GUIDELINES FOR SELECTION OF BRIDGE DECK OVERLAYS, SEALERS AND TREATMENTS

Requested by:

National Cooperative Highway Research Program (NCHRP)
Transportation Research Board
of
The National Academies

Prepared by:

Paul D. Krauss, John S. Lawler, and Kimberly A. Steiner
Wiss, Janney, Elstner Associates, Inc.
Northbrook, Illinois

May 29, 2009

The information contained in this report was prepared as part of NCHRP Project 20-07, Task 234, National Cooperative Highway Research Program, Transportation Research Board.

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DISCLAIMER

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LIST OF ACRONYMS

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NCHRP	National Cooperative Highway Research Program	Cover
WJE	Wiss, Janney, Elstner Associates	vii
AASHTO	American Association of State Highway & Transportation Officials	vii
NBI	National Bridge Inventory	ix
ASR	Alkali Silica Reaction	ix
DEF	Delayed Ettringite Formation	ix
LMC	Latex Modified Concrete	4
MMA	Methyl Methacrylate	5
ADT	Average Daily Traffic	5
HMWM	High Molecular Weight Methacrylate	6
DOT	Department of Transportation	6
FHWA	Federal Highway Administration	9
ADTT	Average Daily Truck Traffic	9
CoRe	Commonly Recognized	10
CSE	Copper Sulfate Electrode	13
GPR	Ground Penetrating Radar	17
ECR	Epoxy-Coated Reinforcing	20
HPC	High Performance Concrete	30
AC	Asphalt Concrete	30
VHE	Very High Early	30
QC	Quality Control	31
PCC	Portland Cement Concrete	33
BIN	Bridge Inventory Number	34
LP	Linear Polarization	36
RH	Relative Humidity	41
SEM	Scanning Election Microscopy	45
FFT	Fast Fourier Transform	47
KU	Kansas University	A-8
SSD	Saturated Surface Dry	A-9
REMR	Repair, Evaluation, Maintenance, and Rehabilitation Research Program	C-1
UV	Ultraviolet	C-2
SBR	Styrene Butadiene	C-7
PVA	Polyvinyl Acetate	C-7
MSDS	Material Safety Data Sheet	C-9
EPDM	Ethylene Propylene Diene M-Class Rubber	C-11
DC	Direct Current	C-12
NACE	National Association of Corrosion Engineers	C-12

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ABSTRACT

Maintenance and rehabilitation of bridge decks is an ongoing concern for Departments of Transportation and a concise, universal set of guidelines is provided to aid transportation engineers with bridge deck rehabilitation decisions. The objective of this study was to develop guidelines for selecting bridge deck treatments for different deck conditions and deck materials. The guidelines provided in this report consider current deck conditions and deck materials and provide a means to make general repair decisions. Much of the information used to develop the guidelines was provided by a survey sent to all US and Canadian Departments of Transportation.

EXECUTIVE SUMMARY

Transportation agencies must extend the service lives of existing bridge decks as funds and the time needed for replacement or major rehabilitation are limited. The use of bridge deck rehabilitation methods varies widely throughout the United States, and a concise, universal set of guidelines is needed to aid transportation engineers with bridge deck rehabilitation decisions. Some agencies have developed their own set of guidelines, but these are often limited and have varying decision criteria for repair selections. While each state will likely view the need for deck repairs differently, a set of guidelines suitable for reference by engineers throughout the country is useful in promoting more consistent and universal procedures for decision making, backed by research and experience. This document provides just such a methodology for selecting bridge deck treatments for different bridge deck conditions and deck materials.

These guidelines were developed based on a survey sent to all US and Canadian Departments of Transportation to obtain information on what criteria are used to make repair decisions to deteriorating bridge decks. Experience with the various repair strategies was also solicited. A review of available literature and the experience of the research team were also used to develop these Guidelines.

Many types of bridge decks, including concrete, timber and steel, occur throughout the US and each type of bridge deck has specific types of rehabilitation methods associated with it that are most suitable for existing deck conditions. Complicated algorithms that attempt to capture all possible scenarios have been avoided, and the intent is to focus on the appropriate factors to consider and to guide the decision making process in a simple, direct manner. The selection of the various deck repair options is performed in two steps. First, the general category of repair that is needed is determined based on the deck condition. The deck characterization process is driven by assessing the following factors:

1. ***Percent Deck Deterioration and NBI Condition Ratings*** - determined by the percent of non-overlapping area of patches, spalls, delaminations, and copper-sulfate half-cell potentials more negative than -0.35V and the national bridge inventory (NBI) condition rating based on examination of the top and bottom deck surfaces.
2. ***Estimated Time-to-Corrosion*** - expressed as the estimated time until sufficient chloride penetration occurs to initiate corrosion over a given percentage of the reinforcing steel.
3. ***Deck Surface Condition*** - consideration of the deck surface condition related to poor drainage, surface scaling, abrasion loss, or skid resistance problems.
4. ***Concrete Quality*** - related to concrete durability (Alkali Silica Reaction (ASR)/Delayed Ettringite Formation (DEF)/freeze-thaw) and strength issues.

The guidelines provided in this report consider these deck characterization factors to make the following general primary repair decisions:

1. ***Do Nothing***
2. ***Maintenance*** that may include:
    a. patching
    b. crack repairs
    c. concrete sealer
3. ***Protective Overlay***
4. ***Structural Rehabilitation*** that may include:
    a. partial deck replacement
    b. full depth deck replacement

Second, the best repair material option within a category is selected based on various site conditions, such as traffic constraints, dead load or overhead limitations, remaining service life, general exposure conditions, application constraints, skid resistance, concrete cover, contractor experience, planned future work, cost or other conditions. In addition, these guidelines provide methods and information useful to help evaluate the deck condition; prepare a deck for an overlay, sealing, crack repair, or other rehabilitation method; and estimate relative costs and durability of the various deck rehabilitation methods.

CHAPTER 1

INTRODUCTION

Maintenance and rehabilitation of bridge decks is an ongoing concern for Departments of Transportation throughout the United States. Transportation agencies must extend the service lives of existing bridge decks as funds and the time needed for replacement or major rehabilitation are limited. The use of bridge deck rehabilitation methods varies widely throughout the United States, and a concise, universal set of guidelines is needed to aid transportation engineers with bridge deck rehabilitation decisions. The objective of this study was to develop guidelines for selecting bridge deck treatments for different deck conditions and deck materials.

Some agencies have developed their own sets of guidelines, but these are often limited. For example, they may only evaluate a few deck properties or cover a narrow range of materials and treatments. The agencies that have developed guidelines often do not share the same test procedures and criteria for decisions. While each state will likely view the need for deck repairs differently, a set of guidelines suitable for reference by engineers throughout the country is useful in promoting more consistent and universal procedures for decision making, backed by research and experience.

Typically, specific rehabilitation actions should be matched to the condition of the existing deck and the deck material, as well as the future expectation for the deck. While some timber and steel bridge decks exist throughout the US, concrete bridge decks are by far the most commonly used and have the most varied methods of rehabilitation, and therefore are the focus of the bulk of these guidelines.

The guidelines provided in this report consider current deck condition and deck materials to make general repair decisions that include, do nothing, continued maintenance or preventative maintenance, overlay, and deck replacement. Other factors, such as lane closure time, costs, and installation issues, are also used to provide guidance as to which rehabilitation methods may be most suitable. In addition, the guidelines provide methods and information useful to evaluate the deck condition, prepare a deck for an overlay, sealing, crack repair, or other rehabilitation method, as well as estimates of relative costs and durability of various deck rehabilitation methods.

Much of the information used to develop the guidelines was provided by a survey sent to all US and Canadian Departments of Transportation, a review of available literature, and the experience of the research team. The various sources of information were compiled, and the result is a set of guidelines that engineers can consult when evaluating the best options to extend the service life of decks and selecting a bridge deck rehabilitation system. The guidelines address rehabilitation options based on the deck materials, deck conditions, desired lifespan of the rehabilitation, and other factors.

CHAPTER 2

SURVEY RESULTS

Survey responses were received from forty-one different states, four Canadian provinces, and Puerto Rico. A total of forty-nine responses were received, with different individuals from three states responding. For the purposes of this report, multiple responses from a single agency are consolidated into one.

DECISION MAKING

The methods of making decisions about whether bridge deck rehabilitation is necessary vary considerably. Twenty-two agencies (48%) report having specific guidelines or procedures used when making decisions on deck treatment and rehabilitation selection. Of these, only ten agencies (22%) have written procedures or decision trees, two agencies are in the process of developing decision trees, and the rest use visual evaluation inspection, sometimes with supplemental testing, and conduct internal discussions to decide the appropriate rehabilitation method/process.

The range of factors considered when making decisions about deck rehabilitation is varied and extensive. When making decisions about which deck treatment to choose, most agencies perform a condition assessment, although the details of what is included in a condition assessment vary from agency to agency. Thirty-three (72%) agencies report basing decisions of which rehabilitation method is most suitable on deck condition, two of which specifically correlate topside and underside conditions. Other agencies, while conducting condition surveys to determine if the deck needs to be rehabilitated, may not have many approved options to choose from, and may have only one rehabilitation option based on a particular deck condition. When assessing current deck conditions, essentially all agencies perform visual inspections. Several agencies examine the extent and size of cracking, spalling and delamination, while others evaluate chloride content of the concrete. Many agencies consider the projected lifetime of the structure and make deck rehabilitation decisions in light of the condition of the rest of the structure, and anticipated future use, or desired lifetime. Deck replacement instead of repair may be considered more favorably if the rest of the bridge also needs significant work during the rehabilitation project.

Some agencies listed specific guidelines used to select between rehabilitation methods. While the guidelines are available, none are mandatory and they are not necessarily used to make decisions for all cases. Guideline examples follow:

- Kansas has some general guidelines, stating that decks with 3-10% distress use a polymer overlay, 10 - 50% distress use silica fume overlay, and >50% distress do further inspection of the deck.
- Virginia uses very early strength overlays when lanes cannot be closed for long periods. Polymer overlays are used on decks in good condition, and gravity fill polymers are used to fill random shrinkage cracks.
- Wyoming uses a rigid overlay of silica fume-modified concrete for decks having extensive spalling and cracking, patching if the extent of spalling and delamination is less than a couple hundred square feet, and a crack healer/sealer if the deck displays cracking but not delamination. If a deck needs increased friction over a sealed surface, a polymer thin-bonded overlay may be used.

- Ontario patches, waterproofs and paves the deck if less than 10% of the deck requires removal, but if more than 10% of the deck requires removal, they apply an overlay and then waterproof and pave with a wearing surface.

The choice to consider full deck replacement is based on different factors in different states. Also, the criteria used to determine when a bridge deck should be replaced vary as illustrated in the flowing list:

- in California, full deck replacement in triggered when subsurface distress exceeds 20% of the total deck area
- in Virginia, full deck replacement is indicated when more than 25% of the deck requires patching, or is spalling or delaminating
- in Illinois, full deck replacement is triggered when more than 35% of the deck requires patching
- in Connecticut, Massachusetts, and Kansas, the deck is replaced if 50% of the deck is in poor condition.

Twenty-six agencies (56%) have a qualified products list or list of approved products that they consult when selecting particular products for use in deck rehabilitation projects. Two agencies (4%) report using information from manufacturers when selecting a rehabilitation system. Fifteen agencies (33%) report having conducted field trials or research on bridge rehabilitation systems. Eleven agencies (24%) use life cycle cost analysis when selecting deck treatments.

Many different techniques are used to evaluate the condition of the bridge deck when deciding if rehabilitation is required, or when choosing between rehabilitation systems, with the survey results shown in Table 1. Visual inspection is the most common and is used by forty-five (98%) of the responding agencies. Hammer or chain sounding is the next most common technique with crack mapping, strength testing, and chloride measurement somewhat commonly used. Half-cell corrosion potentials and petrographic studies are occasionally used. Infrared thermography, freeze/thaw testing, air content measurement, pulse velocity-ultrasonic, ground penetrating radar, and impact/echo are not used by most responding agencies.

Table 1. Number of Agencies That Use the Evaluation Technique to Evaluate Deck Condition (46 Respondents)

Evaluation Technique/Frequency of Use	**Typically**	**Occasionally**	**Never**
Visual Inspection	45	0	0
Hammer or chain sounding	34	10	0
Crack mapping/width measurement	13	24	6
Core sampling and strength testing	13	25	5
Core sampling and petrographic evaluation	5	22	15
Chloride measurement	21	21	4
Half-cell potential measurement	8	20	14
Corrosion rate	2	13	24
Infrared Thermography	0	8	30
Freeze/thaw testing or air content	2	7	30
Pulse velocity-ultrasonic	0	3	35
Ground penetrating radar (GPR)	1	18	19
Impact/echo	1	11	27

CONCRETE BRIDGE DECKS

Overlays

The expected lifetime of overlays depends on the particular type of overlay chosen; however, based on responses from 43 agencies, anticipated lifetimes given ranged from 5 to 30 years, with 10 agencies (23%) predicting lifetimes of 25 years or greater, 21 agencies (49%) predicting lifetimes of 15 years or more, seven agencies (16%) predicting lifetimes of 10 years or greater and five agencies (12%) predicting lifetimes of five years or more.

Table 2 lists the survey results concerning overlay use. Of the overlay options available, asphalt concrete overlays with a waterproofing membrane were the most commonly used. High performance concrete, silica fume-modified concrete, fly ash-modified concrete, and polymer concrete overlays are becoming more commonly used, with many agencies listing these types as “new or experimental” or currently used systems. In addition to these listings, several agencies discussed their use of latex modified concrete overlays in an “other category”. Of these, two agencies report that latex modified concrete overlays are new or experimental, four agencies listed it as current common practice, and three agencies listed it as historic.

Table 2. Number of Agencies That Have Experience With Overlay Type
(40-44 Respondents Depending on Overlay Type)

Overlay Type/Use	New or Experimental	Current Common Practice	Historic Experience (Not Current Practice)	Never
Low slump, low water-cement ratio concrete overlays	4	12	14	11
Asphalt concrete overlay with a membrane	0	30	12	3
High performance concrete overlay	9	17	2	16
Fly-ash modified concrete overlays	7	7	6	24
Silica-fume modified concrete overlays	8	6	6	23
Polymer concrete overlays	12	16	7	9
Latex-modified concrete*	2	4	3	-

* Actual historic and current use of latex modified concrete (LMC) is likely much greater than reported, since it was not listed as a specific option on the survey.
- No Response

Several agencies have only one type of overlay that is used in their jurisdiction. Of the agencies that use multiple types of overlays, cost (both initial and life cycle) or funding is cited as a primary selection factor by ten of the agencies that list criteria. Eight agencies that listed selection criteria listed the age and/or condition of the structure as a primary concern. Six agencies listed durability, anticipated lifetime, or past experience and eight agencies listed construction process, curing time, or traffic volume as primary considerations. Five agencies list the load carrying capacity of the existing bridge as a primary factor in choosing between available overlay systems. Two agencies list the condition of the approaches as a consideration.

Sealers

Of the twenty-eight agencies that responded to a question regarding the anticipated lifetime of sealers, seventeen (61%) stated that they expected five or fewer years lifetime. Five agencies (18%) expect a lifetime of between 5 and about 12 years, while six agencies (21%) anticipate a lifetime of greater than 10 years. Several agencies gave a range of anticipated lifetimes, depending on particular type of sealer.

Table 3 lists the number of agencies that have used various sealer types. Of the sealers used, epoxy, methacrylate (MMA) and silane sealers are the most frequently used. In addition, three agencies wrote in that they use or have used linseed oil. Linseed oil use is likely more wide spread than reported, since it was not listed as a specific option on the survey.

Table 3. Number of Agencies That Use or Have Experience With Sealer Type
(38-44 Respondents Depending on Sealer Type)

Sealer Type/Use	New or Experimental	Current Common Practice	Historic Experience (Not Current Practice)	Never
Silane sealers	4	15	9	12
Siloxane sealers	7	5	13	13
Epoxy sealers	11	13	5	13
Methacrylate sealers	10	11	9	10
Polyurethane sealers	8	4	8	18

Thirty agencies reported using sealers on deck travel surfaces, and twenty-four reported using sealers on barriers and parapets. Of the twenty-seven agencies that responded to a question about selection criteria for sealers, six (22%) list the condition of the deck, three (11%) list cost as a primary concern, three (11%) list application and curing issues, such as curing time or average daily traffic (ADT), and only two (7%) list durability. One agency (South Dakota) stated that trials that have been conducted on sealers. Many other agencies have a limited number of or only one, approved sealer(s). There is currently a lack of field research of the effectiveness of concrete sealers on deck surfaces and to protect cracks. Additional studies are needed to determine if periodic sealing of deck surfaces is cost effective. Trial installations and evaluations may be necessary to verify adequate protection has been provided. Also, there is uncertainty about how long sealers will remain effective, especially in cyclic freezing environments.

Crack Repair and Other Rehabilitation Methods for Concrete Bridge Decks

The expected lifetime of crack repair varies from 3 to 50+ years. Of the twenty-seven agencies that responded to a question on anticipated lifetime of crack repairs, eighteen respondents (67%) generally expect ten or fewer years lifetime, while nine respondents (33%) expect more than 10 years. Most respondents (20 or 74%) expected lifetimes in the range of 5-15 years.

Table 4 lists the crack repair and corrosion protection methods used. Of the other (non-sealer or non-overlay) rehabilitation methods for concrete decks, crack repair is the most commonly used. Cathodic protection and corrosion inhibitors are also used, but not as frequently, and are considered by many to be a new or experimental technique. NCHRP synthesis study (39-03) will provide additional information on the agency use of cathodic protection. Only five agencies report using lithium salts (for ASR mitigation) and this is primarily a new or experimental technique. Some agencies do not feel that it is necessary to use sealers or overlays to protect cracked bridge decks.

Table 4. Rehabilitation Method Used by Agencies
(38-45 Respondents Depending on Rehabilitation Method)

Rehabilitation Method/Use	**New or Experimental**	**Current Common Practice**	**Historic Experience (Not Current Practice)**	**Never**
Epoxy Injection Crack Repair	4	22	8	9
Polyurethane crack repair	5	4	2	26
High molecular weight methacrylate (HMWM) crack repair	7	15	9	10
Lithium salts	4	1	1	34
Cathodic protection	10	6	16	10
Corrosion inhibitors	14	6	8	14

Full Deck Replacement

All respondents expected a full deck replacement to last at least 20 years, with anticipated lifetimes up to 100 years. Six (14%) of the forty-two respondents to the question expected full deck replacement to last 25 or fewer years. Twenty-two respondents (52%) expected lifetimes of 25 - 40 years. Seventeen respondents (40%) expected lifetimes greater than 40 years. Some respondents gave wide ranges and are represented in more than one category listed.

Summary

Table 5 shows a general summary of the information provided by the Department of Transportation (DOT) officials related to the various options for repairing concrete bridge decks. The ranges of values reported for service life, cost and overlay thicknesses were generally wide so mean values of the high and low ranges provided are also shown.

Table 5. Rehabilitation Method Summary

Rehabilitation Method	**Expected Service Life Range (years) [Mean]**	**Cost Range ($/sq. ft.) [Mean]**	**Overlay Thickness (in.) [Mean]**	**Estimated Installation Time**	**Current Use**
Rigid Overlays					
High Performance Concrete Overlays	10 - 40 [16 - 29]	5 - 45 [17 - 25]	1 - 5 [1.6 - 3.5]	>3 days	Mixed
Low Slump Concrete Overlays	10 - 45 [16 - 32]	4 - 45 [13 - 19]	1.5 - 4 [2.0 - 3.1]	>3 days	Static
Latex Modified Concrete Overlays	10 - 50 [14 - 29]	1 - 150 [18 - 39]	1 - 5 [1.5 - 2.7]	<24 hrs (UHELMC)*, 1-3 days (LMC)**	Mixed
Asphalt-Based Overlays					
Asphalt Overlays with a Membrane	3 - 40 [12 - 19]	1.5 - 23.5 [3.1 - 7.6]	1.5 - 4 [2.4 - 3.1]	>3 days	Static

Rehabilitation Method	Expected Service Life Range (years) [Mean]	Cost Range ($/sq. ft.) [Mean]	Overlay Thickness (in.) [Mean]	Estimated Installation Time	Current Use
Miscellaneous Asphalt Overlays	5 - 20 [8 - 15]	1 - 3 [1 response]	0.38 - 2.5 [0.8 - 1.5]	1 - 3 days	Static
Other Rehabilitation Systems					
Polymer Overlays	1 - 35 [9 - 18]	3 - 60 [10 - 17]	0.13 - 6 [0.5 - 1.4]	<24 hrs	Increasing
Crack Repair	2 - 75 [19 - 33]	***	N/A	<24 hrs	Static
Sealers	1 - 20 [4 - 10]	0.33 - 15 [3 - 5]	N/A	<24 hrs	Increasing
Deck replacement	15 - 50 [27 - 32]	15 - 100 [43 - 53]	N/A	>3 days	Static

* Ultra high early cement with latex

**High early (Type III) cement with latex

*** Survey respondents did not provide cost estimates

STEEL BRIDGE DECKS

Of the forty-six responding agencies, twenty-nine (63%) have steel or steel grid bridge decks. The numbers of steel bridge decks in the locations varied from less than 20 in sixteen agencies to more than 20 in eight agencies. The rest of the respondents did not report how many steel bridge decks they had in their jurisdiction.

Table 6 outlines the types of deck rehabilitation used for steel or steel grid bridge decks. No agency lists a rehabilitation method in the "new" category. This appears to indicate that the methods used have been in place for some time (note that "new" was not defined as "new or experimental" in this part of the survey). Asphalt concrete overlays and coating with zinc-rich primers are the most popular rehabilitation methods. In addition to the methods listed specifically in the survey as noted in Table 6, two agencies use galvanized steel decks, and four agencies responded that they have steel grid decking that is filled with concrete but did not discuss rehabilitation strategies.

Table 6. Agencies Reporting Use of Steel Bridge Decks Rehabilitation Methods
(21-27 Respondents Depending on Rehabilitation Type)

Rehabilitation Method/Use	New	Current Common Practice	Historic Experience (Not Current Practice)	Never
Replacement of asphalt concrete overlay	0	10	4	12
Replacement of polymer concrete overlay	0	5	4	15
Coating with zinc-rich primer	0	6	2	18
Applying other coatings	0	1	1	19

TIMBER BRIDGE DECKS

Thirty-five (76%) agencies reported having timber bridge decks in their jurisdiction. Of those agencies with timber bridge decks, eighteen reported having fewer than 100, although, in some cases the total includes bridges in state and local jurisdiction, while in others, it includes bridges in only state jurisdiction.

For timber bridge deck rehabilitation, replacement of the wearing surface with an asphalt concrete overlay is the most frequently used system, as shown in Table 7. No agency reported creosote wood preservatives in their current approaches to rehabilitation of timber bridge decks. Polymer overlay was the only rehabilitation system that was listed as “new” indicating that few new methods for rehabilitating timber bridge decks are available. In addition to the methods listed below, ten agencies responded that they replace worn timbers or replace the deck completely, rather than rehabilitating the deck.

Table 7. Agencies Reporting Use of Timber Bridge Decks Rehabilitation Methods
(29-34 Respondents Depending on Rehabilitation Method)

Rehabilitation Method/Use	**New or Experimental**	**Current Common Practice**	**Historic Experience (Not Current Practice)**	**Never**
Replacement the wearing surface with an asphalt concrete overlay	0	19	5	8
Replacement of the wearing surface with a polymer concrete overlay	3	0	1	26
Apply creosote wood preservatives	0	0	3	27
Apply pentachlorophenol wood preservative solutions	0	1	3	26
Apply water-borne wood preservative solutions containing copper, chromium, or arsenic	0	2	4	24

ADDITIONAL SURVEY RESULTS

A primary goal of the agency survey was to identify methodologies and procedures used by agencies to guide decisions regarding bridge deck maintenance and repair. This information is presented in Chapter 3.

Further, the survey asked a series of questions specific to rehabilitation methods with which an agency may have experience. The respondents chose which methods on which they desired to comment. Some agencies chose not to comment on any rehabilitation method and others provided information on up to four different methods. These survey results are summarized in Appendix A, which includes the state or province represented by the respondent, advantages and disadvantages, use selection and history, anticipated life span, costs, and installation recommendations for the various systems.

CHAPTER 3

AGENCY PROCESSES FOR BRIDGE DECK MAINTENANCE AND REPAIR SELECTION

The processes employed by the agencies that use a formal, prearranged procedure to support decisions about repair selection were reviewed. These processes vary widely in complexity and take the form of written text, tables or flowcharts.

Some of the more structured processes are presented in manuals, like New York's Bridge Deck Evaluation Manual (NY-DOT 1992) and Ontario's Structure Rehabilitation Manual (Manning 1983), which also give extensive background on how to perform a deck survey to collect the desired input information. Others are based on more universally applied but less detailed bridge inspection methods, such as the National Bridge Inventory (NBI) condition ratings defined according to methods outlined by the FHWA (Federal Highway Administration 1995) or Pontis element condition ratings outlined by AASHTO (Subcommittee on Bridges and Structures of the Standing Committee of Highways 2002).

Some of the deck evaluation criteria considered in the various repair selection processes employed by state agencies include (See Chapter 3 Bibliography: IL-DOT 2004, MI-DOT 2007, MO-DOT undated, NJ-DOT 2007, NY-DOT 1992, NC-DOT undated, MTO 2007, OR-DOT 2004, PA-DOT 2007, WA-DOT undated):

- Delamination survey
- Half-cell survey
- Concrete cover survey
- Cracking (extent and width)
- Condition of deck concrete
    - Air content
    - Compressive strength
    - Chloride tests at bar depth
- Deck superstructure and substructure NBI condition ratings
- Deck surface deficiencies (combined percent area spalled, delaminated or patched)
- Deck soffit (underside) deficiencies (combined percent area spalled, delaminated or map cracked)
- Slope and thickness of deck
- Type of steel in deck (epoxy-coated, galvanized or carbon steel)
- Load capacity/deadload limitations
- Average Daily Traffic (ADT) or Average Daily Truck Traffic (ADTT)
- Condition of supporting structure (such as presence of alkali-silica reaction)
- Funding and costs (federal assistance, traffic control, FHWA preferences)
- Complaints by travelling public
- Redundancy of structure to carry traffic
- Presence of stopping condition within 300 ft. of deck
- Desired future lifespan of bridge
- Construction duration
- Life cycle cost
- Plans for future construction in vicinity of bridge

- Contractor expertise
- Social and environmental concerns

Broadly, this list can be broken down into the following categories: deck condition, supporting structure condition, rehabilitation method limitations, costs, and impact on the travelling public. Typically, the deck condition is the starting point for the decision process, which is refined based on the other considerations.

As a means to get a better sense of the overall area of deteriorating deck, three agencies (NJ, NY and Ontario) consider a non-overlapping combination of two or more of the following: 1) the area spalled, delaminated and patched, 2) the area where the chloride concentration at the reinforcing steel is above a threshold level, and 3) the area where a half cell survey resulted in corrosion potentials more negative than -0.350 V versus a copper sulfate electrode.

The decision thresholds applied to these criteria vary widely depending on the objective and point in the decision process at which they are considered. As an example, one decision that must be made early in the process is whether replacement of the deck is prudent. The percentage of deterioration triggering consideration of deck replacement ranges from about 25 to 50% depending on the state (MI-DOT 2007, IL-DOT 2004, NJ-DOT 2007, KS-DOT survey response). NBI condition rating-based methods set limits ranging from 3 to 5 as thresholds for deck replacement decisions (MI-DOT 2007, MO-DOT undated, OR-DOT 2004, WA-DOT undated). Two states also combine consideration of deck soffit evaluations in that decision (MI-DOT 2007, WA-DOT undated). For example, the decision matrix developed by Michigan suggests replacement of a deck with deck NBI condition rating less than or equal to 4 or more than 30% surface deterioration and a soffit rating of less than or equal to 3 or more than 30% soffit deterioration (MI-DOT 2007).

Another potential source of information is data collected according to the AASHTO Guide for Commonly Recognized (CoRe) Structural Elements (Subcommittee on Bridges and Structures of the Standing Committee of Highways 2002). The CoRe Elements guide is used by agencies that use the Pontis bridge management system and provides a framework for tracking information about elements of the bridge including the deck. This system provides for greater differentiation within the deck than the NBI system, which provides only a single rating item for the entire deck. The ratings collected based on the CoRe system are often combined to generate the NBI deck condition rating. Some agencies have created their own definitions for elements not included within the CoRe framework. These non-CoRe elements have been created or existing elements have been modified to account for locally-specific inspection and testing practices. The Appendix to the Guide also provides some recommendations for conditions state descriptions and feasible actions (Subcommittee on Bridges and Structures of the Standing Committee of Highways 2002).

Once it is determined that the deck does not need to be replaced, a number of the criteria are focused on defining the concrete removal repair area. The intent is that the deteriorating concrete must be removed to achieve a durable repair. The thresholds applied to define actions based on the deterioration level vary based on the interpretation of the agencies and the balance they wish to strike between effective repair and the cost of concrete removal and repair. For example, different chloride content thresholds of 0.04 to 0.07% by weight of concrete are referenced as thresholds for the repair decision processes (MO-DOT undated, NJ-DOT 2007, NC-DOT undated, MTO 2007, OR-DOT 2004, PA-DOT 2007). An additional threshold of 0.13% is suggested by one agency if the existing bar is epoxy-coated (NC-DOT undated).

For the purposes of selection, the repair methods are usually classified as: patching, asphalt overlay with a waterproofing membrane, concrete overlay, and deck replacement. However, some processes also consider polymer overlays and sealers as options. A limited number include cathodic protection. In addition, some include a temporary maintenance method, e.g. a asphalt overlay without a membrane, intended to extend the useful life of the deck for 3 years or less until the deck can be replaced (MI-DOT 2007, NDOR). While not stated in the MI-DOT selection guideline, it is believed that asphalt overlays without a waterproofing membrane are not used for longer-term repairs since the asphalt can trap and hold salt-laden water on the deck and promote corrosion of the embedded reinforcing steel. The selection of the desired repair method in Michigan is usually made based on considerations of whether a less expensive alternative is compatible with the deck condition and based on external constraints, such as rehabilitation method limitations, costs, and impact on the travelling public (MI-DOT 2007).

While presented briefly in New York's manual (NY-DOT 1992), strong recommendations for the use of life cycle cost analysis in the decision making process have come out of studies supported by various states (Adams 2002) (Cady 1985). While life cycle cost analysis provides a rational basis for decision making, among the challenges in the use of this type of analysis is accurately predicting the service lives and effectiveness of the alternatives being considered.

CHAPTER 4

DECK CHARACTERIZATION AND REPAIR SELECTION

INTRODUCTION

This chapter guides the decision making process for the selection of various deck repair options. Familiarity with most deck repair options, test methods, and the various factors related to making repair selections is assumed of the user. If you are not familiar with commonly used bridge inspection procedures or techniques, now is a good time to read Chapter 5. Information on specific deck assessment techniques, test methods, and repair options are included in Chapter 5 and the appendices. Chapter 5 "Methods for Deck Evaluation and Characterization" provides guidelines on how to perform the deck characterization to obtain the data needed to make repair selection decisions. Complicated algorithms that attempt to capture all possible scenarios have been avoided, and the intent is to focus on the appropriate factors to consider and to guide the decision making process in a simple, direct manner. At the end of the analysis, engineering judgment is still needed to decide if the recommended method or methods is actually best for a particular bridge deck, considering the numerous variables and site conditions that can occur. Review of the repair option information and related references in the appendices will provide further guidance on each repair technique and help in the development of project specifications and documents.

The selection of various deck repair options is performed in two steps. First, deck characterization is used to identify the general category of repair that is needed based on the deck condition. Second, the best repair material option within the general category is selected based on various site conditions, such as traffic constraints, dead load or overhead limitations, anticipated service life, general exposure conditions, application constraints, previous repairs, skid resistance, concrete cover, reinforcing type, contractor experience, planned future work, special conditions, and costs.

Generally, older decks with previous repairs will require more aggressive maintenance and rehabilitation, such as overlays or partial depth replacement, than newer decks. However based on exposure conditions, even new decks may be good candidates for overlays, since the use of an overlay may result in the longest service life for the least cost. Decks can be overlaid several times if the base deck remains in generally good condition and there is sufficient concrete cover to avoid damaging the top mat of reinforcing during removal of the overlay by milling of the deck surface.

In general, it is assumed that the goal is to keep each bridge deck in service for as long as reasonably possible and at the lowest annual cost. However, when bridge deck replacement is programmed within the next 10 years or so, it makes economic sense to perform only minimum repair and maintenance until the planned deck replacement. Therefore, an important initial step is to determine if the deck will be widened, have major repairs, or be replaced within the next 10 to 15 years and then decide what is needed to maintain the deck until replacement is performed. When deck replacement work is programmed, conservative time estimates are suggested as funding plans can change, delaying the planned work.

DECK CHARACTERIZATION

Deck Characterization identifies the current condition of the deck. A complete and accurate characterization is essential, since this forms the basis for repair decisions. Chapter 5 of this guideline provides additional information on performing the deck survey and obtaining the characterization data. This Deck Characterization process is driven by assessing the following factors:

1. ***Percent Deck Distress and Condition Ratings*** - determined by the percent of non-overlapping area of patches, spalls, delaminations, and copper sulfate electrode (CSE) half-cell potentials more negative than -0.35V, by the NBI condition rating of the deck, and by a separate condition rating of the deck bottom surface. (As outlined in Chapter 5, the rating for the bottom side of the deck is assigned using the 0-9 scale employed for the NBI condition ratings.)
2. ***Estimated Time-to-Corrosion*** - expressed as the estimated time until sufficient chloride penetration occurs to initiate corrosion over a given percentage of the reinforcing steel
3. ***Deck Surface Condition*** - consideration of poor drainage, surface scaling, abrasion loss, or skid resistance problems
4. ***Concrete Quality*** - related to concrete durability (ASR/DEF/freeze-thaw) and strength issues

Based on the assessment of each factor, Table 8 is used to rate the significance of each finding and to direct the user to the most appropriate primary category of repair. One of the following primary categories of repair is then selected for the deck:

1. **Do Nothing**
2. **Maintenance** that may include:
    a. patching
    b. crack repairs
    c. concrete sealer
3. **Protective Overlay**
4. **Structural Rehabilitation** that may include:
    a. partial deck replacement
    b. full depth deck replacement

Each characterization factor and the resulting input for the decision process are discussed below. Any individual assessment factor can result in the need for a higher level of repair in the following hierarchy from 1. Do Nothing, 2. Maintenance, 3. Protective Overlay, to 4. Structural Rehabilitation. The Do Nothing option is selected only if all the factors rate within the Do Nothing category. A higher category is selected if any of the factors indicate the need for that higher level of repair or based on engineering or value judgments.

TABLE 8. Primary Repair Category Guidelines Based on Deck Characterization

Primary Repair Category	Deck Characterization Factor				
	Deck Distress (% Distress, Half-cell potentials < -0.35 V (CSE), and Visual Condition Ratings)		**Time-to-Corrosion Initiation**	**Deck Surface Problems** (Drainage, Scaling, Abrasion Loss, Skid Resistance)	**Concrete Quality Problems** (ASR, DEF, Freeze-thaw, Strength)
1. Do Nothing [2]	i. % Distress	< 1%	"> 10 years" [9]	None	None
	ii. % Distress + 1/2 cell [1]	< 5%			
	iii. NBI Deck [1]	7 or greater			
	iv. Deck Underside Rating[1]	7 or greater			
2. Maintenance	i. % Distress	1 - 10%	"> 5 years" or ">10 years"	None [3]	None [4]
	ii. % Distress + 1/2 cell	1 - 15%			
	iii. NBI Deck	5 or greater			
	iv. Deck Underside Rating	5 or greater			
3. Overlay [7]	i. % Distress	2 to 35% [5]	"Ongoing" to ">5 years" [10]	Yes [3]	Yes [6]
	ii. % Distress + 1/2 cell	10 to 50%			
	iii. NBI Deck	4 or greater			
	iv. Deck Underside Rating	5 or greater			
4. Structural Rehabilitation	i. % Distress	> 35%	"Ongoing"	Yes	Yes
	ii. % Distress + 1/2 cell	> 50%			
	iii. NBI Deck	3 or less			
	iv. Deck Underside Rating	4 or less [8]			

Table Notes:

[1] Preferred evaluation criteria (**ii, iii and iv**)

i. % Distress includes non-overlapping area of %patches, spalls, & delaminations

ii. % Distress plus half-cell <-0.35 V (vs. copper sulfate). Less negative half-cell values may be used if determined to better represent actively corroding areas

iii. NBI condition rating of deck

iv. Condition rating of bottom of deck made using NBI condition rating scale

[2] Select Do Nothing only if all conditions apply.

[3] If only skid resistance is a concern, consider grooving or chip seal instead of overlay.

[4] If cracking due to ASR/DEF is present, deck life can be prolonged 2 to 5 years with HMWM treatment

[5] If deck has existing overlay, replace overlay if overlay distress is greater than about 15 to 20%.

[6] Overlays may prolong deck life of decks with ASR; however, close monitoring is suggested. Compare partial and full depth replacement to cost of overlay and assess overall structure condition and the service life goals.

[7] The value of an overlay should be compared to future replacement costs, funding constraints and traffic disruption if the deck is allowed to continue to deteriorate. Overlays are good options whenever deck replacements are burdensome. If the deck already has been overlaid several times previously and concrete cover is a problem, consider partial or full depth deck replacement.

[8] Replace deck full depth. Partial depth replacement an option if condition rating of Deck Underside is 6 or greater. Assess corrosion condition of lower mat of reinforcing steel due to cracks and leakage.

[9] If the deck is subjected to deicers and has cracks, repair cracks.

[10] Review the chloride content data with depth and determine the optimum depth of concrete removal prior to placing the overlay. If chloride concentrations at most bar depths are below threshold, remove concrete where chloride concentration is greater than 0.04 to 0.07% for black steel or 0.15% for epoxy-coated reinforced decks. Overlays can be applied directly to heavy chloride contaminated decks, but additional service life may be reduced. Consider cathodic protection for heavily salt contaminated decks that chloride cannot be removed by milling.

Note: If the deck is in a northern environment subject to deicer salts and has an asphaltic overlay without a waterproofing membrane, the overlay should be removed and the bare deck examined.

Deck Distress

Two aspects of the existing deck condition are considered to provide an overall rating of the existing deck distress, i) the percent deck deterioration measured as the total non-overlapping area of distress defined as either patches, spalls, delaminations, or areas with half-cell potentials < -0.35 V (CSE), and ii) the condition ratings for the deck (NBI) and for deck bottom surface.

Several different parameters are presented to assess Deck Distress, since the extent of investigation may be limited due to traffic restrictions, time or cast restraints, or lack of access to the deck underside. The preferred parameters to use to rate the deck distress are to determine the % distresses plus half-cell potentials < -0.35V (CSE) of the top surface combined with a visual inspection and condition rating of the deck underside. Determining the Deck Distress solely on the visual NBI inspection of the top deck surface is not recommended.

Percent Deck Distress

Commentary. Deck distress can take multiple forms, such as spalls, delaminations and patches. Half-cell potential surveys can identify other areas that are actively corroding and potentially in need of repair. In this factor, these multiple forms of distress are combined non-redundantly as a percent of the total deck surface. Generally, the traffic lane having the most distress controls the final determination for repair (Fitch 1995); however, while not directly considered in the selection matrix presented here, some consideration may need to be given to the distribution of deterioration across the deck and shoulders or at different spans.

Conducting the work. Inspect and chain drag the deck surface and record the amount and size of patches, spalls, and delaminations. Determine if the deck is original or if an overlay has been placed. On large decks, selected areas that are typical can be surveyed in detail and used to estimate the overall deck condition. Generally, a minimum of at least 25% of the deck area should be surveyed. This should include the traffic lane showing the most visual damage or having the most heavy truck traffic or most deicer exposure and include a middle span, as well as pier and joint locations. The survey locations should be sufficiently balanced so that a generally complete picture of the bridge condition is obtained. Perform a half-cell survey of the entire deck if that is feasible. If that is not practical because of the size of the deck, perform a copper-copper sulfate half-cell survey on a sufficient number of typical areas of the deck to fully characterize the deck condition.

Record on a plan drawing the following items, noting total size of surveyed area and sizes of each distress area:

a. Spalls
b. Patches
c. Delaminations

Determine if an overlay is present and document type and condition. Conduct a half-cell survey using a copper sulfate reference cell at a 3- to 5-foot grid. Plot copper-copper sulfate potential values as contours, and identify area having potentials more negative than -0.35 V on the plan drawing. Note if epoxy-coated deck reinforcing is present in the top mat only or in both top and bottom deck mats. Note if bar electrical continuity is present and if the half-cell measurements can be reliably measured (see Chapter 5).

Note: Ground-penetrating radar (GPR) can be used to detect delaminations in bridge decks, particularly if the delamination has resulted in a wide void within the deck. GPR can also be used to locate reinforcing steel. This technique requires expertise to accurately gather and interpret data. If data collected with GPR is available, any delaminations that are identified should be included in drawings summarizing the observed distress and in calculations of the deck distress.

Input. The Percent Deck Distress is calculated as follows:

Percent Deck Distress = non-overlapping areas of spalls + patches + delaminations, as a percent of area surveyed.
Percent Deck Distress and Half-cell Potentials less than -0.35 V = non-overlapping areas of spalls + patches + delaminations + deck area with half-cell potentials less than -0.35 V (CSE), as a percent of area surveyed.

Note: Depending on the general deck condition, consideration can be given to omitting areas having sound, well-bonded patches from the total area of distress.

Based on the Percent Deck Distress and the Percent Deck Distress and Half-cell Potentials less than -0.35 V (CSE), use Table 8 to determine the suggested category for repair actions. The values shown in Table 8 are based on the survey results, a review of the various state practices and the literature (Cady 1985). Values used by individual state agencies tend to vary widely for some categories, and typical or suggested values are shown. Users are encouraged to modify the recommended limit values shown in Table 8, as needed.

Condition ratings

Commentary. The NBI condition rating system provides a numerical ranking of the deck condition, from 9-excellent to 1-failed, based on its visually rated condition. For decks, the NBI rating is largely controlled by the top surface of the deck. Since the condition of the underside of the deck may be important in the selection of an appropriate repair, it is also recommended that visual assessment of the bottom surface of the deck be recorded independently of the top deck surface. Further, CoRe element level inspection ratings can be used to specifically target deck or superstructure conditions (Subcommittee on Bridges and Structures of the Standing Committee of Highways 2002). A discussion of these inspections and ratings is provided in Chapter 5.

Review of past NBI condition ratings can provide useful information on the history of deterioration of the deck. It is recommended that the past 10 years of NBI deck condition ratings be reviewed. It may be helpful to plot these values versus time. By looking at the history of NBI condition ratings and comparing the ratings to the Percent Deck Distress measured, there may be justification to decrease the current rating by a point if the rating does not match closely with the Percent Deck Distress measured. Generally, a NBI condition rating of 4 or less corresponds to a deck needing more than just routine maintenance, since any further deterioration will make the deck condition intolerable and require high priority corrective action. Much more detailed discussion of NBI condition ratings and cost analysis is provided by Zimmerman et al (2007).

Special considerations must be given to decks having wearing surfaces, such as asphaltic overlays, that can mask the condition of the deck. Additional testing, core sampling, careful examination of the deck underside, and other means should be used to evaluate the condition of the deck. If the deck is in a northern environment subject to deicer salts and has an asphaltic overlay without a waterproofing membrane, the overlay should be removed and the bare deck examined.

Stay-in-place forms limit the inspection of the underside of some decks. Some agencies remove a small portion of the stay-in-place forms to examine the underside condition of the deck. Sometimes water leakage and corrosion of the forms themselves indicate potential problems with the deck.

Input. Determine the current NBI condition rating for the deck surface and assign a condition rating for the deck underside. Compare the condition ratings to the Percent Deck Distress and half-cell data if available and adjust ratings, if necessary. Examine Table 8 and make a determination on the best repair category.

Time-to-Corrosion Initiation

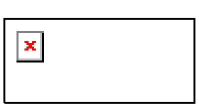
Commentary. The exposure of the deck to deicers is a primary cause of corrosion-related distress. The service life of a deck is dependent on the exposure conditions, the concrete permeability, the concrete cover, and the type of reinforcing steel. Determination of the risk of future corrosion is necessary so that the best repair or preventive strategy can be implemented. Decks that are exposed to deicers but that have accumulated little chloride are good candidates for sealers or membranes. Decks that have high chloride concentrations in the near surface but little chloride at the steel level are good candidates for surface milling to remove the chlorides and then overlaying. The service life of decks with high levels of chloride close to the level of reinforcing can be extended with overlays, but long-term performance may be reduced since corrosion initiation may be imminent. Decks with very high chloride contents, on-going corrosion and damage are good candidates for partial or full deck replacement, although overlays will extend deck life somewhat.

Bridge decks in marine environments rarely corrode as fast as northern decks subjected to deicers. If corrosion is suspected in marine decks, chloride and concrete cover tests should be done on both the top and bottom surfaces on both the windward and leeward sides. Unless the deck is low and immediately on the coast, chloride buildup within the concrete due to air borne salt water spray is usually very slow. Repairing cracks and sealing the deck usually provide good protection to airborne salt spray.

Many factors are considered to estimate the time-to-corrosion initiation of the embedded reinforcing steel. The presence of corrosion-resistant steel, such as epoxy-coated reinforcing, will prolong the deck service life and may affect the choice of repair strategies. The objective of the deck characterization is to estimate the time when active corrosion of the embedded reinforcing steel will occur in a significant portion of the deck.

If the percent original bare deck deterioration due to corrosion, shown as spalls, patches, and delaminations, is greater than 10% or the distress plus copper sulfate half-cell potentials more negative than -0.35 V is greater than 15% of the deck area, consider the corrosion ongoing. If the corrosion-induced distress is less than these values, determine the estimated time-to-corrosion based on chloride content analysis of concrete core samples and concrete cover information. Two methods for making this estimate are discussed, one being a simplified but less precise version that does not require in-depth calculations.

Calculating the Time-to-Corrosion. Chloride diffusion in concrete, driven by a concentration gradient, can be estimated by Fick's Second Law of Diffusion:



Eqn. 1

where C is the chloride concentration at a depth of x from the concrete surface at time t, and D is the effective chloride diffusion coefficient.

If the surface chloride concentration, C_s, and the effective diffusion coefficient, D, are assumed to be constant, the concentration C(x, t) at depth of x and time t is given by (Broomfield 1997):

Eqn. 2

where erf() is the Gaussian error function, and C_0 is the background or original chloride concentration.

Based on this relationship, if the values of C_s and D for a given situation can be determined, they can be used to predict the chloride concentration at any depth or time. For a specific bridge, C_s and D are typically estimated based on the best fit of the relationship shown in Eqn. 2 to profiles of chloride concentration versus depth determined in cores or with powder samples taken from the deck, such as show in Figure 1. This can be done using a least squares fitting method. For this analysis, the term t is assigned as the age of the bridge.

Note that this analysis assumes one-dimensional diffusion of chloride through a uniform concrete (no cracks), that the surface concentration of chloride is constant, and that the resistance of the concrete to chloride penetration is constant over time. These assumptions are not entirely accurate. Cracks will have a significant effect on the local penetration of chloride. The surface concentration of chloride varies throughout the year and can take 10 years or more to accumulate to its maximum concentration. In addition, the resistance of the concrete to chloride penetration will also vary with the maturity of the concrete and with temperature.

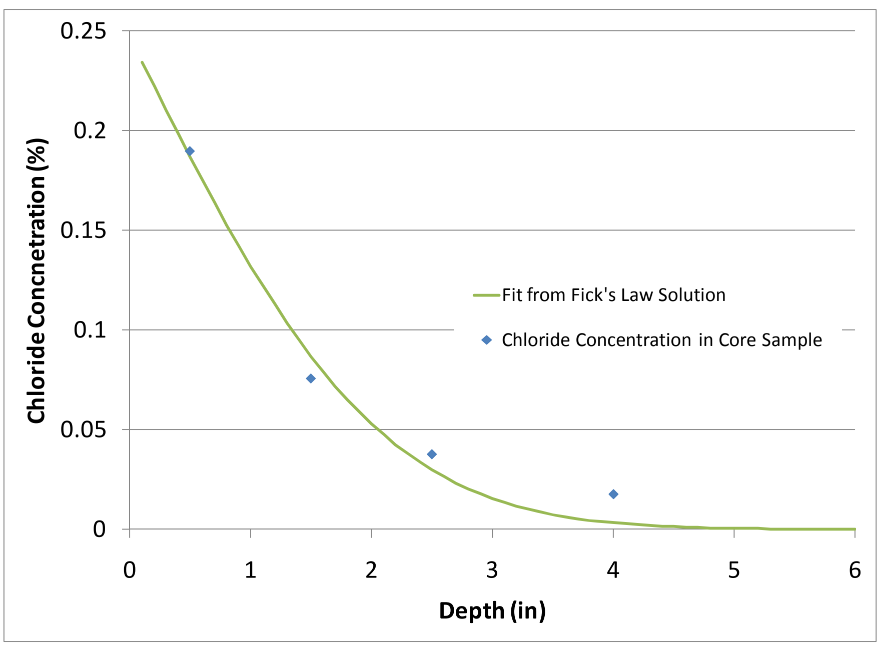


Figure 1. Typical chloride analysis result. Chloride profile was fitted using a least squares fit method to obtain an estimate of effective chloride diffusion coefficient, D, and surface chloride concentration, C_s.

Uncoated carbon steel reinforcing bars are usually passive in concrete, because concrete surrounds the steel with a high pH (approximately 13) medium and acts as a physical barrier isolating the steel from aggressive species in the environment, such as deicers, sea water or carbonation. However, steel will begin to corrode once aggressive species (e.g., chloride ions) penetrate through the concrete cover and reach a certain concentration. This concentration is commonly called the chloride threshold (C_T). It is typical to assume approximately 0.03% by weight of concrete (or 0.2% by weight of cement) as the threshold for uncoated black steel. Alternatively, corrosion could also take place if atmospheric carbon dioxide produces a concrete carbonation front that reaches the reinforcing steel surface causing a decrease of pH at the steel depth, but this mechanism of corrosion initiation is not a primary cause of corrosion in most bridge decks in the United States.

The corrosion resistance of alternative reinforcing steels, such as epoxy-coated reinforcing (ECR) bars, is considered when modeling the onset of corrosion by recognizing that these types of bars have a higher chloride threshold. Significant corrosion of epoxy-coated reinforcing steel only occurs if there is damage or holes (holidays) in the epoxy coating. Therefore, the service life of ECR bars is mostly a function of the quality of the coating and not any particular level of chloride at the coating concrete interface. However, assigning a chloride threshold value is useful for modeling purposes. Based on research, the threshold for epoxy-coated reinforcing steel should be different depending on the configuration of bars within the deck, as corrosion depends on coating damage and available cathode area (McDonald 1998). For a deck with epoxy coated steel in the top mat and uncoated black steel in the bottom mat, the threshold might be conservatively assumed to be approximately 0.15% by weight of concrete (or 1.0% by weight of cement). For a deck with epoxy coated steel in both mats, the threshold might be assumed to be approximately 0.30% by weight of concrete (or 2.0% by weight of cement). For stainless steel rebar, this threshold may be as high as 0.64% by weight of concrete (or 4.1% by weight of cement). It should be noted that the appropriate threshold for corrosion resistant reinforcing steels is a topic of much discussion in the industry, but satisfactory field performance justifies increasing the threshold values for modeling the performance of corrosion-resistant bars.

An approach to predict the onset of corrosion due to chloride penetration in a given bridge deck is to consider the movement of a "chloride threshold front" into the deck. This front is defined as the depth at which the chloride concentration is equal to the chloride threshold, and this depth is expected to increase with time (Figure 2). If the depth of the chloride threshold front is greater than the depth of cover on the top mat of reinforcing steel, then corrosion is likely on-going. If, however, the depth of the chloride threshold front has not reached the steel and the rate of advancement is known, the concept of the chloride threshold front can be used to predict how much time is remaining before corrosion initiates.

The rate of advancement of the chloride threshold front is not constant (Figure 2). However, the instantaneous rate of advancement can be estimated for a given bridge deck based on the following equation using values of C_s and D determined for that set of conditions and for the appropriate chloride threshold, C_T, for the type of reinforcing steel in the deck:

Eqn. 3

where inverf() is the inverse Gaussian error function. This rate, derived by solving Eqn. 2 for the depth, *x*, and taking the derivative with respect to time, *t*, is instantaneous and can be used to estimate the depth of the threshold front for a given period. However, since the rate of advancement is decreasing, a forward estimate will overestimate the depth of the chloride threshold front, conservatively underestimating the time remaining before corrosion initiates.

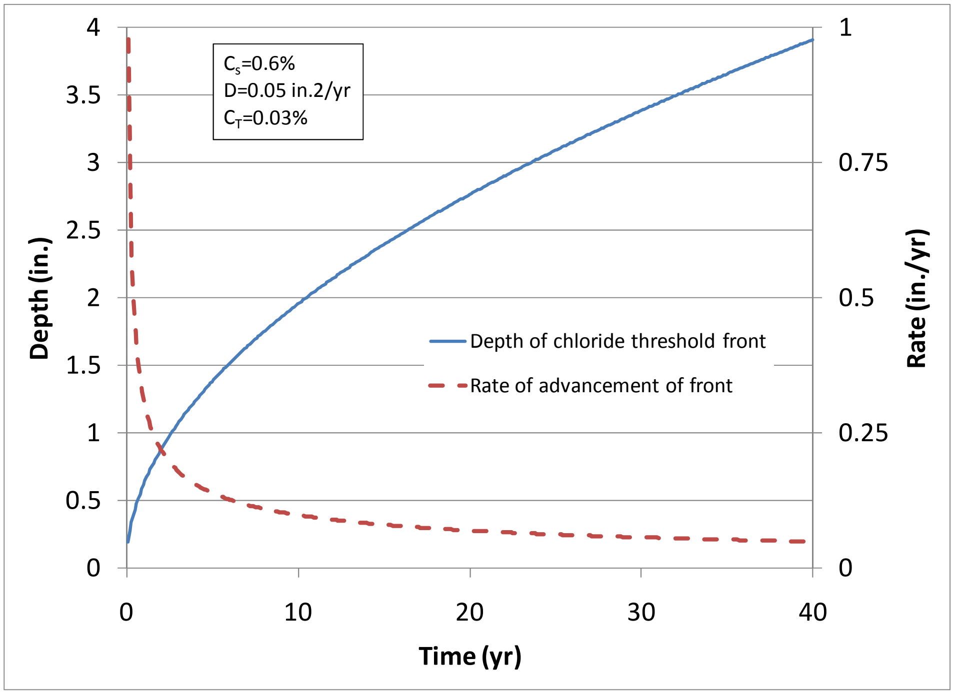


Figure 2. Chloride threshold front depth and rate of advancement versus time for given surface chloride concentration, C_s, chloride diffusion coefficient, D, and chloride threshold, C_T.

Conducting the work. Assess the corrosion-induced distress per the previous section for *Percent Deck Distress*. If bare deck distress is greater than 10% of the surveyed deck area or the distress plus area of half-cells more negative than -0.35 V is greater than 15% of the surveyed deck area, do no further work or test a couple of locations for confirmation, and report corrosion as "Ongoing". Otherwise determine the time-to-corrosion as follows:

1. Take core samples (preferable) or powder samples at precise depths from deck. Core samples can be cut accurately in the laboratory to control the sample depth which is important when making time to corrosion or service life estimates. Controlling sample depth, obtaining a representative sample, and avoiding test sample contamination is much more difficult if drilled powder samples are collected in the field. Take samples at a sufficient number of locations to fully describe the deck exposure conditions, including the shoulder and travel lanes; at least six sample locations are normally recommended.
2. Measure the concrete cover over the top reinforcing steel and plot cumulative distribution. Identify the 20th percentile of low cover values (20% of bars have concrete cover less than this value). Other percentile depths can be chosen by the user, if deemed appropriate.
3. Measure concrete carbonation depth using a pH indicator applied to a freshly broken or drilled surface.
4. Determine extent of characteristic full depth cracking, and estimate the average spacing of the cracks per length of deck.
5. Determine the chloride content of the concrete with depth. If using cores, slices 1/4-in. thick from a 4-in. diameter core are typically sufficient. Determine the chloride concentration at four or more depths within each core. The depths selected should extend at least to the bar depth and include at least one sample close to the surface, e.g. a slice from 1/4 to 1/2 in. Also, determine the background or baseline chloride concentrations using at least two samples from depths great enough that the chloride value is not affected by chloride penetration from the surface. This

provides the chloride concentration in the as-mixed concrete. Acid-soluble chloride is typically determined but water-soluble chloride values can also be used. If baseline acid-soluble chloride is elevated, measure the water-soluble chloride to determine if the baseline chloride is available to cause corrosion (admixed, water-soluble) or if it is bound in aggregates (acid-soluble but not water-soluble). The data or threshold values can be modified to account for bound chloride, if applicable.

Input. Determine whether corrosion is likely to initiate within the next 5 years or within the next 10 years, based on the estimated time-to-corrosion for the 20th percentile (or user-selected percentile) of lowest concrete cover. Two approaches for determining this are given: 1) detailed and 2) simplified. The method by which each approach makes the determination is the same; the difference is the level of rigor in the analysis of the chloride data.

Detailed Approach

1. Plot the measured chloride concentration versus depth for each core or powder sample location.
2. Estimate the effective diffusion coefficient, D, and surface concentration, C_s, for each core by fitting the solution to Fick's law (Eqn. 2)[1]. Set C_0 as the background chloride concentration and the time, t, as the age of the bridge deck.
3. Using the average values (or other user-selected representative values) of D and C_s for all of the tested cores, develop the function (Eqn. 2) describing the chloride concentration with depth and time. Ignore outlier data from cracked core samples. Plot this function with the measured data, and confirm that the observed chloride ingress is well-represented by this model. (The data and curve through the data should look something like Figure 1).
4. Select a chloride threshold for the type of reinforcing steel in the deck in question.
5. Using the function given in Eqn. 2, determine the current depth of the chloride threshold front. If the current depth of the chloride threshold front is greater than the 20th percentile of cover, do no further work and report corrosion as "Ongoing". Note cracking can be accounted for by reducing the percent area of minimum concrete cover by the area affected by the cracking (say the area 2 inches on either side of a crack results in a crack affected area equal to the crack length times four inches). For example, if the deck has a crack affected area of 4 percent, select the rebar depth of the 16th percentile of lowest concrete cover instead of the 20th percentile.
6. Using Eqn. 3, the selected chloride threshold and the average or other representative value of D and C_s, estimate the rate at which the chloride threshold front is moving into the concrete.
7. Estimate the depth of the chloride threshold front in 5 years and in 10 years based on the following:

   Depth in 5 years = current depth + rate of advancement (t) x 5 years Eqn. 4a

   Depth in 10 years = current depth + rate of advancement (t) x 10 years Eqn. 4b

8. If this depth exceeds the 20th percentile cover (or corrected value for cracking) after 5 years, report "time-to-corrosion < 5 years."

[1] This fitting can be performed using 1) Mathcad's genfit() function or 2) by setting up a Microsoft Excel worksheet to calculate the error in terms of the sum of the square of residuals between an actual result and an estimate and using the Excel solver to minimize this error.

9. If this depth exceeds the 20th percentile cover (or corrected value for cracking) after 10 years, report “time-to-corrosion < 10 years.”
10. If the “time-to-corrosion” is greater than 10 years but the carbonation front exceeds the 20th percentile cover, report “time-to-corrosion as < 10 years”.
11. Refer to Table 8 and select Primary Repair Category.

Note, for unchanging exposure conditions, the rate of advancement will decrease with time. Therefore, calculations based on the current rate will provide a conservative estimate on the time-to-corrosion, and should not be considered valid for much more than the 10-year period being considered. Also, tables have been prepared to estimate the rate of advancement based on calculated values of D and C_s, for the chosen chloride threshold. These are given in the Appendix B to this document.

Simplified Approach

1. Plot all the measured chloride concentration data versus depth for each core or powder sample location on one plot.
2. Draw a curve through the data, and confirm that chloride ingress is well-represented by this model. The data and curve through the data should look something like Figure 1. It is sometimes helpful to bracket the high and low boundary conditions to help locate the “average” chloride concentration curve.) Ignore outlier data from cracked core locations since cracks are already considered as on-going corrosion.
3. Select a chloride threshold for the type of reinforcing steel in the deck in question. If the concrete has high background chloride (acid-soluble) that is bound (not water-soluble), adjust test data or increase chloride threshold appropriately.
4. Estimate the depth of the chloride threshold front (where the chloride threshold is exceeded). If the current depth of the chloride threshold front is greater than the 20th percentile of cover, do no further work and report corrosion as “Ongoing”.
5. The surface concentration, C_s, can be estimated from this plot as where the curve intersects the y-axis (i.e., where depth is equal to 0 in.). Note the rapid increase in chloride concentration with decreasing depth as the depth approaches 0 in. that is characteristic of diffusion curve fits (Figure 3).
6. Estimate the effective diffusion coefficient, D, based on the expected concrete quality. The diffusion coefficients provided in the Appendix B tables range from very low (0.05 in^2/yr), moderate (0.10 to 0.20 in^2/yr) to high (0.3 $in.^2$/yr). The D of actual deck concretes vary greatly but many AASHTO-grade deck concretes are in the moderate range of 0.10 to 0.20 $in.^2$/yr.
7. Based on the selected chloride threshold, the estimated values of D and $C_{s,}$ and the age of the deck, use the tables provided in the Appendix B to estimate the rate of advancement of chloride threshold front. Data can be roughly interpolated between tables for ages or within tables for D and C_s values.
8. Using Eqn. 4 and the rate of advancement, determine the expected depth of the chloride threshold front in 5 and 10 years. Review “Detailed Approach” above to address deck cracking.
    a. If this depth exceeds the 20th percentile (or corrected value for cracking) cover after 5 years, report “time-to-corrosion < 5 years.”
    b. If this depth exceeds the 20th percentile (or corrected value for cracking) cover after 10 years, report “time-to-corrosion < 10 years.”
9. If the “time-to-corrosion” is greater than 10 years but the carbonation front exceeds the 20th percentile cover, report “time-to-corrosion as < 10 years".
10. Refer to Table 8 and select Primary Repair Category.

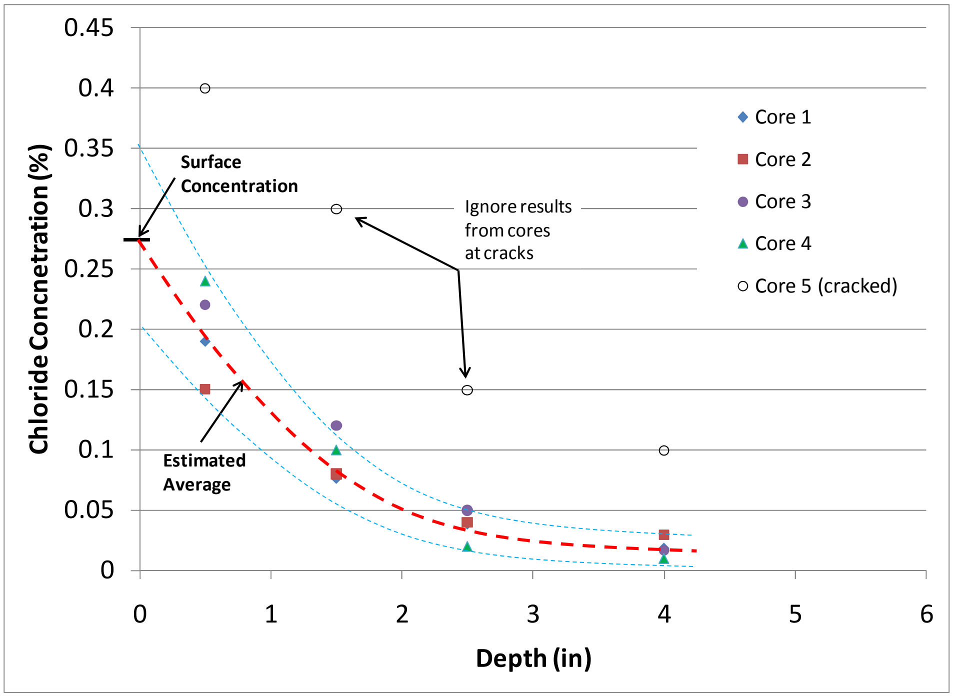


Figure 3. Sample plot of chloride test data from core or powder samples.

Deck Surface Conditions

Commentary. Certain deck surface conditions require improvements to the grade or quality of the riding surface. These conditions may include drainage problems, cross-slope or grade problems, uneven joints, concrete surface scaling, abrasion loss or poor skid resistance. Decks requiring grade corrections or new surfaces are better candidates for overlays or structural rehabilitation than for routine maintenance.

For northern decks, surface scaling sometimes occurs when the air entrainment in the near surface is lowered by poor finishing practices. This deterioration will stop after the poorly air-entrained surface layer deteriorates and is worn away. Alternately, the affected surface concrete can be milled and grooved to restore ride quality.

Conducting the work.

1. Rate the deck surface scaling per the rating schedule defined in ASTM C672 *Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals* (ASTM 2008). If surface scaling is present, take core samples and conduct a petrographic examination according to ASTM C856 *Petrographic Examination of Hardened Concrete* to determine if the scaling potential is only in the near surface (finishing problems) or if the entire concrete deck is poorly air-entrained. If poorly air entrained, perform air content analysis per ASTM C457 *Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete*.
2. Visually assess deck texture and grooves and assess abrasion loss.
3. Measure skid resistance per AASHTO T242 *Standard Method of Test for Frictional Properties of Paved Surfaces Using a Full-Scale Tire*, T278 *Standard Method of Test for Surface Frictional Properties Using the British Pendulum Tester*, (AASHTO 2007)or other method if there is a question concerning surface friction.
4. Visually assess deck drainage after wetting or survey the deck surface to assess if it has adequate slope to drains and lack of bird baths.
5. Examine joint conditions, including grade, slope and transitions.

Input. Determine if the deck requires resurfacing or grinding to correct drainage problems, surface scaling, abrasion loss or skid resistance. Milling or grinding can sometimes correct surface problems, but often an overlay is required to correct more serious problems. Review concrete cover data to determine if grinding can be done to correct grade or slope problems without sacrificing adequate concrete cover. A minimum of 1 1/2-inch cover to the top reinforcing steel may be considered adequate, unless the deck is in a very severe deicing environment, where 2 inches of concrete cover or greater may be desired. If concrete cover will be too small after grinding and grooving, overlay the deck.

If deck scaling is rated 3, 4 or 5 per ASTM C672, take core samples from the deck and determine the depth of deterioration and general entrained air void quality of the concrete. If the concrete is adequately air-entrained except for the near surface, assess concrete cover and grind or overlay. If the bulk of the concrete is not adequately air-entrained to resist further scaling and cyclic freezing damage, overlay the deck or consider full depth replacement. If skid resistance is the sole concern, consider grooving or chip seals in addition to overlays or structural rehabilitation.

Review the deck slope to drains and joint transitions. Determine if the drainage and joint transitions can be improved by local grinding, installing new drains, or if an overlay is required. Overlays can usually be tapered into the deck to meet joint or barriers using local milling and grinding.

Concrete Quality

Commentary. Concrete bridge decks can be seriously affected by internal deterioration mechanisms such as alkali-aggregate reactions or delayed ettringite formation (DEF). Inadequate air entrainment results in concrete that will deteriorate due to cyclic freezing. Low strength or concrete fatigue are other problems that could cause premature deterioration of bridge decks.

Typically, adequate strength or concrete fatigue are not problems for most decks since their required design strengths are usually not high. Further, DEF is not common on decks since most are decks are cast-in-place, thin, and not heat cured. Deterioration due to cyclic freezing, while not common due to the routine use of air-entrainment, does sometimes occur on bridge decks. The service life of decks having poorly air-entrained concrete in cyclic freezing locations usually can be extended by placing an overlay to keep the concrete protected and less saturated with water, but in many cases it may be best to replace the deck.

Alkali-aggregate reactions can be moderate to severe depending on the aggregate properties and cementitious components of the concrete. The presence of alkali-aggregate reactions is a primary concern since deterioration can cause serious loss of integrity and extending the service life of affected decks is difficult. Moderately large areas of concrete can fall away from the deck without significant warning in advanced cases of alkali-aggregate reactions leaving only the reinforcing steel to support traffic. Repair of concrete decks having alkali-silica reactions (ASR) or DEF distress must be considered carefully.

Conducting the work.

1. Examine the concrete for pattern cracking, excessive crazing, scaling, excessive cracking, spalling unrelated to reinforcing corrosion, and other signs of concrete disintegration. If present, remove several core samples from deteriorated and non-deteriorated areas and examine petrographically per ASTM C856 *Petrographic Examination of Hardened Concrete* to determine the cause of the distress. If poorly air entrained, perform air content analysis per ASTM C457 *Standard Test Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete.* Compare air void parameters to accepted values (ACI 201 2008).

2. Test multiple cores for compressive strength. Also test cores for wet static modulus if ASR or DEF is suspected.

Input.

1. Determine if ASR/DEF is a concern for long-term durability.
2. Determine if poor air entrainment and cyclic freezing is a concern for long-term durability.
3. Determine if low strength is a concern for long-term durability.
4. Determine if other deterioration is present that could affect deck durability.

If the deck is affected by ASR/DEF, low strength, or other serious concrete deterioration, consider deck replacement. Deck overlays can be used to strengthen decks and may extend the service life of the deck depending on the extent of the distress. Perform a structural analysis to determine if a bonded overlay will adequately correct low strength problems.

If not replaced, decks affected by ASR/DEF should be inspected often (annually) until an estimate of the rate of deterioration can be established. Generally, the decks should be programmed for replacement, although treatment with high molecular weight methacrylate (HMWM) resin to bond cracks or placing an overlay will extend the service life somewhat.

Summary of Deck Characterization

Based on the four general deck characterization factors that describe the existing deck condition, a selection is made between the primary categories of repair: 1. do nothing; 2. maintain the bridge by patching, sealing and/or crack repair; 3. install an overlay; or 4. do partial or full depth structural rehabilitation. Once this selection is made, specific repair options are selected as discussed within the following sections.

SELECTION OF REPAIR OPTIONS WITHIN PRIMARY CATEGORIES OF REPAIR

After the best category for repair is selected, additional decisions need to be made on the best materials and procedures to use to complete the repair. Appendix A provides information gathered during the survey of DOT officials and provides information on each specific system including advantages, disadvantages, history of use, expected life span, costs, information on installation, and general recommendations and experience. Further information on the technical aspects of the various repair systems and suggested literature are included in Appendix C.

Do Nothing

If the Do Nothing option is chosen, no further action is needed at this time. Reassessment of the deck condition is suggested on a regular basis and more frequently after the deck condition rating drops to a 6 or below. The Do Nothing option makes sense for a deck in satisfactory condition with little corrosion risk in the next 10 years or on a deck that is programmed to be replaced in the near future. It is sometimes most cost effective to allow an older deck in poor condition to deteriorate further prior to scheduled replacement, delaying the need for expenses related to that bridge. However, if the planned funding is delayed or plans change, an additional assessment and more costly repairs may be needed.

Maintenance

The Maintenance option is best for decks showing little or no serious distress and with little risk of deterioration in the near future. If the deck is subjected to deicing chemicals, its cracks should be sealed or repaired. Most visible cracks allow deicers to rapidly penetrate into the concrete deck and corrode reinforcement. If the deck has moderately to highly permeable concrete, a surface sealer can be an effective way to reduce the amount of chloride ingress into the concrete over time. Patching and other treatments further the service life of the existing deck.

Maintenance, such as patching and sealing, of decks with existing overlays is also done. Overlays should also be maintained until they reach an unacceptable condition when they should be replaced or the deck reconstructed.

Patching

Existing spalls and debonded patches should be repaired. Delaminated areas can also be removed and patched, especially if they have surface cracking. It is usually not cost effective to remove and patch areas having highly negative half-cell values (< -0.35V versus copper sulfate half-cell) but that are not delaminated.

Concrete patching is normally performed with a variety of rapid-setting materials that have been tested and approved for use. These materials can often be used during short lane closure periods. Asphaltic-based patch materials are sometimes used for emergency and temporary repairs but normally should be avoided for permanent repairs on concrete bridge decks. The asphaltic patches tend to trap water and deicer solutions within the patch and can cause accelerated deterioration of the surrounding concrete and corrosion of embedded reinforcing steel. If used, asphaltic patches should be replaced with more permanent patches as soon as practical (Sprinkel 1992).

Crack Repair

Most cracks penetrate the deck to the top layer of reinforcing steel or further. Usually, transverse deck cracks penetrate the entire deck thickness, exposing the top and bottom mats of steel as well as any supporting girders or beams to deicer-laden water. Even hairline cracks often allow deicer-laden water to penetrate into the deck. Therefore, if the deck has cracking and is exposed to deicers, it is recommended to apply a penetrating sealer or crack repair resin to extend the deck service life.

If cracks are few and discrete, the cracks can be epoxy injected or topically filled on an individual basis. However, if the cracking is widespread or the deck concrete surface itself requires sealing, a complete topical application is recommended. While cracking exposes only a small percentage of the deck steel, corrosion often initiates rapidly at crack locations and can cause spalling and premature distress.

Crack injection is most commonly performed using epoxy resins although other polymers are sometimes used. Topically-applied crack repair resins include high molecular weight methacrylate resins (HMWM) and sometimes very low viscosity epoxy resins. Concrete surface sealers or penetrating sealers, such as silanes, can also be effective in sealing fine and hairline cracks (approximately 0.010 in. or less). Penetrating sealers do not physically fill and bond the cracks, but make the sides of the cracks hydrophobic, preventing the ingress of water.

Trials and evaluation of any crack repair system is recommended as each deck is unique. Small diameter (2-3 in.) core samples should be taken from treated crack locations to determine the depth of sealer or resin penetration. Typically, penetration depths within the crack of 1/2 in. or greater indicate reasonable protection. The DOT officials surveyed estimated that the mean service life of crack repair treatments were from 19 to 33 years.

Sealers

Sealers reduce the permeability of concrete to deicer chemicals. The application of a surface sealer makes sense if the level of chloride at the bar depth is below or not greatly in excess of the threshold for corrosion (for black steel this level is about 0.03% by weight of concrete [or 0.2% by weight of cementitious content]) and the concrete has high to moderate permeability, such that the sealer will substantially improve the resistance of the concrete to chloride ingress. It may not be cost effective to apply a surface sealer to a deck concrete having very low permeability, since its effect will be minimal. Sealers may be particularly appropriate for decks subjected to aggressive deicers, such as magnesium chloride or saltwater brines. These materials can cause concrete surface deterioration as well as rapid penetration of the concrete cover to cause reinforcing corrosion. If deicers are shown to attack the concrete, protecting all decks using a sealer is recommended. Research into the best sealers to protect the decks from aggressive deicers is recommended prior to widespread use to ensure effectiveness.

Determine the Chloride Diffusion Coefficient based on core samples and chloride profile tests as discussed in Chapter 4, Section “Time-to-Corrosion”. If the Chloride Diffusion Coefficient of the concrete is greater than about 0.1 $in.^2/yr$ ($2.0x10^{-12}$ m^2/s) and the chloride exposure is more than minor, a surface sealer is recommended. However, if the concrete has high chloride contents just above the level of the steel and corrosion is expected within the next 10 years, removing the chloride contaminated concrete and placing an overlay may be a better option to greatly extend the deck service life. For example, if the chloride content at the depth of the 20th percentile of lowest concrete cover is near or only slightly greater than the estimated threshold value for the steel and the chloride at 1/2 inch to 1 inch above the steel reinforcement is more than about 1.5 times the threshold, removing the chloride-contaminated concrete to within 1/2 to 1 in. of the reinforcing and placing an overlay may be a better repair option than just applying a sealer to slow additional chloride ingress. By removing the chloride before widespread corrosion occurs, the deck life can be greatly extended.

If the deck is new, sufficient chloride exposure time may not have passed to be able to accurately determine the chloride profile and concrete Chloride Diffusion Coefficient. Cores can be cut from the deck, or slabs cast, and the samples exposed to chloride ponding tests, per ASTM C1556 *Standard Test Method for Determining the Apparent Chloride Diffusion Coefficient of Cementitious Mixtures by Bulk Diffusion* and the Diffusion Coefficient can be calculated from the ponding test results.

Alternatively, the need for a sealer can be estimated very roughly by measuring the electrical conductivity of the concrete using AASHTO T277 *Standard Method of Test for Electrical Indication of Concrete’s Ability to Resist Chloride Ion Penetration.* If the charged passed over the 6-hour period is greater than about 1500 coulombs, a sealer will likely be beneficial.

Ensure that the deck is dry when the sealer is applied and that the manufacturer’s application instructions are followed. Consider reapplying the sealer after three to five years, especially for newer decks.

Penetrating sealers, such as silane, are most commonly used on bridge decks. Film-forming sealers are not well suited for driving surfaces due to concerns with skid resistance and wear. Many different products are available and the selection of the sealer should be based on review of test data (Pfeifer 1981) and satisfactory use in the field. The DOT officials surveyed estimated that the mean service life of sealers varied from 4 to 10 years.

Specialized surface treatments, such as thin asphaltic membranes or rubberized asphalt surface treatments, are available for use as preventative maintenance treatments. Typically, a thin coarse aggregate hot mix is placed over an asphaltic membrane layer. This can be done with specialized equipment and construction is usually done by specially trained contractors. These materials are placed as a very thin layer so do not have the attributes of a thicker overlay but are used to reduce the infiltration of deicers and provide a new wearing surface.

General

Most patching materials, crack repair materials and sealers can be applied during short traffic closures, but special formulations that will fully cure during short nighttime closures may be needed. The cure of polymer resins is especially sensitive to temperature, solar radiation, and moisture. A trial under simulated job conditions of any material to be used during short night closures is strongly recommended to assess curing and time-to-traffic requirements.

Overlays

Installation of an overlay is often appropriate if the deck has little to moderate deterioration but likely will have deterioration in the future, and the deck is not in need of immediate replacement. Bonded overlays provide a new wearing surface so deck surface conditions, such as cross-slope and grade, joint transitions, drainage, abrasion resistance, skid resistance, or scaling problems, can be improved. Overlays also provide good protection to decks having many cracks. Rarely do existing cracks in bridge decks reflect directly through a new bonded overlay. Overlays are well suited for decks in very high traffic areas where it is expensive and very disruptive to replace the deck using staged construction. For rural, low traffic volume decks, the cost and disruption of deck replacement should be compared to the value gained by installing overlays.

Bonded overlays normally add structural capacity to the deck since the deck is thickened; however, overlays add dead load to the supports and substructure. The amount of increased dead load can be reduced by using thin overlays or by milling concrete cover prior to placing the overlay.

Milling can be used remove deteriorated wearing surfaces and to remove chloride contaminated concrete. Usually it is recommended to leave at least 1/2 to 1 in. of original concrete cover over the reinforcing steel bars to maintain bar encapsulation. If the top portion of the steel is exposed in a chloride-contaminated deck, rapid corrosion of the steel can result in premature bond failures. Milling to near the top reinforcing layer may make future overlays more difficult since little concrete cover is left over the steel. If the reinforcing steel is exposed during milling, the concrete should be removed to at least 3/4 in. below the steel, usually by using small pneumatic hand tools. This is more costly and increases the time needed to install overlays. In general, the depth of milling should be kept to a minimum but ultimately decided based on the condition of the deck surface, the chloride contamination profile within the deck, deadload and elevation considerations, and possibly other factors.

It is important not to damage the bottom mat of reinforcing or the studs attached to the tops of steel girders within areas of deep concrete removal. These bars and studs provide structural integrity and composite action between the deck and girders. Usually, deep removal areas are patched independently prior to placing the overlay concrete.

Overlays can be divided into several general categories related to the time required for installation:

1. Conventional Rigid Overlays (high performance concrete [HPC]), LMC, Low-slump, Fiber-reinforced)
2. Waterproofing Membrane/Asphalt Concrete (AC) Overlay
3. Fast Curing Overlays -Weekend closures (very high early [VHE]-LMC)
4. Very Rapid Curing Overlays- Less than 24 hours or night closures (Polymer overlays)

A basic overlay selection matrix is provided below. The selection of the best overlay system depends on several factors, primarily:

- Traffic constraints on construction closures
- Dead load/clearance restrictions
- Drainage and slope corrections needed
- Previous deck overlays and repairs
- Costs
- Contractor and DOT experience
- Special objectives, such as cathodic protection, deck strengthening, deicer systems, etc.

Overlay Selection Matrix				
	1. Conventional	2. AC/Membrane	3. Very High Early	4. Polymer
Closure Constraints				
No Restrictions	X	X	X	X
Weekend only	-	X	X	X
12hr or less	-	-	-	X
Clearance Restrictions				
Less than 2 in.	-	-	-	X
Dead Load Restrictions				
Less than about 30 psf	*	-	X	X
Less than about 15 psf	-	-	-	X

psf - lbs/sq.ft. deadload

*Latex-modified concrete may be acceptable

Traffic Constraints

Sensitivity to lane closures is a key element to selecting overlay options, especially in urban areas or on bridges with few good detour options. Sometimes this one factor solely limits overlay options, such as when work can only be done during short, nighttime lane closures. Evaluate the traffic volumes (ADT/ADTT) per lane, detour options, safety, and public inconvenience and outcry. Based on these factors, decide what lane closure options are feasible.

No lane closure restrictions. All overlay options acceptable. During selection, consider dead load, grade corrections, previous repairs, material and construction costs, past experience, and contractor abilities.

Shut down limited to 3 days. Most Conventional Rigid Overlays require more than seven (7) days for preparing the deck, installing the overlay and allowing for curing. Short lane closures require staged work and rapid curing materials. Materials that may be able to be placed during short 3-day weekend closures include Waterproofing Membrane/AC Overlay, Fast Curing Overlays (VHE-LMC), and Very

Rapid Curing Overlays (polymer overlays). Proper planning, trial installations, and contactor incentives are suggested. Planning should account for less than optimal weather conditions.

Shut down limited to night work (6 to 24 hours). Night work limits overlay options to Very Rapid Curing Overlays of polymer concretes. Planning, coordination, trial testing, Quality Control (QC) testing, and Contractor experience are important.

Previous Deck Overlays and Repairs

Delaminations in decks having existing overlays can be due to continued corrosion of the embedded steel or more often due to the loss of bond between the overlay and deck substrate. Existing overlays can be milled off and replaced. If practical, an assessment of the bare deck condition should be performed after all or part of the existing overlay is removed. Serious corrosion problems in the original deck may require more aggressive deck removal (partial deck removal) or possibly deck replacement. When bare deck repair quantities exceed about 20 to 60% of the total area, the cost of overlays should be compared with the cost of full deck replacement. However, overlays may still be the preferred option even if the costs are similar, because the time required to perform deck replacements may be too great or the alternate traffic detour routes necessary for deck replacement may be unacceptable.

While there are no set rules, typically only one to two overlays are placed on a bridge prior to deck replacement. However, with adequate care, overlays can be replaced many times. It is best if the top mat of reinforcing steel is not exposed during surface preparations, so milling should be limited to the minimum amount necessary to establish a sound bonding surface and remove highly chloride contaminated concrete. Usually, abrasive steel shot blasting is used to clean and prepare the surface of decks without the need for significant milling.

Corrosion of the embedded reinforcing will slow after the overlay is placed since oxygen, moisture, and chloride becomes limited. The chloride within the original deck concrete will continue to diffuse and will tend toward an equilibrium with depth. Therefore, on some decks where high chloride contents are limited to the near surface, it makes sense to remove the highly chloride-laden concrete cover prior to placing the overlay. This will reduce the risk of the existing chloride contamination initiating corrosion at the top mat of reinforcing.

Review the chloride content data with depth and determine the optimum level of concrete removal prior to placing the overlay. Recommended chloride levels for removal from the agency survey included 0.04 to 0.07% for black steel or 0.13% for epoxy-coated reinforced decks. It is usually not necessary to remove all concrete having chloride contents in excess of the corrosion threshold values. Generally, keep removal depths to a minimum to maintain integral concrete cover and to allow for future milling and overlay replacements, especially if reinforcing steel is corrosion resistant (epoxy-coated).

Dead load/Clearance Restrictions & Drainage and Slope Corrections

Assess the allowable increase for dead load and determine if clearance or grade issues exist overhead or at safety barriers, joints or drains. Conventional rigid overlays are often placed at 3-inch or greater thicknesses, resulting in dead load increases of 36 lbs/sf or more. LMC overlays are typically placed at 1 1/4- to 3-inch thickness, resulting in dead load increases of approximately 15 to 36 lbs/sf. Polymer concrete overlays are placed at 3/8- to 1 1/2-inch thicknesses, resulting in dead load increases of approximately 5 to 18 lbs/sf. Some polymer concrete systems are available that can be placed much thicker, if a wide range of overlay thickness is needed.

Clearance issues at barriers, drains and joints can sometimes be accommodated by milling the concrete cover and tapering the overlay at these areas. However, milling the deck at local areas reduces the integral concrete cover and could increase the risk of corrosion if the overlay cracks or debonds at these often critical areas near joints or overhangs. Determine if dead load or clearance issues exist or there is a need for drainage or slope corrections. Select an overlay best suited for the site conditions.

Costs and Service Life

The DOT officials surveyed estimated that the mean service life of conventional concrete overlays (HPC and Low Slump) and latex-modified concrete (LMC) overlays were about 15 to 30 years and that the mean service life of asphalt concrete overlays with membranes and polymer overlays were about 10 to 20 years.

The DOT officials surveyed estimated that the highest cost overlays were HPC and LMC overlays, with a mean installed cost ranging from 17 to 39 dollars per square foot. Low-slump portland cement concrete (PCC) and polymer overlays were moderately expensive, with a mean installed cost of 13 to 19 dollars per square foot, and the asphalt concrete and membrane overlay was the least expensive overlay system, with a mean installed cost of 3 to 8 dollars per square foot. Complete deck replacement was the most expensive rehabilitation option, with a mean installed cost ranging from 43 to 53 dollars per square foot. Some states use life cycle cost analysis to assist with the selection of the best repair options. Methods to perform these analyses are available elsewhere (Office of Asset Management 2002) (Hawk 2003) and are beyond the scope of this Guideline.

Contractor and DOT experience

Contractor and DOT experience is an important consideration for the selection of overlay systems. Low-slump PCC overlays are commonly used in Iowa with good success. Thin epoxy resin concrete overlays have been used widely in many states including Virginia and New York. Many states have at least some experience with LMC, HPC and AC-membrane overlays. Mixer-blended polyester resin concrete overlays have been used in California for many years with good success. Each state has local contractors that are familiar with the commonly-used repair methods and what is necessary to make them work successfully. Specifying an overlay material that has not been used locally requires training and increased oversight. It is common to place new overlay materials first on small, rural bridges with lower traffic loads where the construction and performance can be easily evaluated with minimal consequences. New materials may offer valuable benefits, and contacting other agencies familiar with these materials can provide valuable experience (see Appendix A).

Other Considerations

Special cases include decks where future maintenance is difficult, decks that require strengthening or decks containing special embedments or existing cathodic protection systems. Research bridge records to determine if the deck has any special considerations. Determine if the deck requires strengthening, and, if so, consider a composite, reinforced concrete overlay for the strengthening upgrade of the deck.

Cathodic protection can be used to reduce the risk of future corrosion distress in a heavily chloride contaminated deck. A variety of cathodic protection systems are available to protect bridge decks. These systems should be considered if the chloride content at and below the reinforcing mat is very high (say greater or much greater than about 0.06% by weight of concrete) and when the serious chloride contamination is not limited to above the top reinforcing steel mat which could be removed by milling. The decision to use cathodic protection should also be based on the system costs verse just waiting and replacing the deck and the agencies familiarity, confidence and commitment to maintain the cathodic protection system. An overlay is often added to provide a wearing surface over the installed anodes. Special conductive polymer concrete overlays have also been used to cathodically protect decks (Caltrans). If the deck has an existing cathodic protection system, deicing system or other embedments, deck repairs must be performed to minimize damage to the existing systems.

DECK REPLACEMENT (Partial or Full Depth)

Partial or full depth deck replacement is used when the deck has serious deterioration, serious concrete durability problems, needs strengthening, or a combination of factors that indicate that other rehabilitation methods are not suitable. Decks with moderate deterioration that require grade or slope corrections may be good candidates for partial depth replacement. Partial depth deck replacement includes removing the existing concrete deck to below the top mat of reinforcing. Some states use low-permeable concrete to replace the upper portion of the deck. A minimum of 1 inch of clearance below the steel is normally recommended to allow for proper consolidation of the new concrete below the upper steel mat. Replacement of damaged and corroded top reinforcing is done before placing the new concrete. Sometimes additional concrete is removed over girders to provide better composite action with the new deck. Shoring of the deck may be needed during partial depth repairs.

Full depth deck replacement may or may not be more costly than partial deck replacement and provides an entirely new deck. Disadvantages may include additional time needed to remove the deck concrete and place formwork and steel. Scheduling, cost and the general concrete quality are the primary factors that should be considered when selecting between partial or full depth deck replacements.

CHAPTER 5

METHODS FOR DECK EVALUATION AND CHARACTERIZATION

The following discussion provides an overview of how to conduct a deck investigation and provides information used to characterize the deck condition. This information is needed to select between repair strategies using the procedure discussed in Chapter 4. Selection of the most appropriate and effective test procedures to assess deck condition requires good judgment, based on the needed information and the time available for the evaluation.

PRELIMINARY PLANNING

Time spent on field investigations of bridge decks is often limited by lane closure requirements, and it is important that this time is used efficiently. Valuable time can be saved if the deck investigation is well-planned. Review of previous deck inspection reports can focus the investigation to specific issues relevant to the deck in question and provides an excellent means to assess the rates of deterioration. Plan drawings and forms to document the deck condition and test results prepared in advance can also save time. Equipment lists are important so that key items are not forgotten. Understanding the traffic control constraints, time necessary for each test or inspection, and potential safety issues, including emergency procedures, are important. Tailgate meetings discussing how to work safely on the deck (increase visibility, hard hats and safety vests, face traffic when possible, stay alert, carry warning whistles, use safety barriers or shadow vehicles, etc.) should be held prior to each deck survey. Preliminary planning includes:

- Review previous deck inspection reports and bridge records, including NBI condition ratings for deck and superstructure elements. Some agencies have added or modified the AASHTO CoRe elements to account for local inspection and testing practices.
- Record general bridge information such as Bridge Identification Number (BIN), Route, County, Nearest City or Town, Feature Carried, Feature Crossed, Year Built, Deck Thickness, Bridge Type, Girder Type, Structure Length and Out-to-out Width, and Traffic Volume (ADT, ADTT).
- Record information on any traffic constraints, closure issues (such as merge lanes), previous deck repairs and exposure conditions.
- Note deck thickness and reinforcing type, spacing, and sizes from as-built drawings.
- Determine if the bridge has weight restrictions or deadload or overhead restrictions that would limit the use of conventional overlays.
- Determine if the deck is programmed for widening or replacement.
- Develop specific plan drawings for the top and bottom deck surfaces and data forms for test and visual inspection documentation.
- Note deck size and develop a preliminary sampling and testing plan.
- Develop an equipment list.
- Implement traffic control and safety planning and meetings.

GENERAL VISUAL INSPECTION

Visual inspection is usually the first and often the most important method for evaluating the surface condition of bridge decks. Valuable information can be obtained by visual inspection that will focus the need for additional testing. The goal is to determine the Percent Deck Distress (defined further below) and to gather information on the quality of the deck surface, on the need for drainage or slope corrections, on cracking patterns, on general concrete distress, and to guide additional testing.

The inspection should start with a quick walk of the entire deck. Variations of the deck condition should be noted. Counting transverse deck cracks in each span provides good information on cracking frequency. Representative areas for in-depth study should be identified on large decks. Typical crack surface widths should be measured using a visual crack gauge or preferably using a magnifier crack gauge. Plan drawings should be marked showing the condition of the in-depth study areas, including cracking patterns, crack widths, spalling, patching, and other distress typical of the overall deck. The amount of mapping will depend on the size of the deck and the uniformity of the deck conditions. Often different spans have different conditions. When this occurs, each span condition should be evaluated separately, since the best repair action for each span may also vary.

Visual inspection is valuable but is dependent upon the visual acuity, experience and training of the inspector. Deck appearance can change dramatically under different light conditions and especially when the deck is wet. If practical, visual deck surveys should be avoided at night or when the deck is completely wet. However, gently wetting a deck and watching it dry can provide valuable information on the microcracking present, since cracks dry slower than the deck surface.

Record the following general information and deck conditions:

- Note if the deck condition changes in different traffic lanes, at abutments, in different spans, or over the piers. Determine if different spans or areas of the bridge deck should be treated differently.
- Comment on surface wear, concrete scaling, grooving, skid resistance and general surface conditions.
- Note transverse cracking frequency and typical crack widths. Determine if cracks are typically full depth by inspecting the underside if possible.
- Note any plastic or pattern cracking and severity. Note general location of pattern cracking on the plan drawings.
- Focus investigation on determining the cause of any significant pattern cracking (crazing, ASR, DEF, etc.), if present.
- Inspect the deck underside and note cracks, leakage and efflorescence, spalling, patches, moist areas, pattern cracking, and other distress.
- Note the condition of joints and approach slabs. Note if traffic impacts occur to the deck due to uneven approach slab or joint conditions.

INSPECTION FOR PERCENT DECK DETERIORATION

Determine the Percent Distress as the percent area of non-overlapping spalls, patches, delaminations and half-cell potentials more negative than -0.35 V vs. copper sulfate electrode.

Visual Inspection

Visually inspect the deck or representative portions of the deck and mark the spalls (S) and repaired (patched) areas (R) on a plan drawing. Measure and record the approximate area of each and the total area surveyed (see Figure 4 example).

Delamination Survey

Most decks should be checked for delaminations. This will provide information on the extent of corrosion-related damage or debonding of concrete overlays. This survey is done using a chain drag and with hammer tapping. Delaminated areas produce a hollow sound when traversed with a steel chain or tapped with a hammer. The effectiveness of this technique will depend heavily on the ambient noise levels, the experience and acuity of the inspector, the chain or hammer size, and the depth of the delaminations. Most bridge deck delaminations can be found with a chain, since they are typically within the top 2 to 3 inches of the deck surface. The exception might be when traffic noise in adjacent lanes is unbroken, making the pitch differences in the sounds made by the chain inaudible. Covering the suspect area with dry sand-blast sand and tapping the area with a hammer often provides clear visual evidence of delaminations as the sand vibrates readily when directly over delaminations. Mark the general outline of the delaminations (using a "D" or cross hatch) on the plan drawing and record the approximate dimensions of each delamination and the total area surveyed.

Corrosion Testing Using Half-Cells

Copper-copper sulfate half-cell tests are performed in accordance with the ASTM Standard Test Method C876, *Half-Cell Potentials of Uncoated Reinforcing Steel in Concrete*. The method involves making an electrical connection between the reinforcing steel and the positive terminal of a high impedance voltmeter, and another between the negative terminal of the voltmeter and the half-cell. The half-cell consists of a copper electrode, enclosed in a plastic housing, surrounded by a saturated copper sulfate solution. The end of the cell consists of a porous disk usually covered with a wet sponge, through which the copper sulfate solution can make ionic contact with the concrete. Other types of half-cells can be used, such as calomel and silver-silver chloride, but when interpreting the results the measured values will need to be adjusted to correspond to copper-copper sulfate half-cell electrode (CSE) values (Broomfield 1997).

The half-cell potential measurements measure the ferric ion concentration in the concrete "solution" and do not measure actual corrosion rates of the embedded steel. Half-cell potential measurements normally work well on decks containing uncoated black steel but may not be reliable for decks containing epoxy-coated reinforcing. The lack of electrical continuity between epoxy-coated bars often prohibit accurate half-cell tests but the lack of continuity is a good indication that the epoxy coating is intact and the bars are well-protected.

Surface carbonation of the concrete can also affect the half-cell results, increasing the ionic resistance and normally making the results less negative. Drilling though the carbonated surface and repeating the measurements using a pencil half-cell should show if the surface condition is adversely affecting the measurements. Also, half-cell potentials tend to be unreliable at badly delaminated or spalled areas, since the ferric ions may have oxidized to rust and intimate contact between the embedded steel and the concrete has been lost.

The moisture content of the deck surface can affect the measurement of half-cell potentials. Decks that are very dry must be locally soaked at each measurement point to allow for accurate and stable potential measurements. The half cell-readings should be stable. If they are not, additional wetting time is required.

Further information about corrosion in the deck can be gained through cyclic potentiodynamic polarization or linear polarization (LP) measurements. These methods provide a means of determining the corrosion rate of a section of embedded reinforcing steel as discussed below and may be a useful addition to the bridge investigation.

By taking readings of half-cell potentials at multiple locations, an evaluation of the corrosion activity of the embedded reinforcing steel (or other metals) can be made. ASTM standard C876 states that there is a 95 percent probability of corrosion if the CSE half cell potential is more negative than -0.35 V (CSE). ASTM C876 also states that corrosion is uncertain when potentials are between -0.20 and -0.35V (CSE). Work on laboratory slabs by Pfeifer (D. W. Pfeifer 1987) defined the threshold of corrosion for bridge deck type slabs to be more negative than about -0.25 V (CSE). Readings more negative than this indicate active corrosion while those less negative indicate no corrosion activity. These values apply well to bridge decks but not to elements in direct contact with soils or seawater, which usually have high negative potentials.

If sufficient readings are taken on a grid pattern, a contour map can be prepared (Figure 4). A computer is usually used to generate the map. On such a diagram, points of equal electrical potential are connected by iso-potential lines. Areas of high negative potential and large potential gradients can be readily identified. Areas of very negative potentials surrounded by much less negative potentials is evidence that corrosion is likely. These areas having steep potential gradients may be better indicators of actively corroding locations than the fixed -0.35mV (CSE) criteria. Deck surfaces altered by carbonation, sealers, or membranes may affect the reliability of the half-cell valves and essentially shift the potential values that indicate active corrosion (usually more positive). Evaluation of the half-cell values and contours to the actual deck condition is recommended. Coring and visually inspecting the condition of the reinforcing in selected areas to verify corrosion activity is recommended. Coring in several “non-suspect” areas is also suggested to verify bar conditions where corrosion is not predicted. Experienced corrosion specialists can assist with this evaluation and train agency staff to properly interpret data for typical bridge types.

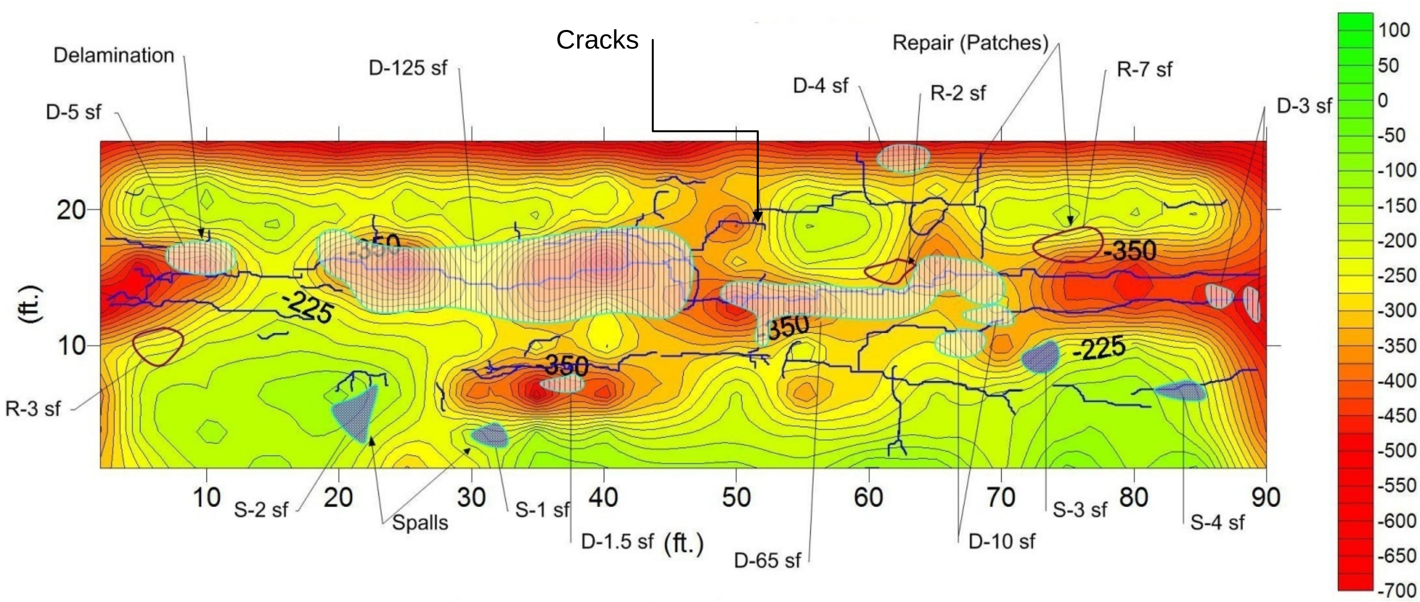


Figure 4. Sample plan drawing showing cracks, patches, spalls, delaminations, and half-cell potential data.

Testing Summary

- Identify visible spalls and patched areas. Plot the spalls and patches and area of each on the plan drawing. Record the total area of spalls and patches as a percentage of the area surveyed. Also, note the type of patch materials that have been used and the quality of the patches. A sample plan drawing is shown in Figure 4.

-Chain drag the deck or selected portions of the deck and mark and record delaminated areas on the plan drawing. Note approximate area (in square feet) of deck delaminated verses area surveyed. If the cause of the delaminations is uncertain, it is a good idea to take several core samples from delaminated areas to identify the cause, especially if the deck has an overlay.

-Make ground connection to reinforcing steel at a minimum of two locations on the span. Check for continuity between connections and record results in ohms. Epoxy-coated reinforcing bars may not be continuous, especially if both top and bottom steel mats are coated. Perform a CSE half cell potential survey of the deck or representative portions of the deck. Typically, the survey should include the travel lane and the shoulder, where salts may accumulate. Mark a grid (typically 3-foot spacing) on the deck. Pre-wet test locations and record deck temperature. Measure stable potential readings. Use a contour mapping program to plot values and identify areas more negative than -0.35V. Note that other thresholds for the CSE potential values may be a better indicator of active corrosion if it is determined that the potential values are offset due to deck moisture conditions, surface carbonation, temperature, or use of a different type of half-cell.

DECK CONDITION RATING

The FHWA NBI condition rating provides a numerical ranking of the overall bridge condition based on its visually rated condition (Federal Highway Administration 1995). The following shows the general rating categories with supplemental information related to this Guideline developed specifically for bridge decks provided in brackets "[]".

Code	Description
9	Excellent condition (Superior to present desirable criteria). [No visible distress]
8	Very Good Condition - no problems noted (Equal to present desirable criteria). [No visible distress except minor areas or fine cracking]
7	Good Condition - some minor problems (Better than present minimum criteria). [Less than 1% patches and spalls]
6	Satisfactory Condition - structural elements show some minor deterioration (Equal to present minimum criteria). [Deck shows minor spalling or moderate cracking]
5	Fair Condition - all primary structural elements are sound but may have minor section loss, cracking, spalling or scour (Somewhat better than minimum adequacy to tolerate being left in place as is). [Less than 10% patches and spalls]
4	Poor Condition - advanced section loss, deterioration, spalling or scour (Meets minimum tolerable limits to be left in place as is).
3	Serious Condition - loss of section, deterioration, spalling or scour have seriously affected primary structural components. Local failures are possible… (Basically intolerable requiring high priority of corrective action). [More than 35% deck distress]
2	Critical Condition - advanced deterioration of primary structural concrete may be present… Unless closely monitored it may be necessary to close the bridged until corrective action is taken (Basically intolerable requiring high priority of replacement).

1 Imminent Failure Condition - major deterioration or section loss present in critical structural components or obvious vertical or horizontal movement affecting structure stability. Bridge is closed to traffic but with corrective action may be put back in light service.
0 Failed Condition - out of service (Bridge closed).

Both the top deck and deck underside surfaces should be examined and rated separately. The condition of the underside of the deck provides a good indication of whether deck cracks are full depth and if they leak. Full depth cracks allow for corrosion of supporting girders as well as embedded reinforcing steel in both the top and bottom steel mats. Wet or patterned cracked areas can indicate serious problems with concrete durability. Spalling and exposed rebar along the underside is evidence of serious corrosion.

Some states use the “AASHTO Guide for Commonly Recognized Structural Elements” to provide a frame work for tracking bridge element conditions. “CoRe” Element assignments can be used to further differentiate deck conditions.

Testing Summary

-Inspect the deck and grade the current NBI condition rating for both the top and bottom deck surfaces. Use CoRe element assignments if desired. Note if major differences exist in different areas of the deck or in different spans and record separate ratings, if appropriate.

-Review past ratings for 10 years or more. Compare the NBI condition rating to the Percent Deck Distress and visual inspection data of the deck underside. Determine the appropriate current NBI condition rating, for the top and bottom deck surfaces. Review any inspector comments and notes on the deck condition from previous reports.

TIME-TO-CORROSION INITIATION

A primary goal of the deck characterization effort is to determine if the deck has ongoing corrosion or to determine an estimated time-to-corrosion for a significant portion of the deck. Factors that are considered include exposure conditions (surface chloride content), the concrete permeability (diffusion coefficient), the concrete cover, and the type of reinforcing steel. The following discussion reviews methods to use during the field investigation for collecting the information required to support the time-to-corrosion determination.

Concrete cover

When modeling deck service life, it is important to know the amount of reinforcing in the deck and its concrete cover. Several good magnetic or eddy-current reinforcing bar locators are available. Most meters are solid state magnetic detectors that measure the change in magnetic flux when metals are near. The unit supplies a constant current to the drive windings of the probe and to a reference inductor, both of which are connected in a bridge configuration to the meter. With no metallic material present, the bridge output is null. If magnetic material is encountered in the field of the probe, an unbalance of the bridge occurs due to a shift in the probe inductance. The unit can be calibrated to known bar covers and sizes. If one of the parameters, either the size of the bar or the cover over the bar, is known, the other parameter can be read directly from the meter. The units typically have an accuracy of about ± 1 bar size (1/8 in.).

Ground penetrating radar (GPR) is also a good means to determine the depth of concrete cover. A large length of deck can be surveyed very quickly and data can be analyzed in the office. However, trained operators are needed to obtain accurate results. Ground penetrating radar is a geophysical non-destructive testing technique for the evaluation of structural elements and materials and is very useful for the detection of embedded objects (steel reinforcement, prestressing/post-tensioning strand, conduit, etc…), material interfaces (such as a slab to sub-base interface), and significant internal defects such as large voiding and flaws in concrete. The technique involves the use of a high-frequency radar antenna which transmits electromagnetic radar pulses along a longitudinal scan at the surface of the concrete. The frequency of the antenna will provide deeper scans with less detail or shallower penetration depths with more detail. A 2600 MHz frequency antenna is commonly used for bridge deck applications. Electromagnetic signals are optically reflected from material interfaces of varying dielectric constant along the propagation path of the wave. The reflected signals are collected by the antennae, amplified and displayed for subsequent interpretation.

GPR is routinely used to measure deck thickness and to determine the position of reinforcing steel within the deck, even on decks overlaid with asphalt concrete wearing surfaces. It can sometimes locate delaminations or large voids in the concrete. The contrast between the electromagnetic properties of embedded steel and that of cured concrete provides a distinct direct reflection from the reinforcing bars. The magnitude and phase of these reflections are analyzed to determine the location of the reinforcing. Due to uncertainties related to the signal speed in different concretes, the results from the GPR unit should be analyzed and verified by coring the concrete and examining the actual reinforcing location.

Based on the expected bar size for the deck being surveyed, the bar spacing and cover should be determined. Cover should be measured at a sufficient number of locations (30 or more), to determine the distribution of bar cover over the deck surface. This can be done by measuring cover on a grid. Typical areas at mid-span and over piers, where variation in cover may be expected, should be included. Drilling to the bar or taking a core at a couple test areas to verify that the meter cover depths and assumed bar sizes are accurate is a good idea. At the conclusion of the survey, the cumulative distribution of cover should be plotted. Figure 5 shows a sample plot. From this plot, the percent reinforcing less than any selected depth can be easily determined.

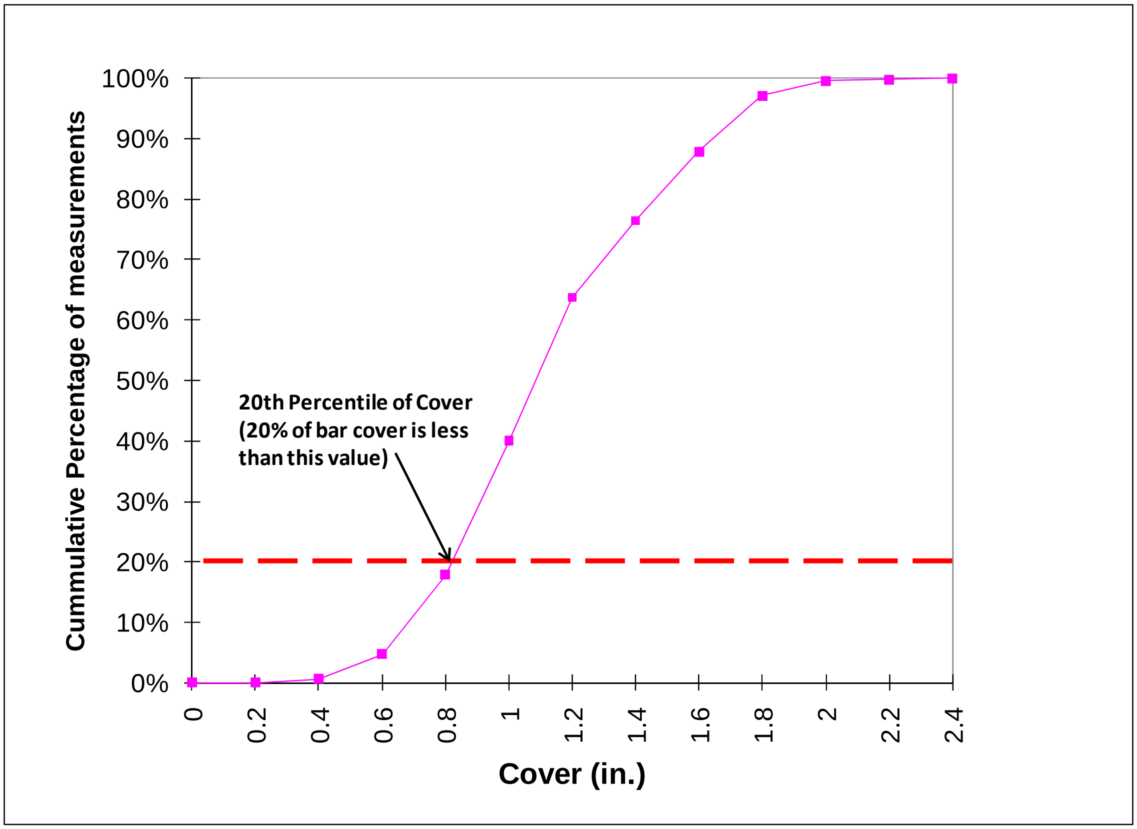


Figure 5. Sample cumulative distribution plot of concrete cover.

Carbonation

Carbonation occurs when carbon dioxide present in the atmosphere reacts with moisture and hydration products, mainly calcium hydroxide [$Ca(OH)_2$], forming calcium carbonate [$CaCO_3$]. Carbonation of portland cement paste has two distinct effects, one chemical and one physical. The chemical effect is to drop the pH of the pore liquid from approximately 13, to somewhat less than 9. The physical effects are irreversible shrinkage that can be equal to that due to drying, and a moderate increase in strength. Carbonation is usually slow on bridge decks, especially in good quality concrete, and may not be evident for many years. Carbonation rates are very dependent upon atmospheric moisture, being nearly zero near 0 or 100% relative humidity (RH), with much higher rates near 50% RH.

The chemical effect of concrete carbonation is important in that the drop of pH from 13 to less than 9 changes any embedded steel system from a passive condition, to one in which corrosion can become active. It is important to distinguish carbonation-induced corrosion from the rapid, chloride-instigated corrosion that produces quick destruction in bridge decks, but given sufficient time, the same sort of damage can be done by corrosion of steel in carbonated concrete. The depth of carbonation can be measured in the core samples by a petrographer or by drilling or chipping the concrete and spraying the freshly exposed surface with a pH indicator such as phenolphthalein.

Chloride Testing, Analysis and Modeling

Studies have shown that chloride contents above about 0.02 to 0.03% by weight of concrete, (1.0 to 1.5 lbs/yd^3) depending on the cement content, (or about 0.2% by weight of cementitious content) can promote corrosion of embedded uncoated steel in non-carbonated concrete (ACI 201 2008). Levels below this threshold can accelerate corrosion in carbonated concrete.

The epoxy coating on epoxy-coated reinforcing (ECR) keeps chloride away from the steel except at areas where it is damaged. If chloride penetrates to the steel surface at defects in the coating, then corrosion can initiate. However, the corrosion rate for ECR is typically less than for black reinforcing, since the coating also reduces the oxygen available to support the corrosion (by slowing the cathodic reaction). Decks with both top and bottom ECR mats are especially effective at reducing corrosion rates at damage sites, since often bars are electrically discontinuous. For modeling purposes, the threshold for epoxy-coated reinforcing steel have been assumed to be about 0.15% by weight of concrete decks with epoxy-coated bars in the top mat only and 0.30% by weight of concrete for a deck with epoxy-coated bars in both top and bottom mats. For stainless steel rebar, this threshold may be as high as 0.64% by weight of concrete (McDonald 1998). Other values can be assumed as these values are only estimates based on experience and, in the cases of ECR, the assumption that some damage is present in the epoxy coating.

For practical use, methods of analysis of chloride in concrete fall into two main groups: water-soluble and acid-soluble. In general, these tests are conducted on samples of concrete that have been ground to a powder. AASHTO T260 *Sampling and Testing for Chloride Ion in Concrete and Concrete Raw Materials* give methods for measuring both acid- and water-soluble chloride concentrations. Acid-soluble testing can also be performed according to ASTM C 1152 *Standard Test Method for Acid-Soluble Chloride in Mortar and Concrete*. The acid-soluble chloride content usually represents the total amount of chloride in the sample, including any chloride bound within the aggregate or chemically combined in the cement paste. The water-soluble chloride content measures the chloride that is readily mobile within the concrete and is measured using AASHTO T260 or ASTM C1218 *Standard Test Method for Water-Soluble Chloride in Mortar and Concrete*. Most field methods for chloride analyses have serious limitations and should not be used for modeling purposes without proper correlation to accurate laboratory tests.

Water-soluble chloride is chloride that, under the ASTM C1218 method, dissolves out of concrete that has been pulverized to pass a 20-mesh screen, after exposure to an excess of water for 24 hours, then a 10 gram sample is analyzed for chloride. The AASHTO T260 water-soluble method is slightly different; the sample is ground to pass a 50-mesh screen and the solution is boiled before the 24-hour soak period and only 3 grams is analyzed. These tests probably represent chloride that is currently available to promote corrosion of uncracked concrete (chloride is not needed to corrode steel at wide cracks since carbonation is usually present). It does not include most of the chloride that is tied up as a chloroaluminate in the cement paste. Because carbonation of the concrete or exposure to sulfate solutions will convert the chloroaluminates to carboaluminates or sulphoaluminates, freeing this chloride, the measured water-soluble chloride values may not accurately predict what water-soluble chloride may be present in the future if carbonation occurs.

Acid-soluble chloride, under AASHTO T260 or ASTM C 1152, is the chloride in the ground sample that is soluble upon treatment with dilute nitric acid. Therefore, the test results may overestimate the chloride readily available to promote corrosion. Any chloride present in the aggregate or chemically bound in the paste may or may not migrate into the cement paste and promote corrosion at a later time. Both water-soluble and acid-soluble chloride determinations may, however, find chloride in the aggregate because the aggregate is pulverized with the concrete.

Another test, ASTM C 1524 *Standard Test Method for Water-Extractable Chloride in Aggregate (Soxhlet Method)* attempts to estimate the chloride available for corrosion by "pulverizing" the concrete to only 1/2-inch size before a continuous water-extraction (Soxhlet) technique. This test is not regularly used due to the time and expense required to complete the test, however, it may most accurately determine the amount of chloride available to promote corrosion.

Typically, concrete samples are tested for acid-soluble chloride to provide a conservative estimate of corrosion risk. Chloride analyses are usually performed on three to five concrete slices of different depths from several core samples. It is prudent to compare the chloride contents from near-surface regions to those deep within the deck to determine whether chloride was present in the concrete as-cast. If acid-soluble chloride concentrations are only slightly above the threshold values or the baseline concrete values are high, then selected samples should also be tested for water-soluble chloride to determine if the chloride is chemically bound in the aggregates or if it was admixed into the concrete as a set accelerator.

If the chlorides are chemically bound in aggregates, (acid soluble but not water soluble) they can be partially discounted in the time-to-corrosion analysis. The generally accepted acid-soluble chloride corrosion threshold for 6-bag mix concrete is 0.03% by weight of concrete or 0.2% by weight of cement. The water-soluble threshold may not be 0.03% by weight of concrete, but is commonly about 75 percent of that, or 0.023% by weight of concrete.

Testing Summary

- Measure the concrete cover over the top reinforcing steel at numerous locations across the deck. Include mid-span and pier sections. Plot data as a cumulative histogram assuming a normal distribution. Identify the 20th percentile of the low cover value (cover depth at which 20% of bars have cover less than this value).
- Take 3- to 4-in. diameter core samples from several locations on the deck. When determining the number of cores to be obtained, consideration should be given to how these cores will be used for subsequent testing. A general rule for core sampling uncovered (non-overlaid) decks for chloride ion testing is one core per 2,000 sq. ft of deck area (Cady 1985). A minimum of seven cores should be taken from small decks: two for carbonation testing and petrographic examination, two for compressive strength testing and three for chloride analysis. Larger decks should be sampled more.
- Test the exposed surface of some of the core samples (or cleaned drilled holes) for depth of carbonation. This can be done in the field or lab by spraying a freshly broken surface with phenolphthalein (clear non-pink indicates pH less than 9) or other pH indicator. Record the depth of carbonation.
- Determine the chloride content of the concrete with depth. It is typical to sample chlorides using 1/4-in. thick slices of a 4-in. diameter core centered at the following depths: 0.375, 1.0, 2.0 and 3.0 in. Test at lower depths also if the 3 in. layer shows significant chloride contamination. Plot chloride content with depth and use this data to estimate the time-to-corrosion as discussed in Chapter 4.
- Determine the extent of full depth cracking and estimate the average spacing per length of deck. Some modeling methods account for cracks by increasing the diffusion coefficient of the concrete by 10 times that of the uncracked deck and assuming that the area 2 inches on either side of the crack is affected. Generally, if cracking is not excessive, the area affected by the corrosion at cracks will remain a small portion of the overall deck area and this corrosion will not control the ultimate service life of the deck but will result in the need for periodic local repairs and patching. For decks subjected to deicers, the crack affected area, (which could be estimated as crack lengths times 4 inches [0.33 ft]) can be accounted for by assuming all areas with cracks are corroding and effectively reducing the percentile amount of steel having the lowest concrete cover. For example, if 3 percent of the deck is affected by full-depth cracking, the depth of lowest top mat concrete cover selected for time-to-corrosion estimate would be reduced from 20% to 17%. This

crack-affected area can also be accounted for by adding the area to the %Distress and CSE half-cell values <-0.35V when calculating the Percent Deck Distress.

DECK SURFACE CONDITIONS

Determine if the deck requires improvements to the grade or quality of the riding surface. These conditions might include serious drainage problems, cross-slope or grade problems, uneven joints, concrete surface scaling, abrasion loss or poor skid resistance. These conditions are usually determined by visual inspection of the dry and wet deck surface, with supplemental testing as needed.

Testing Summary

-Visually inspect the deck surface for indications of serious drainage problems, cross-slope or grade problems, uneven joints, concrete surface scaling, abrasion loss, poor skid resistance, or other conditions that would indicate that an overlay or deck replacement would be favored over leaving the existing deck surface. Flood the deck, if able, and measure the depth of birdbaths and ponding.

-If scaling is present, rate the deck surface scaling according to the schedule given in ASTM C672 *Standard Test Method for Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals* as follows:

Rating	Condition of the Surface
0	no scaling
1	very slight scaling (3 mm [1/8 in.] depth, max, no coarse aggregate visible)
2	slight to moderate scaling
3	moderate scaling (some coarse aggregate visible)
4	moderate to severe scaling
5	severe scaling (coarse aggregate visible over entire surface)

Note the area affected by surface scaling on the plan drawings and measure the affected area and the total area surveyed. Be careful not to confuse scaling caused by cyclic freezing with traffic abrasion due to tire studs or chains that often expose the coarse aggregates. If significant surface scaling is present, take core samples and conduct a petrographic examination to determine if the scaling potential is only in the near surface as a result of poor finishing practices, or if the entire concrete is poorly air-entrained.

- Examine the deck texture and grooves. Measure the groove depths if applicable. Note the amount of abrasion loss of the surface in the wheel paths. If excessive surface wear or texture loss is present measure skid resistance per AASHTO T242 or T278 (or other approved method). If a skid resistance problem is identified, measure the concrete cover over the top reinforcing steel to determine if grinding or grooving is feasible without damaging the steel or causing a significant loss of cover protection.

- Visually assess the transitions at joints and the approach slabs. Determine if grade corrections are needed and the extent needed. Measure curb and barrier heights and configurations to determine if grinding is needed prior to placing an overlay. Note any approach slab or joint settlement that has resulted in unanticipated traffic impacts on the deck.

CONCRETE QUALITY

It is important to determine if the existing concrete deck is in adequate condition for continued maintenance or to receive an overlay. Certain internal deterioration mechanisms such as alkali-aggregate reactions or delayed ettringite formation (DEF) can cause concrete to lose strength and integrity. Low initial strength and fatigue is another problem that could cause premature deterioration of bridge decks.

Alkali-aggregate reactions

Alkali-aggregate reactions, of which alkali-silica reaction (ASR) is most common, occur when susceptible aggregates in concrete react with alkalis (sodium and potassium hydroxides), which primarily come from the cement or fly ash. This reaction produces a gel that swells in the presence of moisture. The process usually is very slow, requiring 15 years or more to develop to a deleterious degree, but the deterioration can be serious. Special attention should be given to these reactions due to their significance to long-term durability. Repairs of structures damaged by alkali-aggregate reactions typically have not been successful in stopping deterioration. However, certain methods, such as sealers and overlays, have been used to extend the service life of decks by bonding cracks and reducing available moisture. Concrete core samples should be removed from suspected ASR-affected decks for petrographic and scanning electron microscopic evaluation by a petrographer experienced in evaluating ASR-affected concretes and tested to determine the extent of reactivity, strength and modulus.

The internal expansion caused by ASR gel usually results in “pattern” or “map” cracking and sometimes popouts of the surface. The cracks may appear wide at the surface, but they are usually very narrow with depth. Dark reaction rims around the aggregates are often, but not always, found. The internal cracks can sometimes be traced to particular reactive coarse aggregate particle. Reaction products form in the microcracks and voids in the concrete paste and may extrude a clear to white gel to the surface in severe cases. The expansive gel imbibes water exerting high hydrostatic pressures within the cement paste that can crack the concrete. Alkali-aggregate reactions can be moderate to severe and are a primary concern when present, since deterioration can cause serious loss of integrity.

DEF

Delayed ettringite formation (DEF) is an internal physicochemical process that may lead to expansion cracking similar to that seen with ASR; however, paste expansion, not aggregate-related expansion, is the cause. DEF is a form of sulfate-related deterioration that causes an internal swelling reaction in the presence of water but without any external ingress of sulfate. The reaction is caused by a number of factors, with cement chemistry (particularly sulfate and aluminate content), and early age heat curing being primary factors. DEF is not commonly found on bridges decks since decks tend to be thin and curing temperatures during hydration are usually not high enough to cause the breakdown of ettringite. However, decks having serious pattern cracking that is not ASR-related should be evaluated for DEF by a trained petrographer and scanning election microscopy (SEM) analysis.

Cyclic Freezing Damage

Cyclic freezing damage results in surface scaling and spalling of the concrete, and is often most severe along the curb where water accumulates. Air entrainment is added to fresh concrete to allow for the internal expansion that occurs during the freezing of water within the concrete. Occasionally, the air entrainment is lost in the near surface due to poor finishing practices, resulting in surface scaling. This deterioration will stop after the poorly air-entrained surface is lost. As discussed previously, the depth and extent of the poorly air-entrained concrete should be determined by coring and petrographic examinations. If the entire deck concrete is poorly air-entrained, more aggressive repair may be needed, such as an overlay or deck replacement. Sealers are usually not effective in preventing cyclic freezing damage of non-air-entrained concrete.

Concrete Strength

Typically, adequate strength is not a problem for most decks, since their required design strengths are usually not high. If large cracks are present over the supports, or between supporting girders, verification of the concrete strength is a good idea. Measuring both the compressive strength and the static modulus of elasticity (wet) provides good information on the concrete quality. Ideally, the deck concrete should have a reserve of strength. If the wet modulus of elasticity is low relative to the concrete strength, (much less than $57{,}000\sqrt{f'_c}$ psi), check carefully for deleterious reactions within the concrete.

Several techniques are available to measure the concrete strength in-situ, such as the rebound test hammer or Windsor probe. However, these techniques are very limited and difficult to use on tined or grooved deck surfaces. These tests only measure the near surface region that can be affected greatly by surface texture, finishing, curing, the presence or lack of coarse aggregate, and other factors. These techniques should be correlated to concrete cylinder or core strengths before they are used quantitatively. Therefore, it is best if several core samples are taken and tested for compressive strength in the laboratory. Generally, they should be tested in the as-received or wet condition, since most decks never dry completely.

Testing Summary

- During the visual inspection, examine the deck surface and underside for pattern cracking, excessive crazing, scaling, excessive cracking, spalling unrelated to reinforcing corrosion, and other signs of concrete disintegration. If the underside is inaccessible or covered with stay-in-place forms, note what information can be observed about the underside condition and how the information was collected, (i.e., binoculars, removal of a section of formwork, leakage and rust staining of forms, etc.). If pattern cracking or concrete distress is present, remove several core samples from the deteriorated and non-deteriorated areas and examine petrographically per ASTM C856 *Petrographic Examination of Hardened Concrete*. Determine if ASR, DEF, or other concrete deterioration mechanisms will limit the life of the repair.
- If poorly air-entrained, perform air content analysis per ASTM C457 *Standard Test Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete*. Compare air void parameters to accepted values (ACI 201 2008). For a typical bridge deck concrete containing 3/4-inch maximum aggregate, the recommended entrained air void properties include the following: 4-1/2 to 7-1/2% total air content, greater than 600 in^2/in^3 specific surface and a spacing factor of less than 0.008 in. Concretes can perform well with less than optimum entrained void parameters, especially if synthetic air-entrained admixtures were used. Therefore, evidence of cyclic freezing distress should be the primary consideration not just minor deviations in the final hardened air void characteristics.
- Test multiple cores for compressive strength and static modulus if strength is a concern.
- Determine the cause of any concrete distress present and risk of future deterioration.

OTHER EVALUATION METHODS (SPECIAL CASES)

Linear Polarization Measurements

Cyclic potentiodynamic polarization measurements or linear polarization (LP) provide a means of determining the corrosion rate of a piece of steel at the time of measurement. Each LP measurement may take between 3 to 15 minutes, so typically half-cell potential measurements are taken first to identify the test areas best suited to corrosion rate (LP) measurements. In typical practice, three to five areas identified by half-cells as corroding, intermediate, and non-corroding are tested using the LP technique. This provides a range of corrosion rates on the deck. Corrosion rates can vary widely on a deck (due to local anodic and cathodic areas). Temperature and moisture conditions also effect corrosion rate values. Further, it is difficult to determine precise corrosion rates since the exact reinforcement area receiving the test current is usually unknown. LP results should be related to other tests (half-cell, chloride content, visual, sounding) to provide an overall assessment of corrosion activity.

The apparatus includes a potentiostat, high-impedance voltmeter, current measuring device, and electrodes. Counter and reference electrodes are placed on the concrete surface. An electrical connection is made to the steel in a similar manner to that required for half-cell potential measurements. The initial potential is measured, and then an electrical current is impressed to shift the potential a predetermined amount. The amount of current required to shift the potential is recorded. This process is continued for several steps of potential and a polarization curve is developed. The polarization resistance, which is proportional to the rate of corrosion, is given by the slope of the curve. The rate of corrosion is typically given as a meter output. The corrosion rate can change dramatically along a short length of bar (between anodic or cathodic areas) and during different seasons and deck conditions. If time is limited, cores for chloride analysis should receive first priority, followed by half-cell measurements, then LP tests.

Pulse Velocity and Impact-Echo

The through-transmission pulse velocity method involves measurement of the transit time and an assessment of the resulting signals from a pulsed stress wave through a concrete. Detected changes in arrival time, amplitude and characteristics of the propagated waves can indicate corresponding changes in the internal makeup of concrete and identify areas of delamination or severe honeycombing. The testing technique is based on procedures outlined in ASTM C597 *Standard Test Method for Pulse Velocity Through Concrete.* Access to both sides of an element is needed so this technique is more commonly used on columns or piers and not decks.

The impact-echo method is a nondestructive method for concrete evaluation that involves introducing mechanical energy, in the form of a short pulse, into a structure. A transducer mounted on the surface of a structure receives the reflected input waves or echoes from the discontinuities (flaws) within the concrete. By determining a propagation velocity, reflected waves can be analyzed with a Fast Fourier Transform (FFT) analyzer to determine internal characteristics of the concrete. This method is better suited for decks than the pulse velocity method, since it can be performed from one side of the deck.

The impact-echo method can detect the size and location of significant flaws in concrete, such as honeycombing, overlay debonding, delaminations, and large subsurface cracks. In addition, the method can measure the thickness of the concrete deck. Areas showing distress should be investigated further by removing cores.

Petrography

Petrographic examination reveals the properties of concrete and aggregates, including the physical condition and can identify potential durability problems. Experienced petrographers can evaluate the following features of the concrete:

- Density of cement paste
- Homogeneity of the concrete
- Occurrence of settlement and bleeding of fresh concrete
- Depth and extent of carbonation
- Occurrence and distribution of fractures
- Characteristics and distribution of voids
- Presence of contaminating substances
- Evidence of alkali-aggregate reactions
- Proportion of unhydrated granules of cement
- Presence of mineral admixtures
- Volumetric proportions of aggregate, cement paste, and air voids
- Air content and various parameters of the air void system
- Composition in terms of aggregate, portland cement and other components, and proportions of each
- Likely presence of admixtures such as air-entraining agents, accelerators, waterproofers, pigments, etc.
- Hydration of the portland cement component, desirable and undesirable hydration reactions, and water-cement ratio estimates
- Textural features related to original consistency and workmanship
- Migration paths of water
- The chemical and physical soundness or unsoundness of the components
- Features of the concrete that reflect causes for failure or poor durability

Petrography generally includes the description of concrete components and physical properties related to permeability, density, absorptions and cracking patterns. The standard light microscopy used to perform the bulk of petrographic analysis can also be supplemented with X-ray diffraction, chemical analysis, scanning electron microscopy, infrared spectroscopy, and many other chemical and physical test techniques. The use of petrographic techniques and chemical testing methods is extremely valuable for evaluating failures or for determining the potential for future deterioration and estimating concrete durability. Concrete petrography is a specialized area, and experienced personnel are essential.

Strength Evaluation Testing (Load test)

If the safety of a deck is suspected due to low strength concrete, missing or misplaced reinforcement, or deterioration of concrete, load tests can be conducted to evaluate the deck strength. A procedure for making a strength evaluation of an existing structure is published by ACI (American Concrete Institute 2008). The test loads can be applied with various materials such as loaded trucks, concrete blocks, or water. The deflections and strains at critical locations are monitored with dial gages and strain gages. The structure is shored so that in case of a failure during the test, complete collapse does not take place.

Acceptance criterion for the structure under load test is that it should not show visible evidence of cracking or spalling. If there is no visible failure, then recovery of deflection criterion is used to determine if the structural strength is adequate.

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APPENDIX A

DOT SURVEY RESPONSES FOR REPAIR METHODS

The transportation agency survey done as part of this project allowed agencies to provide comments and information on specific deck repair methods that they are familiar with. Some respondents did not complete this part of the survey while others provided responses on up to four different repair techniques. The following summarizes the responses.

Portland Cement Concrete Overlays

Agencies Responding

Six (6) - CO, GA, KY, MI, TN, Quebec

These responses include standard concrete overlays, reinforced concrete overlays, high early strength concrete overlays, and concrete overlays that could not be readily categorized as low slump or high performance.

Advantages

- Long life - 4 agencies (67%)
- Quick installation - 1 agency (17%)
- Ride quality - 1 agency (17%)
- Helps in tying the cantilever replacement to original structure with continuous transverse rebars - 1 agency (17%)

Disadvantages

- Construction time - 1 agency (17%)
- High cost - 2 agencies (33%)
- Use of hydrodemolition - 2 agencies (33%)
- Poor bond to the existing concrete - 1 agency (17%)
- A corrosion cell of the bottom mat steel may be set up - 1 agency (17%)
- Not conducive to decks containing slag coarse aggregate concrete - 1 agency (17%)

Use History

These portland cement concrete overlays have generally been in use for a long time. Three agencies (50%) have been using their system for 25 or more years. Two agencies (33%) have been using them for 10 to 25 years, and the final agency (17%) has been using them for 5 to 10 years.

Many agencies use portland cement concrete overlays on many bridges throughout their location. Three (50%) reported 100 or more bridges, two (33%) reported 50 to 100 bridges, and one (17%) reported 10 to 50 bridges.

Three of the agencies (50%) use portland cement concrete overlays as part of their standard specifications, two (33%) use it as a standard special provision, and one (17%) considers the method experimental.

The use of portland cement concrete overlays is either static (3 agencies, 50%) or increasing (3, 50%). No agency reported the use as decreasing.

Selection

Portland cement concrete overlays are chosen primarily because of the good anticipated service life, the good track record on similar projects, and the fact that they are already approved by the department. The table below lists reasons for selection of portland cement concrete overlays.

Reasons for Selection of Portland Cement Concrete Overlays	Yes	No
Easy to install	3	3
Long anticipated service life	5	1
Good track record on similar projects	5	1
Already approved by your department	5	1
Recommended by a colleague	0	5
Research findings were positive	2	4
Inexpensive	0	6
Short lane closures (rapid return of traffic)	2	4
Dead load considerations	0	6
Personal experience	0	6
Presentation by manufacturer's representative	0	6

Portland cement concrete overlays are used primarily for current distress (6, 100% of agencies), and also for preventative maintenance by one agency. No agencies reported using portland cement concrete overlays for new construction. The table below outlines what deck conditions exist and are typically addressed by using portland cement concrete overlays.

Existing Deck Conditions Addressed by Portland Cement Concrete Overlays	Yes	No
Newer deck in good condition (preventative)	0	6
Deck with cracking in good condition with no significant active corrosion	1	4
Deck with cracking and active corrosion (<5% delamination, no spalling)	2	4
Deck with cracking and active corrosion (>5% delamination and some spalling)	2	4
Deck with cracking and active corrosion (>10% spalling/patching)	4	2
Deck with surface deterioration or abrasion loss	2	4

Most responding agencies had a different reason for selecting portland cement concrete overlays. One mentioned that the system has worked well in the past, and contractors are familiar with the overlay system. One agency stated that selection is based on the amount of deck surface deficiencies, and that no similar alternatives exist in the class. One agency uses concrete overlays based on the recommendation of their Material lab, and another uses it for deck cantilever replacement.

Anticipated Lifespan

- Range: 10 to 30 years
- Mean: 15 to 24 years
- Median: 14 to 25 years

Cost

- Range: $6.25 to $74 per square foot
- Mean: $22 to $36 per square foot
- Median: $23 to $6 per square foot

Installation

Most agencies use hydrodemolition to prepare the surface prior to installation of a portland cement concrete overlay. The table below outlines the surface preparation methods used with portland cement concrete overlays.

Surface Preparation Techniques for Portland Cement Concrete Overlays	**Yes**	**No**
No preparation	0	6
Air sweep	0	6
Broom	0	6
Sand blast	1	5
Shot blast	0	6
Water blast	1	5
Water/grit blast	0	6
Hydrodemolition	6	0
Milling	3	3
Crack routing	0	6

Visual inspection and hammer or chain sounding are used most commonly to evaluate the prepared substrate prior to the application of portland cement concrete overlays. The methods of evaluation are outlined in the table below.

Methods Used to Evaluate Prepared Substrate for Portland Cement Concrete Overlays	**Typically**	**Occasionally**	**Never**
Visual inspection	6	0	0
Hammer or chain sounding	3	2	1
Adhesion test to the bare substrate	0	0	4

Thickness

- Range: 1.5 to 6 inches
- Mean: 3 to 3.8 inches
- Median: 3 to 3.5 inches

General Recommendations

Respondents provided several recommendations they would give to their colleagues. One mentioned that portland cement concrete overlays provide a good alternative between repair and replacement. Another respondent considers the system good, but mentioned concerns about the bottom reinforcing mat of steel in the original deck corroding and causing spalls onto the traffic below. Another respondent also commented that the condition of the underside of the deck is of primary concern. The condition of the deck and surface preparation is of concern for multiple respondents. One respondent suggested preparation with hydrodemolition, while another suggests determining the existing cover of the deck to help in determining the removal method.

Low Slump Concrete Overlays

Agencies Responding

Six (6) - KS, MI, MO, ND, SD, Puerto Rico

Advantages

- Durability and long life - 3 agencies (50%)
- Low cost or cost effectiveness - 2 agencies (33%)
- Increased structural capacity - 1 agency (17%)
- Low cure time - 1 agency (17%)
- Ease of construction - 1 agency (17%)

Disadvantages

- Placement issues - 4 agencies (67%)
    - Long cure times
    - Difficulty in placement
    - System cannot be produced by the concrete plant
- Susceptible to cracking - 2 agencies (33%)
- Dead load - 2 agencies (33%)
- Requires well-prepared deck surface and does not permit monolithic overlay and deck repair placement - 1 agency (17%)
- Cost - 1 agency (17%)

Use History

Five of the agencies using low slump concrete overlays (83%) report that their use began more than 25 years ago, while one agency reports that use began 5 to 10 years ago. For locations where low slump concrete overlays are used, the use is fairly widespread. Four of the responding agencies (67%) indicated that the overlays are used in 100 or more bridges in their jurisdiction. One agency stated that the overlays are used on 50 to 100 bridges, and another agency reports having used the overlays on ten or fewer bridges.

The use of low slump concrete overlays is part of the standard specification in five jurisdictions (83%), and considered experimental in one jurisdiction (16%). The use is reported as static by three agencies (50%), increasing by one agency (16%), and decreasing by two agencies (33%).

Selection

Low slump concrete is selected by all responding agencies because of the long anticipated service life and good track record on similar projects. Most agencies use low slump concrete overlays, in part, because they are already approved by the department. The reasons for selecting low slump concrete overlays are provided in the table below.

Reasons for Selection of Low Slump Concrete Overlays	Yes	No
Easy to install	3	3
Long anticipated service life	6	0
Good track record on similar projects	6	0
Already approved by your department	5	1
Recommended by a colleague	1	5
Research findings were positive	4	2
Inexpensive	2	4
Short lane closures (rapid return of traffic)	1	5
Dead load considerations	0	6
Personal experience	3	3
Presentation by manufacturer's representative	0	6

Low slump concrete overlays are used on new construction by three (50%) of the agencies, used for preventative maintenance by four agencies (67%), and used to address current distress on bridge decks by five (83%) of responding agencies. The table below outlines what deck conditions exist and are typically addressed by using low slump concrete overlays.

Existing Deck Conditions Addressed by Low Slump Concrete Overlays	Yes	No
Newer deck in good condition (preventative)	3	3
Deck with cracking in good condition with no significant active corrosion	2	4
Deck with cracking and active corrosion (<5% delamination, no spalling)	2	4
Deck with cracking and active corrosion (>5% delamination and some spalling)	3	3
Deck with cracking and active corrosion (>10% spalling/patching)	6	0
Deck with surface deterioration or abrasion loss	1	5

Two agencies (33%) stated that low slump concrete overlay systems were chosen over similar materials because of contractor preference. One agency reported effectiveness as a reason for selection, and another agency reported a FHWA recommendation as a reason that low slump concrete overlays are selected over similar materials.

Anticipated Lifespan

- Range: 10 to 45 years
- Mean: 16 to 32 years
- Median: 15 to 33 years

Cost

- Range: $4 to $45 per square foot
- Mean: $13 to $19 per square foot
- Median: $10 to $15 per square foot

Installation

Most agencies use sandblasting or milling to prepare the surface prior to installation of a low slump concrete overlay. The table below outlines the surface preparation methods used with low slump concrete overlays.

Surface Preparation Techniques for Low Slump Concrete Overlays	**Yes**	**No**
No preparation	0	6
Air sweep	2	4
Broom	1	5
Sand blast	5	1
Shot blast	0	6
Water blast	2	4
Water/grit blast	0	6
Hydrodemolition	3	3
Milling	5	1
Crack routing	0	6

Visual inspection and hammer or chain sounding are used by nearly all responding agencies to evaluate the prepared substrate prior to the application of low slump concrete overlays. The methods of evaluation are outlined in the table below.

Methods Used to Evaluate Prepared Substrate for Low Slump Concrete Overlays	**Typically**	**Occasionally**	**Never**
Visual inspection	5	0	1
Hammer or chain sounding	5	1	0
Adhesion test to the bare substrate	3	0	1

Thickness

- Range: 1.5 to 4 inches
- Mean: 2 to 3.1 inches
- Median: 1.9 to 3 inches

General Recommendations

One agency recommends that special equipment and good contractors are needed for installation of low slump concrete overlays. Another agency recommends that a wind fence be provided, that the portable mixer be calibrated, and that the bridge vibration from heavy vehicles be checked. A third respondent mentioned that the down times for the lanes is high when installing low slump concrete overlays.

High Performance Concrete Overlays (rigid)

Agencies Responding

Sixteen (16) - AK, AZ, ID, IL, KS, MI, MO, NE, NY, OK, OR, WV, WY, Alberta

The respondents from Kansas and West Virginia each made two separate responses that fit into the high performance concrete overlay category, and these responses are tabulated separately. The agencies responding often use silica fume modified concrete, one agencies uses high performance concrete with steel fiber reinforcement, and other agencies did not specify the materials in their high performance concrete overlays.

Advantages

- Durability - 10 respondents (63%)
- Low cost or cost-effective performance - 6 respondents (38%)
- Density or imperviousness of overlay - 4 respondents (25%)
- Placement and the ability to pour monolithically with deck repair - 1 respondent (6%)

Disadvantages

- Difficulty in installation and propensity to crack during curing - 9 respondents (56%)
- High cost - 5 respondents (31%)
- Long curing times and traffic issues - 4 respondents (25%)
- Delamination of thick overlays on new bridge construction projects - 1 respondent (6%)
- Should not be used with cathodic protection - 1 respondent (6%)

Use History

High performance concrete overlay systems have generally be in use for more than 10 years, with fourteen respondents (88%) indicating that their agency has been using high performance concrete overlays for 10 to 25 years. One respondent (6%) indicated that high performance concrete overlays began to be used 5 to 10 years ago, and another respondent (6%) indicated that high performance concrete overlays have been in use for five or fewer years.

Most respondents (11 or 69%) indicated that the use of high performance concrete overlays is part of their standard specifications, while four (25%) indicated that high performance concrete overlays are used as part of a standard special provision, and one (6%) indicated that its use is experimental.

The use of high performance concrete overlays is increasing in seven (44%) of the respondent’s states or provinces, is static in eight (50%) locations, and decreasing in only one (6%) jurisdiction.

Selection

High performance concrete overlays were often selected because they were already approved by the respondent’s department, have a long anticipated service life, and have demonstrated a good track record on similar projects. No respondent selects high performance concrete overlays because of the rapid return of traffic, as confirmed by the fact that 25% of the respondents selected long lane closures as a disadvantage of high performance concrete overlays. The table below outlines reasons for selection of high performance concrete overlays. In addition to the reasons outlined below, one respondent stated that high performance concrete overlays were selected because of a perception of adequate performance, and another respondent cited a Kansas University (KU) study recommendation.

Reasons for Selection of High Performance Concrete Overlays	Yes	No
Easy to install	6	10
Long anticipated service life	13	3
Good track record on similar projects	12	4
Already approved by your department	14	2
Recommended by a colleague	2	14
Research findings were positive	7	9
Inexpensive	5	11
Short lane closures (rapid return of traffic)	0	16
Dead load considerations	3	13
Personal experience	6	10
Presentation by manufacturer's representative	0	16

High performance concrete overlays are used on new construction by five (31%) respondents, used for preventative maintenance by seven (44%), and used to address current distress by fifteen (94%) respondents. The table below outlines what deck conditions exist and are typically addressed by using high performance concrete overlays.

Existing Deck Conditions Addressed by High Performance Concrete Overlays	Yes	No
Newer deck in good condition (preventative)	3	13
Deck with cracking in good condition with no significant active corrosion	3	13
Deck with cracking and active corrosion (<5% delamination, no spalling)	7	9
Deck with cracking and active corrosion (>5% delamination and some spalling)	9	7
Deck with cracking and active corrosion (>10% spalling/patching)	12	4
Deck with surface deterioration or abrasion loss	6	10

Seven respondents indicated that performance was a reason for selection of high performance concrete overlays over similar systems. Two respondents indicated cost was a reason for selection, and one respondent indicated that FHWA recommendations were used to select this system over others.

Anticipated Lifespan

- Range: 10 to 40 years
- Mean: 16 to 29 years
- Median: 15 to 28 years

Cost

- Range: $5 to $45 per square foot
- Mean: $17 to $35 per square foot
- Median: $17 to $21 per square foot

Installation

Prior to installing a high performance concrete overlay, the surface is most commonly prepared by hydrodemolition. The surface is also commonly prepared by milling, water blasting and sand blasting. The table below outlines the surface preparation methods used with high performance concrete overlays. In addition to those listed below, one respondent uses jackhammering to prepare the surface.

Surface Preparation Techniques for High Performance Concrete Overlays	**Yes**	**No**
No preparation	0	15
Air sweep	4	11
Broom	3	12
Sand blast	6	9
Shot blast	4	11
Water blast	7	8
Water/grit blast	1	14
Hydrodemolition	11	4
Milling	9	6
Crack routing	2	13

All responding agencies use visual inspection to evaluate the prepared substrate. The methods of evaluation are outlined in the table below.

Methods Used to Evaluate Prepared Substrate for High Performance Concrete Overlays	**Typically**	**Occasionally**	**Never**
Visual inspection	15	0	0
Hammer or chain sounding	10	1	2
Adhesion test to the bare substrate	2	4	5

Thickness

- Range: 1 to 5 inches
- Mean: 1.6 to 3.5 inches
- Median: 1.5 to 3 inches

General Recommendations

When asked what recommendation the respondents would make to colleagues, most recommendations related to installation procedures. The systems are sensitive to curing and ambient conditions, and require strict quality controls. One respondent mentioned that money is wasted if adequate quality controls are not in place. Current Wyoming specifications require night time placements and conformance to strict humidity guidelines. A respondent from Missouri warns of delamination if placed in thick lifts, and cites the Creve Couer Bridge over the Missouri River in St. Charles and the Cape Girardeau Bridge over the Mississippi River. Another respondent mentions the need for a saturated surface dry (SSD) condition on the substrate to achieve a good bond, and mentions that delamination occurs over time at the joints.

Latex-Modified Concrete Overlays

Agencies Responding

Seventeen (17) - DE, IL, IN, KS, KY, MA, MI, MO, NC, OK, PA, RI, SD, TN, WA, WV, Ontario

Advantages

- Performs well, protects the underlying deck, or is less permeable than other rehabilitation systems - 11 agencies (65%)
- Short cure time or quick installation - 6 agencies (35%)
    - Two agencies specifically stated use of very high early strength latex-modified concrete (VHE-LMC)
- Long anticipated life - 4 agencies (24%)
- Low cracking - 2 agencies (12%)
    - Some cracks can be self-healing
    - Cracks do not penetrate full depth

Disadvantages

- Cost - 9 agencies (53%)
- Placement difficulties - 8 agencies (47%)
    - Need for specialized equipment
    - Lack of contractor experience
    - Sensitivity to weather conditions
- Cracking or debonding - 4 agencies (24%)
- Long cure time - 2 agencies (12%)

Use History

All of the responding agencies first used latex-modified concrete overlays more than 10 years ago. Eight (47%) began using latex-modified concrete overlays 10 to 25 years ago, and nine agencies (53%) began using latex-modified concrete overlays more than 25 years ago.

In accordance with the amount of time that latex-modified concrete overlays has been in use, its use is fairly widespread. Nine of the respondents (53%) report that latex-modified concrete overlays have been installed on more than 100 bridges in their state or province. Three agencies (18%) report that latex-modified concrete overlays have been installed on 10 to 50 bridges and another three agencies report its use on 50 to 100 bridges in their state or province. Only one respondent (6%) indicated that latex-modified concrete overlays have been installed on ten or fewer bridges in their state or province.

Eight (47%) respondents indicated that the use of latex-modified concrete overlays is part of a standard specification, while for six agencies, (35%) it is part of a standard special provision. Two (12%) of the responding agencies reported that latex-modified concrete overlays are no longer used in their jurisdiction.

Six agencies (35%) reported that latex-modified concrete overlay use is increasing in their state or province. Four (24%) reported that use is static, and seven (41%) reported that use is decreasing.

Selection

Latex-modified concrete overlays were selected by most agencies because of its long anticipated service life, good track record, and the fact that use was already approved by their department. The table below outlines the reasons for selecting latex modified concrete.

Reasons for Selection of Latex-Modified Concrete Overlays	Yes	No
Easy to install	6	11
Long anticipated service life	15	2
Good track record on similar projects	13	4
Already approved by your department	11	6
Recommended by a colleague	1	16
Research findings were positive	6	11
Inexpensive	1	16
Short lane closures (rapid return of traffic)	4	13
Dead load considerations	7	10
Personal experience	2	15
Presentation by manufacturer's representative	1	16

Twelve agencies (71%) select latex-modified concrete overlays for use in preventative maintenance and also for current distress. Only five agencies (29%) use latex-modified concrete overlays on new construction. Conditions addressed by the use of latex-modified concrete overlays are varied and are outlined in the table below.

Existing Deck Conditions Addressed by Latex-Modified Concrete Overlays	Yes	No
Newer deck in good condition (preventative)	5	12
Deck with cracking in good condition with no significant active corrosion	6	11
Deck with cracking and active corrosion (<5% delamination, no spalling)	8	9
Deck with cracking and active corrosion (>5% delamination and some spalling)	10	7
Deck with cracking and active corrosion (>10% spalling/patching)	13	4
Deck with surface deterioration or abrasion loss	6	11

Particular latex-modified concrete overlay products are typically chosen over similar materials because of: performance or perception of performance by five of the thirteen agencies (38%) responding to the question, because of rapid return of traffic by two agencies (15%), and because of low weight or thickness by two responding agencies (15%). One agency (8%) selected a system based on FHWA recommendations.

Anticipated Lifespan

- Range: 10 to 50 years
- Mean: 14 to 29 years
- Median: 15 to 25 years

Cost

- Range: $1 to $150 per square foot
- Mean: $18 to $39 per square foot
- Median: $12 to $20 per square foot

Installation

Most agencies (eleven or 65%) prepare the deck by hydrodemolition or milling. Six agencies (35%) include using air sweep or sand blasting to prepare the deck for latex-modified concrete overlay installation. A listing of how agencies prepare the deck surface prior to installation of latex-modified concrete overlays is provided below.

Surface Preparation Techniques for Latex-Modified Concrete Overlays	**Yes**	**No**
No preparation	0	17
Air sweep	6	11
Broom	4	13
Sand blast	6	11
Shot blast	3	14
Water blast	3	14
Water/grit blast	0	17
Hydrodemolition	11	6
Milling	11	6
Crack routing	1	16

All agencies conduct a visual inspection of the prepared deck surface prior to installation. Ten agencies (59%) typically use hammer or chain sounding, while six agencies (36%) occasionally use hammer and chain sounding, and one agency reported never using hammer or chain sounding. Three agencies (18%) typically and three agencies occasionally use adhesion tests to the bare substrate as an inspection method of the prepared deck. Seven agencies (41%) never use adhesion tests to evaluate the prepared substrate.

Methods Used to Evaluate Prepared Substrate for Latex-Modified Concrete Overlays	**Typically**	**Occasionally**	**Never**
Visual inspection	17	0	0
Hammer or chain sounding	10	6	1
Adhesion test to the bare substrate	3	3	7

Thickness

- Range: 1 to 5 inches
- Mean: 1.5 to 2.7 inches
- Median: 1.5 to 3 inches

General Recommendations

When asked about key recommendations the respondents would make to their peers, four of the ten respondents who answered the question stated that good surface preparation was a key to success of the overlay. Six of the ten stated that monitoring of atmospheric conditions is critical to a good placement. Ontario responded that latex-modified concrete overlays should not be used for decks with more than 6% slope (combined longitudinal and transverse), and structures with a lot of vibration during construction.

Asphalt Concrete Overlays With a Waterproofing Membrane

Agencies Responding

Fourteen (14) - CO, CT, IL, KY, NE, NY, RI, SD, TN, UT, VT, Alberta, Ontario, Quebec

Advantages

- Low cost - 6 agencies (43%)
- Effective - 5 agencies (36%)
- Ease of installation - 4 agencies (29%)
- Quick installation - 4 agencies (29%)
- Improves rideability of the surface - 3 agencies (21%)
- Can be used on questionable decks - 1 agency (7%)
- Use is proven - 1 agency (7%)

Disadvantages

- Installation or other problems resulting in water and/or chlorides getting trapped underneath the membrane - 5 agencies (36%)
- Short life - 4 agencies (29%)
- Dead load - 2 agencies (14%)
- Difficulty of removal - 2 agencies (14%)
- Underlying deck cannot be seen or inspected and effectiveness of membrane is unknown - 2 agencies (14%)
- Require timely maintenance - 1 agency (7%)
- Thickness of overlay needs to be sufficient so that traffic does not pull the asphalt concrete off of the surface - 1 agency (7%)
- Shoving of the membrane over time - 1 agency (7%)

Use History

Asphalt concrete overlays have been in use for many years. Ten agencies (71%) stated that they have been using asphalt concrete overlays with membranes for more than 25 years, and the remaining four agencies (29%) stated that they have been using asphalt concrete overlays for 10 to 25 years. Asphalt concrete overlays are also widely used with thirteen agencies (93%) that asphalt concrete overlays with membranes are used on more than 100 bridges in their jurisdiction, while the remaining agency (7%) said that the overlays are used on 50 to 100 bridges.

Use of asphalt concrete overlays with membranes is part of the standard specifications in thirteen states (93%), and is part of a standard special provision for the remaining (7%) state. The use of asphalt concrete overlays with membranes is static in eight states (57%), increasing in two states (14%), and decreasing in four (29%) states.

Selection

Asphalt concrete overlays with a waterproofing membrane were frequently selected because they are easy to install, inexpensive, and already approved by the department. The reasons for selection of asphalt concrete overlays with a waterproofing membrane are listed in the table below.

Reasons for Selection of Asphalt Concrete Overlays	**Yes**	**No**
Easy to install	12	2
Long anticipated service life	4	10
Good track record on similar projects	9	5
Already approved by your department	14	0
Recommended by a colleague	2	12
Research findings were positive	3	11
Inexpensive	11	3
Short lane closures (rapid return of traffic)	7	7
Dead load considerations	0	14
Personal experience	3	11
Presentation by manufacturer's representative	0	14

Asphalt concrete overlays are used on new construction by six (43%) of agencies, used for preventative maintenance by thirteen agencies (93%), and used to address current distress on bridge decks by ten (71%) of the responding agencies. The table below outlines what deck conditions exist and are typically addressed by using asphalt concrete overlays with a waterproofing membrane.

Existing Deck Conditions Addressed by Asphalt Concrete Overlays	**Yes**	**No**
Newer deck in good condition (preventative)	8	6
Deck with cracking in good condition with no significant active corrosion	9	5
Deck with cracking and active corrosion (<5% delamination, no spalling)	7	7
Deck with cracking and active corrosion (>5% delamination and some spalling)	8	9
Deck with cracking and active corrosion (>10% spalling/patching)	10	4
Deck with surface deterioration or abrasion loss	9	5

When asked why they chose asphalt concrete overlays over similar systems, six respondents mentioned cost. Two respondents mentioned ease of installation, and two agencies mentioned effectiveness or performance.

Anticipated Lifespan

- Range: 3 to 40 years
- Mean: 12 to 19 years
- Median: 10 to 18 years

The asphalt concrete wearing surface can be placed in two lifts with the top lift being replaced mid-life of the system.

Cost

- Range: $1.5 to $23.5 per square foot
- Mean: $3 to $8 per square foot
- Median: $3 to $5 per square foot

Installation

The most commonly used surface preparation method prior to the installation of the asphalt concrete overlay and membrane is sandblasting. A listing of the surface preparation methods used for asphalt concrete overlays is given in the table below.

Surface Preparation Techniques for Asphalt Concrete Overlays	**Yes**	**No**
No preparation	2	10
Air sweep	3	9
Broom	4	8
Sand blast	7	5
Shot blast	2	10
Water blast	1	11
Water/grit blast	0	12
Hydrodemolition	2	10
Milling	4	8
Crack routing	2	10

All agencies responding to the question use visual inspection to evaluate the prepared substrate prior to installation of the membrane and asphalt concrete overlay. Agencies also use hammer or chain sounding. The methods of evaluation are outlined in the table below.

Methods Used to Evaluate Prepared Substrate for Asphalt Concrete Overlays	**Typically**	**Occasionally**	**Never**
Visual inspection	12	0	0
Hammer or chain sounding	6	3	0
Adhesion test to the bare substrate	0	1	6

Thickness

- Range: 1.5 to 4 inches
- Mean: 2.4 to 3.1 inches
- Median: 2 to 3 inches

General Recommendations

The recommendations offered by the respondents were varied. One recommends that the system not be used on bridges with high ADT or within deceleration zones. Another recommends that the user understands the condition of the deck, depth of potholes, and distress. A third recommends selecting the membrane types appropriate for the deck condition (for example, not using sheet membranes on rough surfaces). Grading of the aggregate for pavement directly over the membrane should be sized for minimal potential for puncture, and proper use of the membrane primer and tack coat. Another respondent would only recommend this system when concrete is in relatively good condition. Another respondent recommends using three inches of overlay so that the membrane will not be damaged when resurfacing the top two inches. A final recommendation, which echoes a disadvantage previously stated, is that the use of asphalt concrete overlays mean that the underlying concrete cannot be inspected.

Miscellaneous Asphalt Overlays

Agencies Responding

Three (3) - KY, MO, NY

The responses include systems such as chip sealing, rubberized asphalt, and Rosphalt.

Advantages

- Low cost - 2 agencies (67%)
- Rapid construction - 2 agencies (67%)
- Extended life on fair to poor bridges - 1 agency (33%)
- Flexibility with rubberized asphalt - 1 agency (33%)

Disadvantages

- Unproven status of rubberized asphalt - 1 agency (33%)
- Flexibility (some products are more rigid than rubberized asphalt overlays) - 1 agency (33%)

Use History

The use history of miscellaneous asphalt overlays varies considerably. One agency has been using the system for more than 25 years, one agency has been using it for 5 to 10 years, and the other responding agency has been using it for five years or less. One agency uses miscellaneous asphalt overlays on 100 or more bridges in their jurisdiction, and the other two have used is on 10 to 50 bridges. The use of miscellaneous asphalt overlays is experimental for two agencies, and part of the standard specifications for the other. The use of miscellaneous asphalt overlays is static in two responding agencies, and increasing in the other.

Selection

The primary reason for selecting miscellaneous asphalt overlays is the ease of installation and rapid return of traffic. The reasons for selecting miscellaneous asphalt overlays are provided in the table below.

Reasons for Selection of Miscellaneous Asphalt Overlays	**Yes**	**No**
Easy to install	3	0
Long anticipated service life	1	2
Good track record on similar projects	2	1
Already approved by your department	2	1
Recommended by a colleague	2	1
Research findings were positive	2	1

Reasons for Selection of Miscellaneous Asphalt Overlays	Yes	No
Inexpensive	2	1
Short lane closures (rapid return of traffic)	3	0
Dead load considerations	1	2
Personal experience	1	2
Presentation by manufacturer's representative	1	2

Miscellaneous asphalt overlays are used for preventative maintenance and to address current distress by two agencies each, while no agency uses them for new construction. The table below outlines what deck conditions exist and are typically addressed by using miscellaneous asphalt overlays.

Existing Deck Conditions Addressed by Miscellaneous Asphalt Overlays	Yes	No
Newer deck in good condition (preventative)	2	1
Deck with cracking in good condition with no significant active corrosion	2	1
Deck with cracking and active corrosion (<5% delamination, no spalling)	2	1
Deck with cracking and active corrosion (>5% delamination and some spalling)	1	2
Deck with cracking and active corrosion (>10% spalling/patching)	1	2
Deck with surface deterioration or abrasion loss	1	2

One agency selects miscellaneous asphalt overlays over similar materials because of the innovative applications, while another agency selects them because they are an inexpensive way to extend bridge or deck replacement.

Anticipated Lifespan

- Range: 5 to 20 years
- Mean: 8 to 15 years
- Median: 8 to 15 years

Cost

- Range: $1 to $3 per square foot (only one agency responded)

Installation

Air sweeping, brooming and sandblasting are used to prepare the surface for the miscellaneous asphalt overlays. The table below outlines the surface preparation methods used with miscellaneous asphalt overlays.

Surface Preparation Techniques for Miscellaneous Asphalt Overlays	Yes	No
No preparation	0	3
Air sweep	1	2
Broom	2	1
Sand blast	1	2
Shot blast	0	3
Water blast	0	3
Water/grit blast	0	3
Hydrodemolition	0	3
Milling	0	3
Crack routing	0	3

Visual inspection is the most common method to evaluate the prepared substrate prior to the application of miscellaneous asphalt overlays. The methods of evaluation are outlined in the table below.

Methods Used to Evaluate Prepared Substrate for Miscellaneous Asphalt Overlays	Typically	Occasionally	Never
Visual inspection	3	0	0
Hammer or chain sounding	1	1	0
Adhesion test to the bare substrate	0	0	1

Thickness

- Range: 0.4 to 2.5 inches
- Mean: 0.8 to 1.5 inches
- Median: 1 to 1.5 inches

General Recommendations

One agency recommends further research for the use of these systems.

Polymer Overlay (thin-bonded polymer concrete)

Agencies Responding

Twenty-three (23) - AK, CA (responded about thin bonded polymer overlay and polymer concrete), CO (responded about two types of polymer overlay), GA, ID, IL, KS, MA, ME, MO, NM, NV (responded about thin bonded polymer overlay and polymer concrete), NY, OK, OR (responded about two types of polymer overlay), TN, UT, VT, WY

Responses for all polymer overlays are included in this section. The specific materials discussed include epoxy, epoxy-urethane, polyester, methyl methacrylate thin bonded overlays, and polyester and other polymer concretes.

Advantages

- Quick installation and rapid return to traffic - 15 respondents (65%)

- Easy installation - 9 respondents (39%)
    - No modifications of approaches required
    - No redoing of expansion joints is required
- Light weight or low dead load - 7 respondents (30%)
- Good waterproofing and low chloride permeability - 6 respondents (26%)
- Durability or long life - 6 respondents (26%)
- Skid resistance or good friction characteristics - 5 respondents (22%)

Disadvantages

- Cost - 11 respondents (48%)
- Installation problems - 7 respondents (30%)
    - Inadequate surface preparation can affect adhesion
    - Binder preparation
- Low durability - 4 respondents (17%)
    - High traffic loads
    - Under the wheel path
- Problems occurring during installation can be difficult to correct - 3 respondents (13%)
- Polymer concrete cannot be used as a replacement for bridge deck concrete - 1 respondent (4%)

Use History

The use of polymer overlays is generally increasing, and appears to have become more widespread within the last 10 years. Only one agency (Massachusetts) has used polymer overlays for more than 25 years. Seven respondents (30%) began using polymer overlays 10 to 25 years ago. Nine respondents (39%) began using polymer overlays 5 to 10 years ago, and six respondents (26%) began using polymer overlays within the last five years.

The use of polymer overlays tends to be somewhat limited in many locations and more widespread in some states. Eleven respondents (48%) report that polymer overlays are used on ten or fewer bridges in their state. Three respondents (13%) report that polymer overlays are used on 10 to 50 bridges, five (22%) report that polymer overlays are used on 50 to 100 bridges, and four (17%) report using polymer overlays on more than 100 bridges in their state.

The use of polymer overlays is a standard provision according to five (22%) of the respondents. Ten respondents (43%) indicated that the use of polymer overlays is part of a standard special provision, while eight (35%) reported that the use of polymer overlays is considered experimental.

Fourteen respondents (61%) indicated that the use of polymer overlays is increasing in their state, while seven (30%) reported that use is static, and two (9%) report that the use of polymer overlays is decreasing.

Selection

Most agencies selected polymer overlays because of the rapid return of traffic (20, 87%), easy installation (16, 70%), and low dead load (16, 70%). The table below outlines the reasons for selecting polymer overlays.

Reasons for Selection of Polymer Overlays	Yes	No
Easy to install	16	7
Long anticipated service life	9	14
Good track record on similar projects	12	11
Already approved by your department	11	12
Recommended by a colleague	3	20
Research findings were positive	12	11
Inexpensive	7	16
Short lane closures (rapid return of traffic)	20	3
Dead load considerations	16	7
Personal experience	6	17
Presentation by manufacturer's representative	6	17

Polymer overlays were most commonly used for decks with cracking, but otherwise in good condition with no significant corrosion (15, 65%). Polymer overlays are also used for other conditions including for newer desks. The table below outlines what deck conditions exist and are typically addressed by using polymer overlays.

Existing Deck Conditions Addressed by Polymer Overlays	Yes	No
Newer deck in good condition (preventative)	11	12
Deck with cracking in good condition with no significant active corrosion	15	8
Deck with cracking and active corrosion (<5% delamination, no spalling)	9	14
Deck with cracking and active corrosion (>5% delamination and some spalling)	6	17
Deck with cracking and active corrosion (>10% spalling/patching)	6	17
Deck with surface deterioration or abrasion loss	10	13

Anticipated Lifespan

- Range: 1 to 35 years
- Mean: 9 to 18 years
- Median: 10 to 18 years

Cost

- Range: $3 to $60 per square foot
- Mean: $10 to $17 per square foot
- Median: $7 to $11 per square foot

Installation

The most commonly used surface preparation method for polymer overlays is shot blasting. Other preparation methods are not used as widely. The table below outlines the surface preparation methods.

Surface Preparation Techniques for Polymer Overlays	**Yes**	**No**
No preparation	0	19
Air sweep	3	16
Broom	3	16
Sand blast	5	14
Shot blast	16	3
Water blast	1	18
Water/grit blast	0	19
Hydrodemolition	1	18
Milling	4	15
Crack routing	1	18

All agencies who responded to this question stated that visual inspection is typically used to evaluate the substrate surface prior to installation of the polymer overlays. Also, hammer or chain sounding and adhesion tests to the bare substrate are used by ten or more of the respondents. The table below indicates the methods used to evaluate the prepared substrate prior to installation of the polymer overlays.

Methods Used to Evaluate Prepared Substrate for Polymer Overlays	**Typically**	**Occasionally**	**Never**
Visual inspection	17	0	0
Hammer or chain sounding	11	0	1
Adhesion test to the bare substrate	10	3	3

Thickness

- Range: 0.13 to 6 inches
- Mean: 0.5 to 1.4 inches
- Median: 0.4 to 0.5 inches

General Recommendations

Three respondents recommended that a manufacturer's representative be on site during installation. Three respondents mentioned surface preparation concerns. More than one respondent mentioned that high quality surface preparation is essential, and that a dry surface should be obtained. Another mentioned that the system does not adhere well to green concrete. Two respondents discussed cure time, one stated that cure time can be more than four hours per layer, the other to recommend use if construction time is a concern. Weather can be a factor in the cure of some systems, and it is suggested that installers adhere to temperature and humidity tolerances. One respondent recommended that thin bonded epoxy overlays not be used to repair decks with active corrosion, and another respondent recommended that polymer concrete not be used for partial replacement of a bridge deck section. This respondent also recommended the use of volumetric mixing trucks and paving machines for placement on large areas. Another respondent recommends that one should determine if cracks are working and determine ride quality. Another respondent recommends that colleagues avoid methyl methacrylate thin bonded overlays.

Deck Replacement (including partial deck replacement)

Agencies Responding

Four (4) - CA, RI, Quebec (provided two separate responses)

These responses include complete and partial deck replacement

Advantages

- Long life or durability - 3 respondents (75%)
- Less construction time than a full deck replacement (for partial deck replacement) - 1 respondent (25%)
- Does not require temporary supports (for partial deck replacement) - 1 respondent (25%)
- May reduce substantially the chloride levels in the concrete, especially that in the area around the top rebar mat - 1 respondent (25%)

Disadvantages

- Cost - 2 respondents (50%)
- Construction time - 1 respondent (25%)
- Premature deterioration if repairs are done in concentrated zones - 1 respondent (25%)
- Added dead load - 1 respondent (25%)
- Required staged construction - 1 respondent (25%)

Use History

The deck replacement methods discussed have been used for more than 25 years for three respondents (75%), and for 10 to 25 years for one respondent (25%). Two respondents (50%) use their system on 100 or more bridges, one (25%) on 50 to 100 bridges, and one (25%) on fewer than 10 bridges. Three of the agencies (75%) use deck replacement methods as part of their standard specifications, and the other (25%) uses it as a standard special provision. The use of deck replacement methods is either static (3, 75%) or increasing (1, 25%). No agency reported the use of these methods as decreasing.

Selection

Deck replacement methods are selected because of the long anticipated service life and the fact that they are already approved by the department. The table below lists reasons for selection of deck replacement.

Reasons for Selection of Deck Replacement	Yes	No
Easy to install	2	2
Long anticipated service life	3	1
Good track record on similar projects	1	3
Already approved by your department	3	1
Recommended by a colleague	0	4

Reasons for Selection of Deck Replacement	Yes	No
Research findings were positive	0	4
Inexpensive	0	4
Short lane closures (rapid return of traffic)	0	4
Dead load considerations	0	4
Personal experience	0	4
Presentation by manufacturer's representative	0	4

Partial or full deck replacement is used primarily for current distress (4, 100% of respondents), and also to address new construction problems by one respondent (25%). No agencies use partial deck replacement for preventative maintenance. The table below outlines what deck conditions exist and are typically addressed by deck replacement.

Existing Deck Conditions Addressed by Deck Replacement	Yes	No
Newer deck in good condition (preventative)	0	4
Deck with cracking in good condition with no significant active corrosion	0	4
Deck with cracking and active corrosion (<5% delamination, no spalling)	0	4
Deck with cracking and active corrosion (>5% delamination and some spalling)	0	4
Deck with cracking and active corrosion (>10% spalling/patching)	1	3
Deck with surface deterioration or abrasion loss	2	2

Deck replacement is selected because it is standard practice (1 respondent, 25%), because it is a well-understood time-proven process (1 respondent, 25%), or because the decision can be made without detailed analysis (1 respondent, 25%).

Anticipated Lifespan

- Range: 15 to 50 years
- Mean: 27 to 32 years
- Median: 15 to 25 years

Cost

- Range: $4 to $7 per square foot (provided by one respondent for Deck on Deck Portland Cement Concrete Overlay)

Installation

The table below outlines the surface preparation methods used with partial deck replacement. Respondents also indicated that they use selective partial demolition of the concrete deck.

Surface Preparation Techniques for Partial Deck Replacement	Yes	No
No preparation	0	4
Air sweep	1	3
Broom	0	4
Sand blast	1	3
Shot blast	0	4
Water blast	1	3
Water/grit blast	0	4
Hydrodemolition	1	3
Milling	0	4
Crack routing	0	4

Visual inspection and hammer or chain sounding are used most commonly to evaluate the prepared substrate prior to the application of partial deck replacement. One respondent state that evaluation is generally not performed, since the entire deck is removed (complete deck replacement). The methods of evaluation are outlined in the table below.

Methods Used to Evaluate Prepared Substrate for Partial Deck Replacement	Typically	Occasionally	Never
Visual inspection	3	0	0
Hammer or chain sounding	1	1	1
Adhesion test to the bare substrate	0	0	2

General Recommendations

One respondent stated that it is sometimes better to replace the deck than perform an uncertain repair. Another respondent mentioned that the method is somewhat expensive, particularly in getting hydrodemolition unit on site, and that the method is a conservative means of rehabilitation, without relying on unknown and often unproven new technologies.

Sealers

Agencies Responding

Twelve (12) - AR, CO, IL, ME, MN, NC, OK, OR, PA, SD, UT, WV

This summary includes responses for all types of sealers. The particular types of sealers that respondents referenced are: epoxy, silane, and polyurethane sealers.

Advantages

- Low cost - 6 agencies (50%)
- Effectiveness - 5 agencies (42%)
  - In contrast, 2 agencies commented on short duration of effectiveness
- Ease of installation - 4 agencies (33%)
- Quick installation with little disruption to traffic - 3 agencies (25%)

Disadvantages

- Short lifetime - 4 agencies (33%)
- Performance issues - 4 agencies (33%)
    - Do not work well with cracked concrete
    - Not effective after concrete cracks
    - Over-application can result in a slick surface
    - Do not necessarily shut out water and salts on traffic surfaces
- Installation problems - 2 agencies (17%)
    - Contractor issues
    - Warm temperature requirements

Use History

The timeframe in which responding agencies began to use sealers varies widely. Two (17%) began using sealers more than 25 years ago, five (42%) began using sealers 10 to 25 years ago, three (25%) began using sealers 5 to 10 years ago, and another two agencies (17%) began using sealers within the last five years.

For agencies that use sealers, the use is fairly widespread. Five agencies (42%) have used sealers on 100 or more bridges in their jurisdiction. Three (25%) agencies used sealers on 50 to 100 bridges, three agencies (25%) used sealers on 10 to 50 bridges, and only one agency (8%) used sealers on 10 or fewer bridges.

Of the agencies responding to the question, five (42%) specify sealers as part of their standard specifications. Four (33%), use sealers as part of a standard special provision, and one (8%) agency considers the use of sealers as experimental.

Seven agencies (58%) report that the use of sealers is increasing in their jurisdiction, while four (33%) reported that use is static, and one (8%) reported that use of sealers is decreasing in its jurisdiction.

Selection

Sealers were selected by all agencies for the ease of installation, and by eleven (92%) because of low cost. The other reasons for selection of sealers are outlined in the table below.

Reasons for Selection of Sealers	**Yes**	**No**
Easy to install	12	0
Long anticipated service life	2	10
Good track record on similar projects	5	7
Already approved by your department	9	3
Recommended by a colleague	1	11
Research findings were positive	5	7
Inexpensive	11	1
Short lane closures (rapid return of traffic)	7	5
Dead load considerations	3	9
Personal experience	2	10
Presentation by manufacturer's representative	0	12

For those agencies using sealers, four (33%) use sealers on new construction, ten (83%) use sealers for preventative maintenance, and six (50%) agencies use sealers to address current distress on bridge decks. The table below outlines what deck conditions exist and are typically addressed by using sealers.

Existing Deck Conditions Addressed by Sealers	**Yes**	**No**
Newer deck in good condition (preventative)	7	5
Deck with cracking in good condition with no significant active corrosion	10	2
Deck with cracking and active corrosion (<5% delamination, no spalling)	7	5
Deck with cracking and active corrosion (>5% delamination and some spalling)	4	8
Deck with cracking and active corrosion (>10% spalling/patching)	2	10
Deck with surface deterioration or abrasion loss	3	9

Particular sealers are typically chosen over similar materials because of cost by four of the agencies responding to the question, because of ease of use by one agency, because of low traffic impacts by one agency, and for good performance by two responding agencies.

Anticipated Lifespan

- Range: 1 to 20 years
- Mean: 4 to 10 years
- Median: 4 to 8 years

Cost

- Range: $0.33 to $15 per square foot
- Mean: $3 to $5 per square foot
- Median: $2 to $4 per square foot

Installation

The most common surface preparation for sealers are brooming, air sweeping, and sand blasting. Hydrodemolition and milling are not reported to be used by any agency. The table below outlines the surface preparation methods used with sealers.

Surface Preparation Techniques for Sealers	**Yes**	**No**
No preparation	1	9
Air sweep	6	4
Broom	6	4
Sand blast	5	5

Surface Preparation Techniques for Sealers	Yes	No
Shot blast	1	9
Water blast	2	8
Water/grit blast	1	9
Hydrodemolition	0	10
Milling	0	10
Crack routing	1	9

Visual inspection is used by all responding agencies to evaluate the prepared substrate prior to the application of sealers. The methods of evaluation are outlined in the table below.

Methods Used to Evaluate Prepared Substrate for Sealers	Typically	Occasionally	Never
Visual inspection	10	0	0
Hammer or chain sounding	4	2	1
Adhesion test to the bare substrate	1	2	2

General Recommendations

The recommendations that the respondents made for use of sealers were varied. One respondent stated that broadcasting of sand in the epoxy sealer may be required for application over a large area. Another respondent stated that no film-forming sealers are allowed on driving surfaces. A third respondent said that the concrete must be abrasive blasted, dry and warm, and recommended hot weather for installation. Another respondent commented on the difficulty of product approval with so many different products available on the market.

Crack Repair

Agencies Responding

Seven (7) - FL, ID, MA, ME, RI, WV, WY

All responses related to crack repair are discussed in this section. The agencies responded regarding epoxy or high molecular weight methyl methacrylate crack repair.

Advantages

- Sealing of cracking - 3 agencies (43%)
- Low cost- 3 agencies (43%)
- Quick or easy installation - 2 agencies (29%)

Disadvantages

- Short-term fix - 2 agencies (29%)
- Proper mixing of material is critical - 1 agency (14%)
- Aesthetic concerns - 1 agency (14%)
- Problems with good crack penetration - 1 agency (14%)

Use History

Crack repair began to be used by most agencies (4, 57%) 10 to 25 years ago. One agency (14%) has been using crack repair for more than 25 years, one agency has been using crack repair for 5 to 10 years, and the other agency has been using crack repair for five or fewer years.

Four agencies (57%) have used crack repair on ten or fewer bridges in their jurisdiction. Two (29%) have used crack repair on 100 or more bridges, and one agency (14%) has used crack repair on 50 to 100 bridges. The use of crack repair is part of a standard special provision for four (57%) of the agencies, experimental for two agencies (29%), and part of a standard specification for only one (14%) respondent.

The use of crack repair is static in three states (43%), increasing in two (29%), and decreasing in the other two (29%) of states.

Selection

Crack repair is selected primarily because of easy installation. The reasons for selecting crack repair are provided in the table below.

Reasons for Selection of Crack Repair	**Yes**	**No**
Easy to install	5	2
Long anticipated service life	3	4
Good track record on similar projects	3	4
Already approved by your department	2	5
Recommended by a colleague	0	7
Research findings were positive	2	5
Inexpensive	3	4
Short lane closures (rapid return of traffic)	3	4
Dead load considerations	1	6
Personal experience	0	7
Presentation by manufacturer's representative	1	6

Crack repair is used on new construction by one state (14%), for preventative maintenance by four (57%) agencies, and for current distress by three (43%) agencies. According to the table below, no agencies use crack repair for deck with greater than 5% delamination, or a deck with surface deterioration or abrasion loss. Most agencies used crack repair for decks with cracking, but in otherwise good condition.

Existing Deck Conditions Addressed by Crack Repair	**Yes**	**No**
Newer deck in good condition (preventative)	2	5
Deck with cracking in good condition with no significant active corrosion	6	1
Deck with cracking and active corrosion (<5% delamination, no spalling)	2	5
Deck with cracking and active corrosion (>5% delamination and some spalling)	0	7

Existing Deck Conditions Addressed by Crack Repair	Yes	No
Deck with cracking and active corrosion (>10% spalling/patching)	0	7
Deck with surface deterioration or abrasion loss	0	7

The specific crack repair systems used are selected over similar systems because of positive early test results in one case, because the product is the only successful one tried in another case, because the product has been determined to successfully fill cracks, rather than simply coating the sides, and because one agency considers the product the only real option to more aggressive repairs or treatments. One agency states that the product/material typically is not specified, but no further reasoning was given in response to this question.

Anticipated Lifespan

- Range: 2 to 75 years
- Mean: 19 to 33 years
- Median: 15 to 20 years

Cost

No responding agencies provided feedback on the installed costs of crack repair systems.

Installation

Of the responding agencies, air sweeping, brooming, and waterblasting were the most commonly used surface preparation techniques. Cracks must be dry prior to treatment. In addition to the methods listed in the table below, two agencies drill holes for injection, and one agency builds up caulk dams at the edges of wide cracks.

Surface Preparation Techniques for Crack Repair	Yes	No
No preparation	1	6
Air sweep	2	5
Broom	2	5
Sand blast	2	5
Shot blast	0	6
Water blast	2	4
Water/grit blast	0	6
Hydrodemolition	0	6
Milling	0	6
Crack routing	2	5

Visual inspection and hammer or chain sounding are used by nearly all responding agencies to evaluate the prepared substrate prior to the application of crack repair. The methods of evaluation are outlined in the table below.

Methods Used to Evaluate Prepared Substrate for Crack Repair	Typically	Occasionally	Never
Visual inspection	6	0	0
Hammer or chain sounding	2	2	2
Adhesion test to the bare substrate	0	1	3

General Recommendations

One respondent recommended that the size of the crack should be considered for the type of product used, that the crack should be clean and dry, and that the manufacturer’s specifications should be carefully followed. Another respondent stated that crack repair can be a good temporary solution. A third respondent recommended that the applications be tested to ensure adequate crack penetration.

APPENDIX B

TABLES OF RATES OF ADVANCEMENT OF CHLORIDE THRESHOLD FRONT

The following tables give the rate of advancement for various values of concrete chloride diffusion coefficient (D) and the chloride surface concentration (Cs) for certain chloride thresholds and bridge deck ages. Note that the rate of advancement is zero if the surface concentration is less than the chloride threshold. This is because there is not sufficient driving force for the chloride concentration to ever exceed the threshold.

<u>THRESHOLD = 0.03% (Black Steel)</u>

TABLE. Rate of advancement of chloride threshold front (in./yr)
Bridge age = 10 years, Chloride threshold = **0.03%** by wt. of concrete (black steel).

			Diffusion Coefficient					
			0.05 in.^{2}/yr ($1.0x10^{-12}$ m^2/s)	0.1 in.^{2}/yr ($2.0x10^{-12}$ m^2/s)	0.15 in.^{2}/yr ($3.1x10^{-12}$ m^2/s)	0.2 in.^{2}/yr ($4.1x10^{-12}$ m^2/s)	0.25 in.^{2}/yr ($5.1x10^{-12}$ m^2/s)	0.3 in.^{2}/yr ($6.1x10^{-12}$ m^2/s)
Surface Concentration (% by weight of concrete)	Mild	0.1	0.052	0.073	0.090	0.104	0.116	0.127
		0.2	0.072	0.102	0.125	0.144	0.161	0.176
	Moderate	0.3	0.082	0.116	0.142	0.164	0.184	0.201
		0.4	0.089	0.126	0.154	0.178	0.199	0.218
	Severe	0.5	0.094	0.133	0.163	0.188	0.210	0.230
		0.6	0.098	0.138	0.169	0.196	0.219	0.240
		0.7	0.101	0.143	0.175	0.202	0.226	0.248

TABLE. Rate of advancement of chloride threshold front (in./yr)
Bridge age = 20 years, Chloride threshold = **0.03%** by wt. of concrete (black steel).

Surface Concentration (% by weight of concrete)			Diffusion Coefficient 0.05 in.^{2}/yr (1.0x10^{-12} m^2/s)	0.1 in.^{2}/yr (2.0x10^{-12} m^2/s)	0.15 in.^{2}/yr (3.1x10^{-12} m^2/s)	0.2 in.^{2}/yr (4.1x10^{-12} m^2/s)	0.25 in.^{2}/yr (5.1x10^{-12} m^2/s)	0.3 in.^{2}/yr (6.1x10^{-12} m^2/s)
	Mild	0.1	0.037	0.052	0.063	0.073	0.082	0.090
		0.2	0.051	0.072	0.088	0.102	0.114	0.125
	Moderate	0.3	0.058	0.082	0.101	0.116	0.130	0.142
		0.4	0.063	0.089	0.109	0.126	0.141	0.154
	Severe	0.5	0.066	0.094	0.115	0.133	0.148	0.163
		0.6	0.069	0.098	0.1200	0.138	0.155	0.169
		0.7	0.071	0.101	0.124	0.143	0.16	0.175

TABLE. Rate of advancement of chloride threshold front (in./yr)
Bridge age = 30 years, Chloride threshold = **0.03%** by wt. of concrete (black steel).

Surface Concentration (% by weight of concrete)			Diffusion Coefficient 0.05 in.^{2}/yr (1.0x10^{-12} m^2/s)	0.1 in.^{2}/yr (2.0x10^{-12} m^2/s)	0.15 in.^{2}/yr (3.1x10^{-12} m^2/s)	0.2 in.^{2}/yr (4.1x10^{-12} m^2/s)	0.25 in.^{2}/yr (5.1x10^{-12} m^2/s)	0.3 in.^{2}/yr (6.1x10^{-12} m^2/s)
	Mild	0.1	0.030	0.042	0.052	0.060	0.067	0.073
		0.2	0.042	0.059	0.072	0.083	0.093	0.102
	Moderate	0.3	0.047	0.067	0.082	0.095	0.106	0.116
		0.4	0.051	0.073	0.089	0.103	0.115	0.126
	Severe	0.5	0.054	0.077	0.094	0.108	0.121	0.133
		0.6	0.056	0.080	0.098	0.113	0.126	0.138
		0.7	0.058	0.083	0.101	0.117	0.131	0.143

TABLE. Rate of advancement of chloride threshold front (in./yr)
Bridge age = 40 years, Chloride threshold = **0.03%** by wt. of concrete (black steel).

Surface Concentration (% by weight of concrete)			Diffusion Coefficient					
			0.05 in.^{2}/yr (1.0×10^{-12} m^2/s)	0.1 in.^{2}/yr (2.0×10^{-12} m^2/s)	0.15 in.^{2}/yr (3.1×10^{-12} m^2/s)	0.2 in.^{2}/yr (4.1×10^{-12} m^2/s)	0.25 in.^{2}/yr (5.1×10^{-12} m^2/s)	0.3 in.^{2}/yr (6.1×10^{-12} m^2/s)
	Mild	0.1	0.026	0.037	0.045	0.052	0.058	0.063
		0.2	0.036	0.051	0.062	0.072	0.080	0.088
	Moderate	0.3	0.041	0.058	0.071	0.082	0.092	0.101
		0.4	0.044	0.063	0.077	0.089	0.099	0.109
	Severe	0.5	0.047	0.066	0.081	0.094	0.105	0.115
		0.6	0.049	0.069	0.085	0.098	0.109	0.120
		0.7	0.051	0.071	0.088	0.101	0.113	0.124

THRESHOLD = 0.15% (ECR top mat only)

TABLE. Rate of advancement of chloride threshold front (in./yr)
Bridge age = 10 years, Chloride threshold = **0.15%** by wt. of concrete (ECR top mat only).

Surface Concentration (% by weight of concrete)			Diffusion Coefficient 0.05 in.^{2}/yr (1.0x10^{-12} m^2/s)	0.1 in.^{2}/yr (2.0x10^{-12} m^2/s)	0.15 in.^{2}/yr (3.1x10^{-12} m^2/s)	0.2 in.^{2}/yr (4.1x10^{-12} m^2/s)	0.25 in.^{2}/yr (5.1x10^{-12} m^2/s)	0.3 in.^{2}/yr (6.1x10^{-12} m^2/s)
	Mild	0.1	0	0	0	0	0	0
	Mild	0.2	0.016	0.023	0.028	0.032	0.036	0.039
	Moderate	0.3	0.034	0.048	0.058	0.067	0.075	0.083
	Moderate	0.4	0.044	0.063	0.077	0.089	0.099	0.109
	Severe	0.5	0.052	0.073	0.09	0.104	0.116	0.127
	Severe	0.6	0.058	0.081	0.10	0.115	0.129	0.141
	Severe	0.7	0.062	0.088	0.108	0.124	0.139	0.152

TABLE. Rate of advancement of chloride threshold front (in./yr)
Bridge age = 20 years, Chloride threshold = **0.15%** by wt. of concrete (ECR top mat only).

Surface Concentration (% by weight of concrete)			Diffusion Coefficient 0.05 in.^{2}/yr (1.0x10^{-12} m^2/s)	0.1 in.^{2}/yr (2.0x10^{-12} m^2/s)	0.15 in.^{2}/yr (3.1x10^{-12} m^2/s)	0.2 in.^{2}/yr (4.1x10^{-12} m^2/s)	0.25 in.^{2}/yr (5.1x10^{-12} m^2/s)	0.3 in.^{2}/yr (6.1x10^{-12} m^2/s)
	Mild	0.1	0	0	0	0	0	0
	Mild	0.2	0.011	0.016	0.020	0.023	0.025	0.028
	Moderate	0.3	0.024	0.034	0.041	0.048	0.053	0.058
	Moderate	0.4	0.031	0.044	0.054	0.063	0.070	0.077
	Severe	0.5	0.037	0.052	0.063	0.073	0.082	0.090
	Severe	0.6	0.041	0.058	0.070	0.081	0.091	0.100
	Severe	0.7	0.044	0.062	0.076	0.088	0.098	0.108

TABLE. Rate of advancement of chloride threshold front (in./yr)
Bridge age = 30 years, Chloride threshold = **0.15%** by wt. of concrete (ECR top mat only).

			Diffusion Coefficient					
			0.05 in.^{2}/yr (1.0x10^{-12} m^2/s)	0.1 in.^{2}/yr (2.0x10^{-12} m^2/s)	0.15 in.^{2}/yr (3.1x10^{-12} m^2/s)	0.2 in.^{2}/yr (4.1x10^{-12} m^2/s)	0.25 in.^{2}/yr (5.1x10^{-12} m^2/s)	0.3 in.^{2}/yr (6.1x10^{-12} m^2/s)
Surface Concentration (% by weight of concrete)	Mild	0.1	0	0	0	0	0	0
		0.2	0.009	0.013	0.016	0.018	0.021	0.023
	Moderate	0.3	0.019	0.028	0.034	0.039	0.044	0.048
		0.4	0.026	0.036	0.044	0.051	0.057	0.063
	Severe	0.5	0.030	0.042	0.052	0.060	0.067	0.073
		0.6	0.033	0.047	0.058	0.066	0.074	0.081
		0.7	0.036	0.051	0.062	0.072	0.080	0.088

TABLE. Rate of advancement of chloride threshold front (in./yr)
Bridge age = 40 years, Chloride threshold = **0.15%** by wt. of concrete (ECR top mat only).

			Diffusion Coefficient					
			0.05 in.^{2}/yr (1.0x10^{-12} m^2/s)	0.1 in.^{2}/yr (2.0x10^{-12} m^2/s)	0.15 in.^{2}/yr (3.1x10^{-12} m^2/s)	0.2 in.^{2}/yr (4.1x10^{-12} m^2/s)	0.25 in.^{2}/yr (5.1x10^{-12} m^2/s)	0.3 in.^{2}/yr (6.1x10^{-12} m^2/s)
Surface Concentration (% by weight of concrete)	Mild	0.1	0	0	0	0	0	0
		0.2	0.008	0.011	0.014	0.016	0.018	0.020
	Moderate	0.3	0.017	0.024	0.029	0.034	0.038	0.041
		0.4	0.022	0.031	0.038	0.044	0.050	0.054
	Severe	0.5	0.026	0.037	0.045	0.052	0.058	0.063
		0.6	0.029	0.041	0.050	0.058	0.064	0.070
		0.7	0.031	0.044	0.054	0.062	0.069	0.076

THRESHOLD = 0.30% (ECR top and bottom mats)

TABLE . Rate of advancement of chloride threshold front (in./yr)
Bridge age = 10 years, Chloride threshold = **0.30%** by wt. of concrete (ECR top and bottom mats).

Surface Concentration (% by weight of concrete)			Diffusion Coefficient					
			0.05 in.^{2}/yr (1.0x10^{-12} m^2/s)	0.1 in.^{2}/yr (2.0x10^{-12} m^2/s)	0.15 in.^{2}/yr (3.1x10^{-12} m^2/s)	0.2 in.^{2}/yr (4.1x10^{-12} m^2/s)	0.25 in.^{2}/yr (5.1x10^{-12} m^2/s)	0.3 in.^{2}/yr (6.1x10^{-12} m^2/s)
	Mild	0.1	0	0	0	0	0	0
		0.2	0	0	0	0	0	0
	Moderate	0.3	0	0	0	0	0	0
		0.4	0.016	0.023	0.028	0.032	0.036	0.039
	Severe	0.5	0.026	0.037	0.045	0.052	0.059	0.064
		0.6	0.034	0.048	0.058	0.067	0.075	0.083
		0.7	0.040	0.056	0.069	0.079	0.089	0.097

TABLE. Rate of advancement of chloride threshold front (in./yr)
Bridge age = 20 years, Chloride threshold = **0.30%** by wt. of concrete (ECR top and bottom mats).

Surface Concentration (% by weight of concrete)			Diffusion Coefficient					
			0.05 in.^{2}/yr (1.0x10^{-12} m^2/s)	0.1 in.^{2}/yr (2.0x10^{-12} m^2/s)	0.15 in.^{2}/yr (3.1x10^{-12} m^2/s)	0.2 in.^{2}/yr (4.1x10^{-12} m^2/s)	0.25 in.^{2}/yr (5.1x10^{-12} m^2/s)	0.3 in.^{2}/yr (6.1x10^{-12} m^2/s)
	Mild	0.1	0	0	0	0	0	0
		0.2	0	0	0	0	0	0
	Moderate	0.3	0	0	0	0	0	0
		0.4	0.011	0.016	0.020	0.023	0.025	0.028
	Severe	0.5	0.019	0.026	0.032	0.037	0.041	0.045
		0.6	0.024	0.034	0.041	0.048	0.053	0.058
		0.7	0.028	0.040	0.048	0.056	0.063	0.069

TABLE. Rate of advancement of chloride threshold front (in./yr)
Bridge age = 30 years, Chloride threshold = **0.30%** by wt. of concrete (ECR top and bottom mats).

Surface Concentration (% by weight of concrete)			Diffusion Coefficient					
			0.05 in.^{2}/yr ($1.0x10^{-12}$ m^2/s)	0.1 in.^{2}/yr ($2.0x10^{-12}$ m^2/s)	0.15 in.^{2}/yr ($3.1x10^{-12}$ m^2/s)	0.2 in.^{2}/yr ($4.1x10^{-12}$ m^2/s)	0.25 in.^{2}/yr ($5.1x10^{-12}$ m^2/s)	0.3 in.^{2}/yr ($6.1x10^{-12}$ m^2/s)
	Mild	0.1	0	0	0	0	0	0
		0.2	0	0	0	0	0	0
	Moderate	0.3	0	0	0	0	0	0
		0.4	0.009	0.013	0.016	0.018	0.021	0.023
	Severe	0.5	0.015	0.021	0.026	0.030	0.034	0.037
		0.6	0.019	0.028	0.034	0.039	0.044	0.048
		0.7	0.023	0.032	0.040	0.046	0.051	0.056

TABLE. Rate of advancement of chloride threshold front (in./yr)
Bridge age = 40 years, Chloride threshold = **0.30%** by wt. of concrete (ECR top and bottom mats).

Surface Concentration (% by weight of concrete)			Diffusion Coefficient					
			0.05 in.^{2}/yr ($1.0x10^{-12}$ m^2/s)	0.1 in.^{2}/yr ($2.0x10^{-12}$ m^2/s)	0.15 in.^{2}/yr ($3.1x10^{-12}$ m^2/s)	0.2 in.^{2}/yr ($4.1x10^{-12}$ m^2/s)	0.25 in.^{2}/yr ($5.1x10^{-12}$ m^2/s)	0.3 in.^{2}/yr ($6.1x10^{-12}$ m^2/s)
	Mild	0.1	0	0	0	0	0	0
		0.2	0	0	0	0	0	0
	Moderate	0.3	0	0	0	0	0	0
		0.4	0.008	0.011	0.014	0.016	0.018	0.020
	Severe	0.5	0.013	0.019	0.023	0.026	0.029	0.032
		0.6	0.017	0.024	0.029	0.034	0.038	0.041
		0.7	0.020	0.028	0.034	0.040	0.044	0.048

APPENDIX C

GENERAL DISCUSSION OF REPAIR TECHNIQUES

The following discussion includes various deck treatments and maintenance. The intent is to describe systems that are used to extend the service life of bridge decks and provide references and general information on their use. These systems include the following:

1. Surface Sealers
2. Crack Repair
3. Overlays, Toppings, and Membranes
4. Corrosion Protection Strategies

Background

Adverse installation temperatures, cyclic freezing, solar exposure, thermal changes, poor deck conditions, moisture exposure, and early and heavy traffic loads make bridge deck repairs difficult. A repair material should not be entirely accepted as suitable for all the uses recommended by the product manufacturer. Dozens of repair formulations have been encountered that were totally unsuitable for the recommended repair, for a variety of reasons.

Most materials used for deck repair must be rapid curing, since time for repairs are often limited. Rapid-setting materials should not be specified unless the ingredients are known and the performance adequately demonstrated. Several fast-setting materials currently on the market are unstable under moist conditions. This is because they depend on the setting of plaster for their early strength and on portland cement for later strength development. When wet, plaster (calcium sulfate) causes expansion in the hardened patch resulting in cracking and loss of strength.

ACI Committee Reports 201.2 and 546 discuss the repair of concrete and are excellent references (ACI 2008). Both the U. S. Corps of Engineers and the U. S. Bureau of Reclamation have produced concrete repair manuals. The manual by the Corps of Engineers entitled *Evaluation and Repair of Concrete Structures* provides a standard format for repair techniques. The document includes chapters on evaluation of concrete in concrete structures, causes of distress and deterioration of concrete, selection of materials and methods for repair and rehabilitation, concrete removal and preparation for repair, maintenance of concrete, specialized repairs and case histories. The U.S. Corps of Engineers Repair, Evaluation, Maintenance, and Rehabilitation Research Program (REMR) Notebook includes material data sheets on specific products and test data.

Review of manufacturer's data, contact with other people who have used the materials, and discussions with consultants specializing in repair are all valuable in establishing the anticipated durability of the repair. Within reason, the best repair technique and material should be selected regardless of materials cost, since mobilization and user costs will usually easily justify its use.

SURFACE SEALERS

Application of a sealer to the surface of the concrete can be effective in reducing permeability and ingress of deicers and water. The sealers for bridge decks that have gained the most acceptance are silanes and siloxanes. They are the most easily applied and unlike barrier type coatings, penetrate the concrete slightly. Silanes, being smaller in molecular size, generally penetrate more deeply than siloxanes. Silanes and siloxanes can be used to treat fine (<0.010 in. wide) cracks. While they do not fill cracks, they penetrate the surfaces of the cracks, making them hydrophobic. Barrier coatings such as epoxies and acrylates are also used, but concerns with skid resistance and wear must be addressed for use on decks.

Sealers are most commonly used to reduce deicer penetration and reduce reinforcing corrosion. Concrete distress can be caused by the moisture content of concrete approaching the saturation point, for example, freezing and thawing. Alkali-silica and alkali-carbonate reactions, salt crystallization, and DEF all require moisture to occur. Moisture itself does not normally cause the damage, but the ambient environmental conditions in conjunction with the moisture combine to result in the various modes of concrete deterioration. Sealers may reduce the rate of some of these concrete deterioration mechanisms; however, they may not be fully effective in reducing concrete-related distress.

A large number of materials have been used over the years as coatings or sealers for concrete. The first systematic study of sealers was done in the WJE laboratories, starting in 1979, and reported in NCHRP Report No. 244 *Concrete Sealers for Protection of Bridge Structures* (D. W. Pfeifer 1981). At that time, the most popular material used by many state DOTs was boiled linseed oil. Linseed oil is a drying oil similar to paint without pigment. The material is inexpensive in large quantities and is easy to apply. However, it only lasts for short periods of time and must be reapplied frequently.

Five categories of sealers were found to be effective in the NCHRP 244 study. These are polyurethanes, methyl methacrylate (MMA), certain epoxy formulations, relatively low molecular weight siloxane oligomers and silanes. Many of the polyurethanes have the limitation that they are not durable when exposed to the ultraviolet (UV) rays of the sun. Epoxies, acrylics, and methacrylates are very effective sealers; however, at the viscosities normally used, they do not penetrate into the concrete but leave a continuous film on the surface. This makes them less suitable for deck surfaces, where they are exposed to traffic and wear.

Other materials have been used to a lesser extent. These are sodium or potassium silicates, stearates, silicones, asphaltic emulsions, and cementitious formulations. The silicates are marginally effective in preventing the penetration of water into concrete. High molecular weight silicones, some of which are effective water repellants, do not penetrate the surface and, therefore, are subject to degradation by UV light and traffic abrasion. Asphaltic and cementitious formulations, with or without latex additions, are generally ineffective as sealers and are subject to loss due to traffic wear. Stearates and stearate blends with hydrocarbon resins are partially effective water repellents.

With the use of any type of sealer, surface preparation, including cleanliness and moisture content of the surface, is extremely important. Generally, the surface should be clean and dry prior to placing the sealer. Sand blasting or shot blasting is usually recommended to clean the surface before treatment. With materials that do not penetrate but only adhere to the surface, it is important to provide some mechanical lock or “tooth” for the material to adhere.

Potential sealing and coating systems should be evaluated in a mock-ups before full scale installation. The mock-up should be installed using the actual equipment that will be used for the full scale application. After the system has had a chance to cure, it should be evaluated for its effectiveness as a sealer and its effect on skid resistance. Determination of depth of penetration should be performed at a minimum. Other tests might include measuring the water absorption using a mini-stand pipe technique or taking cores for ponding with salt solution in a laboratory setting.

Penetrating Sealers

The effectiveness of penetration of silane and siloxane sealers is a result of their very small molecular size. These penetrating sealers are able to infiltrate and coat the micro-pores and capillary structure of the concrete paste. Penetrating sealers may achieve penetration depths of 1/4 in. or more, depending on the density and finish of the concrete and the moisture content of the concrete at the time of application. Skid resistance of treated surfaces is normally adequate on deck surfaces with tines or grooves but testing is recommended.

Silanes and siloxanes are both derived from the silicone family. When catalyzed by moisture, these materials react with the silica available in concrete to form a hydrophobic siloxane resin film that repels water but still allows vapor transmission. Available products include 100 percent silanes and water-dispersed silanes designed to meet air pollution control requirements.

Because of their very small molecular size, silanes have the capability to penetrate more deeply. Silanes that have penetrated into the concrete are less subject to loss of effectiveness caused by surface abrasion or weathering. Silane sealers are clear and typically cannot be visually detected on treated surfaces. An advantage of silanes and siloxane oligomers are that they allow water vapor to pass, so the sealed concrete can lose water vapor during dry periods.

The long-term effectiveness of penetrating sealers, such as silane or siloxane oligomers is likely dependent on the degree of penetration. When concrete is cold and damp, effective penetration of these types of sealers can be considerably reduced. The best way to determine the depth of penetration is to core or chisel off a section of the surface region of the concrete and examine it in cross-section after wetting or treatment with a water-borne dye. This type of an examination should be an integral part of the quality assurance procedures for a penetrating sealer application.

Coatings

For the sake of distinguishing between sealers and coatings, coatings are applied in some thickness measured in several hundredths of a millimeter (thousandths of an inch) or more, and generally do not penetrate the concrete. Types of coatings include epoxy resins, polyester resins, acrylics, vinyls, polyurethanes, and cementitious materials. Polyurethanes and epoxies are two of the most commonly used film forming coatings for protecting concrete.

Film forming coatings may negatively affect surface friction. Respondents of the survey conducted as part of the development of this guide reported that sand is broadcast into epoxy coatings for skid resistance. Another respondent reported that film-forming coatings are not allowed on driving surfaces.

CRACK REPAIR

Cracking in concrete occurs for a number of reasons, including plastic shrinkage, drying shrinkage, thermal stresses, deck deflection, fatigue, or reactive aggregate expansion. Some cracks in decks, such as surface crazing or shallow plastic shrinkage cracks do not pose significant problems and do not need to be repaired. However, most deck cracks are transverse, aligned directly with reinforcing steel, and full depth. These cracks allow rapid deicer penetration and can result in premature corrosion of the reinforcing steel and the supporting girders. High molecular weight methacrylate (HMWM), epoxy and urethane resins are used to fill and bond the cracks, by either pressure injection or by topical gravity feed application. Sealers (silanes, etc.) may also be effective in reducing leakage into narrow cracks.

Crack Width and Durability

The characteristics of deck cracking that will lead to problems, such as accelerated corrosion of the reinforcing steel, deterioration of the concrete, leakage to structural components beneath the deck, and appearance concerns are difficult to assess. Cracks that allow water penetration may result in rapid saturation of the concrete, rendering marginally air-entrained concretes or concretes with reactive or unstable aggregates less durable during winter freezing conditions and wetting and drying cycles. Surface cracking may also promote surface scaling due to salt crystallization distress.

Cracks greater than 0.002 in. are barely visible but are approaching the width that allows infiltration of water and salts. Generally, cracking tends to follow directly over the reinforcing bars, increasing the potential for corrosion of reinforcing steel along the entire length of the bar. Numerous investigations on cracked decks have identified water leakage through cracks having surface widths of only 0.002 to 0.008 in. Repair or treatment of cracked decks is recommended whenever the deck will be subjected to deicer chemicals.

Crack Repair Methods

Usual methods for crack repair on bridge decks include epoxy injection, high molecular weight methacrylate (HMWM) or other resin-based topical treatment, or silane and siloxane sealers. Routing and sealing is not commonly done on decks, since sealants generally do not hold up well under high speed truck traffic. Large cracks that need to be structurally reinforced can be treated by rebar stitching.

According to ACI 224 (ACI 2008) cracks as narrow as 0.002 in. may be repaired using epoxy injection. HMWM resin and silane or siloxane sealers will work on cracks of even finer dimensions. HMWM resins have been effective, when properly applied, in bonding and preventing infiltration of deicing solutions into both wide and hairline cracks. However, trial installations and testing are suggested to verify effectiveness.

Crack repairs are easily done on horizontal surfaces by laying a bead of HMWM or low-viscosity epoxy on top of the crack or flooding the surface and allowing gravity to fill the crack. These materials are usually capable of penetrating to a crack width of 0.005 in. or less. Any excess material on the concrete surface can be filled with sand to provide skid resistance or is readily removed by grinding or abrasive blasting.

Resin injection

Epoxy injection generally consists of drilling holes at relatively close intervals along the cracks, installing entry ports, and injecting the epoxy under pressure. Pressure injection of cracks is labor intensive and time consuming, so it is generally limited to decks containing a few large discrete cracks. Epoxy is the most commonly used resin for pressure injection applications, although other resins can be used. Detailed information on epoxy injection is included in ACI Committee 503R and 224 reports (ACI 2008). Personnel experienced in epoxy injection should be used for this work.

Gravity feed techniques

HMWM resins were developed for topical treatment of bridge decks that contain numerous fine cracks. This technology was first developed by Caltrans in 1981 (Krauss 1987). Due to the low viscosity of the HMWM resin, (8 to 20 cps, similar to diesel fuel), it readily flows into cracks. Thin epoxy resins are also used to repair cracks by gravity feed. The HMWM has a high solvent capacity and curing compounds and asphaltic materials should be removed prior to treatment since the resin will dissolve them and thicken. The cracks must be dry, since water will prevent penetration and dilute the resin, also resulting in poor polymerization.

The HMWM monomer is catalyzed to initiate polymerization and then swept, squeegeed, or sprayed on the cracked concrete at a rate of approximately 1 gallon per 100 sq ft. The resin flows into the cracks and polymerizes, filling and bonding them. Dry blasting sand should be broadcast into the resin, before the resin hardens, to improve skid resistance.

HMWM resins tend to be brittle and abrade off the surface when subjected to traffic. They, therefore, do not function as a water repellant membrane but primarily as a crack repair material. HMWM resins are compatible with most silane sealers, so silanes can be applied as a concrete surface sealer, followed by the HMWM to fill and bond the cracks.

CONVENTIONAL DECK OVERLAYS

The purpose of a topping or overlay is to establish a new wearing surface, restore ride quality, and protect the deck. Most portland cement based overlays are placed 2 1/2- to 4-inches thick. They are made composite with the deck, strengthening the deck but creating increased dead load on the superstructure supports. Thinner toppings of 3/8- to 3/4-in. thickness can be applied using polymer grouts or concrete.

Overlays can provide a high strength surface and add protection to the embedded steel from corrosive environments. Overlays are designed to be an integral part of the load-carrying capacity of the structure and can be used to improve drainage and grades. Overlays can also be used to improve skid resistance and provide a highly abrasion resistant surface. For thicknesses between 1/4 in. to 1 in., polymer concretes or grouts are typically used. For overlays between 1-in. to 1 1/2-in. thick, latex-modified concrete (LMC) are typically used. Thicker overlays are usually done with normal portland cement or low slump concrete. LMC and silica fume concretes provide a durable overlay concrete and low chloride permeability but are not very rapid setting, requiring several days of cure.

Silica fume additions reduce the permeability of the overlay concrete significantly, however, it also makes the concrete stronger and less elastic so it is more prone to cracking. Because of the cracking risk, silica fume is normally batched at no more than 5 to 7 percent by weight of cement and special curing procedures and QC testing is specified.

Engineers developing repair strategies should determine if there is in-house or local experience with the use of a particular material in similar applications. If so, consult with the persons familiar with previous repairs and review its performance. Specifying materials that have previous success locally is good practice, since workers are familiar with the material and problems during installation are less likely.

Failures of deck overlays generally occur due to poor surface preparation, excessive shrinkage of the repair material, or thermal incompatibility. Some fine cracks must be expected as the overlay dries and shrinks; however, no large cracks or delaminations should develop.

Surface Preparation for Overlays

Proper surface preparation is essential for any deck overlay. Complete removal of unsound or scaled concrete is very important. Durability of the overlay often depends on the initial adhesion developed to the base concrete. Delaminated deck concrete should be removed. Abrasive blasting, steel shotblasting or hydroblasting using very high pressure water, are the best methods of surface preparation. Deeply scaled and deteriorated concrete should be removed by using milling and small chipping hammers, and these surfaces should also receive a final abrasive blasting. Surface preparation by acid etching is not recommended for decks.

The best adhesion for portland cement-based overlays is achieved on a surface-dry substrate condition. The slightly dry concrete substrate pulls minor amounts of moisture from the repair material and results in a low water content near the interface providing the best bond. The new overlay concrete will not bond as well to a wet, saturated substrate surface and may not bond well to recently placed patches, especially when the patches contain polymer modifiers. Therefore, often patching of deck depressions is done concurrently with the overlay placement. If deck patching must be done, perform testing to ensure that the overlay material will bond well to the patched areas. The surface preparation for application of polymer overlays is similar, except that it is essential that the substrate be kept as dry as possible prior to placement. Moisture can significantly reduce the bond of polymers.

Delaminations due to loss of bond can easily be located by sounding with a chain drag or a light hammer. The bond strength of the topping to the base concrete can be measured by direct tensile pull-off tests. A minimum of 100 psi and preferably 200 psi should be achievable for new overlays. Direct tensile pull-off tests can be helpful to determine the adequacy of the surface preparation and problems such as microcracking due to milling damage. Sometimes test bobbins are affixed directly to the prepared substrate and tested in tension. Virginia DOT requires a minimum of 200 psi prior to overlaying bridge decks with a polymer concrete. Direct tensile and shear bond tests are described in ACI Committee Report 546 (ACI 2008).

If reinforcing steel is encountered during milling or surface preparation, it is best practice to remove concrete behind the steel, so that the steel is completely encapsulated in the overlay material. This is especially important where the steel has begun to corrode, and particularly if chlorides are present. The concrete around the steel should be removed to a minimum of about 3/4 in. below the reinforcing bars. If this is not done, continued corrosion of the steel will exert tensile stresses on the overlay promoting delaminations. The half of the bar in the chloride-contaminated concrete becomes anodic and corrodes at a rapid rate, driven by the other half in the new chloride-free overlay concrete acting as the cathode. Delamination of the overlay can develop due to this corrosion.

Bonding Agents for New to Old Concrete

Primers or bond coats are not usually needed for overlays using portland cement concrete. The paste fraction of the concrete makes a good bonding agent and scrubbing the paste fraction of the concrete into the surface immediately prior to placing the bulk of the material is usually the best practice and reduces the risks associated with using a separate bonding grout or resin that could dry before the concrete is placed and reduce the bond.

Separate cement sand slurries or cement latex slurries can be used successfully as bonding agents, but they must be carefully proportioned, mixed and applied. Continuous field quality control is needed. Slurry coats of just cement and water are sometimes specified; however, a slurry containing sand is preferred to reduce the cement and water content. Several problems can occur when mixing and placing cementitious bond coats. Bond grouts or pastes have high cement and water contents, and as such, high shrinkage. The mix proportions of the grout are important, because if the grout contains excessive water, it will be weak and lower the bond strength. Cementitious bonding grouts should never be spray applied as the spraying makes them prone to rapid drying before the concrete can be placed. When cementitious bond coats dry out before the concrete is placed, the bond is significantly weakened or lost completely.

Non-re-emulsifiable latex emulsions are supplied for use as bonding agents. These latex-modified cement slurries are especially susceptible to rapid drying and must be covered immediately to prevent surface film formation, which will reduce bond. The most common types of latex used in concrete are styrene butadiene (SBR) and acrylics. These latexes can be used as bonding agents when mixed as cement slurry or incorporated into the concrete mixture. However, placing straight latex emulsion directly on the surface will usually decrease the bond strength.

Re-emulsifiable polyvinyl acetate (PVA) bonding agents are marketed that can be placed long before the application of the concrete. These work since the fresh concrete will soften and bond to the dry PVA. However, their performance has not been good for exterior exposures, such as bridge decks, since rain water can re-emulsify the PVA resin and reduce bonding strength.

Epoxy bonding agents have been used for bonding concrete overlays with some success. They are available as epoxy latex emulsions or as 100 percent solids epoxy primers. The epoxy must be long pot life materials and specially designed for bonding new-to-old concrete. As formulations can differ, it should be selected based upon successful past field performance. Usually, the overlay concrete must be placed and obtain some initial setting before the epoxy bonding agent hardens or the bond will be reduced. Special precautions are necessary to achieve a good bond, and personnel who install the repairs should be experienced in using epoxy bonding agents.

Portland Cement-Based Overlays

The primary advantage of using portland cement concrete for bonded deck overlays is that the overlay concrete is closest in composition to the original deck and will work compositely. The final thermal and structural properties of the overlay, such as thermal coefficient of expansion, strength, modulus of elasticity, and creep, will be similar to those of the substrate concrete. However, the new overlay material will shrink due to the hydration and drying, so effort should be made to minimize the shrinkage of the overlay concrete.

The modulus of elasticity of concrete is related to its strength and is a measure of the stiffness of a material. A low modulus material will deflect and deform more under load than a high modulus material. Creep is a measure of long-term deformation under substantial load. An overlay repair material with a slightly lower thermal coefficient, lower modulus of elasticity and higher creep, is optimum so that stresses are minimized. This means that very high strength overlays should normally be avoided to reduce the risk of cracking and delamination. Avoiding high cement content mixes should reduce shrinkage and the risk of cracking.

Supplementary cementitious materials, such as fly ash, slag, and silica fume, are often added to overlay concrete to reduce the chloride permeability. Materials that increase strength, modulus and shrinkage, such as silica fume, should be used cautiously and their effect on cracking, bond, and curing should be considered.

Occasionally, thick (5”) reinforced concrete overlays are placed structurally composite with the deck. Typically bonded pcc overlays are near 3 inches thick and are cast at a moderate to low slump. Overlays containing silica fume or other supplementary materials usually require a continuous 3 to 7 days of wet curing after placement. Rapid setting, Type III portland cement concrete overlays can be placed and cured within weekend traffic closures of about 56 hours or less. Calcium aluminate cements can be used during even shorter periods. The strength needed to support traffic varies based on the type of material, but compressive strengths between 2,500 and 4,000 psi before traffic is allowed are sometimes specified.

Bonded pcc overlays can perform well but are prone to cracking and delaminations along the bond line sometimes occur. Some pcc overlays have performed well for many years and some have had progressively fast delaminations after 5 to 10 years of service

Latex-Modified Concrete Overlays

Polymer modifiers can be used to improve bond and resist cracking. The addition of a latex admixture to normal portland cement concrete enhances its bond strength, tensile strength, improves its resistance to chemicals, and reduces its permeability. The latex emulsions include styrene butadiene, polyvinyl acetate (PVA), acrylics and epoxy emulsions. Styrene butadiene and acrylic are most commonly used.

ACI Committee 548 published a document entitled *Standard Specification for Latex-Modified Concrete (LMC) Overlays.* This document includes recommended specifications for LMC overlays. The LMC mix proportions for overlays are recommended to have a minimum cement content of 658 lb/cu yd, a minimum latex admixture content of 24.5 gal/cu yd, maximum w/c of 0.4, and a slump between 3 to 8 inches. The substrate should be saturated surface dry (SSD) prior to placing the LMC. A bond coat of latex, water, cement, and sand slurry is sometimes applied to the prepared surface, but tests show that excellent bond can also be achieved by scrubbing some of the LMC concrete into the surface immediately ahead of the placement. Rapid application of a minimum 2-day wet curing should be performed to prevent early-age drying of the surface, which can result in cracking. Special fogging and early moist curing is needed to prevent plastic shrinkage cracking.

Latex additives have also been used with rapid-setting (Type III) cements or proprietary rapid-setting cements to speed cure and reduce lane closure times. Rapid-setting latex concrete overlays can be placed within 3- to 4-day periods, often over weekends.

VERY RAPID OVERLAYS

Thin Polymer Overlays

Thin overlays, less than 1-in. thick, are typically installed with polymer resin concretes that do not contain portland cement. Binders such as epoxy, polyester, urethanes or polymer blends are used. Polymer overlays provide a durable, chemical resistant surface that protects the deck and embedded steel from carbonation or chloride ingress. Their main advantage is that they can be placed during very short traffic closures, often during nighttime-only work. The selection of overlay material should be based on demonstrated satisfactory performance and based on the exposure conditions and time required for lane closures.

The base slab must be dry for most polymer toppings. Typical recommended substrate temperatures for placement of polymer toppings are between 50°F and 90°F, although some resins work well outside of this range.

Polymer concretes can be placed by the broom and seed method or mixer blended method. In the broom and seed method, resin is applied to the deck and aggregate is broadcast over the wet resin. This is repeated until the required thickness is obtained. For the mixer blended method, polymer concrete is mixed in small batches or using volumetric mobile mixers. The polymer concrete is then screeded to grade using a vibratory screed or paving machine. Epoxy resins are the most popular for the multilayer broom and seed method and polyester resins are the most popular for the pre-mixed, screeded systems. Generally, polymer resins with a lower modulus, being more flexible, loose skid resistance sooner than higher modulus resins (Sprinkel 1992). However, very high modulus resins may crack or debond due to thermal stresses.

Polymer concretes are generally rapid-setting and quickly develop high compressive, flexural, tensile and bond strengths. The rapid hardening properties of polymer concretes reduce the time required for installation and curing. They have good adhesion to most surfaces, are essentially impervious to water and deicing salts, are not subject freezing and thawing damage, and are highly abrasion resistant.

Appropriate safety precautions should always be observed when working with organic polymer resins. Manufacturers' material safety data sheets (MSDS) should be consulted and understood. Skin contact with most organic polymers should be avoided and precautions to minimize vapor inhalation should be observed for a number of the resins. Flammable solvents, such as acetone, are often used for tool cleanup. Information on proper storage and the expected shelf life of the polymers is important and available from the product manufacturer.

The properties of polymer concrete are based on the polymer, the aggregate and the additives or curing agents used. Resin selection should be based upon demonstrated long-term performance in similar applications. The curing times and strength development can be formulated over a wide range and vary based on material and deck temperatures and sun exposure.

One of the main advantages of polymer concretes, besides their rapid strength gain, is their high flexural and tensile strengths. Generally, polymer concretes have flexural strengths four to seven times higher than portland cement concrete. The bond strength of polymer concrete to hardened dry portland cement concrete is generally excellent and can exceed the tensile strength of the portland cement concrete. Bond to wet portland cement concrete can be adequate but is usually significantly less than the bond to dry portland cement concrete.

Depending on the formulation, the thermal coefficient of expansion of polymer concretes can be over three times as much as conventional portland cement concrete. Even normal temperature variations can cause delaminations of improper polymer concrete formulations. Polymer materials typically have higher creep characteristics than portland cement concrete, so when bonded, polymer materials may not crack due to shrinkage and thermal stresses, since creep tends to relieve these stresses.

Epoxy polymer concrete

Epoxy resins used for polymer concrete are typically two component systems and may be a blend of epoxy and urethane resins. Because of their structure, epoxy resins form strong bonds with portland cement concrete, steel, and most construction materials. Epoxy resin cure times and strengths can vary dramatically. Epoxies generally are relatively slow setting and continue to gain strength for weeks. They are resistant to most chemicals and can be formulated to cure under a wide variety of moisture and temperature conditions. Some epoxy resins are available that cure and bond under water. They have good adhesion properties, high tensile strengths and excellent abrasion resistance. Epoxy resins tend to have high viscosity and putty like mortar consistency that may be sticky to finish. Compared to other thermosetting resins, epoxies have low shrinkage.

Epoxy resins are not tolerant to significant deviations from the designed component mix ratio. The two components must be mixed close to the specified ratio or a significant decrease in strength and other properties may occur. Batching should be done in complete units or by using accurate volumetric or weight measures. The individual component containers should be thoroughly mixed prior to combining. Equipment is available for automatic metering of resins that helps ensure proper mix ratios are obtained. The ACI Committee 503R and 548 provides guidelines for the use and application of epoxy compounds and recommended mix designs.

Methyl Methacrylate (MMA)-based polymer concrete

Methyl Methacrylate (MMA)-based polymer concrete overlays have been used on bridge decks for many years. While sometimes successful, problems with bond and long-term durability have also been seen. The resins have a moderately high modulus of elasticity and thermal coefficient of expansion making them susceptible to cracking and delamination.

The MMA resin can be formulated to cure over a wide variety of temperatures and is well-suited for use in cold weather repairs. MMA concretes have good adhesive properties, and can be feather edged, if necessary. They also have excellent flow characteristics.

The MMA resins are flammable and have high fuming making working with them difficult. Trained workers and proper handling and safety practices are required during the handling mixing and placing operations. Eye and skin protection should be used, as well as chemical respirators. Extended exposure to the vapors may cause dizziness, headaches or nausea. As with many other resins, contact with the skin may cause a rash and should be avoided.

Polyester-styrene polymer concrete

Polyester-styrene polymer concrete includes several generic types of resins including isophthalic, vinyl ester-, and fumarate-based resins. Polyesters have excellent resistance to acids. The California Department of Transportation has over 20 years of success using mixer-blended polyester concrete overlays on bridge decks subjected to heavy traffic, including recently on several major San Francisco Bay crossings. High molecular weight methacrylate resin (HMWM) is typically used as a bonding agent for these overlays.

Polyester resins are commonly manufactured with styrene, which is volatile, and catalyst materials must also be handled properly. Appropriate safety precautions should be observed for storage, handling, and placement.

Polyester resins are very rapid setting so are well suited for placement during short night-time lane closures. Modified volumetric mixers and modified slip-form paving machines allow for high production and installation rates during these short lane closures.

Urethane polymer concrete

Urethane polymer concrete can be placed over a wide variety of temperatures and can be formulated to be very rapid curing. Due to the low resin viscosity and the rapid curing times, pre-placed aggregates can be used for patching. Two-component mixing guns are well-suited for mixing and distributing the resin.

The advantages of a urethane patching material are that set times may be very rapid, it may be used in cold conditions, it bonds well to portland cement concrete and asphaltic concrete, and it is relatively easy and rapid to place. However, some urethane resins expand uncontrollably when mixed with water or moist aggregate. Careful attention must be given to the resin formulation and the substrate surface and aggregate must be dry. Primers, such as epoxy, have been used to increase the bond strength to concrete.

The modulus of elasticity of urethane concretes are typically low (0.4×10^6 psi). Due to the low modulus, the compressive strengths and flexural strengths are also lower than some other resins. However, the low modulus material has several advantages for patching and overlays, as they can accommodate long-term thermal and shrinkage strains better than a high modulus material and have a reduced the risk of cracking or delaminations.

Membranes and Asphalt Concrete Overlay

Membranes include liquid applied acrylics, urethanes, neoprenes, vinyls, rubberized asphalts, silicones and preformed membranes such as rubberized asphalts, neoprenes and butyl rubbers, hypalons, vinyls, and ethylene propylene diene M-class rubber (EPDM). In deicing environments, asphalt concrete overlays should not be placed directly on the deck concrete, without a membrane, as the asphalt concrete will hold chloride-laden water against the concrete surface and cause accelerated corrosion and deterioration that is difficult to identify until serious problems occur. Deck membranes are applied to protect the underlying deck, but require a traffic bearing surface be applied to protect the membrane from damage. The long-term performance of membrane systems is strongly affected by the integrity of the overlay and the moisture content of the concrete.

The steps used in installation of an asphalt concrete/membrane system will vary with the particular system chosen. Prior to installation of a membrane and asphalt concrete overlay, the deck surface must be prepared. The deck can be prepared by a number of methods, but it needs to be clean and dry, any curing compounds must be removed, and the deck must be flat and smooth. A rough surface can lead to localized damage to the membrane.

A primer is generally placed on the concrete prior to the installation of a membrane. Primers can be used with sheet membranes and liquid-applied membranes. The membrane needs to be installed within the specified time limits after the application of the primer. The prime coat may require an hour or longer to cure. When applying a sheet membrane, ensure that the manufacturer's instructions as to bonding and lapping are followed. The membranes should be tack free before placing the overlay and the asphalt concrete overlay may require 1 hour or more to cool before traffic can be allowed.

In some locations, a protection layer consisting of protection board (asphalt and mineral filler between sheets of asphalt-impregnated felt) or roofing felt is used. The purpose of the protection layer is to provide protection to the membrane during the overlay construction process. A tack coat is sometimes used to improve adhesion to the membrane or protection layer.

The asphalt concrete is applied over the membrane or protection layer. Often, two layers of asphalt concrete are applied. The bottom layer is the base course, and the top layer is the surface or wearing course. In some cases, the wearing course can be removed and replaced for a partial rehabilitation of the asphalt concrete overlay. It is very important not to damage the existing membrane during any localized repairs or replacement of the wearing surface. If the membrane is damaged, water can be trapped beneath the membrane and cause premature deck deterioration. For further information, the reader is referred to reference (D. G. Manning 1995).

CORROSION PROTECTION STRATEGIES

Corrosion Inhibitors

Corrosion inhibitors can be added to concrete to provide extra protection to the embedded reinforcing steel against deicer salts. The most commonly used inhibitors are calcium nitrite based. Since most overlays are not reinforced, inhibitors are usually not added to overlays. If the deck is being replaced partial or full depth, corrosion inhibitors can be added to the new concrete to help protect the reinforcing. Several surface-applied corrosion inhibitor chemicals are marketed, but their effectiveness has not been proven and they are currently not considered a reliable method to extend the service life of decks.

Cathodic Protection

Cathodic protection is an electrical method used to stop or slow active corrosion. Low levels of electrical current are applied to the deck area, making the embedded steel cathodic and preventing further corrosion. Direct current (DC) is typically supplied through a rectifier to a noble wire mesh or coating on the surface of the concrete. It is important that uniform current is supplied to ensure all areas are protected and to prevent areas of high current density that can deteriorate the concrete at the anode. Cathodic protection can effectively stop corrosion and is especially useful in concrete decks containing large amounts of chloride and active corrosion. The systems must be carefully designed and should be frequently monitored.

Thermally-applied sacrificial CP coatings or anodes can be applied to the underside of the deck to protect the bottom mat of steel. This may be useful on heavily chloride contaminated decks that have epoxy-coated top mats but black bar bottom mats or when partial depth deck repairs are made and corrosion control is needed for the bottom mat reinforcement. Specialty contractors are needed for this work.

Sacrificial cathodic protection is commonly used in structures in contact with soil or sea water and has been used experimentally in deck repairs. Typically, zinc or magnesium anodes are placed in slots on the deck or within concrete overlays. The anodes corrode in preference to the embedded steel. Further information on cathodic protection systems can be obtained from National Association of Corrosion Engineers (NACE).