection and repair:

- **Standard Specification Section 706.03 Concrete Bridge Floors.** This excerpt specifies when crack repairs are required on new concrete bridge deck construction.
- **Standard Specification Section 711 Concrete Bridge Deck Repair and Overlay.** This section specifies the application of a rigid cementitious overlay.
- **Standard Special Provision G-19-0316 Multi-Layer Epoxy Polymer Overlay.**
- **Standard Special Provision G-22-1015 Crack Epoxy Injection.**
- **Standard Special Provision G-27-1015 Concrete Bridge Deck Repair with Silica Fume Concrete.** This special provision provides requirements for silica fume concrete overlays.
- **Standard Special Provision G-30-1015 Penetrating Concrete Sealers.**
- **Standard Special Provision G-39-1016 Cold Liquid-Applied Membrane.** This special provision specifies the application of waterproofing membranes to concrete bridge decks.
- **Standard Special Provision G-41-1015 Polyester Polymer Concrete Overlay.**

New York (State)

The following specifications and excerpts used by the New York State DOT were identified as relevant to bridge deck crack inspection and repair:

- **Standard Specifications Section 559 Protective Coatings for Structural Concrete.** This section includes specifications for the application of penetrating sealers.
- **Standard Specifications Section 578 Bonded Concrete Overlay for Structural Slabs.** This section specifies the application of portland cement concrete overlays at least 3 inches thick.
- **Standard Specifications Section 584 Specialized Overlays for Structural Slabs.** This section specifies the application of "specialized" concrete overlays, specifically microsilica concrete overlays and portland cement concrete overlays with supplementary cementitious materials.
- **Standard Specifications Section 717 Concrete Protective Coatings.** This section contains the material requirements for Waterproofing Membranes (717-02) and Penetrating Type Protective Sealers (717-03), the latter of which is referenced by Section 559 Protective Coatings for Structural Concrete.
- **Standard Specifications Section 734 Concrete Slab Overlays.** This section specifies the material requirements for Thin Polymer (Epoxy) Overlay Wearing Surface for Structural Slabs (734-01).
- **Special Specification 555.80010001 Crack Sealing by Epoxy Injection (Prevention).**
- **Special Specification 557.2500NN16 Crack Sealing Using High Molecular Weight Methacrylate - Linear Cracks.** This specification provides the requirements for crack-chasing.
- **Special Specification 557.2600NN16 Crack Sealing Using High Molecular Weight Methacrylate - Flooding.** This specification provides the requirements for applying a flood coat.
- **Special Specification 559.1696--25 Protective Sealing of Structural Concrete.** This specification provides the requirements for applying a penetrating sealer to new or existing concrete.
- **Special Specification 584.21010001 Ultra-High Performance Concrete (UHPC) Overlay.**
- **Special Specification 584.310*X*nn18 Overlay Concrete, Class DP with Internal Curing-Type *X* Friction.**
- **Special Specification 584.330*X*0002 Overlay Concrete, Latex Modified Concrete-Type *X* Friction.**
- **Special Specification 584.40000005 Polymer Concrete Overlay Wearing Surface for Structural Slabs (PCO).** This specification provides the requirements for premixed polymer concrete overlays; the specific type of polymer is not specified.
- **Special Specification 584.40000009 Polymer Overlay Wearing Surface for Structural Slabs (PPC).** This specification provides the requirements for premixed polyester polymer concrete overlays.
- **Special Specification 584.50010018 Thin Polymer (Epoxy) Overlays for Structural Slabs.**
- **Special Specification 595.50000018 Sheet-Applied Waterproofing Membrane.** This specification provides the requirements for furnishing and installing sheet waterproofing membranes on bridge decks.

- **Special Specification 595.60000018 Hot-Applied Rubberized Asphalt Waterproofing Membrane.** This specification provides the requirements for furnishing and installing hot-applied waterproofing membranes and contains some content regarding the HMA overlay to be placed over the membrane.
- **Special Specification 595.98200018 Spray-Applied Waterproofing Membrane.** This specification provides the requirements for furnishing and installing spray-applied waterproofing membranes. Specifics regarding bridge decks and HMA paving are not included.

North Dakota

The following specifications and excerpts used by the North Dakota DOT were identified as relevant to bridge deck crack inspection and repair:

- **Standard Specifications Section 602.03 Materials.** This excerpt is from Section 602 Concrete Structures and identifies the requirements for waterproofing membranes.
- **Standard Specifications Section 602.04 Construction.** This excerpt is from Section 602 Concrete Structures. It addresses application procedures for Penetrating Water Repellent Treatment (602.04J) and Waterproofing Membrane (602.04K).
- **Standard Specifications Section 650 Overlay of Concrete Bridge Decks.** This section specifies the application of portland cement concrete overlays.
- **Standard Specifications Section 822 Penetrating Water Repellent.** This section provides the material requirements for "penetrating water repellents," which are penetrating sealers.

Ohio

The following specifications and excerpts used by the Ohio DOT were identified as relevant to bridge deck crack inspection and repair:

- **Standard Specifications Section 511.19 Joints, Cracks, Scaling and Spalls.** This excerpt belongs to Section 511 Concrete for Structures and specifies when a flood coat is to be applied over cracks in new bridge deck construction.
- **Standard Specifications Section 512 Treating Concrete.** This section covers a variety of treatments or repairs that can address bridge deck cracking:
  - **Section 512.03 Sealing of Concrete Surfaces.** The scope of this section is assumed to include penetrating sealers, although they are not identified explicitly.
  - **Section 512.04 Sealing Concrete Bridge Decks with HMWM Resin.** This section specifies the application of a flood coat.
  - **Section 512.05 Soluble Reactive Silicate (SRS) Concrete Treatment.**
  - **Section 512.06 Treating Concrete Bridge Decks with Gravity-Fed Resin.** This section specifies the application of a flood coat.
  - **Section 512.07 Sealing Cracks by Epoxy Injection.**
  - **Section 512.08 Waterproofing.**
- **Standard Specifications Section 705.15 High Molecular Weight Methacrylate (HMWM) Resin.** This excerpt is from Section 705 Concrete Incidentals and provides the material requirements for HMWM resins.
- **Standard Specifications Section 705.23 Concrete Sealers.** This excerpt is from Section 705 Concrete Incidentals and is referenced by Section 512 Treating Concrete. It contains the material requirements for “Non-Epoxy” sealers (705.23B).
- **Standard Specifications Section 705.24 Soluble Reactive Silicate.** This excerpt is from Section 705 Concrete Incidentals and is referenced by Section 512 Treating Concrete. It provides the material requirements for soluble reactive silicates.
- **Standard Specifications Section 705.25 Gravity-Fed Resin.** This excerpt is from Section 705 Concrete Incidentals and is referenced by Section 512 Treating Concrete. It provides the material requirements for gravity-fed resins, which are required to be epoxy-based.
- **Standard Specifications Section 705.26 Epoxy Injection Resin.** This excerpt is from Section 705 Concrete Incidentals and is referenced by Section 512 Treating Concrete. It contains the material requirements for epoxy injection resins.
- **Supplemental Specification 847 Bridge Deck Repair and Overlay with Concrete Using Scarification and Chipping.** This specification includes microsilca modified concrete, latex-modified concrete, and superplasticized dense concrete overlays.
- **Supplemental Specification 848 Bridge Deck Repair and Overlay with Concrete Using Hydro-Demolition.** This specification includes microsilca modified concrete, latex-modified concrete, and superplasticized dense concrete overlays.
- **Supplemental Specification 856 Bridge Deck Waterproofing Asphalt Surface Course.**

- **Supplemental Specification 858 Thin Polymer (Epoxy) Overlays for Structural Slabs.**

South Dakota

The following specifications and excerpts used by the South Dakota DOT were identified as relevant to bridge deck crack inspection and repair:

- **Standard Specifications Section 491 Bridge Deck Polymer Chip Seal.** This section specifies the application of a multi-layer polymer overlay.
- **Standard Specifications Section 550 Bridge Deck Preparation and Resurfacing.** This section specifies the application of latex-modified concrete and low-slump dense concrete overlays.
- **Standard Specifications Section 805 Materials for Polymer Chip Seals.** This section provides the material requirements for the materials used in Section 491 Bridge Deck Polymer Chip Seal and is referenced by the section.

Virginia

The following specifications and excerpts used by the Virginia DOT were identified as relevant to bridge deck crack inspection and repair:

- **Standard Specifications Section 213 Damp-Proofing and Waterproofing Materials.** This section provides the material requirements for damp-proofing and waterproofing materials.
- **Standard Specifications Section 217 Hydraulic Cement Concrete.** This section includes the material requirements for latex-modified concrete overlays and rigid cementitious overlays using supplementary cementitious materials.
- **Standard Specifications Section 243 Epoxy-Resin Systems.** This section provides the material requirements for epoxy-resin systems used to waterproof concrete and is referenced by Section 416 Waterproofing and Section 431 Epoxy Bridge Deck Overlays.
- **Standard Specifications Section 252 Gravity-Fill Polymer Crack Sealers.** This section provides the material requirements for gravity-fill polymer crack sealers, which may be a variety of polymer materials.
- **Standard Specifications Section 412.03(b)5 Crack Repairs.** This excerpt is from Section 412 Widening, Repairing, and Reconstructing Existing Structures and describes the various types of crack repairs used by the Virginia DOT. They include:
  - Section 412.03(b)5a Crack Repair Type A (V grooving)
  - Section 412.03(b)5b Crack Repair Type B (Epoxy injection)
  - Section 412.03(b)5c Crack Repair Type C (Gravity Filled Polymer Sealing). This excerpt considers both crack-chasing and flood coat methods.
  - Section 412.03(b)5d Crack Repair Type D (Epoxy and Carbon Fiber Mesh)
- **Standard Specifications Section 416 Waterproofing.** This section specifies the application of "waterproofing materials" on bridge decks. Instead of an asphaltic membrane, "waterproofing materials" refers to an epoxy-resin material, the requirements for which are in Section 243 Epoxy-Resin Systems.
- **Standard Specifications Section 425 Rigid Concrete Bridge Deck Overlays.** This section considers silica fume concrete, latex-modified concrete, high early strength latex-modified concrete, and very-early-strength latex-modified concrete overlays.
- **Standard Specifications Section 428 Concrete Surface Penetrant Sealer.**
- **Standard Specifications Section 429 Bridge Deck Waterproofing Membrane Systems.** This section specifies the application of waterproofing membrane systems to bridge decks and includes some provisions for applying the asphalt overlay as well.
- **Standard Specifications Section 431 Epoxy Bridge Deck Overlays.** This section specifies the application of a multi-layer epoxy polymer overlay.
- **Supplemental Specifications SS217-002020-01 Section 217 Hydraulic Cement Concrete.** This supplemental specification provides amendments to Section 217 Hydraulic Cement Concrete and is included for completion.

- **Special Provision SP404-000110-00 Filling and Sealing Pattern Cracks in Concrete Decks and Overlays.** This special provision specifies the application of a flood coat.
- **Special Provision SP404-000120-00 Sealing Linear Cracks in Concrete Decks and Overlays Using Epoxy and Carbon Fiber Mesh.**

Wisconsin

The following specifications and excerpts used by the Wisconsin DOT were identified as relevant to bridge deck crack inspection and repair:

- **Standard Specifications Section 502.2.11 Crack and Surface Sealers.** This excerpt is from Section 502 Concrete Bridges and identifies the material requirements for crack and surface sealers used on concrete structures.
- **Standard Specifications Section 502.3.13 Concrete Crack and Surface Sealing.** This excerpt is from Section 502 Concrete Bridges and specifies when crack sealing by crack-chasing or a flood coat is to be conducted (502.3.13.1) prior to applying the protective surface treatment (502.3.13.2), which consists of a penetrating sealer.
- **Standard Specifications Section 509 Concrete Overlay and Structure Repair.** This section specifies the application of rigid cementitious overlays.
- **Special Provision SPV.0035.xx Concrete Masonry Overlay Silica Fume Modified.**
- **Special Provision SPV.0180.xx Polyester Polymer Concrete Overlay.**
- **Construction and Materials Manual Section 525.3 Crack Survey and Sealing.** This section provides further guidance for crack surveying and sealing operations.
- **Construction and Materials Manual Section 528 Concrete Deck Removals, Overlays, and Structure Repairs.** This section provides amendments to Section 509 and is included for completion.