Use of Polymer Overlays or Sealers on New Bridges

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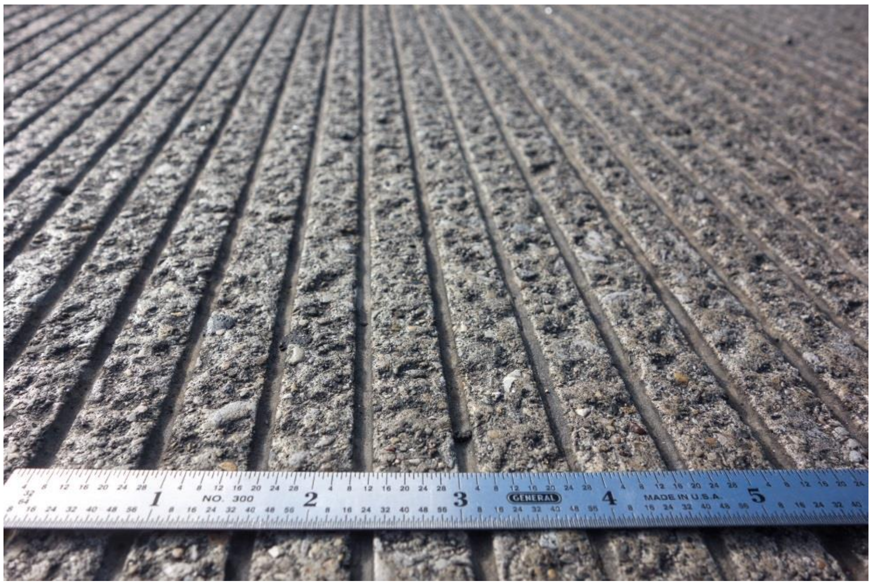

Final Report
September 22, 2017

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16. Abstract

Polymer overlays and penetrating deck sealers are used as preventive maintenance options to extend the service life of concrete bridge decks. Overlays and sealers protect concrete structures from deterioration by inhibiting the ingress of chlorides, chemicals, and moisture and by slowing active corrosion. Identifying the optimum time for installation of overlays and sealers is key to maximizing the benefit to cost ratio of this type of maintenance. This report provides an overview and analysis of the use of polymer overlays and penetrating deck sealers to achieve extended service life objectives. It includes a description of the materials used as polymer overlays and sealers; recommended practices for application and installation; additional considerations for construction; service life modeling of various preventive maintenance options; and an analysis of the relative service life costs. The literature indicates that polymer overlays are often applied to bridge decks in good to moderate condition with a median age of 20 years, while for sealers the recommended practice is to apply sealers to new bridge decks 3 to 6 months after construction, with reapplication often scheduled after 4 to 5 years. Service life modeling and life-cycle cost analysis results indicate that the greatest extensions in service life of northern bridges with typical life of 50 years are obtained when sealers are applied shortly after construction and polymer overlays are applied within the first 5 years of service. For bridges with desired service life of 100 years, polymer overlays should be reapplied through the life of the deck, at 25 years interval or less. It is recommended that bridges with desired service life exceeding 50 years be analyzed on a case-by-case basis.

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EXECUTIVE SUMMARY

Constructing concrete bridge decks with extended service lives is of paramount importance for Departments of Transportation (DOTs). Cracking of the concrete and corrosion of the reinforcing steel due to environmental exposures can limit the service life of bridge decks. Further, the quality of the deck directly affects the public through ride quality, bridge appearance, and maintenance-related delays. Progressive deterioration of concrete bridge decks strain department maintenance resources.

One option to ensure long term durability and extended service life of concrete bridge decks is Preventive Maintenance (PM) using polymer overlays and sealers. Overlays and sealers provide protection from deterioration mechanisms as they inhibit not only the ingress of chlorides, chemicals, and moisture but can also slow active corrosion. Identifying the optimum time to install overlays or sealers is key to maximizing the benefit to cost ratio of this type of maintenance.

This report provides an overview and analysis of the use of polymer overlays to achieve extended service life objectives. Included is a summary of federal- and state-sponsored reports and surveys on the use of polymer overlays and penetrating deck sealers. The summary includes a description of the materials used in polymer overlays and sealers; recommended practices for installation; additional considerations for construction; a discussion on service life and timing of installation based on surveys; and an analysis of relative preventive maintenance costs. Service life models were also developed to investigate the effect and timing of using polymer overlays or sealers as preventive maintenance options on new bridge decks.

The literature indicates that state DOTs are currently using polymer overlays and penetrating deck sealers to maintain existing bridges (seal cracks, slow corrosion, and restore skid resistance) and to extend the service life of new bridges. While most often used on decks exhibiting deterioration, both systems are more effective when applied on sound bridge decks that are not yet chloride (deicer) contaminated. Surface conditions (temperature, moisture content, cleanliness, etc.) are crucial for successful installation and performance of polymer overlays and sealers. Polymer overlays provide more possible advantages for bridge deck maintenance compared to sealers, including restoring skid resistance, improving drainage, increased wear resistance, and improved appearance. Both systems can seal cracks with small widths and can slow down the ingress of chloride. However, polymer overlays are more effective in the latter as they provide additional cover to the reinforcing. Polymer overlays have a service life of approximately 25 years compared to 5 years for sealers, but are also 3 times more expensive. Based on review of the literature, the best-performing polymer overlays are multi-layer epoxy (MLE) and premixed polyester concrete (PPC), while silanes and siloxanes are the most widely used penetrating deck sealers.

The literature indicates that polymer overlays are often applied to decks in good to moderate condition with a median age of 20 years, while sealers are optimally applied 3 to 6 months after construction (preferably prior to exposing the deck to deicing salts) and are often scheduled to be reapplied every 5 years. It was determined from service life modeling results that polymer overlays and sealers should be applied early to obtain the most benefit on the service life. The service life modeling results indicated that the best results are obtained when the sealer is applied soon after construction and the polymer overlay is applied within the first 10 years.

The focus of this report is to assess the benefit of polymer concrete overlays or sealers to protect new bridge structures. The service life models and life-cycle cost analysis results indicated that the best option is to install polymer overlays on new bridge decks with reapplication at the end of the overlay's service life, approximately every 25 years or less. This option is well suited for bridge decks where a service life

exceeding 75 years is desired. The polymer overlay will not only protect the bridge but it will also periodically restore the skid resistance, appearance and riding quality of the deck surface.

A hybrid preventive maintenance approach is recommended for bridges with typical service life of 50 years. This hybrid approach includes applying a sealer immediately after construction and installing an overlay within the first 5 years. This option yields a service life of 53 years compared to a base case of 21 years if no treatment is applied, considering corrosion initiation only. This optimal use of preventive maintenance can double the expected service life of bridge decks at a fraction of the construction cost (approximately 10%). Life-cycle cost analysis considering a period of 100 years also showed savings in agency costs of approximately 16% if this approach is used compared to no preventive maintenance, not including user costs. It is recommended that bridges with desired service life exceeding 50 years be analyzed on a case-by-case basis to determine optimal maintenance plans for the specific project expectations, exposure and materials used at the site.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1. INTRODUCTION

1.1 Background

Concrete bridge decks are the most exposed elements of bridges, which makes them susceptible to deterioration and reduction in service life. Cracking and resistance to chloride ingress have major impacts on the service life of concrete bridge decks and the bridge as a whole, especially in northern states where deicers are widely used. Annual use of deicers continues to increase and deicer practices have become more aggressive to both steel and concrete through pretreatment of brines and use of aggressive deicer solutions such as magnesium chloride. Other concrete distress mechanisms that affect bridge decks include alkali-silica reaction, carbonation, cyclic freezing, and other chemical attack (such as by magnesium, sulfate, or acids); however, these distress mechanisms are often of secondary importance to cracking and corrosion.

In new bridges, early-age concrete cracking can occur as a result of concrete chemical and drying shrinkage, thermal-induced stress, freeze-thaw damage, formwork settlement and traffic loading. A survey conducted by Wiss, Janney, Elstner Associates (WJE) in 1996 (Krauss and Rogalla 1996) indicated that more than 100,000 bridge decks in the United States suffered from early-age transverse cracking. While cracking does not constitute an immediate threat to the structural performance of a bridge deck, cracking facilitates the ingress of chlorides, chemicals, and moisture. These have an impact on the durability of bridge decks as they cause or accelerate corrosion of reinforcing steel and lead to other concrete-related distress.

In northern states, such as Iowa, chlorides from deicing salts penetrate through the concrete cover or through cracks to reach embedded reinforcing bars. The reinforcement will begin to corrode when chlorides reach a sufficient concentration, commonly called the chloride threshold, C_T, at the level of the reinforcement. Corrosion-resistant reinforcement, such as epoxy-coated reinforcement (ECR), galvanized reinforcement, and stainless steel reinforcement have been used to provide greater chloride thresholds and slower corrosion rates.

Corrosion-resistant reinforcement, primarily ECR, combined with increased concrete cover and low permeability concrete are used to construct longer-lasting bridge decks. These various approaches have been relatively successful at providing 30 to 40 years of acceptable performance. Additional measures are needed to extend the lives of these currently-constructed decks another 30 to 40 years, or to construct new bridge decks with service lives of 50 to 100 years.

Polymer concrete (PC) overlays and sealers are routinely used by DOTs throughout the United States for maintenance and rehabilitation of in-service bridge decks. Polymer concrete overlays act as both a barrier coating and a wearing surface for the deck. Polymer overlays are mostly used to extend service life of deck, restore surface friction, restore uniform appearance of deck surface, repair spalled and cracked surfaces, and waterproof the deck (Fowler and Whitney 2011). Iowa DOT has extensive experience with and has successfully used low-slump, portland cement concrete overlays to extend deck service life (Anderson 1990). Polymer overlays have the advantage of being much faster to install, a significant advantage in urban areas. Being thinner, they also add less dead load. The scope of this report is limited specifically to rapid-setting, polymer overlays that can be installed during short lane closure periods. Literature indicates that different types of polymer binder materials have been used by different states including epoxy, polyester, and methacrylate. Epoxy overlays are more commonly used nationwide, although polyester polymer concrete has been successfully used in California and other states since the 1980s (Krauss 1988).

Sealers do not change the deck surface profile and are intended to reduce chloride ion or moisture ingress into the deck, thereby protecting the reinforcing bars from corrosion. Sealers are often classified as: 1) penetrating sealants (such as silane and siloxane), which protect the deck by creating a hydrophobic barrier to repel water and chloride ions; and 2) film formers and pore blockers (such as linseed oil and epoxy), which create a barrier to prevent passing of water and chloride particles into the concrete substrate (Johnson et al. 2009).

Optimum timing for application of polymer overlays and sealers is needed to maximize the value and length of service life extension of existing and new bridge decks. A recent survey of 13 states indicated that most DOTs apply polymer overlays as a repair measure to restore friction and seal cracks. The survey found only two states, Illinois and Utah, have currently implemented them as a preventive maintenance measure for new bridge decks (CTC & Associates 2012), although in our direct experience, many other transportation agencies have also installed polymer concrete overlays on new construction to extend the service life of bridge decks.

In WJE's experience, polymer concrete overlays and sealers have been used on newly-constructed bridge decks for projects with design requirements of 75 to 100 years. One key approach of these projects is to use portland cement concrete or polymer concrete overlays designed to be replaced at regular intervals throughout the service life of the bridge to minimize the initial ingress of deicer solutions. Overlay replacement is to be based on deicer ingress with the goal to prevent elevated chloride at the bar depth sufficient to initiate corrosion. One of these projects, East End Crossing (Lewis and Clark), a new bridge over the Ohio River located near Louisville, Kentucky, is using a number of design measures, including overlays, ECR, and low-permeability concrete, to reach a 100-year service life design requirement. On the main span, the deck used a combination of an overlay installed at the time of construction combined with methacrylate or epoxy sealers to seal early-age shrinkage cracks that may appear after initial construction. On the approach bridges, low-permeability concrete combined with penetrating silane sealers was used for initial construction, and a future overlay will be installed in approximately 30 years' time. Polymer overlays were also included on sections of the bridge to address construction problems related to concrete cover. Polymer overlays are included as an approved strategy for achieving 100 year or longer service lives on many major design-build bridge projects, for states such as New York and Michigan among others.

Conceptually, installation at the time of initial construction provides the benefits of protection before deicers are applied, whereas installation at a later date defers the installation cost, but permits the concrete to be exposed to deicers and moisture early in its life. Both approaches have merit, but may have very different impacts on service life, maintenance activities, and life cycle costs.

1.2 Scope of Work

The main objective of this study is to develop guidelines for Iowa DOT that can aid in identifying optimum timing for application of polymer concrete overlays or sealers on new bridge decks and its effect on expected service life. Considerable studies have been published to discuss the use of polymer concrete overlays and sealers as a maintenance technique for in-service bridge decks. This study focuses on reviewing relevant studies and surveys related to assessing the performance of polymer concrete overlays and sealers and determining the best practices and timing for their application. This study also includes an example optimization for the timing of polymer concrete overlay and sealer applications for a typical bridge deck in Iowa. Service life modeling was conducted to assess the impact of delaying preventive maintenance on the new bridge deck and to determine the benefit to cost ratio of applying the chosen system at different times from construction. The results of the survey and the service life modeling were used to develop recommendations for selection of penetrative maintenance options.

1.3 Definition of Abbreviations and Terms

This section includes a list of abbreviations and brief definitions of each term used in the report.

Binder:	Resin used to bind aggregate or other materials together in a cohesive form
Broom and seed:	Also known as multiple-layer overlay and consists of placing repeated layers of polymer resin on the deck followed by broadcasting of aggregate
ES:	Epoxy slurry
HMWM:	High molecular weight methacrylate
MLE:	Multiple-layer epoxy
MLEU:	Multiple-layer epoxy urethane
MLP:	Multiple-layer polyester
MMA:	Methyl methacrylate
MMS:	Methyl methacrylate slurry
Monomer:	A small molecule, usually in liquid form, which can bind with other molecules to form large polymer molecules
PC:	Polymer concrete
PPC:	Premixed polyester concrete
Polymer:	Product of polymerization, more commonly an elastomer or resin consisting of large molecules formed by polymerization
Polymer Overlay:	An overlay formed using aggregate bound in a polymer binder. Installation types include multiple-layer overlay, slurry overlay and premixed overlay
Slurry Overlay:	Overlay installed by placing premixed polymer resin and fine aggregate in a fluid condition
Sealer:	Liquid materials surface-applied to concrete used to protect deck surface from chloride or moisture ingress and seal cracks

1.4 Cracking in Bridge Decks

Early age cracking is one of the main reasons of deterioration in new bridge decks (Xi et al. 2003). Cracks allow moisture and deicing salts to penetrate the concrete deck which may lead to premature corrosion of reinforcement and freeze-thaw damage of the bridge deck in addition to damage of structural components beneath the deck (Cuelho and Stephens 2013). As concrete has low tensile strength, cracking of the deck can occur for several reasons. Cracks can be classified based on the state of the concrete whether it is before or after hardening. Cracks can occur before hardening due to construction movement (movement of form or sub-grade movement), chemical shrinkage (autogenous), high surface evaporation (plastic), and frost damage (premature freezing and scaling) (Cuelho and Stephens 2013). After hardening cracks can occur due to volumetric movement (drying shrinkage, thermal contraction, and creep), structural design (design load and fatigue), and chemical reactions (alkali-aggregate reaction, freeze-thaw damage, and corrosion). Transverse cracking in new bridge decks is the most widely reported type of cracking (Krauss and Rogalla 1996). These types of cracks are usually full-depth, unlike plastic shrinkage cracks, and commonly vary in width between 0.002 inch and 0.025 inch.

A study by Krauss and Rogalla (1996) indicated that cracks with surface widths of 0.002 inch to 0.008 inch can result in water leakage through the deck. It is noted that these crack widths are less than the range of "acceptable" crack widths for design per ACI Committee 224 which limits crack width to 0.007 inch to 0.012 inch, which is also recognized by Wenzlick (2007) in a study for Missouri DOT.

Dynamic ("moving") cracks can be particularly problematic for overlays and sealers. Because the crack changes in width, bonded materials installed either above or within the crack will likely crack and form a reflective crack, and may still allow deicers and moisture to penetrate. Dynamic cracks may be present due to daily thermal cycles, structural loads (such as negative-moment cracks over supports), or other cyclic behavior.

Crack widths in this report are reported by a number of researchers in both qualitative (wide, narrow, etc.) and quantitative measurements. The importance of cracking to either the structural or durability of a bridge deck varies based on its location in the element, length, frequency, and width. However, the AASHTO Manual for Bridge Element Inspection (2013) provides commentary on qualitative measures of crack widths. This manual is sourced as a reference, because many state DOT inspectors follow the guidelines laid out in the manual. These values are summarized in the table below:

Table 1.1. Qualitative Description of Crack Widths (AASHTO MBEI-2013)

Qualitative Description	**Crack Width (inches)**	
	Prestressed Concrete	**Conventionally-Reinforced Concrete**
Insignificant	<0.004	< 0.012
Moderate	0.004 to 0.009	0.012 to 0.050
Wide	> 0.009	> 0.050

While cracks listed in Table 1.1 may be insignificant from a structural standpoint, finer cracks have often been noted to leak through bridge decks and leaking cracks are not insignificant from a service life and durability standpoint.

1.5 Layout of Report

This report includes seven chapters, including Chapter 1 - Introduction.

Chapters 2 and 3 provide background and review of available literature and surveys on the use of polymer concrete overlays and sealers, respectively. The chapters include a description of the materials used for polymer concrete overlays and sealers, recommended practices for application and quality assurance testing, construction considerations, and a summary of survey results and expected costs.

Chapter 4 describes the method of selection for the use of polymer concrete overlays and sealers as preventive maintenance options. It includes description of steps for deck characterization and the advantages and disadvantages of polymer concrete overlays and sealers.

Chapter 5 provides an example for optimum timing of preventive maintenance using polymer concrete overlays and/or sealers. Service life models were developed for a typical bridge in Iowa and the results of the expected service life for the different models are provided.

Chapter 6 provides a summary of current practices for preventive maintenance as indicated in the literature. Recommendations for optimum timing of applying preventive maintenance are provided based on the results of the service life models and the benefit to cost ratio.

Chapter 7 summarizes the findings, conclusions, and recommendations for future implementation of polymer concrete overlays and sealers evaluated for this report.

CHAPTER 2. LITERATURE REVIEW AND SURVEY RESULTS ON THE USE OF POLYMER CONCRETE OVERLAYS

2.1 Polymer Concrete Overlays

The use of polymer overlays is reported to have started in the 1950s with the first systems consisting of single layers of coal tar epoxy broomed on the concrete deck with fine aggregates broadcast over the surface (ACI 548.5R-16). Oil-extended epoxy overlays were also used in the 1960s. The use of polymer concrete (PC) overlays consisting of resin (polyester-styrene, and methyl methacrylate monomer) and aggregate systems started in the mid-1970s where the overlays were typically applied using the broom-and-seed method; the resin is applied to the deck and aggregate is broadcast into the wet resin. After curing, excess aggregate is removed and usually one or two additional layers are applied. One of the main issues with the early polymer overlays was cracking and delamination due to thermal incompatibility, especially for thicker layers of overlay. Development of materials and construction methods specifically for rapid-setting polymer overlay applications started in the 1980s as the interest in this type of construction increased for use in high traffic urban bridges. This led to increased performance of the overlays as resins with larger elongation and lower modulus were developed to reduce problems associated with thermal incompatibility (Fowler and Whitney 2011) and aggregate shape and gradations were optimized to reduce resin contents.

Literature indicates that different types of polymer binder materials have been used by different states including epoxy, epoxy-urethane, polyester, and methacrylate. Epoxy-type polymer overlays are more commonly used nationwide, although polyester polymer concrete was successfully used in California and other Western states since the 1980s (Krauss 1988) and is now used in many other states.

The thickness of polymer overlays varies based on the materials used and the overlay as well as the method of application of the overlay. Typical thicknesses of polymer overlays range between 3/8 and 1 inch although thicker overlays of the polyester (PPC) have been successfully used. Recently, ultra-thin overlays of thicknesses ranging from 1/8 to 3/8 inches has also been used (CTC & Associates LLC 2012).

2.2 Materials Used in Overlays

2.2.1 Polymer Concrete

Polymer concrete (PC) is a composite material that is formed by the polymerization of a monomer or polymer and dry concrete aggregate mixture. The composites used to create polymer concrete do not include any hydrated portland cement phase. Polymerization typically take place through the use of certain chemicals, or catalysts, to combine the monomer and polymer molecules into polymer chains and three-dimensional networks (Mendis 1989; Kukacka et al. 1975). Through this process a liquid resin is transformed into a solid mass (the binder). Aggregates are then bound together by the polymer network to form polymer concrete.

The various chemical binders have different chemical compositions and, therefore, result in polymer concrete with varying uncured and cured properties. Uncured properties of polymer binders include viscosities of the individual or mixed components, gel time (working life), and flash point temperature. Important cured properties of polymer binders include compressive strength, tensile strength, tensile elongation, thermal expansion coefficients, permeability, modulus of elasticity, and bond strength. Note that the curing and cured properties also may vary greatly based on ambient temperature. Specifications published by AASHTO and ACI that provide recommendations for the material properties of different types of binders for polymer overlays include:

- AASHTO-AGC-ARTBA Joint Committee - Task Force 34 Report: Guide Specifications for Polymer Concrete Bridge Deck Overlays
- ACI Committee 548 - ACI 548.5R-16: Guide for Polymer Concrete Overlays
- ACI Committee 548 - ACI 548.8-07: Specification for Type EM (Epoxy Multi-Layer) Polymer Overlay for Bridge and Parking Garage Decks
- ACI Committee 548 - ACI 548.9-08: Specification for Type ES (Epoxy Slurry) Polymer Overlay for Bridge and Parking Garage Decks
- ACI Committee 548 - ACI 548.10-10: Specification for Type MMS (Methyl Methacrylate Slurry) Polymer Overlays for Bridge and Parking Garage Decks

The uncured and cured material properties of different polymer concrete binders as found in the literature are presented in the following sections.

2.2.2 Epoxy-Based Polymer Concrete Overlays

Epoxy is a general term for a class of compounds that are generally formed from a chemical reaction of two components: an epoxy resin and a curing or hardening agent, typically combined at ratios ranging from 1:1 to 1:3. Overlays constructed using epoxy binders typically have high bond strength and low initial shrinkage, and their properties are not affected by high alkalinity; therefore, these materials are suitable for application on concrete substrates. Epoxy overlays are typically installed using multiple-layer method (also known as broom and seed method). It is noted that many of the applications using epoxy based polymer concrete overlays do not require the use of primers. However, low-viscosity epoxies can be used to seal cracks prior to the application of the overlay (ACI 548.5.R-16); note that these low-viscosity epoxies are not suitable for use as a binder for the overlay itself. Typical ranges of uncured and cured properties for epoxy binders for polymer overlays are shown in Table 2.1; properties of specific products may vary.

Table 2.1. Typical uncured and cured properties of epoxy binders for polymer concrete overlays (ACI 548.5R-16, AASHTO-AGC-ARTBA 1995)

Property		**Value**	**Test Method**
Uncured	Viscosity	700 to 2500 cps*	ASTM D2556 No. 3 at 20 rpm. Brookfield RVT
	Gel time	15 to 45 minutes	ASTM C881 at 73°F
	Flash point	200°F minimum	ASTM D3278
Cured	7-day tensile strength	2000 to 5000 psi	ASTM D638 (Type I)
	Tensile elongation	30% to 70%	ASTM D638 (Type I)
	Modulus of elasticity	130,000 psi maximum	ASTM D695 compressive modulus
	Compressive strength	1000 psi at 3 hr 5000 psi 24 hr minimum	ASTM C579, Method B
	Thermal compatibility	Pass	ASTM C884, Method B
	Adhesive strength at 24 hr	250 psi minimum	ASTM C1583
	Rapid chloride permeability test at 28 days	100 coulombs maximum	AASHTO T 277 / ASTM C1202

*cps: centipoise

2.2.3 Polyester-Based Polymer Concrete Overlays

Polyester binders consist of two-component systems: a polyester-styrene resin and a small dose of promoter/initiator which is typically organic peroxide (Ribeiro et al. 2003). The properties of the polyester resin control the overall properties of the binder system, while the type of initiator primarily only affects the curing rate (ACI 548.5R-16). Typical uncured and cured properties for polyester binders for polymer concrete overlays are shown in
Table 2.2. Polyester overlays are typically installed using premix method being screeded to grade. Fine aggregate is broadcast on the surface for initial skid resistance

Curing and strength gain of polyester-based polymer overlays can be rapid, and accelerators are sometimes used in cool weather. Due to the presence of styrene, an aromatic compound, polyester-based overlays produce a strong odor during application. Typically, the use of primers is necessary with polyester systems; most commonly high molecular weight methacrylate (HMWM) is used. The polyester binder manufacturer's recommendations for the priming material should be followed.

Table 2.2. Typical uncured and cured properties of polyester binders for polymer concrete overlays (ACI 548.5R-16, AASHTO-AGC-ARTBA 1995)

Property		**Value**	**Test Method**
Uncured	Viscosity	100 to 400 cps	ASTM D2556 No. 3 at 20 rpm. Brookfield RVT
	Gel time	15 to 45 minutes	ASTM C881 at 73°F
	Flash point	100°F minimum	ASTM D3278
Cured	7-day tensile strength	1700 to 5000 psi	ASTM D638 (Type I)
	Tensile elongation	30% to 70%	ASTM D638 (Type I)
	Modulus of elasticity	130,000 psi maximum	ASTM D695 compressive modulus
	Compressive strength	1000 psi at 3 hr 5000 psi 24 hr minimum	ASTM C579, Method B
	Thermal compatibility	Pass	ASTM C884, Method B
	Adhesive strength at 24 hr	250 psi minimum	ASTM C1583
	Rapid chloride permeability test at 28 days	100 coulombs maximum	AASHTO T 277 / ASTM C1202

2.2.4 Methacrylate-Based Polymer Concrete Overlays

Methacrylate binders consist of two-component systems: a methyl methacrylate (MMA) resin and a small dose of initiator, which is typically organic peroxide. MMA monomer is the main component in the resin. Methacrylate overlays are slurry systems and, therefore, are combined with aggregates to form a thin overlay (ACI 548.5R-16). Typical uncured and cured properties for methacrylate binders for polymer concrete overlays are shown in Table 2.3.

Methacrylate primers are required with methacrylate overlays to increase the bond between the overlay and concrete substrate. Due to the sensitivity of MMA to wet conditions (as with most polymer overlays), the surface of the concrete must be completely dry before applying the overlay. Methacrylate top coats are also available and are used to lock in and encapsulate broadcast aggregate to the overlay. Typical uncured and cured properties for methacrylate primers and topcoats are shown in Table 2.4 and Table 2.5, respectively.

Table 2.3. Typical uncured and cured properties of methacrylate binders for polymer concrete overlays (ACI 548.5R-16, AASHTO-AGC-ARTBA 1995)

Property		**Value**	**Test Method**
Uncured	Viscosity	40 to 150 cps	ASTM D2556 No. 3 at 20 rpm. Brookfield RVT
	Gel time	10 to 30 minutes	ASTM C881 at 73°F
	Flash point	46°F minimum	ASTM D1310
Cured	7-day tensile strength	1000 to 2000 psi	ASTM D638 (Type I)
	Tensile elongation	30% to 70%	ASTM D638 (Type I)
	Modulus of elasticity	75,000 psi maximum	ASTM D695 compressive modulus
	Compressive strength	1000 psi at 3 hr 5000 psi 24 hr minimum	ASTM C579, Method B
	Thermal compatibility	Pass	ASTM C884, Method B
	Adhesive strength at 24 hr	250 psi minimum	ASTM C1583
	Rapid chloride permeability test at 28 days	100 coulombs maximum	AASHTO T 277 / ASTM C1202

Table 2.4. Typical uncured and cured properties of methacrylate primer (ACI 548.5R-16)

Property		**Value**	**Test Method**
Uncured	Viscosity	40 to 150 cps	ASTM D2556 No. 3 at 20 rpm. Brookfield RVT
	Gel time	20 to 40 minutes	ASTM C881 at 73°F
	Flash point	43°F minimum	ASTM D1310
Cured	7-day tensile strength	2500 to 6000 psi	ASTM D638 (Type I)
	Tensile elongation	2% to 10%	ASTM D638 (Type I)
	Modulus of elasticity	75,000 psi maximum	ASTM D695 compressive modulus
	Rapid chloride permeability test at 28 days	100 coulombs maximum	AASHTO T 277 / ASTM C1202

Table 2.5. Typical uncured and cured properties of methacrylate top coat (ACI 548.5R-16)

Property		**Value**	**Test Method**
Uncured	Viscosity	40 to 150 cps	ASTM D2556 No. 3 at 20 rpm. Brookfield RVT
	Gel time	10 to 300 minutes	ASTM C881 at 73°F
	Flash point	43°F minimum	ASTM D1310
Cured	7-day tensile strength	2500 to 6000 psi	ASTM D638 (Type I)
	Tensile elongation	30% to 70%	ASTM D638 (Type I)
	Modulus of elasticity	75,000 psi maximum	ASTM D695 compressive modulus
	Rapid chloride permeability test at 28 days	100 coulombs maximum	AASHTO T 277 / ASTM C1202

2.2.5 Aggregates

Different types of aggregates can be used in the overlays including silica, basalt, tap rock and quartz. All the aggregates used should be clean, dry and free from dirt, clay, asphalt, etc. Aggregate size and gradation are very important for workability, skid resistance, and wear. Aggregate content and resin content are directly related, which affect the overall uncured and cured material properties. Currently, polymer concrete overlay manufacturers provide the required filler aggregates specifically developed to obtain the desired physical properties from the overlay, such as flowability and permeability. AASHTO-AGC-ARTBA Task Force 34 report provides guidance regarding the required aggregate gradation and hardness for different types of polymer concrete overlays (AASHTO-AGC-ARTBA 1995). Sprinkel (2003) provides a summary of typical aggregate gradations for different types of polymer concrete overlay and different methods for overlay application.

Table 2.6. Typical aggregate gradation, percentage passing sieve (AASHTO-AGC-ARTBA 1995, Sprinkel 2003, ACI 548.5R-16)

Sieve No.	Multiple layer overlays	Slurry Overlays: Sand	Slurry Overlays: Fine Fillers	Premixed Overlays
0.13				100
0.10				83-100
No. 4	100			62-82
No. 8	30 to 75			45-64
No. 16	0 to 5	100		27-50
No. 20		90-100		
No. 30	0 to 1	60-80		12-35
No. 40		5-15		
No. 50		0-5		6-20
No. 100				0-7
No. 140			100	
No. 200			98-100	0-3
No. 270			96-100	
No. 375			93-99	

For aggregate broadcasting applications, ACI 548.5R-16 provides recommendation for the required aggregate size for polymer concrete overlays on bridge decks, similar to multiple-layer overlays gradation as shown in Table 2.6. These recommendations are identical to those outlined in AASHTO-AGC-ARTBA Task Force 34 report. In addition, the aggregate should have a Mohs scale hardness of 7 or greater if angular-silica is used or hardness of 6 or greater if basalt is used. Aggregate must be dry when added to polymers and the moisture content in the aggregate should be less than 0.2% when tested in accordance with ASTM C566 and the weight loss should meet the requirements of AASHTO T 103 (ACI 548.5R-16).

2.3 Recommend Practices for Installing Polymer Concrete Overlays

Three different methods have been used to install polymer concrete overlays: multiple-layer overlay, slurry overlay, and premixed overlay. All of the methods require that the surface of the concrete bridge deck be cleaned and adequately prepared to achieve good bond with the overlay as discussed in following sections.

2.3.1 Multiple-Layer Overlay

Multiple-layer overlays, also known as broom-and-seed overlays, are built through applying a polymer binder or resin on the top of a prepared concrete deck, followed by broadcasting of gap-graded aggregate over the surface (Figure 2.1). Unbounded aggregate is then removed once this layer is cured, and a new layer is then applied. This process is typically applied to form two or three layers, with an approximate overlay thickness of 1/4 to 3/8 inch. The resin content in this type of application is typically 25% by weight (AASHTO-AGC-ARTBA 1995, Sprinkel 2003) or higher. Contractors may favor this method due to the less labor and equipment involved; however, the resulting surface does not correct elevation or grade deficiencies and may result in a rough riding surface.

Figure 2.1. Typical placement of resin for multiple-layer concrete overlay (Courtesy: KwikBond Polymers). Resin is applied followed by an aggregate broadcast.

2.3.2 Slurry Overlay

Slurry overlays are built through mixing the polymer concrete binder (which can be epoxy, polyester or methacrylate) with fine aggregates and applying the slurry to the concrete deck with hand tools, as shown in Figure 2.2. To achieve the desired surface texture, aggregates (No. 6 to 16) can be broadcast on the surface similar to the multiple-layer method. Some slurry mixes require the use of a prime coat to improve bond and seal coat to lock in surface aggregate. Manufacturer recommendations should be followed for primer and seal coat applications. This process typically results in an approximate overlay thickness of 3/8 inch, but ranges from 1/4 to 3/4 inch. The resin content in this type of application is typically near 24% by weight (AASHTO-AGC-ARTBA 1995, Sprinkel 2003). Equipment and labor may be more than broom and seed methods but birdbaths and other minor surface deficiencies can be corrected. The high resin content makes the system prone to delamination in locations with extreme temperature swings and skid friction may decrease with time. Further, it can be difficult to apply to decks with steep grades or cross slopes.

Figure 2.2. Typical placement of slurry concrete overlay (Courtesy: Transpo)

2.3.3 Premixed Overlay

Premixed overlays are built though mixing the polymer concrete binder (which can be epoxy or polyester) with graded coarse and fine aggregates. Similar to slurry overlays, a primer is typically applied to increase the bond between the overlay and the bridge deck. The overlay is then placed and finished similar to conventional concrete using vibratory compaction by a vibratory screed. Aggregates can be broadcast on the finished surface to obtain the desired surface texture and increase initial friction. This process typically results in an approximate overlay thickness of 3/4 to 1 inch, but they can be much thicker. The resin content in this type of application is typically 12% by weight (AASHTO-AGC-ARTBA 1995, Sprinkel 2003). This lower resin content not only reduces cost but also reduces shrinkage and improves thermal compatibility. Figure 2.3 shows typical application of premixed polymer concrete overlay.

Figure 2.3. Typical placement of premixed polyester concrete overlay using a vibratory screed (Courtesy: KwikBond Polymers).

2.3.4 Specifications

AASHTO and ACI have published four national specifications for application of polymer concrete overlays as follows:

1. Guide Specifications for Polymer Concrete Bridge Deck Overlays, AASHTO-AGC-ARTBA Task Force 34, Washington, D.C., 1995.
2. Specification for Type EM (Epoxy Multi-Layer) Polymer Overlay for Bridge and Parking Garage Decks, An ACI Standard, Reported by ACI Committee 548, ACI 548.8-07, American Concrete Institute, Farmington Hills, Mich., 2007.
3. Specification for Type ES (Epoxy Slurry) Polymer Overlay for Bridge and Parking Garage Decks, An ACI Standard, Reported by ACI Committee 548, ACI 548.9-08, American Concrete Institute, Farmington, Hills, Mich., 2008.
4. Specification for Type MMS (Methyl Methacrylate Slurry) Polymer Overlays for Bridge and Parking Garage Decks, An ACI Standard, Reported by ACI Committee 548, ACI 548.10-10, American Concrete Institute, Farmington, Hills, Mich., 2010.

2.4 Construction Considerations and Test Methods

Polymer concretes have high ability to bond to clean, dry, sound concrete bridge decks. Installation of polymer concrete overlays on severely deteriorated decks is not recommended as failure within the substrate will be likely to occur (AASHTO-AGC-ARTBA 1995) resulting in spalling of the bonded, composite overlay. In addition, due to the bold exposure of decks and the different coefficients of thermal expansion of these materials as compared to concrete, proper surface preparation is a very important factor to ensure good, long lasting bond between the overlay and bridge deck. It is recommended to apply overlays to surfaces that are clean, dry, and physically sound. Active, moving cracks should not be bridged with bonded composite overlays, but a joint should be installed at these locations. Recommended practices for successful application of polymer concrete overlays include: evaluating the concrete surface before applying the overlay, repairing the surface, sealing large cracks in the bridge deck, and cleaning and preparing the surface (Carter 1997).

2.4.1 Initial Evaluation

Evaluating the bridge deck includes visual inspection and sounding of the deck to detect deteriorated or degraded areas. Different methods can be used for this purpose, including chain drag, hammer sounding, infrared thermography, material sampling (i.e. coring), impact echo, and impulse response methods. Literature sources also recommend chloride-contaminated concrete should also be located, removed and replaced (AASHTO-AGC-ARTBA 1995), although practically, the amount of removal should be limited to areas and depths that are likely to initiate corrosion in the deck reinforcement if left in place and it is usual to avoid exposing embedded reinforcing steel. Polymer overlays are often applied to chloride contaminated decks, often with active corrosion, with reasonable success. The polymer overlay will prevent moisture penetration into the deck, thereby eventually slowing the corrosion rate of the embedded steel as the concrete dries. Some continued spalling or damage should be anticipated on actively corroding decks after the overlay is placed although at a lesser rate than if no overlay was applied. However, even better performance is achieved if the overlay can be applied prior to active corrosion in the deck.

Cores or drilled powder samples[1] can be used to evaluate the chloride concentration at different depths in the bridge deck. Half-cell potential measurements per ASTM C876 can be used to detect areas with high probability of corrosion that may lead to corrosion initiation and damage propagation in the future. It is recommended to remove all concrete around corroding steel and clean the exposed steel by abrasive blasting to remove the chloride contamination surrounding the steel; however, in practice this is not always practical. Literature sources also recommend that concrete with compressive strength less than 2000 psi should also be removed, although practically, this is a rare occurrence for bridge deck concrete.

ACI recommendations include that all removed concrete (delaminated, chloride contaminated, and weak) should be replaced by portland cement concrete (ACI 548.5R-16). For the purpose of the overlay, the repair concrete should have properties that enable good placement in a repair patch (i.e. good consolidation, flowability, low shrinkage, etc.), but need not have physical properties that are in excess of the surrounding deck concrete. The concrete should be left to cure for 28 days prior to applying the overlay[2]. Materials that will cause out-gassing, such as rapid-setting magnesium phosphate cement concrete, should not be used for patching or repairing the bridge deck, as they have adverse effects on the long term performance of the polymer overlay (ACI 548.5R-16). Bond strength tests should be completed to all repair materials prior to installing the overlay as some additives can inhibit good bond. Polymer overlays that are premixed and screeded can be used to fill in spalls or voids in the deck prior to or during overlay placement to speed construction; manufacturer recommendations should be followed for such applications.

[1] Drilled powder samples are used by some researchers to obtain chloride content measurements; however, as compared to coring, powder samples are subject to much greater variability and scatter in data, limiting their usefulness for predictive modeling.

[2] The need for 28-day cure is primarily to allow moisture to equilibrate for ordinary portland cement-based repair materials. The polymer materials discussed in this report are not highly sensitive to the alkaline pH in recently-cast portland cement concrete, but may be sensitive to high moisture content or vapor drive that could occur from a newly-placed material. Some cementitious repair materials are specially designed for shorter curing and drying periods and may have overlays placed in less than 28 days.

Polymer concrete overlays are not intended to be used for structural concrete repairs. Moving cracks and large stationary cracks in the bridge deck will reflect through the overlay if not repaired prior to overlay application or treated as a joint. Moving cracks should not be bridged by the overlay material alone, and may require elastomeric sealants or other details to limit moisture ingress into the crack. For large stationary cracks, it is recommended that cracks are filled prior to applying the overlay (Sprinkel 1997, Sprinkel 2003). The repair material used for patching or filling the cracks should be compatible with the overlay. Typically lower-viscosity polymer (epoxy or methacrylate) materials can be used for this purpose. All materials used for repairing the concrete substrate should be allowed to cure properly prior to applying the overlay (AASHTO-AGC-ARTBA 1995).

For newly constructed bridge decks, polymer concrete overlays should be applied at least 28 days after casting the deck. This will allow proper curing of the bridge deck and will also decrease moisture content of the concrete surface to prevent excessive moisture vapor pressure (AASHTO-AGC-ARTBA 1995).

2.4.2 Surface Preparation

Surface preparation includes cleaning and preparing the surface of the bridge deck for overlay application. Uneven surfaces should be corrected prior to the application of overlay as irregularities may lead to increased local stresses. Avoid rapid changes in overlay thickness. The surface of the concrete should be dry and clean of dirt, oil laitance and other materials that can affect the bond between the concrete and overlay. Surface preparation can be achieved by shot-blasting or abrasive blasting. Wet abrasive blasting and hydroblasting are effective but are generally not done as it will result in a wet surface that will require additional time to dry prior to overlay placement. Other impact based methods such as chipping hammers and scabblers may also be used especially to remove thicker portions of concrete material or of edge detail work. However, these methods may lead to micro-cracking in the prepared surface and, therefore, should be followed by shot-blasting to correct for the micro-fracturing (Nader and Mendis 1997).

The prepared surface should be evaluated prior to installing the overlay. This can be achieved using visual inspection of the prepared surface and comparison to the specified roughness; for example, a minimum surface profile CSP 5 as defined by ICRI 310.2R. Other surface profiles may be recommended by product manufacturers depending on bonding performance of specific materials. Adhesive strength tests should also be conducted to evaluate the bond strength of the polymer concrete overlay to the deck, which are discussed further in the next section.

Proper handling and storage of polymer components is essential and excessive heat must be avoided. Due to the sensitivity of polymer concrete binder reactions to temperature, take special consideration of the manufacturer recommendations regarding the ambient and surface temperature during polymer concrete overlay placement. The viscosity of the polymers decreases with an increase of temperature, and at high temperature the polymer may be too thin for proper broom and seed applications. Other properties are also affected by temperature changes including curing time and workability. Maximum temperatures for placement are commonly limited to 95°F (ACI 548.5R-16). Cold temperatures increase resin viscosity and slow reaction time and cure. Fowler and Whitney (2011) report minimum placement temperature by DOTs in the range of 50 to 60°F, while the minimum temperature recommended by North Carolina DOT is 75°F. It is noted that some resin formulations can be placed at much colder temperatures.

2.4.3 Quality Control

Quality control/assurance tests should be performed to verify the quality and the adequacy of the polymer concrete overlay materials as well as the quality of the substrate surface preparation. The uncured and cured properties of the binder and overlay should be tested and verified. The moisture content and soundness of the aggregate should also be evaluated. Details regarding the properties of binder, polymer concrete overlay and aggregate are provided in Section 2.2 *Materials Used in Overlays*. A list of recommended material tests can be found in Table 2.1 through Table 2.3. Caltrans *California Test 551* (CA551) provides a useful reference for testing polymer overlay and deck repair concretes.

The substrate tensile strength and overlay bond strength should also be evaluated based on ASTM C1583 or test methods described in ACI 503R or CA551. A number of minimum bond strength values has been specified for overlay materials, often ranging between 100 and 250 psi (Sprinkel 1997; ACI 548.8-07; Sprinkel 2016). A minimum direct pull strength of 250 psi strength should be readily achieved for polymer overlays placed on clean, sound concrete. It is recommended to remove and replace the concrete if the tensile strength is below the recommended value.

Surface preparation and resin formulation are the most important factors in developing adequate bond between the polymer concrete overlay and the bridge deck. Surface roughness and tensile bond strength should be evaluated to develop and verify proper surface preparation techniques. For example, shot-blasting properties such as the forward speed, size and flow of abrasive material, and number of passes should be established to achieve the desired roughness and bond strength (ACI 548.5R-16). A minimum surface roughness of ICRI CSP 5 profile has been used; however, material suppliers' recommendations in a recent survey indicated that a surface roughness of ICRI CSP 7 is desirable, with a minimum roughness of ICRI CSP 6 (Fowler and Whitney 2011). Typically, large amplitudes are not needed for excellent bond but a well cleaned surface is important. Tensile bond strength tests should also be conducted per the general requirements of ASTM C1583 or ACI 503R. The bond test should not be performed if the temperature is more than 80°F (AASHTO-AGC-ARTBA 1995) as failure may occur at values less than 250 psi. The results can then be compared to the criteria per ACI 548.5R-16 where acceptable strength should result in the following:

- Minimum tensile rupture strength of 250 psi from an average of three tests regardless of the depth of failure.
- Failure in the base concrete at a depth of at least 1/4 inch over more than 50 percent of the test area for three of four tests.

The application rate of the different types of polymer concrete overlay should conform to the requirements of the AASHTO-AGC-ARTBA Guide Specification. Sprinkel (2003) provided a summary table for typical application rates for multiple-layer epoxy, methacrylate slurry and premixed polyester overlays. Recommended application rates of resin and aggregates for multiple-layer polymer concrete overlays are also provided in ACI 548.5R-16.

Polymer concrete overlays should be sufficiently cured prior to opening to traffic. This is to ensure that the overlay will not deform under traffic loads and lose bond or aggregate. The curing time varies based on the type of binder used, binder and initiator content, and ambient temperature. A minimum compressive strength of 1000 psi per ASTM C579, Method B is recommended for verifying that the overlay has sufficiently cured for traffic. Minimum recommended time for deck overlays that have been successfully applied is shown in Table 2.8 (Sprinkel 2003).

Table 2.7. Typical polymer concrete application rates (Sprinkel 2003)

Overlay	**Multiple Layer Epoxy (kg/m^2)**	**Methacrylate Slurry (kg/m^2)**	**Premixed Polyester (kg/m^2)**
Thickness (mm)	6.4	7.6	19.1
Prime Coat	-----	0.41+0.14/-0	0.41+0.14/-0
Layer 1 resin	1.1±0.14	2.7±0.27	5.29±0.41
Layer 1 aggregate	5.4±0.54	6.5±0.54	38.6±0.54
Layer 2 resin	2.2±0.14	-----	-----
Layer 2 aggregate	7.6±0.54	7.6±2.7	-----
Seal Coat resin	-----	0.68+0.14/-0	-----
Approx. resin content (%)	25	24	13

*1 kg/m2 = 1.84 lb/yd2, 1 mm = 0.039 inch

Table 2.8. Minimum curing time for different types of binder (Sprinkel 2003)

Property	**Epoxy**	**Polyester**	**Methacrylate**
Cure Time @ 90°F (32°C)*, h	2	2	2
Cure Time @ 75°F (24°C)*, h	3	3	3
Cure Time @ 60°F (16°C)*, h	6-8	5-6	4

*Based on time required to obtain a minimum compressive strength of 1,000 psi

2.4.4 Storage, Handling and Safety

All polymer overlay materials should be stored in dry, cool places to prevent them from getting wet or hot. The materials should also be placed away from open flames or sources of ignition, at a temperature between 50 and 90°F. The safety data sheets and manufacturer recommendations for storage and handling of the polymer overlay materials should be followed at all times. Some polymer resins are toxic and only safe to be used if handled appropriately. Personal protective equipment should be used while handling the polymers as specified by the manufacturer. A plan to dispose of excess material and empty containers should be established per the local environmental requirements (ACI 548.5R-16).

2.5 Summary of Survey Results in Literature

The literature includes a number of studies investigating the use of polymer concrete overlays by different states. Of these studies, some included surveys of past experience with different types of overlays. This section aims to summarize the results of these studies.

2.5.1 Use of Polymer Concrete Overlays

Fowler and Whitney (2011) conducted a survey of different states and Canadian provinces to investigate the use of polymer concrete overlays. They reported the responses they received from 40 states and 7 provinces. According to the survey, states had installed approximately 2400 polymer concrete overlays (also referred to as thin polymer overlays [TPOs]) while 140 polymer concrete overlays were installed by provinces. This represents a 400% increase on 555 overlays installed by the states as reported by Sprinkel (2003).

Among the surveyed states, California has installed the highest number of overlays with 520 overlays installed, starting in 1983. Seven other states have also reported the use of more than 100 overlays. A breakdown of the number of overlays installed by state can be found in Fowler and Whitney (2011).

The common reasons reported by the states for the use of overlays include (Fowler and Whitney 2011):

- Restoring surface friction (most cited reason)
- Extending life of the bridge including additional cover (second most cited reason)
- Restoring uniform appearance of deck surface
- Restoring surface to previous spalled, cracked, and repaired deck
- Waterproofing the deck

The results of the survey also indicated that the majority of the states use epoxy-based polymer concrete overlays and that the preferred method of construction is multiple-layer overlay. However, in California and other west coast states, the preferred method is premixed polyester concrete (PPC) overlay. Most of the states that install overlays regularly have specifications available.

Fowler and Whitney (2011) reported that polymer overlays are no longer considered for use in three states (Florida, Iowa, and Montana) and two provinces (Alberta and British Columbia). Florida reported that polymer overlays have been installed on segmental bridges, but that they do not currently have major deck degradation problems requiring overlays (Fowler and Whitney 2011). According to Fowler and Whitney (2011), Montana cited that it was too time consuming to enforce specifications for successful overlay installation installed by local contractors that may not have the proper experience. Iowa reported not using polymer overlays due to the poor performance of a trial overlay installed in 1986 (Fowler and Whitney 2011). Our correspondence recently with Iowa DOT indicates that Iowa had one polymer concrete deck overlay project last year. In Canada, Alberta reported several problems with initial overlay installation but achieved satisfactory results later on. However, the use of overlays was discontinued due to wet, rainy conditions and difficulty of achieving proper inspection in some part of the province. British Columbia reported installing two overlays and discontinued its use after poor performances.

CTC & Associates LLC (2012) conducted a survey to investigate the use of ultra-thin polymer concrete overlays ranging in thickness from 1/8 to 3/8 inch. The survey included 13 states: California, Illinois, Kansas, Michigan, Missouri, New York, Ohio, Oregon, Utah, Virginia, Washington, Wisconsin, and Wyoming. All states surveyed reported the use of ultra-thin polymer overlays and provided a list of approved materials (mainly epoxy-based binders), which can be found in CTC & Associates LLC (2012). The age of the deck when overlays were used varies, but it was reported that the median age is 15 to 20 years. Common reasons for applying ultra-thin overlays:

- Restoring surface friction
- Sealing cracks on fairly new bridge decks with good condition rating and low delamination
- Some states reported using ultra-thin overlays on older decks (10 to 40 years) and on decks with delamination of up to 15%.

Both Illinois and Utah also reported using overlays on new bridge decks as a preventive measure, as a sealer or when the contractor has made an error. Utah reported using overlays on all new decks (CTC & Associates LLC 2012). For new bridge decks, polymer overlays can provide additional protection to the concrete and reinforcing steel by preventing the absorption of chloride ions.

2.5.2 Overlay Performance

Sprinkel (2003) reported the deck performance for a number of bridges in Virginia with different types of overlays with ages varying from 6 to 19 years. The overlays tested were multiple-layer epoxy (MLE) overlays, multiple-layer epoxy urethane (MLEU) overlays, premixed polyester (PP) overlays, multiple-layer polyester (MLP) overlays, and methacrylate slurry (MMS) overlays.

Figure 2.4 shows the tensile bond strength for the different overlays measured using Virginia Test Method - 92, Virginia Department of Transportation (similar to ASTM C1583 and ACI 503R). As shown in the figure, the results MLE overlays, MLEU overlays, and PP overlays indicate no change in the tensile bond strength over time. MLP overlays showed a loss in strength with time and may fail after approximately 10 years, while no sufficient data was available for MMS overlays (Sprinkel 2003). It is noted that Sprinkel (1989) reported that for some bridges, low initial tensile bond strength was reported when traffic was allowed on the bridge after shot-blasting and before overlay application.

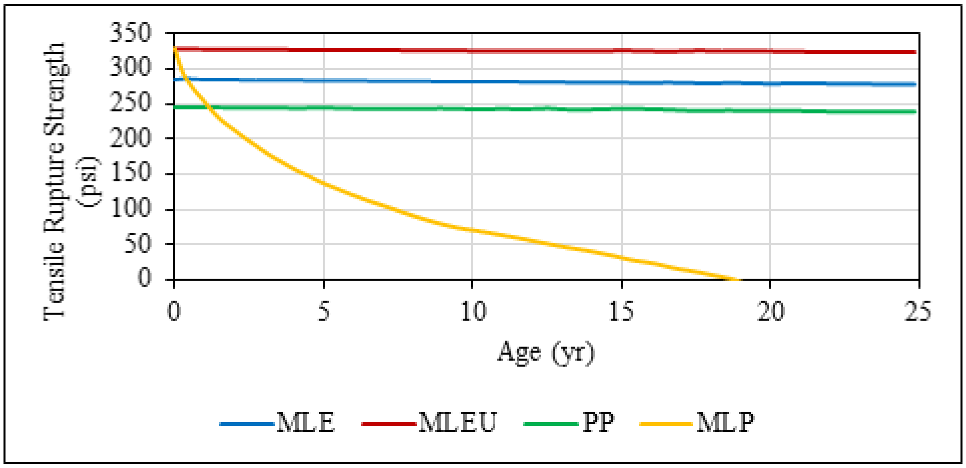

Figure 2.4. Tensile rupture strength versus age of polymer concrete overlay (Reproduced from Sprinkel 2003).

Electrical conductivity (AASHTO T 277) of the top 2 inches of the overlay and the deck was evaluated over time by Sprinkel (2003), as shown in Figure 2.5. As can be seen, the lowest conductivity is provided by the MMS overlay, while MLE, MLEU and PP overlays exhibited very low conductivity throughout their life. The MLP overlays increased conductivity over time at a sharper rate than any of the other materials evaluated and exceeded 1000 Coulombs after 10 years in service.

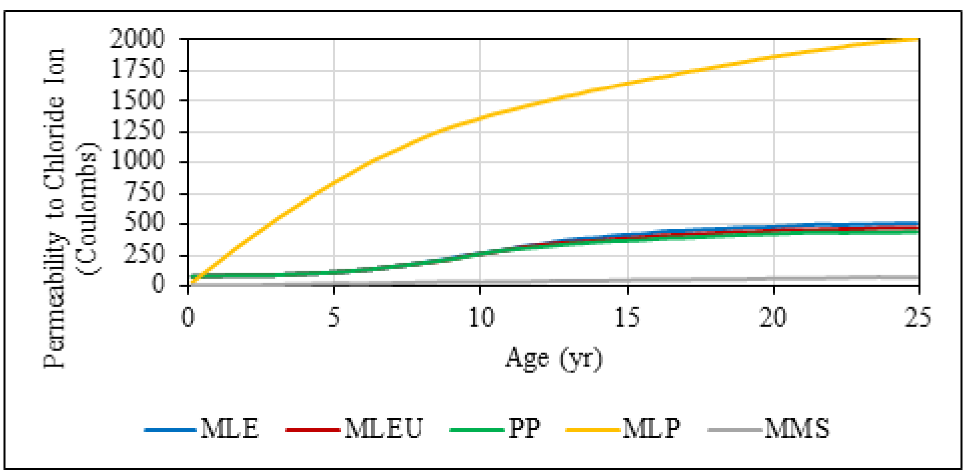

Figure 2.5. Permeability to chloride ion versus age of polymer concrete overlay (Reproduces from Sprinkel 2003).

Sprinkel (2003) also evaluated the skid resistance of the different overlays using bald tire skid number (ASTM E 524). As shown in Figure 2.6, new overlays had bald tire skid number of 50 to 60 while aging overlays had a value of 30 to 50 after approximately 20 years of service. The only exception was MMS overlays, which typically showed continued decrease in skid resistance with age. While PP overlay started with the lowest skid resistance, skid resistance increased with age and was the highest after 25 years.

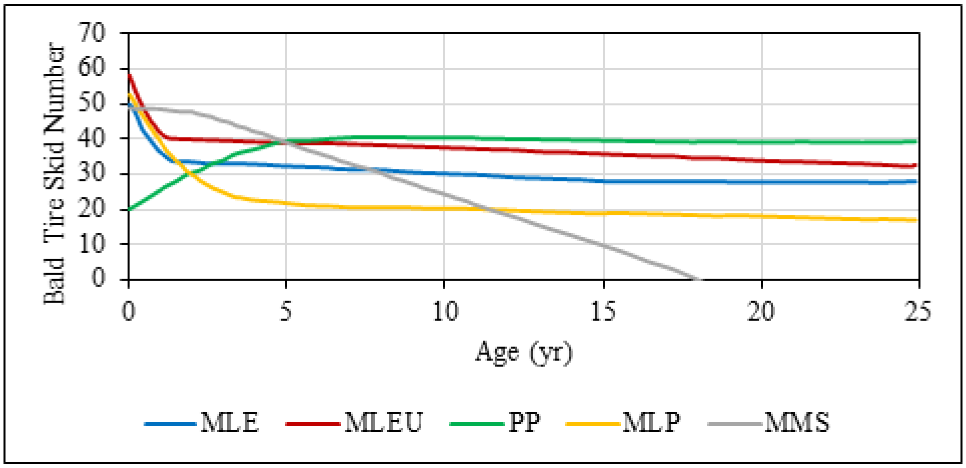

Figure 2.6. Bald tire skid number (ASTM E 524) versus age of polymer concrete overlay (Reproduced from Sprinkel 2003).

Fowler and Whitney (2011) survey reported several case studies on the use of polymer concrete overlays. This includes studies in Alabama, California (Krauss 1988), Kansas, Louisiana, Michigan (Nabar and Mendis 1997), Montana, New York (NYS-DOT 2007), Ohio (Nabar and Mendis 1997), Pennsylvania, Texas (Zalatimo and Fowler 1997), Virginia (Nabar and Mendis 1997, Sprinkel 2003), Washington (Wilson and Henley 1995, Nabar and Mendis 1997), Alberta (Carter 1993, 1997) and Panama (Fowler and Whitney 2011). In general, epoxy overlays were the most common type of polymer concrete overlay. Good performance was observed in the majority of cases. Cracking and limited delamination were observed in some cases but were mainly attributed to the poor condition of the original bridge deck.

Kansas Department of Transportation (KDOT) reported experience indicating successful installations of polymer overlays and good performance achieved. The main purpose of using the overlays in Kansas was to protect the deck from deicer and chloride intrusion. Washington and New York DOTs also investigated the use of different types of overlays. Epoxy and polyester overlays were reported to have good performance; however, methacrylate overlays were found to deteriorate over time in terms of tensile bond strength, frictional resistance, and observed delamination. Alabama also reported excellent performance of epoxy overlays after 8 years of service (Fowler and Whitney 2011). In California, Krauss (1988) reported successful installation and good performance of premixed polyester overlays. Methacrylate primers are used with this type of construction to seal cracks and enhance bond strength (AASHTO-AGC-ARTBA 1995). Washington State DOT also uses polyester polymer concrete (PPC) overlays with high molecular weight methacrylate (HMWM) primer. Recent bridge inspections indicate that very good to excellent performance has been reported for 17 out of 22 bridges in Washington (Anderson et al. 2013).

For ultra-thin polymer overlays, CTC & Associates LLC (2012) reports that the performance has been satisfactory. Some problems have been reported with this type of overlay but they generally coincide with the initial deteriorated bridge deck condition. Ultra-thin polymer overlays are only recommended to be installed if the condition of the deck is good.

2.5.3 Causes of Failure

Reviewed literature indicates that majority of failures are observed when the condition of the bridge deck is poor, with excessive cracking and delamination when the overlay is placed. Therefore, some states have established limits on the bridge deck condition where the use of polymer concrete overlays is permitted. According to the survey by Fowler and Whitney (2011), the most identified causes of failure are:

- Poor condition of bridge deck
- Inadequate preparation of repaired areas ("not sufficiently dry and/or not roughened")
- Poor overall surface preparation
- Installation during cold and damp weather
- Insufficient drying of the deck prior to installation
- Construction errors
- Poor quality control
- Snow chains used on overlay

Carter (1993, 1997) also reported observations on causes of failure of overlays in Alberta. A main factor observed was contractor experience. Overlays placed by experienced contractors generally performed better than overlays placed by a contractor with less experience. Errors in mixing and measuring resin components were observed, leading to defective polymer overlays. Moisture content in the deck also played a major role in overlay performance. Areas near gutters and other low areas where ponding occurs usually have higher moisture contents, which can result in a poor bond between the overlay and deck. Carter (1993) suggested that patching should be completed well prior to surface preparation and that patches should be wet cured to reduce shrinkage and debonding. It is also recommended to use shot-blasting for surface preparation; water-blasting should not be allowed.

Carter (1997) reported that some polymers may lose flexibility when subjected to ultraviolet radiation and aging. Delaminations were observed when polymer concrete overlays with high tensile strength were used. Due to the cold climate in Alberta, thermal compatibility was major factor for number of failures, especially for thick polymer overlays. As temperature drops to -40 °F, the overlay becomes more brittle and shrinks. Concrete has a smaller coefficient of thermal expansion than polymers, which, if material temperatures are uniformly decreasing, results in high shear stresses at the bond line. Since the shear stress is a function of the overlay thickness, Carter (1997) recommended using thin polymer overlays in cold climates.

Reflective cracks can also reduce the protection provided by the overlay to the bridge deck. The recommended practice is to seal and bond all cracks prior to applying the overlay (AASHTO-AGC-ARTBA 1995). It is also recommended to seal cracks that reflect through the polymer overlay surface as they appear.

Material incompatibility can cause failure and debonding of the polymer concrete overlay. A case reported by Fowler and Whitney (2011) indicates that HMWM primer caused severe delamination of the epoxy-based slurry overlay used on the Bridge of the Americas in Panama. Laboratory tests conducted on the material used on the bridge showed that a good bond was achieved initially but that the bond deteriorated after several months if the concrete had been primed with the methacrylate. Similar anecdotal observations have been made regarding the loss of bond strength with time when epoxy overlays are placed on high-molecular-weight methacrylate resin treated surfaces (Fowler and Whitney 2011).

2.5.4 Cost of Overlay

Several factors influence the overall cost of installing an overlay. These include the direct cost of materials, labor, and equipment; surface preparation; and traffic control. While the in-direct costs of traffic delays has been ignored in this analysis, it can be an important factor for selecting rapid curing polymer overlays over conventional concrete overlays. The costs are expected to vary based on the type of binder used and the project bidding requirements. However, for comparison purposes, costs published by Fowler and Whitney (2011), Anderson et al. 2013 and Texas Department of Transportation low bid item list are summarized in Table 2.9.

Table 2.9. Cost of polymer concrete overlays

Source	**Overlay Type, Location**	**Installation Year**	**Cost/yd^2**
Fowler and Whitney 2011	MLE, Virginia	2005	$50
Fowler and Whitney 2011	Not specified, Kansas	2001-2008	$55, Average cost*
Fowler and Whitney 2011	Epoxy-urethane, Alaska	2007	$95
Texas low bid item list	Multi-layer polymer overlay (epoxy or MMA)	2016-2017, two projects	$45 to $86, Range
Anderson et al. 2013	PPC, Washington	2003-2007, five projects	$77.4 to $153 Weighted average = $96.6

*Including shot blasting and overlay placement

Although a detailed cost study was not performed, the listed prices indicate that PPC overlays may be more expensive than MLE overlays, with exception to Alaska were generally higher prices are expected. Anderson et al. (2013) reported that a PPC manufacturer indicated that $90/yd^2 is a reasonable price for PPC overlays of large bridge decks. This price includes surface preparation and overlay installation. Anderson et al. (2013) also reported that Caltrans are seeing reduction in costs for PPC to as low as $63/yd^2 installed. Prices will vary based on location, contractor experience, and the size of the project.

Although the price of overlay materials may be higher than regular concrete on a volumetric basis, the overall cost of polymer overlays is usually less than the cost of regular concrete overlays. This primarily attributed to the fact the polymer overlays require less curing time and, therefore, less traffic control, which is a major factor in the overall cost of the maintenance. This also makes overlays a more attractive solution for bridges with heavy traffic that cannot be closed for extended periods of time. Kansas DOT reports that the cost of traffic control for polymer concrete overlays is approximately 12% of that required for silica fume concrete overlays (Fowler and Whitney 2011).

According to Sprinkel (2003), the overall price of multiple-layer epoxy polymer concrete overlay in Virginia is about 36% of that for conventional concrete overlay, assuming a 15 year service life for the polymer overlay and a 30 year life for the conventional concrete. This comparison includes miscellaneous costs associated with conventional concrete overlays including building up approach slabs and replacing joints. The price of premixed polyester overlay is slightly higher than multiple-layer epoxy overlays, while methacrylate slurry is the most expensive of the three types (Sprinkel 2003).

CHAPTER 3. LITERATURE REVIEW AND SURVEY RESULTS ON THE USE OF DECK SEALERS

3.1 Sealers

Sealers are typically used to reduce permeability and the limit the ingress of water and deicing salts into reinforced concrete bridge decks. By doing so, sealers are intended to extend the service life of the deck by extending the time to initiation for corrosion of reinforcing steel. The ability of sealers to protect the deck from water ingress potentially reduces the rate of deterioration from other types of concrete distress. While moisture itself is not a direct cause of damage, presence of high moisture contents helps accelerate different types of concrete degradation mechanisms such as freeze-thaw damage, alkali-silica reaction, delayed ettringite formation, and salt crystallization. However, sealers are not likely to prevent these various concrete degradation mechanisms.

Sealers can be mainly classified into two categories: deck sealers and crack sealers. Deck sealers are used to coat the entire deck with a penetrating or barrier sealer, which slows moisture and chloride ingress. Crack sealers are typically applied in local areas of the deck to seal cracks and to prevent rapid ingress of moisture and chloride ions. Different chemicals have been developed and used as sealers including silanes, siloxanes, linseed oil, methacrylate, epoxies and polyurethanes. Crack sealers are most commonly epoxy or high molecular weight methacrylate (HMWM). An overview of materials used in deck and crack sealers is presented in this chapter. This report mainly focuses on deck penetrating sealers (silanes, siloxanes, silicates). Other types of sealers including film formers and crack sealers will only be briefly discussed.

3.1.1 Deck Sealers

Deck sealers are typically classified into two categories; penetrating sealers and film formers (coatings). The performance of different types of sealers is typically measured through the following: depth of penetration, vapor transmission, and chloride ingress (Johnson et al. 2009).

Penetrating sealers are made of materials with small molecules to penetrate and bond to the concrete. They protect the concrete by forming a hydrophobic layer in the treated area. Penetrating sealers do not produce a continuous membrane as a physical barrier to prevent water from penetrating the concrete rather they allow the concrete to form a chemical repulsion of water (Aitken and Litvan 1989). Depending on the density, finish, and pore structure of the near-surface of the concrete, penetrating sealers may achieve a depth of 0.25 inch. Commonly used penetrating sealers are silanes, siloxanes, siliconate and linseed oil; although some researchers reported that the latter should not be classified as penetrating sealer (Soriano 2003).

Film formers (coatings) and pore blockers are used to form a physical barrier on the concrete deck surface. Film formers are typically applied with a thickness in several thousands of an inch and cannot penetrate into the concrete paste. Different types of film forming sealers include epoxy, polyester, acrylics, polyurethanes, and HMWMs resins. Linseed oil was one of the first sealers to be used, but epoxies and polyurethanes are the two current most commonly used film forming sealers. One notable drawback for film forming sealers is that they may negatively affect surface friction. Krauss et al. (2009a) indicated that some DOTs broadcast sand into epoxy coatings for improved skid resistance, while other DOTs do not allow coatings on driving surfaces. Film forming sealers may have low ability to pass water vapor (Cady 1994).

3.1.2 Crack Sealers

Crack sealers are used primarily to fill cracks in concrete decks to prevent passage of moisture and deicing salts through the crack, thereby providing protection to the deck reinforcement from corrosion damage. Different types of materials can be used for sealing deck cracks including HMWMs, epoxy and urethane resins. Typical methods for using these materials to fill and bond the cracks are through injection or gravity feed.

Correlation is often observed in bridge decks between cracking and deterioration because cracks have a higher transport rate for chlorides and oxygen than sound concrete. For long service life, cracks allowing chloride penetration to the reinforcement should be treated and adequately sealed soon after formation in areas subject to direct contact with deicers.

In WJE's experience on recent major new bridge projects, there has been significant discussion regarding the minimum crack width that is required to be sealed for long-term (100 year) service life. As a starting point, some projects have referred to AASHTO LRFD Bridge Design Specifications, Section 5.7.3.4, that provides an equation to calculate crack width due to flexure. In this section, Class 2 exposure is defined as areas with an increased risk of corrosion and results in an upper bound of 0.013 inch for cracks. Other industry guidelines have lower values, including Section 6.6 of ACI 357.3R-14 that states "Although a direct correlation between concrete surface crack widths and corrosion of reinforcement has not been clearly established, control of crack widths is considered desirable for structures located in salt-water or brackish water." ACI 224R recommends a maximum surface crack width under service loads in seawater and seawater-sprayed structures of 0.006 inch (0.15 mm) and also provides guidance on calculation of expected crack widths based on reinforcement distribution. The authors believe that the 0.006 inch (0.15 mm) crack limit is generally reasonable for decks subject to deicers but note that they have seen hairline through-deck cracks that have water staining and leakage on the deck underside during deck surveys. Preferably, all visible cracks should be filled soon after construction and over the deck life to achieve long-term service life.

3.2 Materials Used in Deck Penetrating Sealers

3.2.1 Silane, Siloxane and Siliconate Sealers

Silanes, siloxanes and siliconates are silicon-based materials that are used to manufacture penetrating sealers. These materials are classified as hydrophobic sealers or "water-repellents" as they form a surface zone that slows water and salts from penetrating the concrete surface.

Silane and siloxane sealers have gained wide acceptance over the years (Krauss et al. 2009a). Silanes are smaller particles than siloxanes and, therefore, usually penetrate more deeply. The small molecule size of both materials allows them to penetrate fine cracks (<0.010 inch wide) and form a hydrophobic layer. Silanes and siloxanes also do not have significant effects on skid resistance, which makes them suitable for uses on concrete decks (Krauss et al. 2009a). Silane and siloxane sealers are typically clear in color and cannot be visually detected on the applied surfaces. Silanes and siloxanes also allow the passage of water vapor so the concrete can lose water vapor in dry periods. Silanes and siloxanes are less effective than coatings in sealing larger-width cracks, say 0.010 inch wide or greater and can lose effectiveness when continuously ponded.

Different products are available for silanes including solvent-based, water-based and 100% solids. The percentage of solids in solvent-based and water-based silanes ranges up to 40%. Literature indicates that the 100% solids products had a slightly greater depth of penetration as they contain more active silanes (Johnson et al. 2009). Multiple coats can be applied to achieve deeper penetration. The 100% solids products also have little or no volatile organic compound (VOC). However, these products have higher viscosity which can affect the adequacy of their application.

Siloxanes are also available in two different types: solvent-based and water-based products. These products have different solids content ranging up to 20%. Being larger molecules, they may be preferred over silanes for use on more porous substrates, but silanes are usually selected for treating bridge decks that have overall good quality concrete.

3.2.2 Silicates

Silicates are inorganic silicon materials that are used to manufacture deck penetrating sealers. Silicates act as pore blockers. These materials behave differently than hydrophobic sealers as they block water by reacting with the hydrated calcium components of the cement paste and filling the capillary structure of the concrete. This occurs as silicates initiate a chemical reaction with free calcium in the concrete to form a crystalline structure that fills small cracks (Johnson et al. 2009). Due to their nature, silicate sealers tend to block the water vapor from leaving the concrete deck, which may lead to durability problems, mainly freeze-thaw damage (Johnson et al. 2009). However, our experience and reported results by Wenzlick (2007) indicates that these materials are not effective in crack sealing and scaling resistance. Silicate-based sealers are less expensive than silanes but are typically less effective at blocking deicer penetration.

3.2.3 Linseed Oil

Linseed oil is a type of penetrating deck sealer that block pores in the concrete. Linseed oil is one of the earliest sealing treatments to be applied to concrete and has been used across several states between 1950s through the 1980s (Johnson et al. 2009). Various types of linseed oil preparations have been used including raw, boiled, oxidized and modified linseed oil. However, an NCHRP report published by WJE in 1982 indicates that boiled oil is more effective than other preparations as it forms a polymeric film on the concrete surface (Pfeifer and Scali 1981). To maintain effectiveness frequent reapplication is needed. Linseed oil has been known to be effective for protecting concrete against salt scaling. Wenzlick (2007) stated that a typical practice by the Missouri DOT (MoDOT) at the time of his report was to use linseed oil on all new bridge decks to protect concrete from scaling.

Typically linseed oil is mixed with mineral spirits or kerosene to reduce its viscosity, which allows for a deeper penetration in the concrete deck but that can cause environmental concerns or limitations. Typical penetration depths range from 1/16 to 1/4 inch. A major drawback with linseed oil is that over-application may lead to a slippery surface (Kubie et al. 1968), which can lead to safety issues when used on bridge decks. It is reported that linseed oil can deteriorate as it is vulnerable to lime in the concrete. Linseed oil is also considered to be less effective in resisting moisture penetrating through concrete due to its reported poor long-term performance (Whiting 1992).

3.2.4 Epoxy Sealers

Epoxy sealers are widely applied and can have different formulations with a range of chemical compositions and physical properties. Epoxy can be used in penetrating sealers, film formers (coatings), and crack sealers (Behm and Gannon 1990).

Film forming epoxy sealers are more common than epoxy penetrating sealers as the relatively high viscosity of epoxy make it difficult to penetrate the surface of the deck. Therefore, epoxy coatings are typically more exposed to traffic and wear, which decrease their useful service life. Because epoxy has low skid resistance, sand or fine aggregates are broadcast into the wet resin**.**

3.2.5 Methacrylate Sealers

Methacrylate monomers are used to produce two types of deck and crack sealer products: high molecular weight methacrylate (HMWM) and reactive methyl methacrylate (MMA). HMWM is a widely used material that has been used as a crack sealer but also provides some improved moisture resistance to the deck. The use of HMWMs began in the early 1980s for bridge deck crack repair by the California Department of Transportation (Caltrans) (Krauss 1985). Due to its very low viscosity, HMWMs have the ability to penetrate small cracks on the concrete surface with a crack width less than 0.006 inch (ACI RAP-2 2009). HMWM is commonly formulated as a three-component material that includes monomer resin, initiator and promotor.

MMAs are two-component materials that consist of reactive methyl methacrylate and a 50% dibenzoyl peroxide powder (Soriano 2003). MMAs have very low viscosity and have been used to impregnate concrete. They tend to be highly volatile so their use is not widespread.

3.3 Recommend Practices for Installing Sealers

Deck penetrating sealers are typically installed by topical treatment of the deck. A thin layer of the sealant is spread on the surface and left to cure. The topical treatment methods are applicable for different type of sealers. A common application method consists of mounting a spray bar on the back of a truck and spraying the sealer onto the deck surface. Other states use hand sprays to apply the sealer. It is reported that applying the sealers in more than one pass may lead to a faster curing of the sealer (Johnson et al. 2009). Multiple passes may also be specified to ensure even coverage of the material. The sealer manufacturer recommendations for application procedure and rate of application should be followed.

Silanes and siloxanes are the two most commonly-used type of penetrating sealer based on the literature. For these types of penetrating sealers, the use of solvent-based products is recommended for reapplication purposes. This recommendation is attributed to the fact that previous application may repel water-based products. It is noted that solvent-based sealers have a higher VOC content compared to water-based sealers and may be limiting if local or state regulations restricts the VOC content of applied materials. An advantage for water-based sealers is that they have lower evaporation rate which makes them more suitable for high temperature and windy conditions (Johnson et al. 2009).

For crack sealers, crack injection is typically used to apply products with high viscosity such as epoxies, while gravity-feed techniques (topical treatment) are mainly used to apply products with low viscosity such as HMWMs or low-viscosity epoxies. Curing times for the various crack sealers are usually specified in the product data sheets. Treated decks can usually be open within few hours after the application of sealers (Rahim et al. 2006).

3.4 Construction Considerations and Test Methods

3.4.1 Surface Preparation and Temperature

The main factors that affect the quality of installation of deck penetrating sealers are temperature of application and deck surface condition (cleanliness and moisture content). In general, surface preparation is not required prior to application of sealers; however it is often beneficial. A study by Soriano (2003) tested three different surface preparation techniques prior to application of sealers: sandblasting, broom/forced air, and no surface preparation. The tests were conducted on three different bridges and cores were taken to evaluate sealer penetration depth. The results indicated that the deck without surface preparation achieved the best performance when the deck did not have excessive debris. The study recommended the use of power-brooming/forced air if excessive debris is present. Krauss et al. (2009a) indicated in a survey that the most common surface preparation are brooming, air sweeping, and sand blasting. According to the survey, none of the responding agencies use hydrodemolition and milling. Generally, sealers should not be applied to any concrete surfaces with less than 28 days of curing (Pfeifer and Scali 1981).

It is reported that the presence of curing compounds on the surface of the deck significantly decreases the depth of penetration of deck sealers (Bush 1997). Therefore, it is recommended to remove all curing compounds from the deck surface before applying sealers.

In general, it is not recommended to apply sealers over cold or damp concrete (Pfeifer and Scali 1981). The concrete surface should be dry prior to the application of sealers. This allows the material to wick into the concrete in order and achieve deeper penetration. However, manufacturers have not done a good job in defining optimum moisture conditions for sealing.

The manufacturer recommendations for temperature during sealing application should be followed. The recommended range of temperatures at the time of sealer application and at least 12 hours after is typically between 40 and 100 °F (Krauss 2000, Rahim et al. 2006, Pincheira and Dorshorst 2005, Johnson et al. 2009). Application on windy days should also be avoided due to the volatility of some types of sealers. Therefore, weather forecasts should be checked prior to sealer application to avoid windy conditions on the day of application and to avoid rain events at least 2 days before and 1 day after sealer application.

3.4.2 Quality Control

Sealers are primarily used to prevent the ingress of moisture and chloride ions through preventing capillary action at the deck surface (Rahim and Jansen 2006). Different test methods have been used to evaluate the performance of deck sealers. The literature indicates that the main evaluation parameters are chloride ingress, depth of penetration, absorption and vapor transmission (Johnson et al. 2009). Other less common tests used to evaluate sealers include scaling resistance using ASTM C672, skid resistance, freeze-thaw resistance using ASTM C666, and rapid chloride permeability using AASHTO T277 / ASTM C1202.

Whiting (1992) indicated that most two common test methods for evaluating sealer performance include NCHRP 244 Series II and AASHTO T259/T260 (also known as 90-day-ponding test). The former method is used to test for chloride ingress, absorption, and vapor transmission while the latter is solely used to measure chloride ingress. ASTM C642 is used to measure absorption through sealed surface. Oklahoma DOT also developed methods for testing penetration depth (OHD L-40) and vapor permeability of sealers. Details regarding the application of tests can be found in relevant literature.

It is noted that different states establish their product lists for sealers based on different acceptance criteria for the performance evaluation tests. For example, a study by Wenzlick (2007) for Missouri DOT examined the merit of using four different tests to evaluate the performance of deck sealers as follows: 1) AASHTO T529, Standard Test Method for Resistance of Concrete to Chloride Ion Penetration, 2) ASTM C672, Standard Test Method for Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals, 3)

AASHTO T277, Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration, and 4) ASTM C642, Standard Test Method for Density, Absorption, and Voids in Hardened Concrete. The results of the study recommended that only AASHTO T259 (90 day ponding) and ASTM C642 (Absorption) should be used. Criteria were developed for acceptance of sealers based on the results of the study. Johnson et al. (2009) reports in a recent survey that North Dakota uses the same test methods for evaluating deck sealers; however, different acceptance criteria are set for the ASTM C642 test. Wisconsin uses the same tests as North Dakota and Missouri but also uses two additional tests to maintain acceptable environmental standards. These tests are ASTM D5095 (Determination of Nonvolatile Content), and EPA Method 24 (Volatile Organic Compound Content).

Measurements that may be used for QA/QC evaluation of sealers after placement include depth of penetration, chloride ion concentration, and skid resistance (Johnson et al. 2009, Liang et al. 2014). Typically depth of penetration can be evaluated by applying water to a split core sample. The depth of penetration can be then determined by observing whether the concrete will bead or the water will be able to soak the concrete. Another method for evaluating depth of penetration is to remove a portion of the surface region and test it using water-borne dye. Chloride depth can be determined by extracting concrete dust from different depths in the deck and measuring the chloride levels in the laboratory. Concrete cores can be extracted and sliced at different depth to determine the chloride concentration profile. Liang et al. (2014) reported different tests to measure skid resistance including Yaw Mode Method (Mu-Meter), Stopping Distance Method: ASTM E445 (Locking 4 Wheels) and ASTM E303 (Locking Diagonal Wheels), and Slip Mode Method (Swedish Road Research Skid Meter). They recommended using ASTM E303 British Pendulum Tester (BPT) for skid resistance measurements as it is a low cost, portable test that can be applied in different orientations.

Krauss et al. (2009b) conducted a survey that included questions regarding typical field application quality assurance tests. The survey indicated that most common evaluation criteria are application rate, concrete temperature, concrete surface condition, and concrete moisture. Other tests include core sampling, sealer penetration depth, surface absorption, water permeability, skid resistance, bond strength and mock-ups. Surface resistivity is a quick measurement technique that can be used to assess concrete surface moisture content to determine if the concrete is dry enough to receive sealer. Details regarding the test methods and their frequency of use by the states can be found in Krauss et al. (2009b).

3.5 Summary of Survey Results in Literature

This section summarizes relevant literature of DOT-sponsored research projects that included surveys or testing related to the use of deck sealers. The literature indicates that the penetrating sealers perform better than film formers. The most common types of penetrating deck sealers are silanes and siloxanes, although silicates and HMWMs have also been used for deck sealing applications. The improved performance of the penetrating sealers is attributed to their ability to penetrate the concrete surface, which makes them less exposed to traffic and wear (Krauss et al. 2009a). Silanes and siloxanes furthermore maintain better skid resistance when compared to other sealers such as linseed oil and epoxies. It is reported that most states have discontinued the use of linseed oil because it almost required reapplication annually (Johnson et al. 2009). Deck sealers are generally effective in sealing cracks with width < 0.010 inch and crack sealers are needed to seal cracks with greater width; however, results can vary depending on the characteristics of the cracks. The literature results reported differences in the expected lifetime of sealers; however, a maximum of 5 years for reapplication was generally recommended.

Pfeifer and Scali (1981), of WJE, conducted the first systematic study to evaluate sealers published in NCHRP Report No. 244 *Concrete Sealers for Protection of Bridge Structures.* The study indicated that linseed oil, the most popular sealer at the time, is inexpensive and easy to apply but was not very durable and needs to be reapplied frequently. The study found five categories of sealers that were found to be effective: methyl methacrylate (MMA), certain epoxy formulations, polyurethanes, relatively low molecular weight siloxane oligomers, and silanes.

Carter and Forbes (1986) tested a total of 57 sealers to evaluate their properties in terms of absorption testing, vapor transmission and depth of penetration. The specimens were cast using typical concrete mixes in Alberta and their surfaces were treated with light sandblasting to remove laitance prior to sealers application. The top six performing sealers during the weight gain tests were epoxies, chlorinated rubbers, acrylics, silanes, siloxanes, and methacrylates, respectively. For vapor transmission, silanes had the best performance on average. Although it failed the absorption criteria, linseed oil had the highest penetration depth followed by silanes. Chloride testing was performed on a number of sealers and indicated that the effectiveness of the sealers decreases with time.

Cady (1994) produced a synthesis on the use of sealers by conducting a literature review and a survey. The study found a large variety of sealer products and classified them in groups including:

- Silanes, Siloxanes, Siliconates
- Epoxies
- Gum Resins and Mineral Gums
- Linseed Oil
- Stearates
- Acrylics
- Silicates and Fluorosilicates
- Urethanes and Polyurethanes
- Polyesters
- Chlorinated Rubber
- Silicones
- Vinyls
- Combination Systems

The study indicated that sealers can be used for preventive maintenance and that life-cycle cost analysis should be performed to evaluate their use. Cady (1994) recommended several steps to help with selection of sealers including developing rational test protocols for product qualification, quality assurance for products and field application, and field testing for performance. The study also recommended developing national data bases for acceptable sealer products, in-place costs for sealers, observed field service lives and reapplication times, and overall sealer performance.

Soriano (2003) conducted a study for South Dakota Department of Transportation to evaluate the use of alternative sealers for bridge decks. The study indicated that most of the decks in South Dakota exhibit some form of cracking. Based on the recommendations of the study, linseed oil should not be categorized as a penetrating sealer as it has low ability of penetrate the deck. The study indicated that sealers with low viscosity (15 cps) have a good penetration depth. It was recommended that sealers should be used prior to chloride ingress to achieve best results in increasing the service life of deck. The proposed practice is to apply the sealers 3 to 6 months after construction and to reapply every 5 years.

Rahim et al. (2006) reported the results of a survey conducted for California Department of Transportation on the use of HMWMs as deck and crack sealer. The results of the survey indicates that among 41 states that responded to the survey, 17 states have used HMWM as either deck or crack sealer. Some states use HMWMs as both crack and deck sealers. With regard to time of application, 14 states apply HMWMs after cracks have initiated, while only three states use HMWMs before cracks initiate (as both a deck and crack sealer).The survey results indicated that the states generally use HMWMs for cracks as small as 0.0625 inch; however, ACI RAP-2 (2009) indicates successful application for cracks less than 0.006 inch in width. Some states reported that the cracks had to be visible to the inspector before they are sealed with HMWMs.

The study indicated that sealers can be used for both new and old decks. The recommended timing for application for new decks is 3 to 6 months after construction to allow time for the new concrete to dry and micro-cracking or restraint cracking to occur but before chloride contamination has occurred. A period of 4 to 5 years was also recommended for reapplication of most sealers. Rahim et al. (2006) reported that Alberta uses a 4 year cycle for sealer reapplication.

Wenzlick (2007) reported in a study for Missouri Department of Transportation that applying linseed oil was the standard practice for all new bridge decks in Missouri to reduce scaling; linseed oil was applied initially by the contractor and at some time after one year of service by maintenance crews. However, the excessive curing time of linseed oil for some applications and its low ability to penetrate dense concrete decks have prompted the need to use other types of sealers. Wenzlick's study of silanes, silicates, and linseed oil indicated that penetrating sealers may not be effective in sealing cracks with crack widths between 0.012 and 0.025 inch. He recommended that cracks with widths greater than 0.025 inch be filled by a crack sealer prior to application of deck sealers. Wenzlick (2007) also reported the manufacturer-expected service life for different types of sealers varies from 5 years for HMWMs to 10 years for silanes and silicates.

Johnson et al. (2009) conducted a literature search and survey for Minnesota Department of Transportation to evaluate the performance of deck and crack sealers. The survey results indicated that silanes are the most common deck penetrating sealer. The states reported that solvent-based silanes, typically 40% concentration, are used more than water-based silanes. The study indicated that most common tests for deck sealer acceptance are AASHTO T259 (90-day ponding) and ASTM C642 (absorption). For quality control, depth of penetration and chloride content are usually used. It was found the silanes sealers typically outperform siloxanes and that solvent based-products have superior performance over water-based products. Johnson et al. (2009) recommended a temperature of application between 40 and 100 °F and a dry period prior to application of sealers of at least 2 days.

A survey by Krauss et al. (2009) indicated that silanes are among the most used sealers by the responding states. The reported advantages of using sealers included low cost, effectiveness, and ease and speed of installation. Several disadvantages were also reported including the short lifetime, performance issues (especially with cracked concrete decks), and installation problems (especially during warm weather). The mean reported anticipated life span was between 4 and 10 years. The survey results indicated that 7 out of 12 states use sealers on newer decks with good condition as a preventive measure, while 10 states use sealers on decks with cracking but in good condition. It is noted that the survey included both crack and deck sealers. A second study by Krauss et al. (2009b) indicated that 26 states are currently using sealers, with 23 states reporting using silane based sealers.

Additional studies are available in the literature that were conducted for DOTs in Indiana (Chang 1992), Kansas (Meggers 1998), Iowa (Krauss and Boyd 1999), Wisconsin (Pincheira and Dorhorst 2005), and

Illinois (Morse 2009), and Colorado (Liang et al. 2014). The results of these studies generally agree with the summary reported in this section.

3.6 Cost of Sealers

The price of materials used for deck sealers has been reported in a number of studies and summarized as shown in Table 3.1. The results show that HMWM and epoxy is more expensive than silane, while linseed oil is the least expensive sealer. The cost of silane is primarily a function of the amount of silane solids applied. Prices reported by Wenzlick (2007) and Soriano (2003) are for materials only. Liang et al. (2014) reported costs for installation but it was not clear if this pricing also included road closures.

Table 3.1. Cost of concrete sealers

Source	Sealer Type	Cost/ft^2	Cost/yd^2
Soriano 2003* material only	100% Silane	$0.35-0.40	$3.15-3.60
	40% Silane	$0.16-0.20	$1.44-1.80
Wenzlick 2007* material only	Silane	$0.18	$1.62
	Reactive silicate	$0.18-0.70	$1.62-6.30
	HMWM	$0.45	$4.05
	Linseed oil	$0.02	$0.18
Liang et al. 2014** installed	HMWM	$2.20	$19.80
	Epoxy	$1.50-1.75	$13.50-15.75
	Silane	$1.50	$13.50
TxDOT Low Bid Unit Prices 2017 (Item 428 6001, 12-month rolling average, 4 projects)	40% Silane	$0.55	$4.97

* Cost of materials only reported per square foot
** Prices reported per square yard installed

CHAPTER 4. PREVENTIVE MAINTENANCE METHOD SELECTION

4.1 Introduction

Preventive maintenance is the selection of activities planned to be performed prior to damage or degradation of the structure to avoid such occurrences. Both polymer concrete overlays and sealers can and have been used for preventive maintenance purposes for new and old bridge decks. The main purpose of preventive maintenance is to ensure that the design service life of the bridge deck can be achieved with the optimized cost-benefit ratio.

The selection of the preventive maintenance method should be dependent on the condition of the concrete deck (Krauss et al. 2009a). Polymer concrete overlays are generally more expensive than sealers; however, they also provide several advantages including superior skid resistance, longer service life and better protection to the deck. Therefore, it is crucial that the selected method be evaluated based on the needs and resources of the agency. This chapter provides an overview for selection of preventive maintenance options for new bridge decks.

4.2 Deck Characterization

Deck characterization is the first step in selecting appropriate preventive maintenance options for both new and old decks. Krauss et al (2009a) published an NCHRP report titled “Guidelines for Selection of Bridge Deck Overlays, Sealer and Treatments” which includes a breakdown of necessary steps to select maintenance options for bridge decks. While the report focuses on existing bridge decks, several of the methods discussed can also be used for new bridge decks. In addition, if the application of the preventive maintenance is to be delayed for more than 10 years, a more detailed deck characterization study should be conducted. According to Krauss et al. (2009a), deck characterization includes assessing the following factors:

- Deck deterioration and National Bridge Inventory (NBI) condition rating: This includes percent of delaminated area, repair patches, spalls, half-cell potential measurements, and NBI condition rating of top and bottom surfaces.
- Estimated time-to-corrosion: This includes estimating the time required for the chlorides to reach corrosion threshold at the reinforcement level.
- Deck surface condition: This includes evaluating the condition of the surface for scaling, abrasion loss, and skid resistance.
- Concrete quality: This is related to concrete durability against degradation mechanisms including alkali-silica reaction, delayed ettringite formation, freeze-thaw damage, and strength

While new bridge decks are not likely to have problems related to corrosion damage and delamination, other problems such as cracking or construction errors (small concrete cover) can affect the long-term performance and service life of the bridge.

For new bridge decks, recommended practice for deck characterization should include a survey of cracks (density and widths) and as-built reinforcing cover (using GPR). Service life modeling of the design provides valuable information on whether an overlay is needed to achieve the service life goals. This will help determining the best options for preventive maintenance.

4.3 Evaluation of Preventive Maintenance Options

Due to differences in the cost, performance and expected service life of polymer overlays and sealers, a decision has to be made in order to select which method to use. Selection of preventive maintenance options for new bridge decks is a function of several factors including:

1. The design service life of the bridge deck: This is an important factor as desired service life for bridge deck may defer based on the importance or location of the bridge. For example, many DOTs currently specify design service life of 75, 100, or 125 years for signature bridges. Other bridges may be functionally obsolete within much shorter periods of time. The approach for selecting preventive maintenance for signature bridges may defer from the approach selected for ordinary bridges or bridges that are easily replaced.
2. Deck characterization results: The deck design and condition affects the proper selection of the preventive maintenance options. For example, polymer overlays are more appropriate than sealers to be used for bridges with small concrete cover as a result of design or a construction error, or bridges with drainage or grade problems. Also, surface sealers such as silanes may not be appropriate for bridge decks with excessively wide cracks.
3. Time of applying the preventative maintenance: Selection of the preventative maintenance option is also affected by the age of the bridge. Bridge decks with 10 or more years of service should be first evaluated to determine the extent of repairs necessary prior to applying polymer overlays or sealers. Poor sealer or overlay performance is expected if applied on significantly deteriorated bridge decks.
4. Cost-to-benefit ratio: Another important factor for determining the best preventive maintenance is the cost-to-benefit ratio. While applying polymer overlays or sealers will increase the initial cost of the construction, the benefits associated with the extended service life and reduction in future maintenance may exceed that initial cost.

4.3.1 Polymer Concrete Overlays

Polymer overlays provide several advantages over sealers when applied to new or old bridge decks including:

- Improve skid resistance.
- Restore bridge appearance and repair mildly cracked surfaces.
- Reduce absorption of moisture and chloride ions more effectively.
- Slow the migration of previously absorbed chloride ions for older bridge decks and reduce the rate of corrosion by limiting oxygen availability.
- Reduce the rate of concrete damage from cyclic freezing and thawing of moist concrete.
- Screeded systems can improve ride quality and grade.

Polymer overlays are more expensive than sealers but they provide overall better protection for the bridge deck. Polymer overlays are likely better options than sealers in several cases including:

- Loss of corrosion protection due to reduced concrete cover as a result of construction errors. Polymer overlays can be used in this case as they will restore cover and increase the corrosion protection provided to the steel reinforcement. The high resistance of chloride diffusion of polymer overlay may yield a longer service life compared to the design condition of the deck for a given cover.
- Decks with low skid resistance. Polymer overlays can restore skid resistance while sealers typically do not affect or reduce the skid resistance of the deck.

- Decks already exposed to chlorides. While deck sealers can slow down the ingress of chloride and moisture through the deck, Polymer overlays are nearly impermeable to moisture which can slow the rate of corrosion as the deck concrete dries out. This is more beneficial as it stops additional chloride ingress, reduces moisture and humidity in the concrete, and reduces oxygen availability, reducing corrosion rates. Also the surface preparation for polymer overlays can include milling and/or shot-blasting which removes the surface layer with highest chloride concentration.
- Decks with surface damage such as scaling. Overlays will basically provide a new surface for the deck compared to sealers which do not affect the surface condition. Pre-mixed and screeded overlays can improve deck drainage, grade elevations, and ride quality.

Polymer overlay materials are not suggested for major concrete repairs and should not be used for large deck or spall repairs due to potential thermal incompatibility. Polymer overlays can help with sealing static cracks with small crack widths such as shrinkage cracks as reported in a survey study by Fowler and Whitney (2011). However, it is reported that wide or moving cracks will eventually reflect through the overlay after its application. Therefore, it is recommended to seal cracks with width wider than 0.040 inch prior to applying the overlay (Fowler and Whitney 2011) or to treat moving cracks as joints. Crack sealers that are compatible with the PC overlay can be used for this application. As noted, HMWM crack treatments should not be used prior to installation of epoxy overlays but can be used prior to polyester overlays. Alternatively, due to uncertainty regarding which cracks are likely to reflect through the overlay, Carter (1993) recommended that a crack survey should be conducted 1 or 2 years after the overlay application and any cracks be sealed with materials compatible with the overlay.

Based on the literature search presented in Chapter 2, the use of multiple-layer epoxy (MLE) overlays and premixed polyester overlay (PPC) is recommended. Both overlays have good reported performance and, therefore, the service life models presented in Chapter 5 will only focus on these types. PPC overlays are more appropriate to use on surfaces with irregularities as they tend to have a greater thickness while MLE overlays are appropriate to use on decks with good initial ride quality and drainage. The reported service life for polymer overlays is between 20 and 25 years but is largely dependent on successful application of the polymer overlay (Carter 1993, Sprinkel 1997, Fowler and Whitney 2011).

4.3.2 Sealers

Deck sealers are primarily used to reduce absorption of chlorides and moisture through the concrete surface and through cracks with small crack width; thereby, protecting the concrete. Concrete sealers are not effective in sealing cracks with large widths or in improving skid resistance. Cracks with larger widths should be sealed with a crack sealer. Crack sealers usually have a minimum specified crack width for effective penetration.

Based on the literature presented in Chapter 3, silane sealers are the most widely used among states due to their superior depth of penetration compared to other types of sealers including siloxanes, siliconates and HMWMs. An effective combination for cracked decks is using dual systems by treating the concrete with silane followed by using HMWM to fill and seal cracks. (Rahim et al. 2006). This combination can increase the protection offered by the sealer as silanes form a hydrophobic surface layer and seal hairline cracks while the HMWM fills and structurally bonds visible cracks. However, this system will be more expensive and will require more time as the silane should cure first before applying the HMWM.

It is noted that selecting proper materials for sealer reapplication purposes is crucial as some sealers cannot penetrate decks with prior sealer application such as water-based sealers. The literature indicates that solvent-based sealers should be used for reapplication and that a high content of solids increases the resistance to chloride ions and improves penetration depth. Johnson et al. (2009) indicates that the most common products that fits that description are 40 percent solvent-based silane sealers.

The service life models discussed in Chapter 5 will only consider the use of silane or siloxane sealers. Based on the literature presented in Chapter 3, the expected service life of sealers is assumed to be 5 years; however, Wenzlick (2007) reports manufacturer expected service life of 10 years for silanes.

CHAPTER 5. PREVENTIVE MAINTENANCE OPTIMIZATION EXAMPLE

5.1 Introduction

Model simulations were performed to assess the relative impact of polymer overlays and sealers on the service life of new bridge decks in Iowa. The assumed materials, dimensions, and reinforcement layouts for the representative bridge deck were selected based on typical design parameters specified by the Iowa DOT. Per the requirements of Section 5.2 of the *Iowa DOT LRFD Bridge Design Manual* (2017), the bridge deck was assumed to be 8 inches thick, with 2.5 inches concrete cover to the top mat reinforcing bars and 1 inch cover to the bottom mat reinforcing bars. The concrete was assumed to meet the requirements of a C-4WR or C-V47B concrete mixture as specified in *Materials I.M. 529 - Portland Cement (PC) Concrete Proportions* (2016), and the reinforcement in the top and bottom mats was assumed to be epoxy-coated Grade 60 steel, also as specified in the *Iowa DOT LRFD Bridge Design Manual*.

Four options were examined for the deck:

- Case 1: New bridge deck with no preventive maintenance
- Case 2: New bridge deck with sealer
- Case 3: New bridge deck with overlay
- Case 4: New bridge deck with delayed application of overlay

Multiple different sealers and overlays were considered for each case. Since the primary impact of sealers and overlays in extending the service life of bridge decks is a reduction in the rate of chloride ingress through the deck, chloride-induced corrosion of the reinforcing steel was examined as the controlling deterioration mechanism for the example bridge deck. Other deterioration mechanisms such as carbonation-induced corrosion and distress from freezing and thawing were ignored.

5.2 Bridge Deck Materials

5.2.1 Concrete Mixtures

The concrete mixture examined for the example bridge deck was based on the requirements given in Section 241 of the *Iowa DOT Standard Specifications for Highway and Bridge Construction* (2015), Concrete Bridge Decks. The mixture was assumed to contain no supplementary cementitious materials (SCMs) and to conform to the mix proportions specified in *I.M. 529* for C-4WR or C-V47B concrete mixtures. While SCMs (e.g., fly ash and slag) are permitted by the Iowa DOT Standard Specifications, their exact influence on the long-term diffusion properties of concrete is debated and is considered beyond the scope of this report. The use of SCMs generally increases the service life of bridge decks exposed to aggressive environments, and may be considered as a viable option for use in bridge decks with extended service lives; however, laboratory testing of diffusion coefficients and aging factor (m) is recommended prior to service life modeling of these mixtures.

The apparent diffusion coefficient for the base concrete mixture was estimated from measurements obtained by WJE during a previous evaluation of Iowa bridge decks (Donnelly et al. 2011). 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. The average apparent diffusion coefficient estimated for the uncracked cores was 0.086 in^2/yr. Assuming the mixtures contained no fly ash or slag, the average apparent diffusion coefficient at 28 days (D_{28}) was estimated from the data to be 0.317 in^2/yr.

To simplify the model and provide comparison baseline data, the bridge deck concrete was assumed to remain uncracked throughout its service life, and the diffusion coefficient of concrete only changed as a function of the age and composition of the concrete, as described in Attachment A. If cracks are left untreated, this assumption will result in an unconservative estimate of service life, especially for the untreated control case because chlorides penetrate more rapidly through cracked concrete than uncracked concrete.

5.2.2 Polymer Overlays and Sealers

Penetrating deck sealers and polymer concrete overlays were considered as preventive maintenance options within the model. The deck sealers were assumed to be silane or siloxane, and the overlays were assumed to be premixed polymer concrete (PPC) or multiple-layer epoxy (MLE). The penetrating deck sealers were assumed to be of negligible thickness and primarily affected the build-up of chloride ions at the surface of the concrete bridge deck; no distinction was made between silane and siloxane sealers. The two overlays were modeled as distinct layers applied over top the concrete base layer, with each layer having a defined thickness based on typical values reported in the literature. As previously discussed, a typical thickness for a PPC overlay is 3/4 to 1 inch, while a typical thickness for an MLE overlay is 1/4 to 3/8 inch; therefore, the PPC overlay was modeled as having a thickness of 1 inch and the MLE overlay was modeled as having a thickness of 0.4 inches.

5.2.3 Environmental Exposure to Chlorides

The primary source of chlorides that induce corrosion in Iowa bridge decks is from salts used to de-ice the deck surfaces during winter months. 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 this model, the surface chloride concentration (C_s) was modeled as a constant value over the year, based on the average surface chloride concentrations measured and estimated by WJE during the previous evaluation of bridge decks in Iowa (Donnelly et al. 2011). The surface chloride concentrations were estimated for the 44 cracked and uncracked cores previously described. Since the bridge decks ranged in age from 17 to 32 years, it was assumed that the chlorides had ample time to build-up at the surface and that the chloride concentrations measured near the surface were relatively unaffected by seasonal fluctuations in chloride application, and representative of typical surface chloride concentrations across the state. The average surface chloride concentration estimated for the cores was 6650 ppm (0.665 percent by weight of concrete), with an average 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. Note that historically, deicing practices in Iowa have relied upon a continued increased use of deicers salts and brines. If this trend continues, preventative practices will be even more important.

5.3 Evaluation of Concrete Deck Service Life

5.3.1 Basis for Probabilistic Modeling

The methodologies presented in *fib Model Code 2010* (Bulletins 65 and 66, 2010) and *fib Model Code for Service Life Design* (Bulletin 34, 2006) were used as guidelines to estimate the relative service life of the concrete deck with each of the four preventive maintenance options. WJE used the full probabilistic approach in considering corrosion-related durability limiting mechanisms. The probabilistic approaches laid out in the Model Code are based on a reliability philosophy, which is widely considered to be the most appropriate means of estimating service life during design. The philosophy recognizes that, during design, our understanding of the factors that affect service life (such as cover, concrete performance, etc.) will be incomplete but that the likely final as-built condition of these factors can be estimated based on probability distributions. Therefore, estimates of critical parameters were made and considered relative to the anticipated exposure conditions to estimate the likelihood of achieving the desired service life.

5.3.2 Probabilistic Modeling of Corrosion-Related Deterioration

The following is a brief discussion of the probabilistic model used for assessing service life, where durability is expected to be controlled by corrosion of reinforced concrete. The modeling approach is described in more detail in Attachment A.

Corrosion-related deterioration of reinforced concrete generally has two stages: 1) time elapsed for corrosion to begin, i.e., initiation time (t_i), and 2) time elapsed where corrosion continues and build-up of corrosion product occurs and distress happens, i.e., propagation time (t_p). Corrosion propagation continues until the volume of corrosion product exceeds the threshold needed to crack or spall the concrete and cause surface damage. This concept is the basis for service life modeling.

The probabilistic approach to service life modeling considers the range of potential inputs to the model (i.e., the corrosion-controlling parameters of the bridge as constructed). A Monte Carlo simulation is run to account for the interaction between the considered variables, and the percentage of combinations expected to result in corrosion is calculated versus time. Latin Hypercube Sampling is used to reduce the number of simulations required for model convergence. The likelihood that the modeled element will reach a given age without developing corrosion based on those inputs can then be determined from this relationship.

For the model considered in this example, the "end of service" is defined as occurring when 10 percent of the Monte Carlo simulations result in corrosion initiation in the top mat of steel.

5.3.3 Modeling of Epoxy-Coated Steel Corrosion

As described in Attachment A, the chloride threshold (C_t) for epoxy-coated steel has been assumed by WJE 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 assumption of a normal distribution is based on statistical analysis of the limited data published regarding the chloride threshold for epoxy-coated bars. 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.

5.3.4 Modeling Effect of Sealers

The deck sealers are modeled as reducing the build-up of chlorides at the surface of the bridge deck. For example, a sealer with 100 percent effectiveness is modeled as reducing the build-up of surface chlorides by 100 percent (i.e., to a concentration of 0), while a sealer with 80 percent effectiveness is modeled as reducing the build-up of surface chlorides by 80 percent (i.e., to a concentration 20 percent of the assumed surface concentration). For this example, the sealers were assumed to be 100 percent effective at the time of application and to decrease linearly to 20 percent effectiveness by 5 years. Sealers were modeled as being applied immediately after construction, with reapplication every 2, 4, or 6 years.

5.3.5 Modeling Effect of Polymer Overlays

Polymer overlays are modeled as a discrete layer on top of the base concrete layer, and therefore require a diffusion coefficient to define the transport of chlorides to the base concrete layer. The diffusion coefficients through the overlay were based on the average ASTM C1202 test results reported by Sprinkel (2003) for PPC and MLE overlays. As previously shown in Figure 2.5, Sprinkel reported average Coulomb values ranging from approximately 50 at 0 years to 500 at 25 years for 2-inch thick samples cut from cores containing the full depth of the overlay and part of the base concrete. For the purposes of this analysis, it was assumed that the Coulomb values are primarily a function of the ionic migration through the overlay layer, and that therefore, the values can be used to estimate the ionic diffusion through the overlay material. Coulomb values were converted to diffusion coefficients using the Nernst-Einstein equation, according to methods defined by Barde et al. (2009) and Lu (1997). A plot showing the estimated diffusion coefficients is shown in Figure 5.1. Note that these values are less than one-half of the chloride diffusion coefficient measured the mature base concrete.

A four-parameter equation was fit to each set of data to define the chloride diffusion coefficients for each overlay material over time. The best-fit equations are given below:

$$D_{PPC}(t) = 0.0049 + \frac{0.034}{1+\exp[-0.32(t-10.2)]}$$

$$D_{MLE}(t) = 0.0054 + \frac{0.039}{1+\exp[-0.32(t-11.0)]}$$

where D is the diffusion coefficient of the overlay in in^2/yr and t is the age of the overlay, in years. It was assumed that D for the overlay is normally distributed with a coefficient of variation of 0.2, similar to the assumed distribution of D for the base concrete. The two equations reach an asymptotic value after approximately 25 years; however, it is generally assumed that the service life of the polymer overlay is 25 years based on previous findings from the review of the literature.

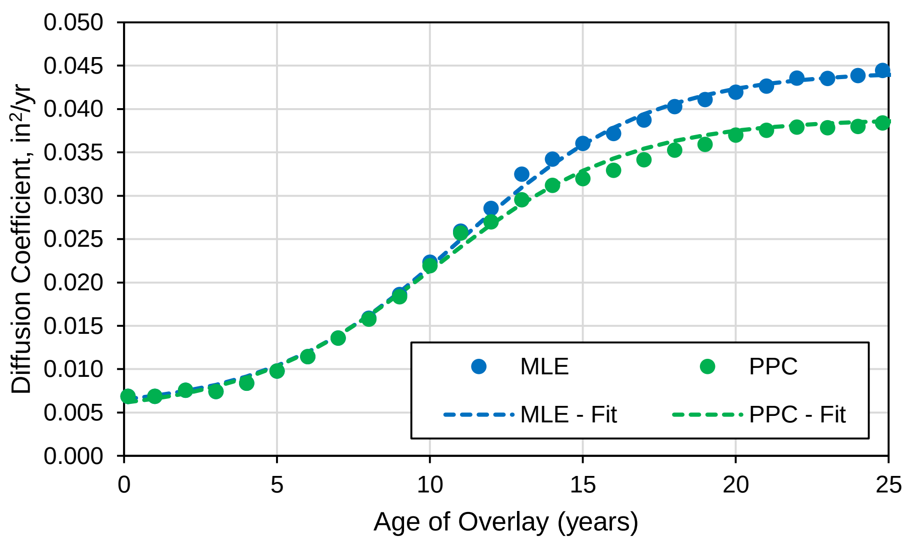

Figure 5.1. Diffusion coefficients for PPC and MLE overlays, estimated from Sprinkel (2003)

5.3.6 Modeling Effect of Delaminations at Concrete/Overlay Interface

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 model, the overlays were assumed to delaminate according to a Weibull distribution, which is commonly used in reliability analysis to model failure events like delaminations. In the absence of sufficient information available in the literature, WJE selected a Weibull distribution based on our understanding of delaminations in polymeric deck overlays. A Weibull distribution with a scale parameter of 37 and a shape parameter of 3 was selected (Figure 5.2), which resulted in a 0.2 percent probability of delamination after 5 years, 6.4 percent probability of delamination after 15 years, and 26.5 percent probability of delamination after 25 years. Note that this function was developed for modeling purposes and is likely conservative for a properly installed overlay. Further field study is needed to understand the actual rate of delamination of both MLE and PPC overlays on bridge decks.

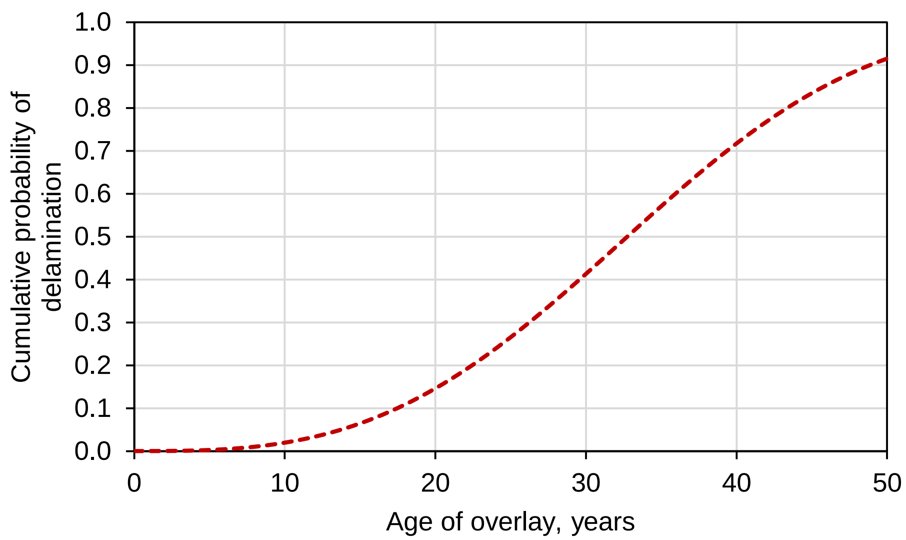

Figure 5.2. Probability distribution function assumed for overlay delamination (Weibull distribution with scale parameter 37 and shape parameter 3).

When delamination occurs between the overlay and base concrete layers, it is assumed that the overlay no longer provides an effective barrier to chloride ingress at the base layer. Chloride concentrations throughout the overlay build up linearly over time until the surface concentration of chlorides is reached throughout the overlay and at the interface. A build-up period of 5 years was selected for this model, consistent with the build-up of chlorides at the surface of the bridge deck.

5.4 Example Bridge Deck Model and Results

The inputs into the service life model are listed in Table 5.1. These input parameters are consistent with the parameters previously described. 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*. To simplify the analysis, the effect of cracking (either early age or structural cracks) on corrosion initiation was ignored.

Table 5.1. Service life model input parameters

Description	Value	Unit
Mean annual temperature (Des Moines, IA)	51	°F
Propagation time	0	years
Desired service life	100	years
Probability of failure	10	%
Surface chloride concentration build-up time	5	years
Surface chloride concentration (normally distributed)	Average: 6,650 Standard deviation: 1,330 Coefficient of variation: 20%	ppm
Cover depth (normally distributed)	Average: 2.50 Standard deviation: 0.31 Coefficient of variation: 12%	inch
Critical chloride threshold (normally distributed)	Average: 1,760 Standard deviation: 536	ppm
Diffusion coefficient of concrete, D_{28}	0.317	in^2/yr
Diffusion decay parameter, m	0.20	--

Case 1: New bridge deck with no preventive maintenance

Case 1 simulated a new bridge deck with no overlays or sealers to establish a baseline service life for the example bridge deck. With no preventive maintenance, the base mix concrete was found to have a service life of 21 years, a reasonable result. Note that this service life represents the time to corrosion initiation and does not include propagation and subsequent time for corrosion-related damage of the bridge deck; it is possible that the Case 1 concrete could remain in service for an additional 5 to 10 years after corrosion initiation before corrosion-related damage would require repairs.

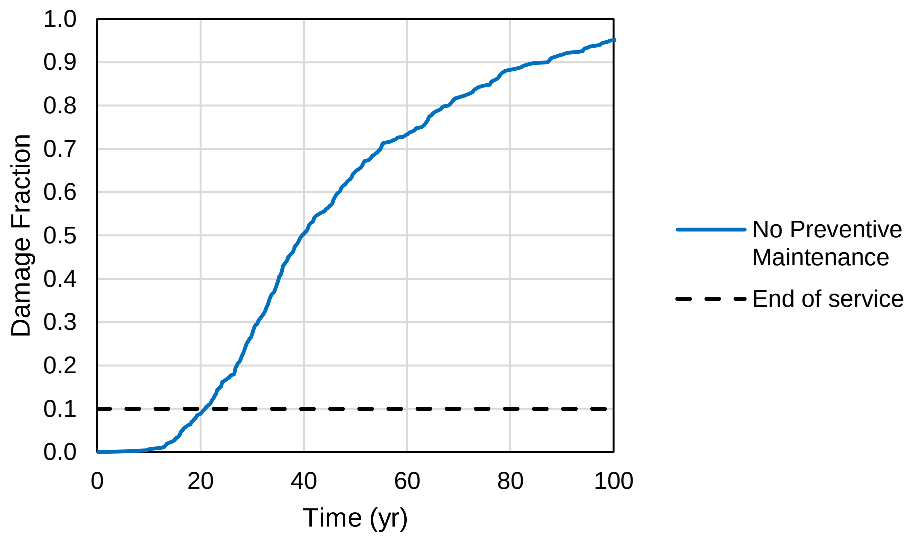

Figure 5.3. Damage fraction (i.e., probability of corrosion initiation) for bridge deck with no preventive maintenance.

Case 2: New bridge deck with sealer

Case 2 simulated a new bridge deck of base mix concrete with a deck sealer. The sealer was assumed to be 100 percent effective at the time of application, decreasing to 20 percent effectiveness after 5 years. If the sealer is only applied once to the new bridge deck, the expected service life is increased to 24 years (+3 years service life). If the sealer is reapplied every 6 years, the expected service life is increased to 25 years (+4 years service life). This marginal increase in service life is related to the decreasing effectiveness of the sealer over the 6-year interval. More frequent reapplication intervals maintain the higher average effectiveness for the deck sealer and offer greater extensions of service life. For a 4-year reapplication interval, the service life is extended to 29 years (+8 years service life), and for a 2-year reapplication interval, the service life is extended to 40 years (+19 years service life).

For the parameters assumed by the example simulation, frequent reapplication of the deck sealer provides the greatest increase in service life over a single application; however, the benefits are only marginal if the reapplication interval is 4 years or greater. It is noted that these results are based on a deck without any cracks for comparison purposes between sealers and overlays. In real structures, sealers will help seal early age cracks from shrinkage or other sources, which will provide better protection to the concrete deck and may yield a larger increase in the expected service life (assuming that the service life of decks with no preventive maintenance will decrease due to presence of cracks).

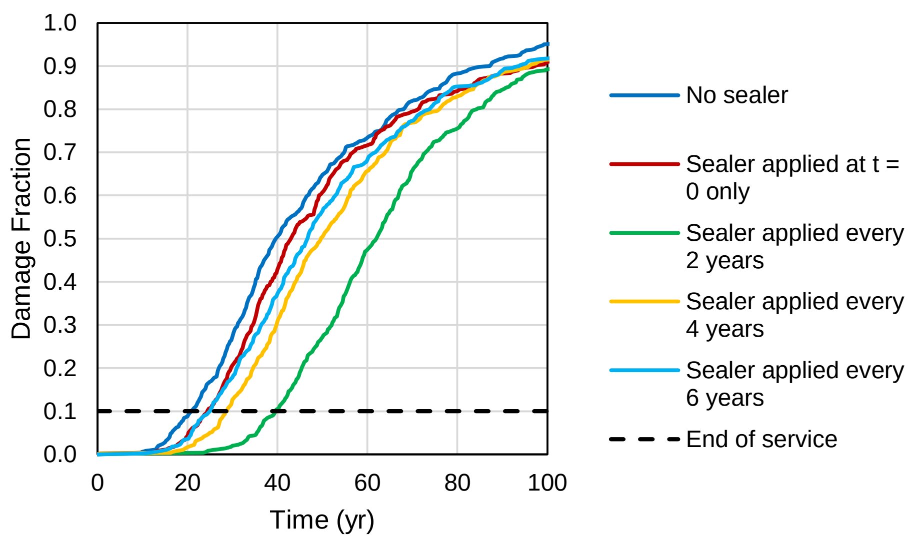

Figure 5.4. Probability of corrosion initiation for concrete deck with deck-penetrating sealers.

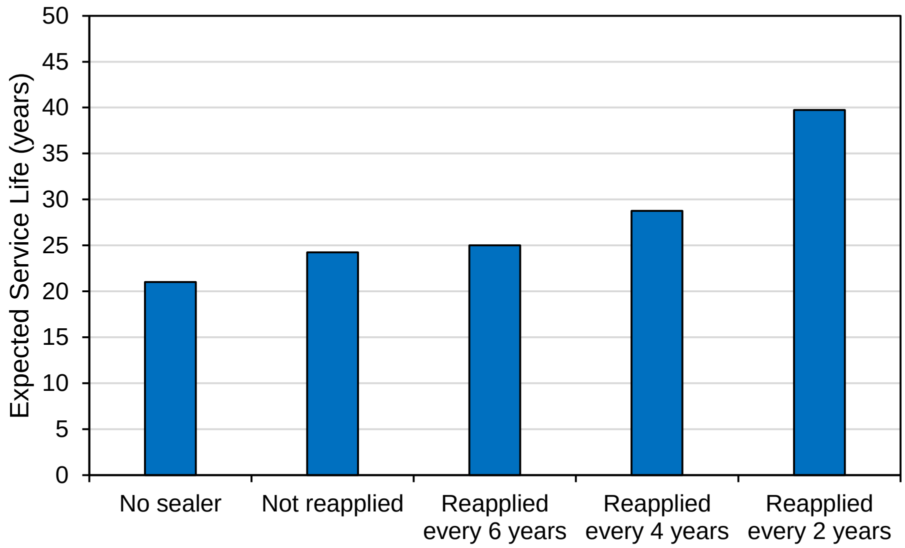

Figure 5.5. Expected service life for concrete deck with deck-penetrating sealers reapplied at various intervals.

Case 3: New bridge deck with overlay

Case 3 considered a new deck of base mix concrete with either a PPC or MLE overlay. PPC overlays were assumed to be 1 inch thick, and MLE overlays were assumed to be 0.4-inches thick. Both overlays were assumed to be applied shortly after deck placement (at t = 0) and require reapplication after 25 years. Reapplication was assumed to consist of removal of the overlay and the top 1/2 inch of concrete base layer, followed by placement of a new overlay layer having the same thickness as the previous layer. This, in effect, reduces the bar cover by 1/2 inch with each overlay application, and limits the deck to not more than four overlay replacements before the top mat of steel is exposed during surface preparation. Although the model permits the overlay to remain in service beyond 25 years, service may be limited to 25 years or less by cracks reflected from the bridge deck, reduction in skid resistance over time, or wear which were not considered in the simulations.

The 1-inch PPC overlay was found to increase the service life of the base mix concrete to 43 years (+ 22 years service life) with a single application and to 93 years (+72 years service life) when replaced every 25 years. The 0.4-inch MLE overlay was found to increase the service life of the base mix concrete to 41 years (+21 years service life) with a single application and to 47 years (+26 years service life) when replaced every 25 years. The primary difference between the PPC and MLE overlays is the thickness of each overlay where the PPC overlay provides 1 inch of highly-chloride resistant material, whereas the MLE overlay only provides 0.4 inch of chloride-resistant material. This 0.6-inch difference in material thickness is the primary reason for the improved performance of the PPC overlay compared to the MLE overlay. All the reported analyses assume that the deck is not cracked and, therefore, does not consider the effect of cracks on the service life. Also the analyses assume that both MLE and PPC overlay have the same percentage delamination at the end of service life.

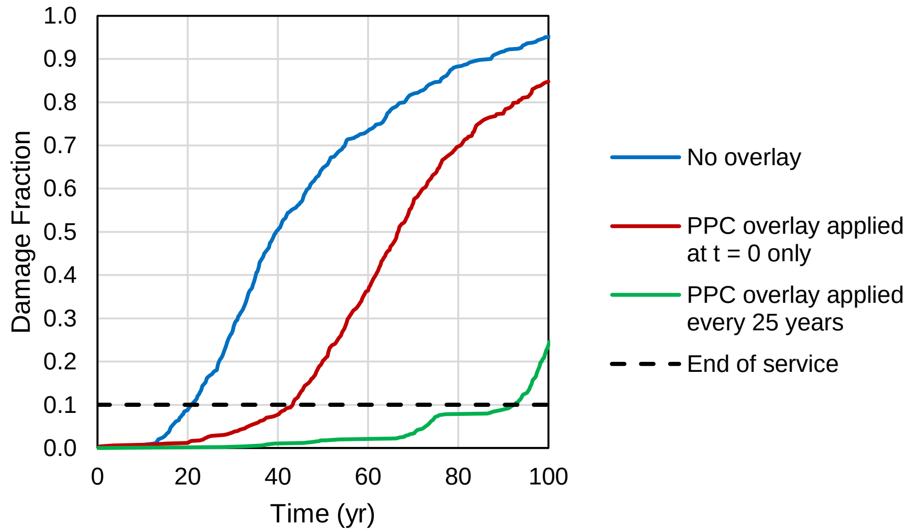

Figure 5.6. Probability of corrosion initiation for concrete deck with PPC overlays applied at t = 0.

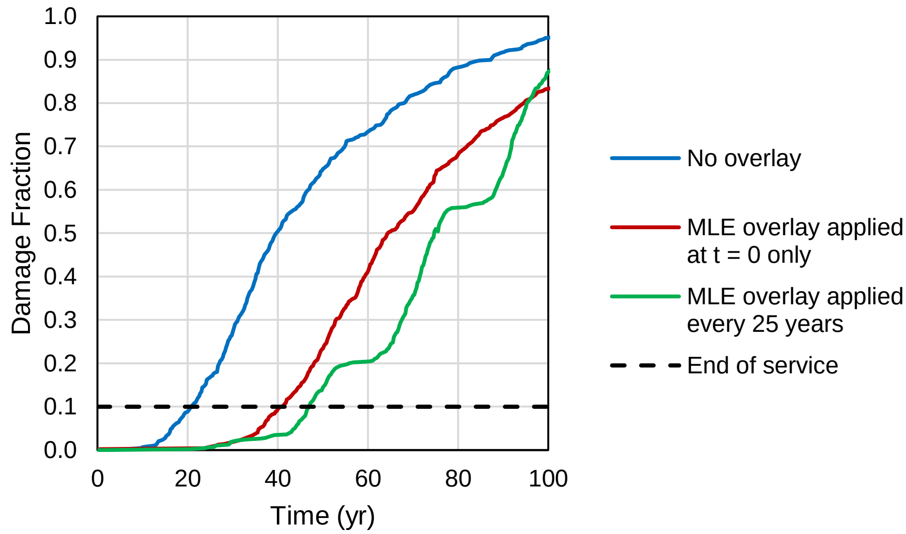

Figure 5.7. Probability of corrosion initiation for concrete deck with MLE overlays applied at t = 0.

Case 4: New bridge deck with delayed application of overlay

Case 4 considered a new bridge deck with a delayed application of the overlay, such that some amount of chlorides were present in the bridge deck base layer. The purpose of the Case 4 simulations was to determine the optimal time for the initial overlay application; therefore, only a single overlay application was simulated. Two surface preparations were considered in the simulations: 1) removal of the top 1/2 inch of the deck surface prior to application of the overlay; and 2) shot blasting of the deck surface prior to application of the overlay. Option 1 permits the removal of chlorides penetrating the top 1/2 inch of the deck, but at the expense of a 1/2-inch reduction in the overall cover to the top mat of reinforcing steel. Option 2 maintains the top 1/2-inch of bar cover, but also retains all chlorides that have penetrated the deck prior to the overlay application.

The model results for Option 1 (1/2-inch deck removal) are shown in Figure 5.8. For the PPC overlay, the maximum deck service life is approximately 43 years and occurs for any overlay application time within the first 10 years of service. After the first 10 years of service, the chlorides have penetrated the deck such that 1/2-inch removal of the deck surface during overlay application does not remove sufficient chlorides to significantly reduce the probability of corrosion of the reinforcing steel after overlay application. The performance of either overlay type is essentially equivalent at this point because enough chlorides remain in the deck concrete to initiate corrosion of the reinforcing steel with continued diffusion.

For the MLE overlay, the maximum service life is obtained when the overlay is placed on the deck at time t = 0 (no delay in application). This is because the thickness of the MLE overlay (0.4 inch) is less than the PPC. Although the MLE has a much lower diffusion coefficient than the concrete substrate, as modeled, it still allows some chloride to penetrate through to the substrate. Reducing the protective overlay material thickness results in the smaller extension of service life as compared to the PPC.

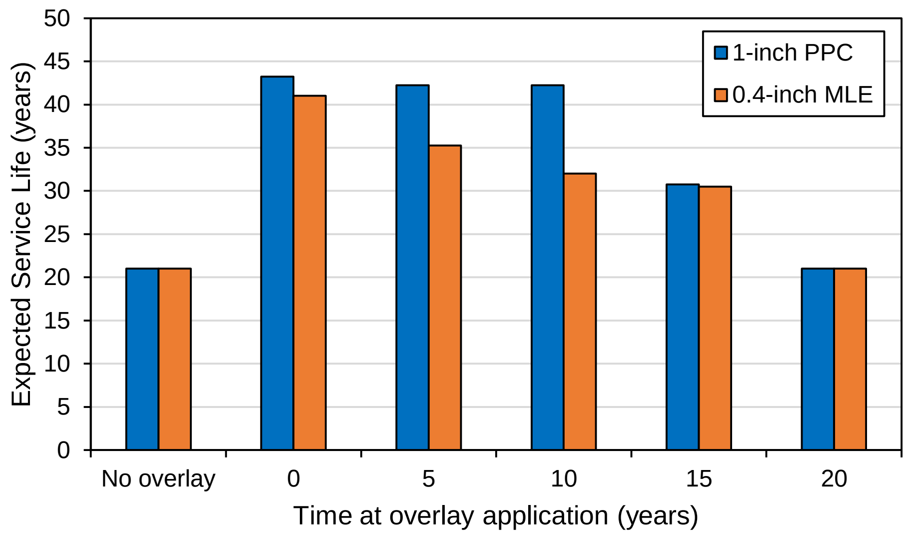

Figure 5.8. Expected service life for concrete deck with delayed overlay application. 1/2-inch deck removal was included in the initial overlay application for the service life shown at application ages of 5 years or more.

The model results for Option 2 (shot blasting of the deck surface) are shown in Figure 5.9. Shot blasting of the deck surface, without removing concrete, increases the overall service life of the deck for delayed applications of up to 5 years for both the PPC and MLE overlays. A maximum service life of 46 years is obtained for the 1 inch PPC overlay when the overlay is applied 5 years after deck construction. Despite limited removal of the top surface, the optimal service life for a 0.4-inch MLE overlay is still obtained when the overlay is applied at time t = 0 (no delay in application).

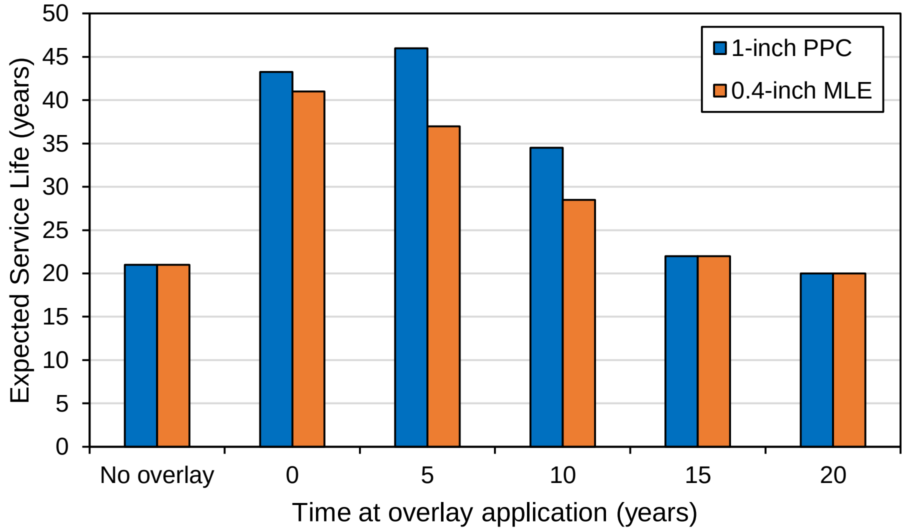

Figure 5.9. Expected service life for concrete deck with delayed overlay application. Shot blasting of the top surface of the deck was included in the initial overlay application for the service lives shown.

A comparison of the two surface preparations (shot blasting versus 1/2 inch deck removal) is shown in Figure 5.10 for a 1-inch PPC overlay and in Figure 5.11 for a 0.4-inch MLE overlay. The results demonstrate that the two surface preparations each provide different benefits to service life at the various ages of overlay application. If installation occurs within the first 5 years of service, the chloride ions have not significantly penetrated the deck surface, and therefore, shot blasting is found to provide a greater benefit to service life. However, if installation occurs after 10 or more years of service, greater amounts of chlorides have penetrated the bridge deck and to a greater depth; therefore, removing the top 1/2 inch of the deck wearing surface provides the greater benefit at these ages. For overlay installations occurring between 5 and 10 years of service, similar benefits are expected to be obtained by either preparation method; in these cases, surface preparation decisions may be instead made on the basis of cost or other criteria.

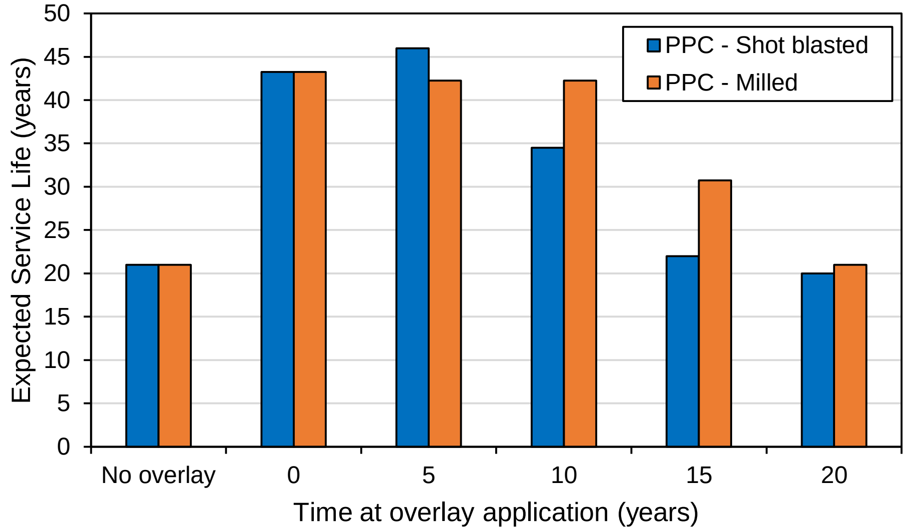

Figure 5.10. Expected service life for various surface preparations of concrete deck with 1-inch PPC overlay.

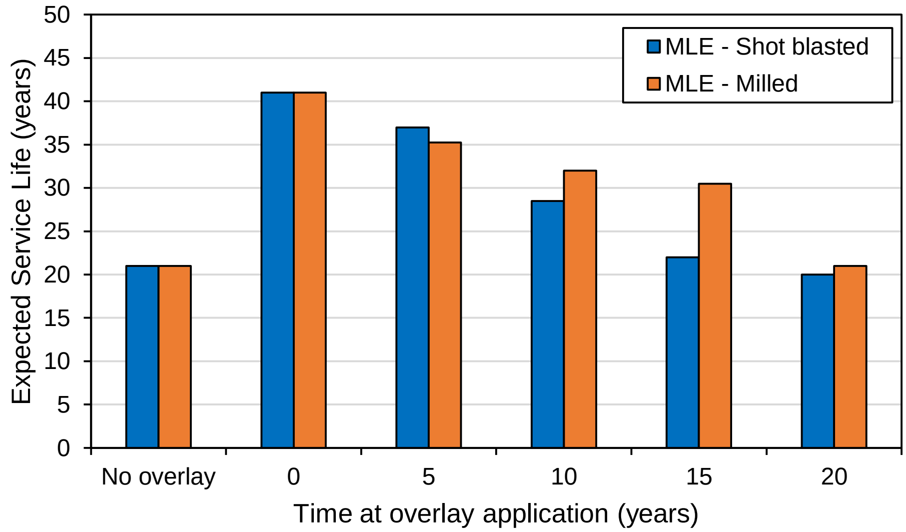

Figure 5.11. Expected service life for various surface preparations of concrete deck with 0.4-inch MLE overlay.

Based on the outcomes of the Case 4 simulations, a final simulation was performed to examine a combination of deck-penetrating sealers applied at time t = 0 and a 1-inch PPC overlay applied at time t = 5 years (with shot blasting of the surface). As before, only a single overlay application was considered to examine the optimal timing of the initial overlay placement; however, overlay replacements every 20 to 25 years would be recommended in practice. Based on the model simulations, the combined deck sealer and PPC overlay results in a total expected service life of 53 years for the example bridge deck, an increase of 32 years relative to the Case 1 simulation with no preventive maintenance.

5.5 Summary

Summaries of the simulation results for the example bridge deck are shown in Table 5.2 (Cases 1-3), Table 5.3 (Case 2), and Table 5.4 (Case 4). Overall, the greatest expected service life estimates were found for preventive maintenance programs that included a polymer overlay replaced every 25 years. The 1-inch PPC overlay was found to provide a greater extension of bridge deck service life than the MLE overlay due to the PPC overlay's combination of very low chloride diffusivity and greater (1 inch) thickness. It is also noted that choosing to remove 1/2 inch of substrate material for each reapplication also contributed to extended service life. Removal of 1/4 inch of substrate material or more frequent reapplications of the overlay may lead to a longer service life for the case of using MLE overlay. However, as modeled, the PPC overlay always will result in a longer service life extension given that both systems are assumed to have the same deterioration (delamination and cracking) rate.

Based on the outcomes of this study, in order to achieve the longest service life extension for an ordinary new concrete bridge deck in Iowa, the preventive maintenance program in Iowa should consist of:

1. Application of a deck-penetrating sealer shortly after (3 to 6 months) construction of the new bridge deck to seal small cracks and reduce the build-up of chlorides on the surface of the bridge deck. It is recommended to apply sealer before first application of deicing salts.
2. Application of a polymer overlay within the first 5 to 10 years of service, with surface preparation consisting of shot blasting or other approved means of preparing the surface and sealing of all cracks; and
3. Replacement of the overlay every 20 to 25 years thereafter to further extend the service life. Surface preparation with 1/4 to 1/2 inch deck removal should be considered based on the condition of the substrate at the time of overlay replacement. Sealing of all wide and moving cracks prior to application of the overlay is also recommended.

Table 5.2. Summary of service life model results for Cases 1-3 (new deck, treatment at year 0)

Preventive Maintenance Interval	No Preventive Maintenance	Sealer Only	Overlay Only	
			1-inch PPC	0.4-inch MLE
Treatment applied at 0 years only	21	24	43	41
Treatment reapplied at end of service life of protective material (6 years for sealer; 25 years for overlay)	21	25	93	47

Table 5.3. Summary of service life model results for Case 2 (new deck, sealer treatment at year 0)

Sealer Reapplication Interval (years)	Expected Service Life (years)
No sealer	21
No reapplication	24
2	40
4	29
6	25

Table 5.4. Summary of service life model results for Case 4 (new deck, delayed application of overlay)

Deck Age at Overlay Application (years)	**Prepare surface only, limited depth of removal**		**Remove top 1/2" of surface prior to overlay**	
	1-inch PPC	**0.4-inch MLE**	**1-inch PPC**	**0.4-inch MLE**
No overlay	21	21	21	21
0	43	41	43	41
5	46	37	42	35
10	35	29	42	32
15	22	22	31	31
20	20	20	21	21
Sealer at 0 years + Overlay at 5 years	53	41	--	--

CHAPTER 6. OPTIMUM TIMING OF PREVENTIVE MAINTENANCE

6.1 Summary of Current Practice

The literature indicates that polymer overlays and sealers should not be used on concrete bridge decks with severe distress or spalling and that neither option should be considered as a rehabilitation method (although polymer concrete can be used in repairs). For polymer overlays, many reported failures have been attributed to the poor condition of the deck prior to applying the overlay (Fowler and Whitney 2011). Some states have guidelines to limit the use of polymer overlays based on the measured degree of distress in the deck. For example, Missouri recommends using polymer overlays for decks with less than 5% of the deck requiring repairs (Fowler and Whitney 2011) while Kansas recommends using polymer overlays if the degree of distress is between 3 and 10% (Krauss et al. 2009a). It is noted that Harper (2007) indicated that decks with more than 5 to 10% distress prior to overlay installation continued to have problems after overlay installation. For sealers, the literature indicates that they are not effective in sealing cracks with a crack width larger than 0.025 inch. Therefore, decks with wide cracks, active corrosion, or spalled areas are not be good candidates for sealers applications.

A survey by Fowler and Whitney (2011) provides recommendations by contractors and suppliers for successful installation of polymer overlays. Both parties agreed that the overlay should be only placed on sound, clean and dry deck surfaces. Also the overlay should be placed by a contactor with experience in such systems.

6.2 Optimum Timing for Application of Preventive Maintenance

The main purpose of using polymer overlays and sealers on bridge decks is to extend the service life of the deck and to reduce the need for conducting extensive maintenance in the future. Both methods have the ability to limit chloride and moisture ingress, which protects the decks from distress due to corrosion of reinforcing, freeze-thaw damage and scaling. However, the time of application of either method usually affects the performance and the benefit gained from the preventive maintenance.

6.2.1 Current Practice

A survey found that current practice in many states is to apply overlays to bridge decks with a median age between 15 to 20 years. Currently, Illinois and Utah use polymer overlays on new bridge decks to protect the concrete from distress or to correct the concrete surface when construction errors are made (e.g., small concrete cover); Utah uses polymer overlays on all new bridge decks (CTC & Associates LLC 2012). In addition, many other states specify using polymer overlays on bridges with an extended design service life including New York and Kentucky. Although timing of installation is not specifically cited, it is recommended that the deck be sound and/or repaired and that all chloride contaminated concrete be removed prior to application of overlay. This indicates that for optimum timing and cost, overlay installation should be early enough in the service life of the bridge deck to avoid extensive repairs prior to installation.

It is recommended that sealers be applied at an early age to ensure that the cracks are not severely contaminated (Meggers 1998). Sealers are also less effective if they are placed after chloride ingress has occurred, as sealers do not have the ability to remove chlorides that have already penetrated the deck. The literature indicates that most of the states that use deck sealers apply them immediately after construction (Soriano 2003, Johnson et al. 2009). However, some states also apply sealers to old decks. Sealer reapplication is also a widely used practice with reapplication times ranging from 3 to 6 years. In summary, the best reported practices include an initial application of the deck sealer within 3 to 6 months of construction and reapplication at 5-year intervals.

6.2.2 Recommendations for Optimum Timing

Service life models were performed in Chapter 5 to study the effect of using preventive maintenance options on new bridge decks. As the results showed, a single application of the deck sealer did not significantly improve the service life of the model bridge deck, as it only added 3 years of service compared to the base case (no treatment). Reapplication of sealers every 2 years nearly doubled the service life compared to the base case by adding 19 years service life, while reapplication every 6 years only added 4 years of service life (similar to single application of sealer). This difference in effectiveness is attributed to the high rate of deterioration of sealers which highlights the need for frequent reapplication if extended service life is desired.

Installation of a PPC overlay with 1/2 inch deck removal every 25 years resulted in an expected service life of 93 years (+72 years service life). This is about 4 times the expected service life of 21 years of the base case with no preventive maintenance. Installation of a MLE overlay with a 1/2 inch deck removal every 25 years resulted in an expected service life of 47 years (+26 years service life). The difference in service life between PPC and MLE was mainly attributed to the fact that MLE overlays are typically applied with less thickness than PPC overlays (0.4 inch vs 1 inch) and therefore provide less overall resistance to chloride penetration. These results are based on the assumption that both overlays will have the same delamination ratio at the end of their assumed service life of 25 years. The delamination rate over time for the overlays used in this report requires further field data to refine the assumed values.

It is also noted that the influence of cracking is ignored in service life models presented. The presence of cracks will reduce the service life for decks without preventive maintenance and for decks containing overlays. Sealers and overlays may therefore have a greater benefit on service life than currently shown by the modeling results, as the main benefit of sealers and overlays is their ability to seal fine early-age cracks and to prevent chloride and moisture ingress through cracks.

Several ages of initial overlay installation were also considered to evaluate maximum life extension. The results agree with the recommendations found in the literature where early application of preventive maintenance generally yielded a longer expected service life. As shown in the results, the greatest benefit was found when the PPC overlay was installed after 5 years of service, with a surface preparation that included limited removal of the deck surface; this case yielded 46 years of service life compared to 21 years for the base case with no preventive maintenance. For MLE overlays, the optimum time of application was found to occur immediately after deck construction. This is due to the difference in thickness between the two systems, where PPC overlays are more than twice the thickness of MLE overlays and, therefore, provide greater protection from chloride ingress during the initial years.

The results also show that after 10 years, greater service life is achieved when deck preparation consists of 1/2-inch removal of the deck surface rather than shot-blasting of the surface with no significant depth of removal. Although substrate removal reduces the overall concrete cover, it also removes the contaminated layer of concrete with the highest chloride concentrations, which reduces the overall concentration of chlorides in the deck. At 10 years' delay of installation, the PPC overlay still provides greater benefit than the MLE overlay; however, after 10 years, both systems yield the same predicted service life, as the chloride concentration in the bridge deck is large enough that, even with 1/2-inch removal during surface preparation, sufficient chlorides remain in the deck to cause initiation of corrosion in the steel reinforcement. At 20 years' delay in installation, neither overlay will extend the service life of the bridge deck, as the assumed failure criteria of 10% probability of corrosion initiation in the top mat of steel is reached shortly after the overlay is installed. If the substrate concrete is less permeable than assumed for the base case, or more substrate material is removed during surface preparation, a longer delay between original construction and overlay installation may be feasible. This can be modelled on a case-by-case basis if chloride concentration with depth is measured.

The option found to result in the longest service life without the need for preventive maintenance reapplication was to use a deck sealer 3 to 6 months after construction (prior to application of deicing salts) and then to install an overlay within the first five years. The proposed approach yielded a service life of 53 years, a 32 years increase in service life compared to base case, which may be a realistic service life for the majority of bridges in Iowa. This hybrid preventive maintenance approach maximizes the benefit from each of the maintenance options, as sealers will help seal early age cracks and protect the deck from chloride ingress, and overlays will further restrict chloride and moisture ingress through the deck. Applying the overlay after 5 years will also allow most of the shrinkage to occur in the deck and, therefore, reduce its potential to cause additional cracking in the overlay. Periodic removal and replacement of the overlay and upper concrete surface will provide additional service life. It is noted that some maintenance of the overlay may be required to ensure its proper performance; the focus of this maintenance would be primarily on sealing large cracks and repairing any delaminated areas. Compatibility of all materials used is also essential for successful performance.

6.3 Cost-Benefit Ratio

One of the most important aspects of choosing a preventive maintenance scheme is the cost-benefit ratio. A limited analysis is presented in this section based on the costs of different maintenance and repair approaches provided by Iowa DOT as follows:

- Sealers (price from literature) $13.50 per yd^2
- Polymer deck overlay (one project only) $42.75 per yd^2
- Class O PCC deck overlay $89.00 per yd^2
- Class HPC-O deck overlay $105.00 per yd^2
- Class A repair, in conjunction with overlay $226.00 per yd^2
- Class B repair, in conjunction with overlay $534.00 per yd^2

Based on these estimates, the cost of applying sealers is approximately 32% of that of overlay on an area basis. However, sealers provide less service life benefit as analyzed in Chapter 5. The price of installing a polymer overlay is approximately 48% of the price of low-slump portland cement concrete (Class O PCC) overlay and 41% of high performance concrete (Class HPC-O) overlay. Polymer concrete overlays result in more savings when compared to conventional overlays if installed during service as they require less curing time and, therefore, less traffic control and shorter lane closure times.

Life-cycle cost analysis (LCCA) was conducted to assess the cost of seven selected maintenance options considering a 100-year service life for a generic bridge deck. In order to achieve the 100 years, deck replacement may be required based on the chosen preventive maintenance option. The life-cycle cost analysis was conducted using RealCost software by the Federal Highway Administration (FHWA). The software is available free of charge on the FHWA website and can be downloaded using the following link https://www.fhwa.dot.gov/infrastructure/asstmgmt/lcca.cfm. The software was primarily developed for LCCA of pavements, but the same concepts can be applied to the case of bridge decks. Additional information regarding the software can be found in Walls and Smith (1998).

The life-cycle costs considered by the software include agency costs and user costs. For the purpose of this analysis, user costs are neglected as they vary based on the location and the traffic conditions of the bridge, for example urban bridges versus rural bridges. However, for real cases, user costs and traffic delays may be governing factors for preventive maintenance selection, especially for critical bridges in urban areas which can have significant effects on the performance of the transportation network.

The service life estimates presented in Chapter 5 were used to conduct the LCCA. A generic bridge deck of an area 1000 yd^2 was selected for the analysis. For each of the seven selected maintenance options, it was assumed that bridge deck replacement is required 10 years after the estimated service life presented in Chapter 5. This was done to account for the fact that a bridge deck will only be replaced after a certain amount of corrosion propagation and damage has occurred. The seven maintenance options considered in the analysis are:

- Option 1 - No Preventive Maintenance: This option assumes no preventive maintenance is applied on the new bridge deck. The cost of new deck is applied at the time of construction and again with every deck replacement. Based on service life modeling results, deck replacement is required every 31 years (21 service life + 10 years to allow certain amount of damage to occur). Therefore, for a 100 year service life, the deck will be replaced three times.
- Option 2 - Apply Sealer on New Deck, No Reapplication: This option assumes that a sealer is applied once at the time of construction. The cost of the sealer application is added to the cost the new deck. Based on service life modeling results, deck replacement is required every 34 years (24 service life + 10 years to allow corrosion propagation and damage to occur). Therefore, for a 100 year service life, the deck will be replaced two times.
- Option 3 - Apply Sealer on New Deck, Reapply every 2 years: This option assumes that a sealer is applied at the time of construction and every 2 years thereafter up to the end of service. The cost of sealer application is added to the cost of the new deck and is added again every 2 years. After reaching a service life of 40 years, the sealer is not reapplied and no maintenance is assumed during the damage propagation period. Based on service life modeling results, deck replacement will be required every 50 years (40 service life + 10 years to allow corrosion propagation and damage to occur, no maintenance is assumed during this period). Therefore, for a 100 year service life, the deck will be replaced one time.
- Option 4 - Apply Sealer on New Deck, Reapply every 6 years: This option assumes that a sealer is applied at the time of construction and every 6 years thereafter up to the end of service. The cost of sealer application is added to the cost of the new deck and is added again every 6 years. After reaching a service life of 25 years, the sealer is not reapplied and no maintenance is assumed during the damage propagation period. Based on service life modeling results, deck replacement will be required every 35 years (25 service life + 10 years to allow corrosion propagation and damage to occur, no maintenance is assumed during this period). Therefore, for a 100 year service life, the deck will be replaced two times.
- Option 5 - Install Polymer Overlay after 5 years of Construction, No Reinstallation: This option assumes that a polymer overlay is installed after 5 years of construction. The cost of the new deck is added at time of construction, while the cost of overlay is added after 5 years of construction. Based on service life modeling results, deck replacement will be required every 56 years (46 service life + 10 years to allow corrosion propagation and damage to occur, no maintenance is assumed during this period). Therefore, for a 100 year service life, the deck will be replaced one time.
- Option 6 - Install Polymer Overlay on New Deck, Reinstall every 25 years: This option assumes that a polymer overlay is installed at the time of construction and every 25 years thereafter up to

the end of service. The cost of overlay is added to the cost of the new deck and again every 25 years. Based on service life modeling results, deck replacement will be required every 103 years (93 service life + 10 years to allow corrosion propagation and damage to occur, no maintenance is assumed during this period). Therefore, for a 100 year service life the deck will not be replaced.

- Option 7 - Apply Sealer on New Deck, Install Polymer Overlay 5 Years after Construction: This option assumes that a sealer is applied at the time of construction and an overlay is installed 5 years after construction. The cost of the sealer application is added to the cost of the new deck, while the cost of overlay is added 5 years after construction. Based on service life modeling results, deck replacement will be required every 63 years (53 service life + 10 years to allow certain amount of damage propagation to occur, no maintenance is assumed during this period). Therefore, for a 100 years the deck will be replaced one time.

The life-cycle cost analyses assumed that the cost of a new deck or full deck replacement is approximately equal to the cost of a Class B repair, per square yard of deck area replaced. For each of the considered maintenance options, the cost of sealer application ($13.50/ yd^2) or overlay installation ($42.75/ yd^2) was added to the analysis at the time of application. The analyses did not consider any deck repairs during the life of the deck.

Net present value is typically used to estimate the cost in LCCA. This includes using a discount rate to calculate all of the accrued costs during the life of the analyzed structure and subtracting a salvage value for the residual life after the considered period for analysis, 100 years in this analysis. A discount rate of 4% was used, based on historical trends indicating that the real value of money is approximately 4% and a range of 3 to 5% is acceptable (Walls and Smith 1998). The salvage value was calculated by multiplying cost of the preventive maintenance by the fraction of its service life that still remains (e.g., 16 years remaining for an overlay with a 25 year design life, or 64 percent). It is represented in the analysis as a negative number because it reduces the total life-cycle cost of the preventive maintenance.

Life-cycle costs for each of the considered preventive maintenance options are shown in Table 6.1, while the details of the costs accrued and salvage value for each of the maintenance options are shown in Table 6.1. It is noted that the values shown in Table 6.2 are not reduced by the discount rate, although the discount rate is factored into the overall costs presented in Table 6.1. As seen in Table 6.1, the program calculates three values: undiscounted sum, present value and EUAC (Equivalent Uniform Annual Cost). The results of the analysis show that the best option is Option 6 - Install Polymer Overlay on New Deck, Reinstall Every 25 Years; followed by Option 7 - Apply Sealer on New Deck, Install Polymer Overlay 5 Years after Construction. Both options include installing an overlay on the bridge deck and result in cost reductions of 20% and 16%, respectively, compared to the base case with no preventive maintenance. It also is noted that the overall life-cycle costs for options containing sealer application (Options 2, 3, and 4) are very similar to the cost of no preventive maintenance. However, these results may change if user costs are included, as the number of deck replacements and associated traffic disruption increases if no preventive maintenance takes place.

Based on the results, for bridges with required service life of approximately 50 years, the best option is to apply sealer on the new deck and install an overlay within the first 5 years. If the required service life is more than 50 years, reapplication of polymer overlay is required.

The analysis presented in this study is only based on probability of corrosion initiation. Factors such as ride quality and other concrete degradation mechanisms were not considered. The results presented in this section are for general guidance only. For bridges with long service life, analysis should be done on case-by-case basis.

Table 6.1. Life-cycle cost analysis results for selected maintenance options

	Agency Costs ($1000)						
	Option 1:	**Option 2:**	**Option 3:**	**Option 4:**	**Option 5:**	**Option 6:**	**Option 7:**
Total Cost	No preventive maintenance	Sealer, No Reapplica-tion	Sealer, Reapply every 2 years	Sealer, Reapply every 6 years	Overlay after 5 years, No Reinstalla-tion	Overlay, Reinstall every 25 years	Sealer, Install Overlay after 5 years
Undiscounted Sum	*$1,722.58*	*$1,610.48*	*$1,608.00*	*$1,720.15*	*$1,029.01*	*$683.62*	*$935.38*
Present Value	**$744.97**	**$729.20**	**$778.50**	**$ 760.62**	**$629.96**	**$600.63**	**$627.02**
EUAC	$30.40	$29.76	$ 31.77	$31.04	$25.71	$24.51	$25.59

Table 6.2. Costs accrued and salvage values at different years for selected maintenance options

Expenditure Stream, Agency Costs ($1000)								
Year		**Option 1:** No preventive maintenance	**Option 2:** Sealer, No Reapplication	**Option 3:** Sealer, Reapply every 2 years	**Option 4:** Sealer, Reapply every 6 years	**Option 5:** Overlay after 5 years, No Reinstallation	**Option 6:** Overlay, Reinstall every 25 years	**Option 7:** Sealer, Install Overlay after 5 years
0	2017	534.00	547.50	547.50	547.50	534.00	576.75	547.50
1	2018							
2	2019			13.50				
3	2020							
4	2021			13.50				
5	2022					42.75		42.75
6	2023			13.50	13.50			
7	2024							
8	2025			13.50				
9	2026							
10	2027			13.50				
11	2028							
12	2029			13.50	13.50			
13	2030							
14	2031			13.50				
15	2032							
16	2033			13.50				
17	2034							
18	2035			13.50	13.50			
19	2036							
20	2037			13.50				
21	2038							
22	2039			13.50				
23	2040							
24	2041			13.50	13.50			
25	2042						42.75	
26	2043			13.50				
27	2044							
28	2045			13.50				
29	2046							
30	2047			13.50				
31	2048	534.00						

Expenditure Stream, Agency Costs ($1000)								
Year		**Option 1:** No preventive maintenance	**Option 2:** Sealer, No Reapplication	**Option 3:** Sealer, Reapply every 2 years	**Option 4:** Sealer, Reapply every 6 years	**Option 5:** Overlay after 5 years, No Reinstallation	**Option 6:** Overlay, Reinstall every 25 years	**Option 7:** Sealer, Install Overlay after 5 years
32	2049			13.50				
33	2050							
34	2051		547.50	13.50				
35	2052				547.50			
36	2053			13.50				
37	2054							
38	2055			13.50				
39	2056							
40	2057							
41	2058				13.50			
42	2059							
43	2060							
44	2061							
45	2062							
46	2063							
47	2064				13.50			
48	2065			547.50				
49	2066							
50	2067			13.50			42.75	
51	2068							
52	2069			13.50				
53	2070				13.50			
54	2071			13.50				
55	2072							
56	2073			13.50		534.00		
57	2074							
58	2075			13.50				
59	2076				13.50			
60	2077			13.50				
61	2078					42.75		
62	2079	534.00		13.50				
63	2080							547.50
64	2081			13.50				

Expenditure Stream, Agency Costs ($1000)								
Year		**Option 1:** No preventive maintenance	**Option 2:** Sealer, No Reapplication	**Option 3:** Sealer, Reapply every 2 years	**Option 4:** Sealer, Reapply every 6 years	**Option 5:** Overlay after 5 years, No Reinstallation	**Option 6:** Overlay, Reinstall every 25 years	**Option 7:** Sealer, Install Overlay after 5 years
65	2082							
66	2083			13.50				
67	2084							
68	2085		547.70	13.50				42.75
69	2086							
70	2087			13.50	547.50			
71	2088							
72	2089			13.5				
73	2090							
74	2091			13.5				
75	2092						42.75	
76	2093			13.5	13.5			
77	2094							
78	2095			13.5				
79	2096							
80	2097			13.5				
81	2098							
82	2099			13.5	13.5			
83	2100							
84	2101			13.5				
85	2102							
86	2103			13.5				
87	2104							
88	2105			13.5	13.5			
89	2106							
90	2107			13.5				
91	2108							
92	2109			13.5				
93	2110	534						
94	2111			13.5	13.5			
95	2112							
96	2113			13.5				
97	2114							

Expenditure Stream, Agency Costs ($1000)								
Year		**Option 1:** No preventive maintenance	**Option 2:** Sealer, No Reapplica-tion	**Option 3:** Sealer, Reapply every 2 years	**Option 4:** Sealer, Reapply every 6 years	**Option 5:** Overlay after 5 years, No Reinstalla-tion	**Option 6:** Overlay, Reinstall every 25 years	**Option 7:** Sealer, Install Overlay after 5 years
98	2115			13.5				
99	2116							
100	2117	-413.42	-32.22	0	-84.36	-124.49	-21.34	-245.12

CHAPTER 7. CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

This report provides a summary of current practices by state DOTs for applying polymer concrete overlays and penetrating sealers as preventive maintenance approaches for new bridge decks. The study included a literature review of federal and state sponsored research reports and surveys with focus on optimum timing. Service life models were also performed to investigate the effect of using polymer overlays and sealers on service life of a typical bridge deck in Iowa. To simplify the analysis, the deck was assumed to be free of any cracks, and the end of service life was based on 10% probability of chloride induced corrosion in the top mat of reinforcing steel. The findings of this study can be summarized as follows:

- Polymer overlays and sealers are currently being used by many states as preventive maintenance measures for both new and old bridge decks; however, neither system should be used on severely deteriorated decks or decks in need for major repairs, as they will not be effective. Several states have guidelines that limit the use of polymer overlays and sealers to decks that meet certain criteria.
- The main uses of polymer overlays include restoring skid resistance of decks, protecting the deck from chloride and moisture ingress, protecting reinforcing steel with low concrete cover in case of construction errors, and extending service life of bridge decks for special projects. Deck condition, adequate surface preparation, and temperature during placement have the greatest effect on the quality of the overlay installation and, subsequently, its performance.
- Polymer overlays can be expected to have a service life of approximately 25 years when properly installed on well-prepared surfaces. This is true for multi-layer epoxy (MLE) and premixed polyester concrete (PPC) overlays, which have been shown in field applications to provide protection to the deck for periods exceeding 20 years. However, reflective cracks extending from the deck to the overlay may cause local distress if not sealed or repaired prior to or after overlay installation. Some delamination in the overlay is also expected to occur with time.
- Deck sealers are mainly used to seal cracks with small crack widths and to slow chloride and moisture ingress. Sealers should only be used on clean, dry surfaces and at temperatures within the manufacturer recommendations. Cold and damp concrete surfaces are not good for sealers application.
- Penetrating sealers are better suited than film forming barrier coatings for bridge deck surfaces. Silanes and siloxanes are the most widely used penetrating sealers. High molecular weight methacrylates (HMWMs) are also used as both deck and crack sealers. Sealers are not effective for bridges where chloride ingress has already occurred or for sealing wide cracks. The best current practice for service life extension is to apply sealers within 3 to 6 months after bridge construction and reapply every 2 years. However, this is the most expensive option for sealers application as illustrated by the life-cycle cost analysis. In general, the life-cycle cost analysis showed that sealer reapplication, although it increases the service life, is less cost effective than the no preventative maintenance option. The use of sealer was also associated with higher life-cycle cost compared to polymer overlays.
- Polymer overlays have several advantages over sealers, including restoring skid resistance and appearance. Both systems have the ability to seal small cracks. For polymer overlays, wide or moving cracks may reflect through the overlay and, unless repaired or sealed, deterioration may continue at the cracked areas.
- Preventive maintenance models show that polymer overlays provide superior protection and service life to the bridge deck compared to sealers. This is expected as polymer overlays provide better

protection to the steel by adding a layer with low chloride diffusion limiting moisture and oxygen, while sealers only slow down chloride and moisture ingress at the surface of the deck.

- The results of the service life modeling show that optimum timing for installing preventive maintenance is within the first 10 years of bridge construction. This agrees with the recommendations found in the literature.
- The service life models result indicate that PPC overlays yield longer service life when compared to MLE overlays. This is mainly attributed to the greater thickness of the PPC overlay. The two proposed polymer overlays, PPC and MLE, are available by different manufacturers and have a good record of performance. PPC offer greater thickness and, therefore, greater protection compared to MLE but it will also be associated with higher stresses at the interface (Choi et al. 1996). Literature and experience indicates that while thicker overlays are subject to higher stresses at the interface, thinner overlays are subject to higher crack reflection and wear. It is noted that the service life models assume that both overlays will have the same delaminated area at the end of their service life. In reality, this rate of delamination is dependent on material formulation, surface preparation, traffic levels, and weather exposure. Rate of deterioration of different overlay material was not investigated as it is out of the scope of this report.
- Life-cycle cost analysis (LCCA) indicated that the use of preventive maintenance approaches will result in significant savings. The results show that the most cost-effective option over a 100-year period of service is to install an overlay at the time of construction and to reinstall it every 25 years. For bridges with expected life of 50 years, the service life models and LCCA indicate that the best results were obtained when a hybrid preventive maintenance approach is used, which consists of applying a sealer immediately after bridge construction and installing a polymer overlay after approximately 5 years. This approach maximizes the benefit from each system as sealers will seal early age cracks forming on the deck while overlays will be applied prior to any significant chloride ingress. Applying the polymer overlays after 5 years will also give sufficient time for shrinkage cracks to form in the deck, which may limit the reflection of these cracks through the overlay.

Although the service life models did not include the effect of cracking, cracks do form in bridge decks starting at early age. If not sealed, cracks sufficiently wide to allow moisture movement increase the risk of premature deterioration at local areas in the bridge deck. Applying either polymer overlays or sealers will help seal the majority of cracks in bridge decks. The proposed hybrid approach for application of sealers early in the life of the bridge, within the first 3 to 6 months and before using deicing salts, followed by polymer overlay installation is recommended. It is noted that sealer reapplication is recommended if a polymer overlay will not be installed within the first 5 years.

All of the results related to the service life models are limited by the assumptions used to create the models and are only intended to provide comparisons between different cases. The presence of cracks in real bridge decks may have a significant effect on the results. The assumed end-of-service condition in the model represents a conservative estimate for actual conditions. At this level of damage, real bridge decks will typically show minor signs of deterioration from corrosion, including rust staining, cracking, and limited delaminations or spalls.

7.2 Implementation

The contents of this report may be used as general guidelines for Iowa DOT to choose optimum timing for application of preventive maintenance such as polymer overlays and penetrating deck sealers. The provided preventive maintenance optimization example can be used to obtain a general indication of the expected benefits of using preventive maintenance at early ages and reapplication throughout the life of the deck. Given the limitations and assumptions associated with the example, it is recommended to use the example for guidance only. Specific studies should be conducted for bridges with a design service life of 50 years or more.

The literature review results for material specification and surface preparation are in general agreement with Iowa DOT Special Provisions (for example SP-120011 and SP-150132) for multi-layer polymer concrete overlays, with exception of few material test methods. The contents and references provided in this report could be used to develop Standard Specifications for the use of PPC polymer overlays and sealers based on the existing Iowa DOT special provisions.

The findings of this report indicate that application of sealers on new bridges helps seal early age cracks and reduce the potential for surface damage in the deck and that installation of polymer overlays at early ages has the greatest beneficial effect of service life extension. The cost-benefit analysis showed that significant life cycle cost savings may be achieved if preventive maintenance is applied within the first 10 years. Therefore, it is recommended that these preventive maintenance approaches be applied early in the life of new bridges.

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ATTACHMENT A - WJE SERVICE LIFE MODELING METHODOLOGY

WJE SERVICE LIFE MODELING METHODOLOGY

Rev. 2.2 – March 2016

I. 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 WJE's 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 or corrodes 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 cathode 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.

I.a. Carbonation

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.

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 in Figure 2. Generally, corrosion rates increase significantly as relative humidity within the concrete increases beyond 75 percent. The rates

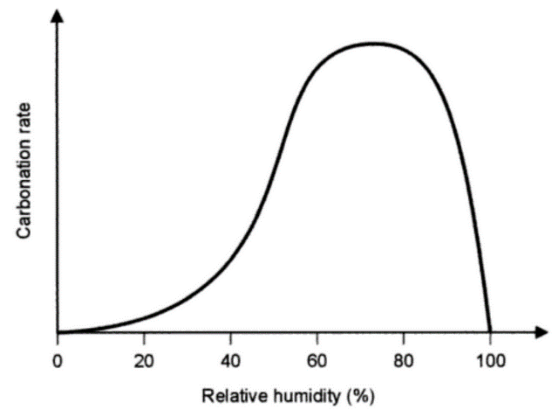


Figure 1. Schematic showing the effective of relative humidity on carbonation rate (from Bertolini, Elsener, Pedeferri, & Polder, 2004).

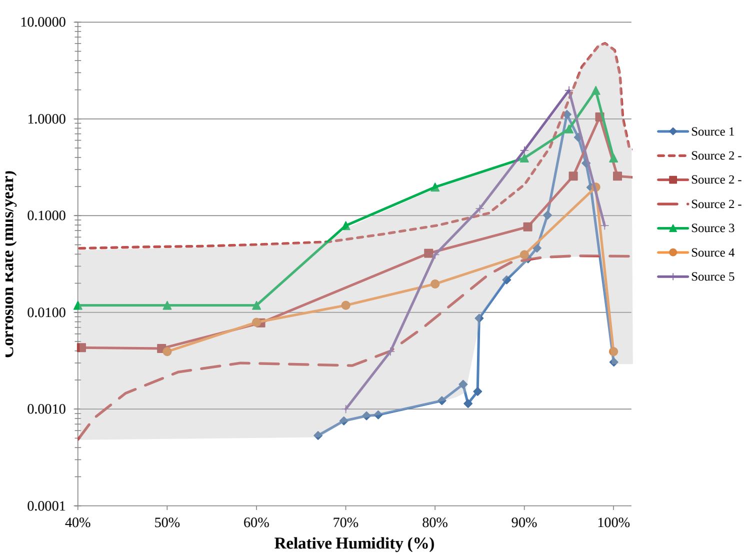


Figure 2. Corrosion rate in carbonated concrete versus relative humidity.
Sources:
1) *Tuutti, 1982;*
2) *Alonso & Andrade, 1993*
3) *Parrott, 1994*
4) *Bamforth, 2004*
5) *RILEM TC 130-CSL, 1996*

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).

I.b. 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's model, 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 values in a mass relative to weight of concrete basis.

It is important to recognize that corrosion is not certain at any particular chloride concentration, since multiple factors (including cement content and chemistry, moisture conditions, temperature, and corrosion condition of surrounding bars) affect the influence of chloride concentration on corrosion. The likelihood, severity, and rate of corrosion increase as chloride concentrations increase, as illustrated in Figure 3.

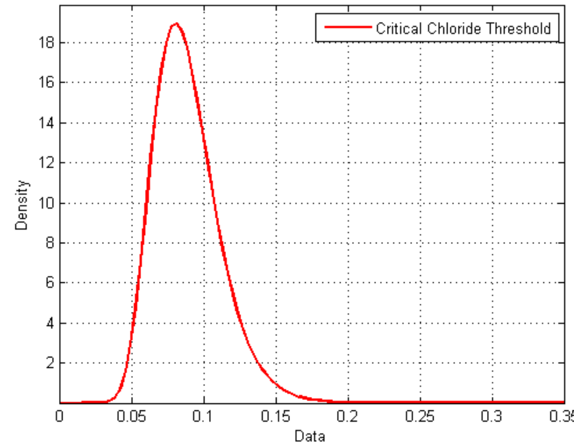


Figure 3. Example probability distribution for critical chloride threshold for concrete; units for chloride concentration are percent by weight of concrete.

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, total chloride content (bound plus free chloride) is used as the basis for modeling corrosion thresholds, unless noted otherwise.

I.b.i. 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 (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.

I.b.ii.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 11 states. In these studies, 45 structures were evaluated and more than 350 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.

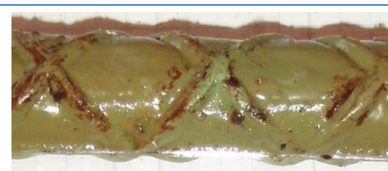
Value	Description	Representative photographs Epoxy-coated	
1	No evidence of corrosion		Not Active
2	A number of small, countable corrosion spots		
3	Corrosion area less than 20% of total surface area		Active
4	Corrosion area between 20% to 60% of total surface area		
5	Corrosion area greater than 60% of total surface area		

Figure 4. Figure of typical reference photos for categorizing active and non-active epoxy-coated bar corrosion.

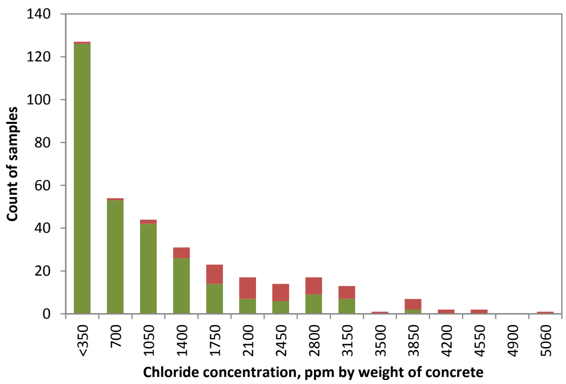


Figure 5. Histogram of actively-corroding versus non-active extracted ECR samples from evaluated bridge decks and substructures. Actively corroding bars are red and non-active bars are in green.

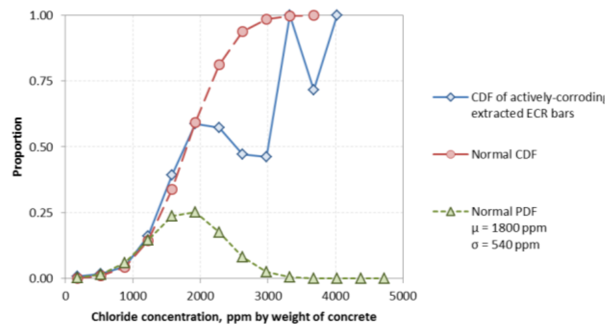


Figure 6. Plot of cumulative distribution of actively-corroding epoxy-coated reinforcing bars, relative to the chloride concentration at the bar depth. Normal cumulative and probability distributions fit to the data are also shown.

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.

I.b.iii. Supplementary Cementitious Materials

The effect of supplementary cementitious materials on the chloride threshold is adjusted based on the 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 P. B., 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.

$$Cement_{eqv} := CM \cdot [1 - max[0.010(\%FA - 10), 0] - max[0.005 \cdot (\%SG - 20), 0] - 0.025 \cdot \%SF]$$

Equation 1

Where:

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%)

I.b.iv. Summary of Chloride Thresholds

For modeling purposes, the chloride threshold is described by a statistical distribution for each type of the reinforcement material (uncoated or epoxy-coated reinforcing). This threshold is adjusted from weight of cement to weight of concrete based on assumed or estimated mix proportions. The table below provides a summary of the standard distributions used to estimate the chloride thresholds used by WJE for modeling.

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: 1.15 std. deviation: 0.35

II. MODEL DESCRIPTION

II.a. 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 serviceability criteria (i.e. acceptable amount of spalls on a deck) or a structural criteria (i.e. percentage of delaminated area allowed before reducing the capacity of the element). The specific service life criteria that can be tolerated varies by element type and is discussed in the main body of the report.

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 definition of service life to estimate the time remaining before the end of life is reached. The purpose of this modeling is to assist in identification of appropriate repair approaches and 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.

II.b. Basis for Corrosion Model

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 related to serviceability concerns, such as cracking, delaminations and spalls.

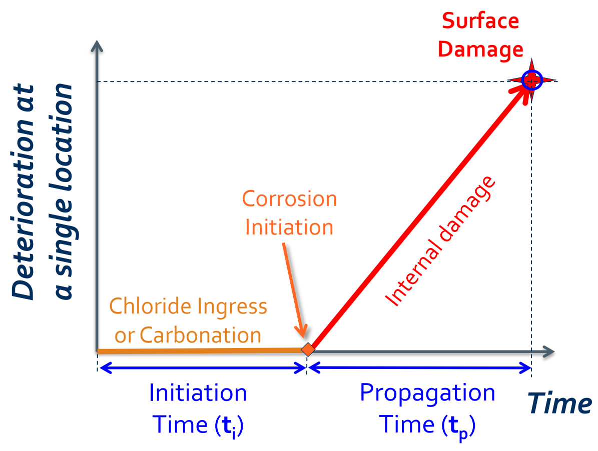
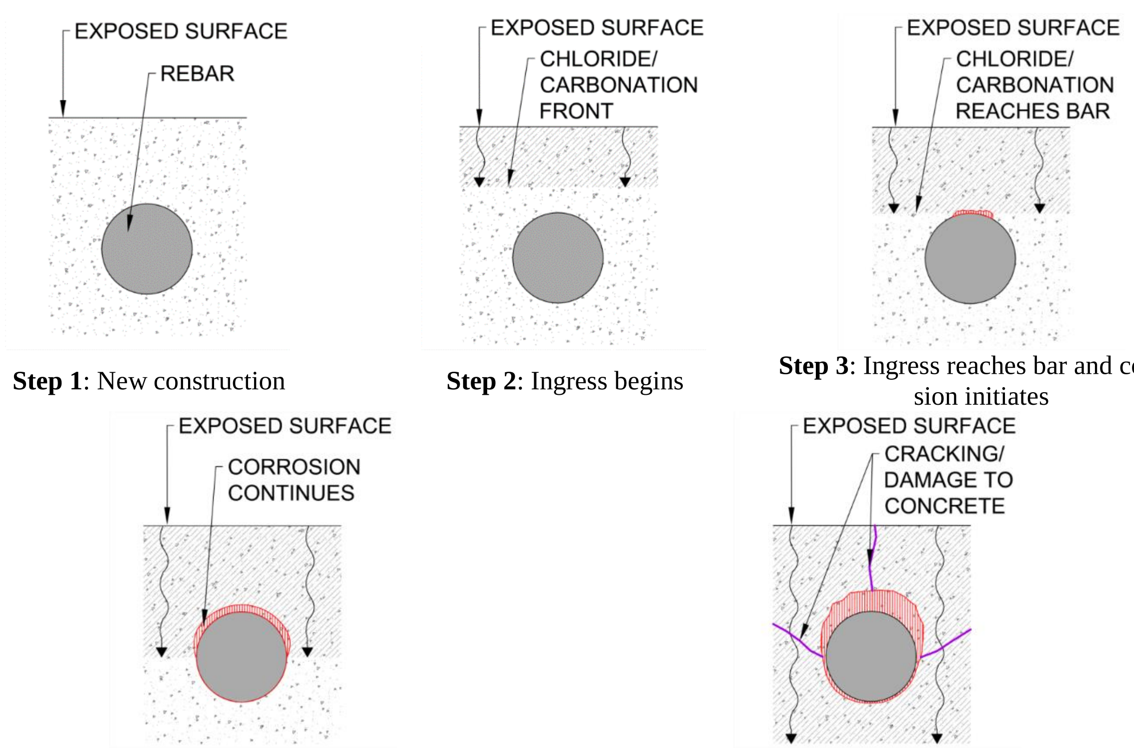


Figure 7. Corrosion sequence (from Tuutti 1982).

This concept can be applied to concrete experiencing corrosion-related damage by considering the sequence that leads to delamination and spalling. For a single bar location undergoing environmentally-induced corrosion, this includes the following steps, as illustrated in Figure 8.

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.

An established probabilistic modeling approach developed by Sagüés (Sagüés, 2003) was adapted and used as the basis for the service life model. This approach determines the amount of surface area of the structural element that is affected by corrosion based on statistical distributions of 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. For example, chloride-induced corrosion can



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.

be expected to initiate where cover is low, the ability of the concrete to resist chloride ingress is low, and the chloride exposure is high, and 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 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 $\underline{x}$ represents the vector of random variables, and $f(\underline{x})$ 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 $d(\underline{x}, t)$ 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) 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 slab structural element exhibiting damage through a given time then can be used to determine the percent area of the structural element where corrosion has initiated versus time.
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. The details of the implementation of this factor for this project are discussed in the main body of this report.

Because of the complexity of the probabilistic analysis, 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).

$$f(\underline{x}) = f(chloride\ exposure, transport\ rates, corrosion\ threshold\ ) \qquad \textit{Equation 2}$$

$$f(\underline{x}) = f(carbonation\ rate, cover) \qquad \textit{Equation 3}$$

$$g(\underline{x}, t) = d_{crit} - d(\underline{x}, t)\ \ where \begin{cases} g(\underline{x}, t) \leq 0, & corrosion\ initiation \\ g(\underline{x}, t) > 0, & no\ corrosion \end{cases} \qquad \textit{Equation 4}$$

$$p_f = \int_{g(\underline{x}, t) \leq 0} f(\underline{x}) d\underline{x} \qquad \textit{Equation 5}$$

$$t_{damage} = t_i + t_p \qquad \textit{Equation 6}$$

The processes by which initiation and propagation are modeled differ for carbonation- and chloride-related corrosion. The process for each are outlined in the following sections.

II.c. Modeling Carbonation-related Corrosion

II.c.i. 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.

$$carbonation\ depth\ (t) = A\sqrt{t} \qquad \textit{Equation 7}$$

where A is a constant determined based on field or laboratory depth measurements from the structure, and t is time since construction. This is the most common model for quantifying carbonation (Parrott, 1987). The various field and laboratory measurements of carbonation are collected and analyzed. Typically, either a normal distribution or a lognormal distribution are considered to appropriately model the carbonation rate constant.

II.c.ii. 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).

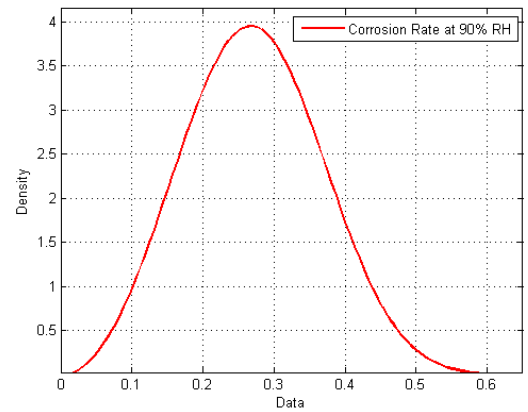


Figure 9. Corrosion rate at 90% relative humidity using an assumed Weibull fit; units are mils/year.

II.c.iii. 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 P. , 2004) is used 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

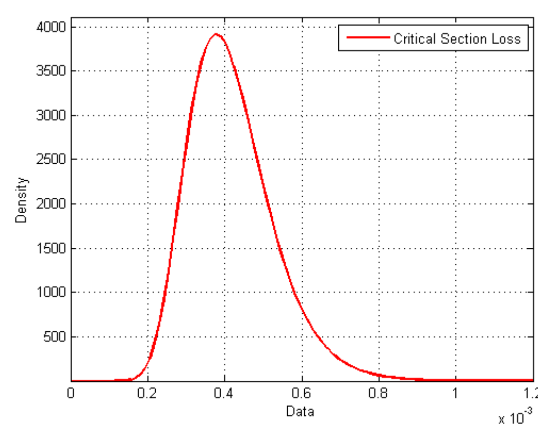


Figure 10. Critical section loss based on carbonation model run for deck slab underside; units are inches.

a stochastic variable, as represented by the plot in Figure 10.

The relationship for critical section loss, given in U.S. customary units, is:

$$X_c = 3.30 \times 10^{-3} + 2.91 \times 10^{-4}\left(\frac{c}{\varphi}\right) - 6.14 \times 10^{-6} f_{st} \quad \textit{Equation 8}$$

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

Tensile strength is calculated based on ACI 318-11 Eq. 9-10 from an estimate of compressive strength (one standard deviation lower than the average measured compressive strength).

II.d. Modeling Chloride-related Corrosion

II.d.i. 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).

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:

$$\frac{\partial C}{\partial t} = D_a \frac{\partial^2 C}{\partial x^2} \quad \textit{Equation 9}$$

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, the concentration $C(x, t)$ through a uniform medium at depth of x and time t is given by the following solution:

$$C(x,t) = C_s - (C_s - C_0) \times \operatorname{erf}\left(\frac{x}{2\sqrt{D_a t}}\right) \quad \textit{Equation 10}$$

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

$$D_a[V_{i+1} - 2(D_a + K)V_i] + D_a V_{i-1=} = -D_a U_{i+1} + 2(D_a - K)U_i - D_a U_{i-1} \quad \textit{Equation 11}$$

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*

concentration with depth over time is used. This solution is based on a Crank-Nicholson discretization of Equation 5, for which the general form is provided in Equation 11 (Chapra & Canale, 2002).

II.d.ii. Apparent Diffusion Coefficient

Apparent diffusion coefficients are affected by a number of factors; one of the most important is the age of the concrete. Influences of concrete age (maturity) are considered relative to an apparent diffusion coefficient at 28 days (D_{28}), with decreases in diffusion coefficient considered through 25 years. Beyond 25 years, the apparent diffusion coefficient is assumed to be constant at the 25-year value.

$$D(t,m) = D_{28} * \left(\frac{28\ days}{t}\right)^m \qquad \textit{Equation 12}$$

where:

D_{28}: diffusion coefficient at reference age of 28 days
t:age of concrete considered
m:ageing constant for diffusion

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.

$$m = 0.2 + 0.4 \cdot \left(\frac{\%FA}{50} + \frac{\%SG}{70}\right) \qquad \textit{Equation 13}$$

where:

m: ageing factor based on mixture proportions
%FA:percentage of fly ash
%SG:percent of slag cement

II.d.iii. Chloride Surface Concentration

Chloride surface 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 (Lee & Krauss, 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, chloride surface concentration is best characterized by extracting cores, measuring chloride contents, and fitting curves to the chloride profiles.

Chloride surface 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.

II.d.iv. Exposure Zones

The parameters that govern chloride transport (surface chloride concentration C_s and apparent diffusion coefficient D_a) are anticipated to vary for each exposure zone on a structure. Statistical distributions for C_s and D_a are determined based on chloride profiles measured in core samples taken from these zones. For each chloride profile, a fitting process based on the finite difference solution described above for calculating chloride concentration with depth over time is applied to determine values for C_s and D_a that coincide with the observed conditions [1]. An example of a chloride profile and the resulting fit is shown in Figure 11.

[1] In some instances (certain exposures and/or carbonated concrete), chloride profiles exhibit lower chloride concentration in the near surface region, with peak levels occurring in a general range of 1/2 to 1 inch in depth and decreasing concentrations at greater depths. For these profiles, fitting is performed considering only the chloride concentrations measured starting at the depth at which

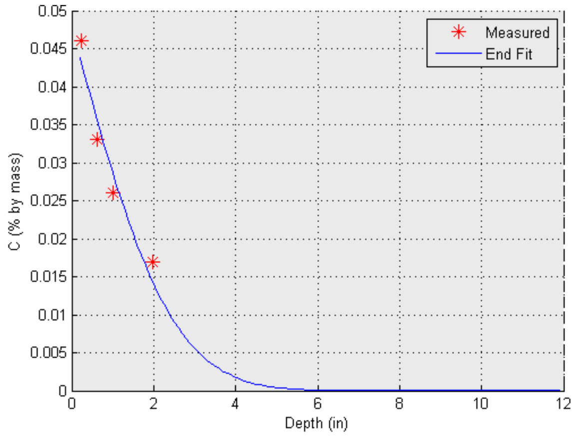


Figure 11. Chloride profile (blue line) defined in terms of the surface chloride concentration C_s and apparent diffusion coefficient D_a as fit to measured chloride profile.

The results of the fits, i.e. the C_s and D_a 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. 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. During the Monte Carlo analysis, where the use of a normal distribution resulted 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.

II.d.v. 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 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. The details of the implementation of this factor for this project are discussed in the main body of this report.

II.e. Modeling Concrete Cover

Where available, the distribution for concrete cover is modeled based on the depths measured by nondestructive 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.

Where cover data is not available, the mean cover depths is assumed to be equal to the project-specified cover. 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.

the peak value was observed. This process is based on the assumption that diffusion will dominate chloride transport below the measured peak.

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