



Longer Lasting Bridge Deck Overlays

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Kentucky Transportation Center
College of Engineering, University of Kentucky Lexington, Kentucky

in cooperation with
Kentucky Transportation Cabinet
Commonwealth of Kentucky

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Research Report
KTC-18-06/SPR14-472-1F

Longer Lasting Bridge Deck Overlays

David Hunsucker, P.E.
Research Engineer

Kean H. Ashurst Jr., P.E.
Research Engineer

Brad W. Rister, P.E.
Program Manager

David Allen, P.E.
Research Engineer

and

Eileen Grady
Research Scientist

Kentucky Transportation Center
College of Engineering
University of Kentucky
Lexington, Kentucky

In Cooperation With

Kentucky Transportation Cabinet
Commonwealth of Kentucky

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16. Abstract The objective of this report is to determine the most effective method for bridge deck overlay construction and repair by assessing current practices; examining new products and technologies; and reviewing NCHRP (National Cooperative Highway Research Program) guidelines, state standard specifications, ASCE (American Society of Civil Engineers) infrastructure ratings, and original bridge core chloride penetration data. Based on the review, this report offers the following conclusions. Latex modified concrete (LMC) overlays perform well, provide a long service life, and are the most commonly used method of bridge deck rehabilitation. Ohio considers microsilica concrete (MSC) overlays as state of the art due to their lower permeability. Superplasticized dense concrete (SDC), fly-ash modified concrete (FAMC), and polymer modified concrete (PMC) are other acceptable choices for bridge deck overlays. Silane or epoxy sealers may be used as a low-cost preventative approach to slow the deterioration of concrete bridge decks. Waterproofing membranes have produced mixed results but have the potential to be an effective system if installed correctly. Rosphalt® can be an expensive material but offers benefits such as minimizing traffic disruption due to shorter installation periods and increased durability. The two most important conclusions drawn from this research are the importance of a comprehensive approach when selecting a bridge deck rehabilitation method, and the importance of properly following instructions when installing overlays or waterproofing membrane systems.			
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Table of Contents

Definitions And Terms	iii
Executive Summary	iv
1. Introduction and Background	1
2. Literature Review Summary.....	3
3. Bridge Core Chloride Case Study	8
a. Methodology	10
b. Conclusions.....	15
4. National Cooperative Highway Research Program Recommendations and Guidelines	16
5. State Standard Specifications	18
a. Kentucky	18
b. Indiana.....	19
c. Ohio.....	20
d. West Virginia	21
e. Virginia	22
f. Tennessee	23
g. Washington	24
6. American Society of Civil Engineers Infrastructure Report Card.....	25
7. Discussion	27
8. Summary and Recommendations	30
References.....	31
Appendix A.....	34
Appendix B	39
Appendix C	42

List of Figures

Figure 1. KY 32 over Scrubgrass Creek, Nicholas County 9

Figure 2. Old Sonora Road over I-65, Hardin County..... 10

Figure 3. Depth to Steel, KY 32, Nicholas County 11

Figure 4. Depth to Steel, Old Sonora Road Bridge (CR 1189), Hardin County..... 12

Figure 5. Typical Cores from Nicholas County 12

Figure 6. Typical Cores from Hardin County 13

Figure 7. Corrosion at the Level of the Steel, Hardin County 13

Figure 8. Corrosion Associated with a Crack in the Concrete Deck, Hardin County 14

Definitions and Terms

LMC	Latex modified concrete
MSC	Microsilica concrete
SDC	Superplasticized concrete
FAMC	Fly-ash modified concrete
PMC	Polymer modified concrete
Sealer	A water repellent applied to concrete which also reduces ingress of chlorides; can be either topical or penetrating.
Silane Sealer	A type of penetrating sealer made of silane which is a molecular compound which chemically reacts with concrete to block moisture.
Epoxy Sealer	A type of topical sealer made of epoxy, which forms a protective film over concrete to block moisture.
Waterproofing Membrane System	A complete system to protect concrete bridge decks made of a waterproofing membrane as well as any supplementary materials to ensure adhesion.
Waterproofing Membrane	One part of a waterproofing membrane system for concrete bridge decks; can be either constructed in place or preformed. Constructed-in-place membranes are liquid and applied with spray equipment or rollers. Preformed membranes are fabricated strips that are rolled into place.
Rubberized Asphalt	A polymer-modified asphalt possessing negligible permeability, which requires little curing time and eliminates the need for a waterproofing membrane when applied as a bridge deck overlay.

Executive Summary

The search for an effective bridge deck protective system has been a focal point for researchers since concrete bridge deck deterioration was first identified as a critical problem in the 1970s. Bridge deck protection or rehabilitation methods can be divided into two general categories — concrete overlays and waterproofing membrane systems. This report reviews research and state standard specifications for both categories of overlays as well as new or experimental methods. Based on the review, this report offers the following conclusions. Latex modified concrete (LMC) overlays perform well, provide a long service life, and are the most commonly used method of bridge deck rehabilitation. Ohio considers microsilica concrete (MSC) overlays as state of the art due to their lower permeability. Superplasticized dense concrete (SDC), fly-ash modified concrete (FAMC), and polymer modified concrete (PMC) are other acceptable choices for bridge deck overlays. Silane or epoxy sealers may be used as a low-cost preventative approach to slow the deterioration of concrete bridge decks. Waterproofing membranes have produced mixed results but have the potential to be an effective system if installed correctly. Rosphalt® can be an expensive material but offers benefits such as minimizing traffic disruption due to shorter installation periods and increased durability.

The two most important conclusions drawn from this research are the importance of a comprehensive approach when selecting a bridge deck rehabilitation method, and the importance of properly following instructions when installing overlays or waterproofing membrane systems. Based on these conclusions, it is recommended that the Kentucky Transportation Cabinet (KYTC) begin experimental use of the following bridge deck rehabilitation methods: MSC, SDC, FAMC, and PMC overlays. Further use of rubberized asphalt and waterproofing membranes should be considered and monitored for performance. This investigation into alternative methods may result in an expanded roster of options for bridge deck rehabilitation. Guidelines should be developed for selecting the best bridge deck rehabilitation method. Furthermore, it is recommended that adequate installation instructions be prepared for all approved bridge deck rehabilitation methods.

1. Introduction and Background

Premature deterioration of concrete bridges is a persistent and frustrating problem for agencies responsible for maintaining bridges as well as the traveling public. Approximately 53% of the 13,000 bridges owned and maintained by the Kentucky Transportation Cabinet (KYTC) have a Federal Highway Administration (FHWA) sufficiency rating of less than 80%. To improve the condition of the Commonwealth's bridges, as well as to mitigate future degradation, it is important to focus on improving bridge deck performance.

Concrete bridge deck deterioration produced by delamination and spalling was first observed as a pressing problem in the 1970s. These effects can result from various mechanisms, including corrosion of embedded steel reinforcement, repeated freezing and thawing, deicing salt-induced scaling, or reactive aggregates. Bridge deck deterioration is inevitable, but it may be significantly delayed by implementing an effective bridge deck protection system, the pursuit of which has garnered much research since the 1970s.

The two most commonly used bridge deck protective systems are overlays and waterproofing membranes. Research performed by the Kentucky Transportation Research Program during the 1970s focused on improvements in durability of bridge-deck concrete (1). Kentucky was a pioneer in the development of latex overlays and first used latex mortar (1969-73) for deck rehabilitation. In 1973, KYTC switched to a concrete formula from the mortar-type mixture. Low-slump concrete became feasible and competitive, but was required to be placed at a slightly greater thickness than latex concrete due to its lower chloride impermeability. Both latex-modified and low-slump concrete overlays perform well, but latex-modified concrete (LMC) has traditionally been more popular for use in overlays due to its ease of application (2).

KYTC also experimented with waterproofing membrane overlays on nine bridges during the mid-1970s at the request of the FHWA (1). There are two broad categories of waterproofing membrane overlays: constructed-in-place systems and preformed membrane systems. Constructed-in-place systems use spray equipment or rollers to apply a liquid membrane, while preformed systems are simply rolled into place. The waterproof membrane must then be overlaid with an asphalt riding surface, using supplementary materials to ensure proper adhesion. Waterproofing membrane overlays are a relatively complex protective system because their effectiveness depends on successful cooperation among all parts.

In the mid-1960s, Kentucky specifications required use of Class AA concrete and in the early 1970s, increased concrete cover to deter corrosion of the embedded steel reinforcements (1). However, the benefits of those requirements were not widely recognized because epoxy-coated reinforcements were promoted by the FHWA shortly thereafter. Advances in milling machines and overlay pavers further improved deck overlaying practices. It has been found that high strengths are not necessarily required for durable concrete. In fact, they may undermine durability due to the higher modulus of elasticity, or stiffness of the concrete. Concrete decks with high strength, high modulus mixtures are prone to developing cracks. The optimum mixture for concrete used in bridge decks must be designed to minimize permeability and cracking while maximizing ease of placement and finishing (3).

Concrete bridge deck deterioration continues to be a prevalent problem throughout the United States, and many investigations have sought to develop longer lasting and more effective bridge deck overlays. The objective of this research is to determine the most effective method for bridge deck overlay construction and repair by assessing current practices; examining new products and technologies; and reviewing NCHRP (National Cooperative Highway Research Program) guidelines, state standard specifications, ASCE (American Society of Civil Engineers) infrastructure ratings, and original bridge core chloride penetration data. The report concludes with recommendations KYTC should adopt to ensure the Commonwealth is practicing the most up-to-date methods for bridge deck overlay construction and repair. An effective bridge deck protection system seeks to maximize strength to resist cracking while minimizing the ingress of moisture and chlorides. It should also be relatively easy and economical to install and maintain when compared to a complete replacement of the bridge deck.

2. Literature Review Summary

In 1974, Rahal investigated the effects of several experimental finishing techniques on the durability of bridge decks (4). The initial conditions of 13 variously constructed bridge decks in the state of Kentucky were recorded to establish a baseline against which future evaluations could be compared. The three experimental bridge deck construction techniques studied were a broomed finish, compaction using an impacting rotary disk finishing machine, and bi-layered construction. Several conventional bridge decks, finished with a burlap drag but not compacted, were also included for control purposes in this comparative study. After installation, all bridge decks received a resin-based curing compound followed by wetted-burlap or plastic cover. Finally, a double application of linseed oil completed each bridge deck construction.

Rahal assessed the electrical resistance, corrosion potentials, and skid resistance of bridge decks. Various concrete properties were also analyzed by testing cores taken from each bridge deck. The electrical resistivity tests did not show any significant results and no corrosion of steel was found in any of the decks. Skid resistance testing suggested that although the broom-finished decks wore more rapidly, they were more skid resistant than conventionally finished surfaces. All of the concretes appeared to be of good quality, although core testing did not produce any conclusive results. Insufficient time had passed for the bi-layered deck to be adequately assessed. Included in the research report was a memo to the State Highway Engineer of Kentucky at the time, noting the importance of a comprehensive approach for constructing durable bridge decks. Areas for consideration were the quality of aggregates, design and control of concrete mixture, construction methods, design of the deck systems, and maintenance.

In 1987, Havens et al. inspected 119 experimental bridge deck overlays to evaluate performance and provide recommendations for future overlay construction (1). Included were nine membrane bridges, 87 latex concrete overlays, and 23 low-slump overlays. Eight of the nine membrane bridges inspected were in good condition. Although blisters and cracks made for an unsightly appearance of the membrane-treated bridge decks, these surface imperfections did not significantly affect their performance. Membranes did not suffer from any other pressing problems and their use (with the possibility for repeated overlays) was recommended to prolong the life of a bridge without the need for re-decking. The overlays were originally placed on both new and existing bridge decks on various routes throughout the state. Most of the overlays were rated in good to excellent condition. Havens reported that none of the overlay methods were discernibly superior to the others. However, an attendant finding of this study, made during the survey of rigid concrete overlays, was the existence of specific deck crack patterns for each style of bridge and deck system inspected. Havens et al. attributed those crack patterns to temperature and deck flexure effects. Natural deck cracks were the product of differences in thermal expansion between the reinforcing steel and concrete. Load-induced cracks were determined to be specific and recognized as working cracks. Some bridge types (e. g., continuous steel I-beam type) appeared more prone to deck cracking than others (e. g., pre-stressed concrete I-beam type). Researchers determined that susceptibility to cracking was related to the stiffness of the superstructure and deck. Researchers also concluded that high-strength bridge decks may prove counterproductive due to the associated high modulus of elasticity, which could result in the development of restraint-induced stress sufficient to produce cracks.

In another 1987 report, Havens evaluated the experimentally finished bridge decks reported on by Rahal in the 1970s (5). Researchers concluded that while the broom-finished decks were initially more skid resistant than their conventional burlap drag-finished counterparts, wear over time lowered skid resistance. Conversely, the conventional drag-finished bridge decks exhibited an increase in skid resistance over time that was eventually comparable to that of the broom-finished decks. The use of saw-cut grooves was also suggested to increase skid resistance. Havens also recommended epoxy-coated reinforcing steel to protect against bridge deck deterioration due to corrosion caused by chloride infiltration. Masonry coatings tended to be unsuccessful, but their failure often resulted from improper application. The use of segmental bridges proved to be both time- and cost-inefficient because they experienced numerous problems during both construction and installation. Further investigation into the use of microsilica as a concrete additive in bridge decks was recommended. The microsilica concrete (MSC) overlay examined in this study met durability requirements, but difficulties encountered during installation resulted in an unsatisfactory surface.

Research in 1995 by Hunsucker and Stone investigated the use of new concrete types and admixtures for use in bridge deck construction. One such study found no significant advantage in using Pyrament blended concrete (PBC) as opposed to conventional Class AA concrete (6). PBC is a rapid-setting, high-performance cement that exhibits high strength and low permeability. However, the rapid setting proved to be a problem, as workers did not have adequate time to finish the deck surface, resulting in a very uneven surface. PBC exhibited high compressive strengths, but underwent excessive cracking that negated the low chloride permeability.

Another study by Hunsucker and Stone evaluated the performance of Class S concrete, or shrinkage compensating concrete, designed to minimize shrinkage cracking (7). Compared to a conventional Class AA concrete bridge deck, the Class S concrete bridge deck exhibited slightly higher durability and suffered fewer, less severe cracks. Class S concrete also far exceeded the compressive strength requirement. Hunsucker and Stone recommended further use of Class S concrete for bridge deck construction.

Hunsucker and Stone also evaluated the performance of experimental bridge decks constructed with a Class AA concrete modified with a high-range water reducing admixture (8). A high-range water-reducing admixture produces a higher slump to flowing concrete which is easy to install and benefits from a high compressive strength. Hunsucker and Stone compared the deck modified with this admixture to a control deck constructed with conventional Class AA concrete. During installation of the experimental bridge deck, workers experienced problems incorporating the admixture into the concrete in the proportions necessary to meet requirements, likely due to lack of experience. This lack of experience was also likely to blame for the poor appearance of the experimental bridge deck, which required repairs to improve rideability. Both bridge decks suffered from cracking, and although the experimental deck possessed a greater number of cracks, the cracks in the control deck were more severe. The experimental deck was more durable and registered a higher compressive strength than the conventional bridge deck. Overall, Hunsucker and Stone recognized the benefits of modifying concrete used in bridge decks with a high-range water reducing admixture but recommended more extensive training and preparation prior to any future use of high-range water reducers in Class AA concrete for bridge decks in order to minimize the difficulties experienced throughout this study.

Asphalt overlays are an alternative to concrete overlays but require an additional waterproofing membrane to be effective. Rosphalt is polymer-modified asphalt that has negligible permeability when mixed and compacted in accordance with specifications. Rosphalt mixtures require no curing time and eliminate the need for an additional waterproofing membrane when applied to bridge decks as a protective overlay. Several studies have investigated the performance of Rosphalt overlays, with varying results.

Sprinkel and Apeageyi compared two experimental Rosphalt overlays to one conventional asphalt overlay with epoxy membrane for the Virginia Center for Transportation Innovation and Research in 2013 (9). The first Rosphalt overlay was constructed on a bridge deck in the northbound lane (NBL) of I-85. The second Rosphalt overlay was constructed on the Norris Bridge. The asphalt overlay with epoxy membrane was then constructed on the parallel bridge deck in the southbound lane (SBL) of I-85. Sprinkel and Apeageyi concluded that the all three Rosphalt overlays could be installed more rapidly than their traditional concrete counterparts. Inspections of the bridges for leaks, however, produced less-than-satisfactory results. Both the SBL and NBL bridges on I-85 suffered from leaks through cracks or joints located in the bridge decks themselves, and neither the epoxy membrane in the SBL nor the Rosphalt in the NBL was able to stop those leaks. The Norris Bridge was not inspected for leaking, but tests indicate that its Rosphalt overlay was less permeable and more fatigue and rut resistant than the overlays on I-85, and therefore should be more durable. Sprinkel and Apeageyi did not recommend Rosphalt for bridge deck overlays because it is more expensive compared to other options, but they did suggest any cracks in a concrete bridge deck be patched before installation of asphalt overlays with epoxy membranes to augment their performance.

Value Engineering Study of I-64 Riverside Rehabilitation evaluated the use of Rosphalt through an investigation of a rehabilitation project of the I-64 Riverside Expressway (including three bridges in need of rehab) in Louisville, Kentucky (10). The authors analyzed several options for bridge deck rehabilitation to ensure the most appropriate one was chosen. The original proposition for bridge deck rehabilitation involved milling off the entire existing deck overlay, along with 0.25 inch of the bridge deck itself. Then a Rosphalt overlay of 1.5 inches would be installed on the bridge deck, as Rosphalt has waterproofing properties that have been shown to provide protection against corrosion.

The first alternative proposed milling off the entire existing deck overlay along with a depth of 0.75 inch of the bridge deck itself. Then a 2-inch-thick dense concrete/latex-modified overlay would be installed on the bridge deck. This type of overlay has been used with success in Kentucky and other states — it bonds well to the deck, protects against corrosion, and lasts 15–20 years. The second alternative proposed milling off a 0.5-inch depth of the existing deck overlay, then installing a 1.5-inch-thick, dense concrete/latex-modified overlay. Both alternatives were ultimately dismissed due to concerns over costs. The first alternative involving a 2-inch-thick latex concrete overlay would incur an additional total cost of more than \$7 million. The second alternative involving a 1.5-inch thick latex concrete overlay would incur an additional total cost of more than \$2 million. The originally proposed Rosphalt overlay was selected as the most appropriate option for bridge deck rehabilitation.

Maine DOT evaluated the effectiveness — over one year — of Rosphalt 50, which was used to resurface the decks of three bridges (11). Factors of importance included skid resistance, permeability, durability, and cost-effectiveness. Based on visual observations, the wearing surfaces of all three bridge decks were in generally good condition. Centerline joints were well-knit and the seals around curbs and drains intact. Minimum levels of frictional resistance were met on all bridges. Density and chloride content test results were mixed. Rosphalt 50 is not the cheapest option but significantly reduces traffic disruption due to its ease of application. Overall, Rosphalt 50 has performed favorably and as expected.

Rowe et al. compared three trial pavements constructed with Rosphalt modifier materials against laboratory samples (12). In both field and laboratory evaluations, Rosphalt performed successfully as a waterproof layer, demonstrated good flexibility, and resisted permanent deformation. The criteria used to make these determinations were pulled from ASTM and AASHTO tests and standards. Rosphalt was considered impermeable because its hydraulic conductivity was below 1×10^{-7} cm/sec when evaluated in accordance with ASTM D5084. The mixture's flexibility was tested using ASTM D4760, and it achieved greater flexibility than conventional asphalt mixtures due to the use of thermo-plastic elastomeric modifiers. The ability of the Rosphalt mixture to resist permanent deformation was attributed to the use of the modified binder. Cores taken from the trial Rosphalt pavements exhibited average deformation of 2.4 mm at 8000 cycles at 64°C, which is far below the AASHTO TP63 threshold of 10 mm at 8000 cycles at 64°C.

Griffin et al. investigated structural bridge deck overlays (SBDO) as another bridge deck rehabilitation option (13). SBDOs increase the load that the bridge structure must support, but also provides increased load carrying capacity to counteract the higher dead load. Griffin et al. assessed load carrying capacity on three spans of a bridge constructed with varying support systems: a span with simply-supported precast, pre-stressed concrete I-girders on the I-64 Bridge over KY 32; a span with continuous cast-in-place reinforced concrete haunched girders on the I-64 Bridge over Triplett Creek; and a span with simply-supported cast-in-place reinforced concrete girders on the I-64 Bridge over Triplett Creek. These three types of bridge construction represent the majority of bridges in Kentucky.

Effects such as strain and displacement were measured before and after construction of an SBDO on the above bridge spans, using the same controlled methods, to assess the effect on load carrying capacity of the constructed SBDO. Previous studies reported that SBDOs could increase the load carrying capacity by 20 to 25%, but this study only found an increase of 17 to 23%. Overall bridge stiffness also increased while the load distribution between adjacent girders was enhanced by implementation of the SBDO. These findings support the use of SBDOs as a reliable rehabilitation option that is much more time and cost-efficient compared to a complete replacement of a bridge deck.

Chiaw and Harik investigated the use of stainless steel clad (SSC) rebars and micro-composite multi-structural formable steel (MMFX) rebars as two experimental, corrosion-resistant reinforcement options for bridge deck construction (14). SSC rebars consist of a carbon steel core encased by stainless steel. MMFX rebars use a patented chemical composition and proprietary steel microstructure to resist corrosion. Compared to conventional carbon steel, epoxy-coated steel, and galvanized steel, SSC rebars cost only slightly more than half than conventional carbon

steel rebars and have the lowest overall cost based on a 75-year economic life cost analysis. The manufacturer of MMFX claims that MMFX steel is economical to produce, as the material has less than 1% carbon content, approximately 8-10% chrome, and only a negligible amount of nickel. For the purpose of comparison in this study, one span of a bridge in Scott County, Kentucky, was reinforced with SSC rebars while another span on the same bridge was reinforced with MMFX rebars. Both the SSC and MMFX bridge decks appeared to be in excellent condition during visual inspections conducted approximately one year after construction, with both suffering only from undetectable or immeasurable cracks. This study found that the performance of the MMFX reinforced deck was better than the SSC deck, as well as to a conventional steel. The researchers reported that the MMFX decks also exhibited higher moment capacities than the SSC decks — 57% higher in the positive moment region and 85% higher in the negative moment region. Direct substitution of conventional steel with MMFX may not be the best option as the high strength potential of the MMFX would be underutilized.

Frosch et al. conducted a thorough review of available bridge deck protective systems in order to provide recommendations for Indiana Department of Transportation (INDOT) (15). The authors concluded the following: LMC overlays, thin polymer overlays, and waterproofing membranes with asphalt overlays are both the most widely used systems as well as the most advantageous. Each option has its own advantages and disadvantages, therefore the best choice depends upon the particular rehabilitation project. LMC overlays have proven performance and offer the longest service life, but they are expensive and require an extended curing period. Thin polymer overlays are light, flexible, and easily and quickly installed, but do not provide much durability or additional service life. Waterproofing membrane systems have the potential to be the most effective protective system as long as they are installed correctly, however, waterproofing membrane systems are expensive and their installation is time-consuming.

Frosch et al. made several recommendations derived from evaluations regarding Indiana's use of bridge deck protective systems. LMC overlays should be used as a preventative measure or as a rehabilitative measure when damage is significant. Thin polymer overlays were recommended for use as a preventative measure on new bridge decks, or in situations where quick installation was the most important concern. Finally, Frosch recommended that INDOT lift the moratorium on the use of waterproofing membranes with asphalt overlays, because waterproofing membrane systems are potentially beneficial when installed correctly. In particular, newly constructed bridge decks and decks requiring reconstruction of approaches and joints would benefit most from a waterproofing system. However, in order to ensure their proper installation, the importance of adequate standards and specifications for waterproofing membranes was emphasized.

3. Bridge Core Chloride Case Study

To better understand the extent of protection that bridge deck overlays provide against ingress of chloride ions, two bridges were chosen for a case study to determine the condition of the steel in the bridge decks and determine if chloride penetration had occurred. During wintertime snow and ice events, chloride ions from chloride-based deicing salts can cause deterioration of the concrete surface and corrode the reinforcing steel. There are three basic mechanisms for the distribution and transportation of chloride ions through concrete: capillary absorption, hydrostatic pressure, and diffusion. Diffusion is the movement of chloride ions driven by an ion concentration gradient. In this case, the concrete has a continuous liquid phase along with the ion concentration gradient.

The most common method of chloride ion infiltration into the concrete of bridge decks is capillary absorption. A bridge deck exposed to the environment encounters wetting and drying cycles; when water containing chlorides comes into contact with a dry surface it is drawn into the pore structure of the concrete through capillary suction; absorption is driven by moisture gradients. Most of the time the depth of drying is small and this method of transportation will not bring the chloride ions to the depth of the reinforcing steel (16, 17). However, in instances where the bridge deck is in need of an overlay because of poor quality, extensive deterioration, or cracks in the deck, ingress of chloride-contaminated water occurs, bringing chloride ions into contact with the reinforcing steel and initiating corrosion of the steel.

Numerous test methods have been developed and used over the years to measure the penetration of chloride ions into concrete. The following is a list of the most popular tests:

- *AASHTO T259 (Salt Ponding Test),*
- *AASHTO T277 (Rapid Chloride Permeability Test),*
- *Bulk Diffusion Test (Nordtest NTBuild 443),*
- *Electrical Migration Techniques,*
- *Resistivity Techniques,*
- *Pressure Penetration Techniques,*
- *Indirect Measurement Techniques, and*
- *Rapid Migration Test (CTH).*

A form of the Rapid Migration Test (to be discussed later) was used in this case study.

Both bridges investigated are located in Kentucky; since the field data were collected both were demolished. The first bridge was on KY 32 over Scrubgrass Creek in Nicholas County; it was built in 1932 (Figure 1).

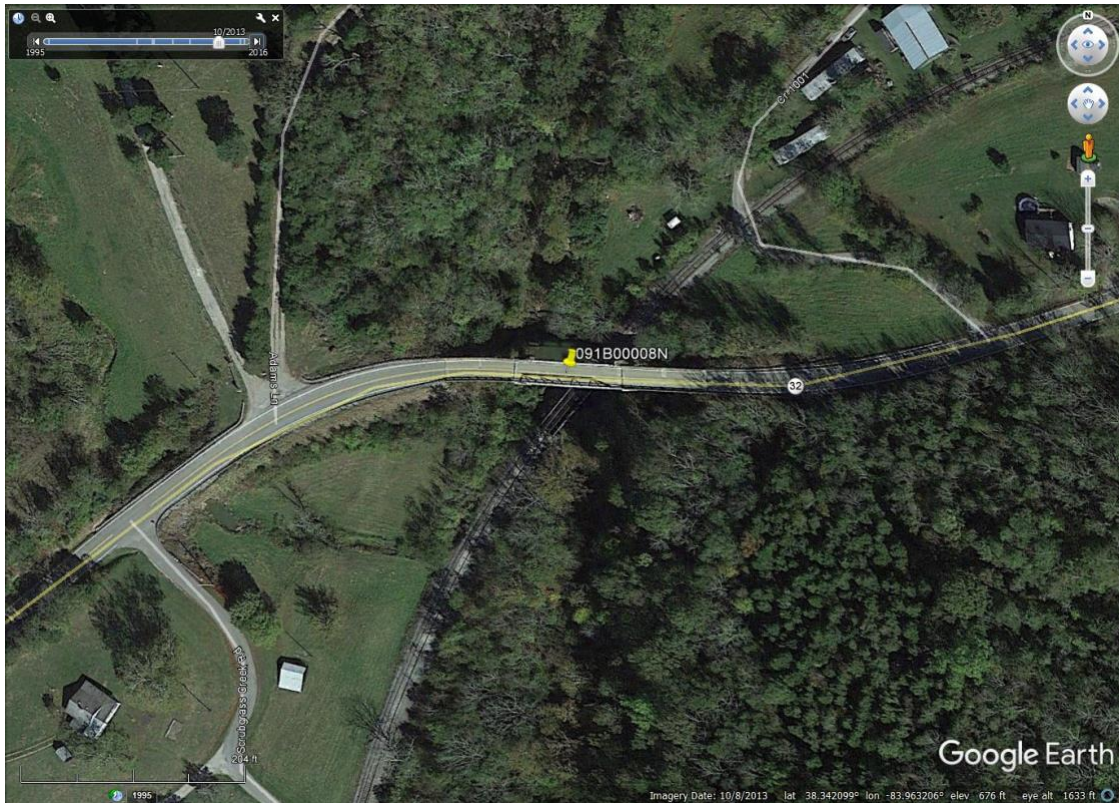


Figure 1. KY 32 over Scrubgrass Creek, Nicholas County

According to a KYTC Structure Inventory and Appraisal Sheet, the bridge was last inspected on August 27, 2014. Inspection notes indicated the wearing surface was latex concrete/similar and describe the concrete deck as protected with rigid overlay.

The second bridge was on Old Sonora Road (CR 1189) over I-65 in Hardin County; it was built in 1959 (Figure 2).

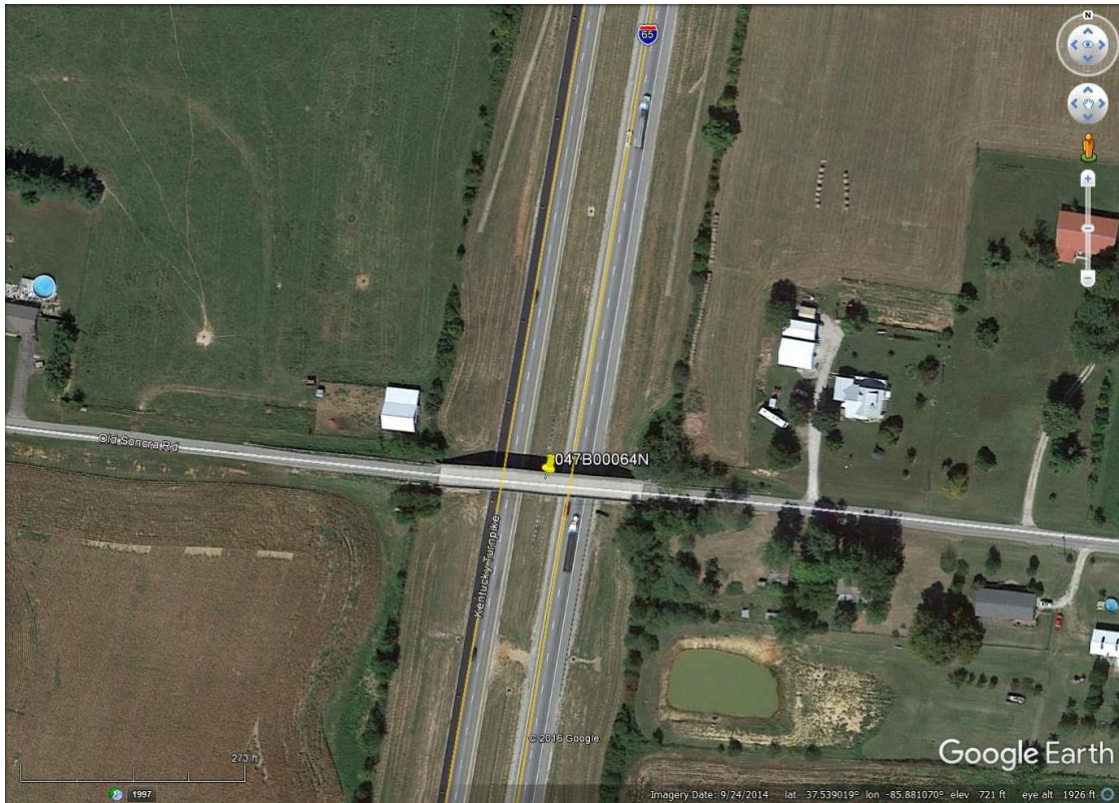


Figure 2. Old Sonora Road over I-65, Hardin County

Because it was a county road, this bridge had likely only been exposed to deicing salts in the five years leading up to its demolition. It was last inspected on November 10, 2014. Inspection notes indicated the wearing surface was monolithic concrete; no overlay was present. The absence of an overlay was confirmed by examining maintenance records, which show that in 2007 approval was given for an overlay deck to be placed over a bare concrete deck. However, it was never assigned to a project. Maintenance records for both bridges can be found in Appendix A.

a. Methodology

Thirty-one core samples were collected from each bridge's deck. The cores were collected over a known location of reinforcing steel in the deck. The length of each core was measured (from the surface of the deck to the level of the reinforcing steel), and a selected number of samples were tested for chloride penetration in the laboratory. The thicknesses of the bridge deck cores were measured and catalogued. They are presented graphically in Figures 3 and 4.

The average depth to steel for the KY 32 bridge over Scrubgrass Creek was 4.08 inches. The coefficient of variation was 14.0 percent. Although the coefficient of variation was not exceptionally large for the entire deck, there was considerable variation in thickness over short distances along the deck.

The average depth to steel for the Old Sonora Road Bridge was 2.12 inches. The coefficient of variation was 13.8 percent. The coefficient of variation was very similar for both bridges, however, there was less variation in thickness over short distances on the Old Sonora Road Bridge. There was a consistently small increase in deck thickness from one end of the bridge to the other. However, it was small — just over 0.2 inch.

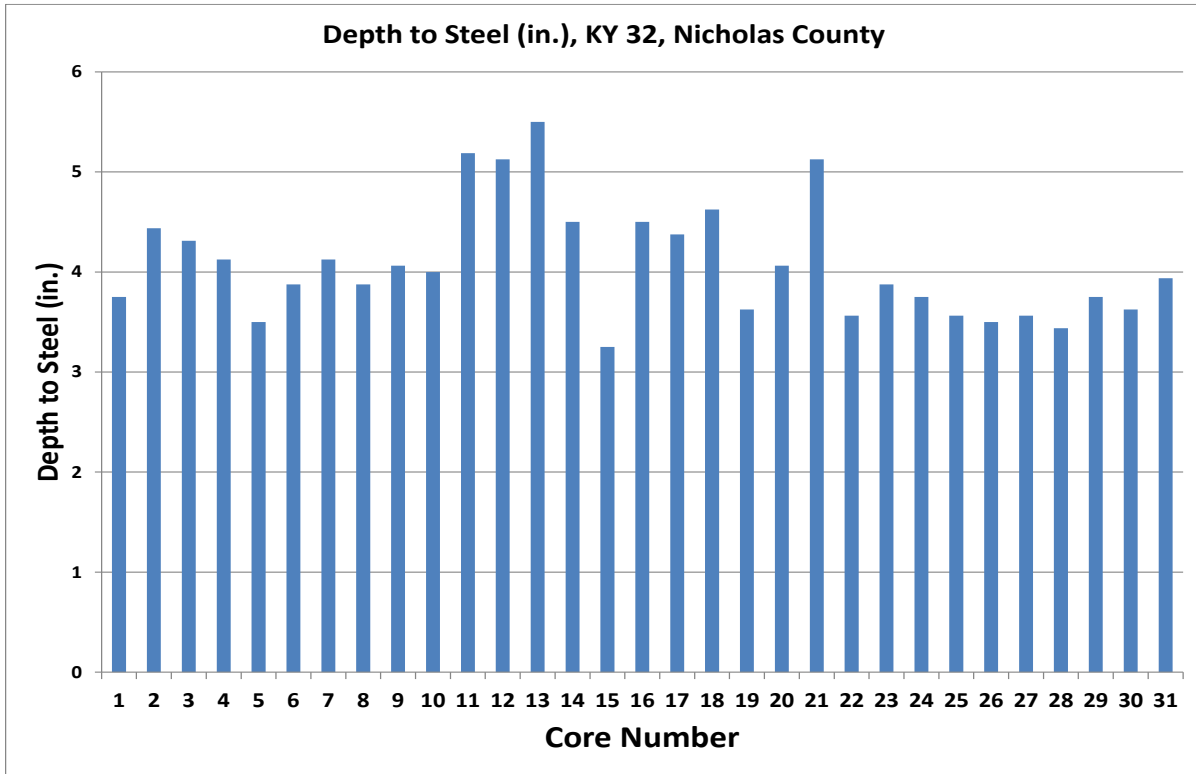


Figure 3. Depth to Steel, KY 32, Nicholas County

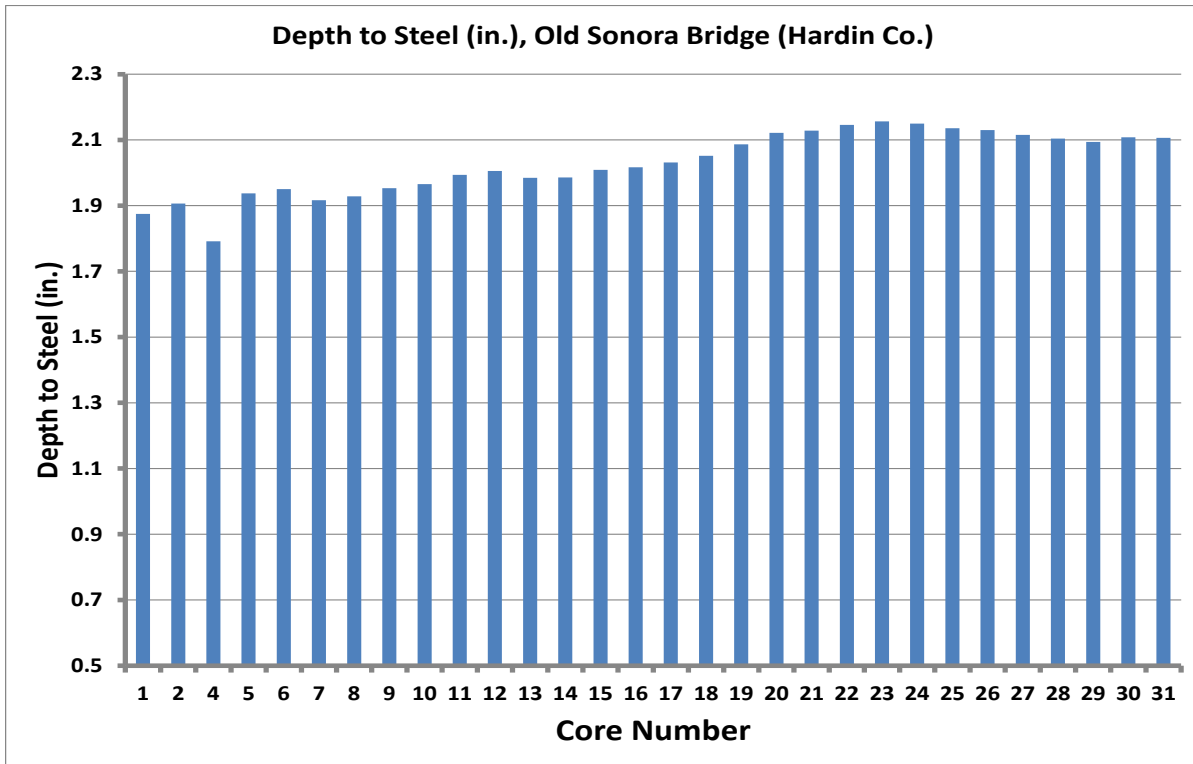


Figure 4. Depth to Steel, Old Sonora Road Bridge (CR 1189), Hardin County

Figures 5 and 6 show the general conditions of the cores. Based on these photographs, there appears to be very little corrosion at the level of the steel for each bridge.



Figure 5. Typical Cores from Nicholas County



Figure 6. Typical Cores from Hardin County

However, two of the cores from Hardin County showed some corrosion. Figures 7 and 8 depict the corrosion. In both cases, the corrosion is associated with a crack in the concrete.



Figure 7. Corrosion at the Level of the Steel, Hardin County

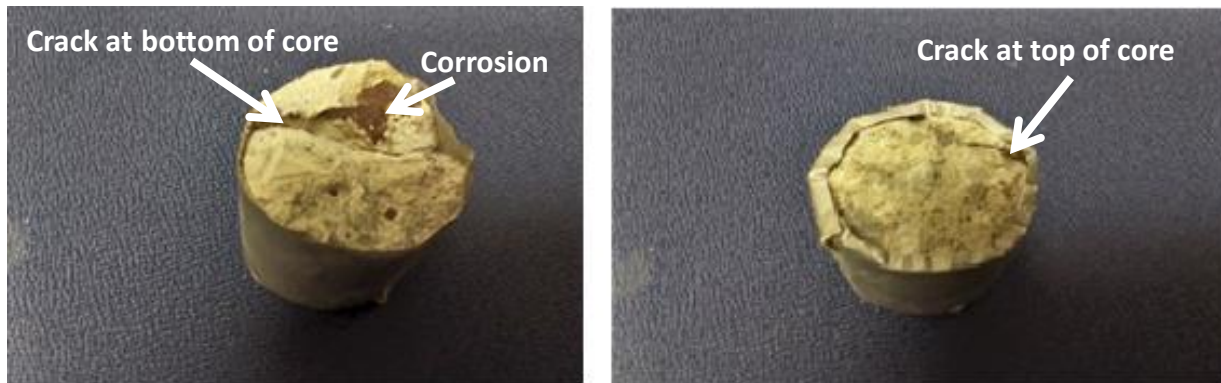


Figure 8. Corrosion Associated with a Crack in the Concrete Deck, Hardin County

The Rapid Migration Test (CTH) was used to determine if chlorides had migrated from the surface of the bridge deck down to the level of the steel. This test is described by Stanish et al. (16), and those authors are quoted here:

The depth of chloride penetration is determined by using a colorimetric technique in which a silver nitrate solution is used as a colorimetric indicator. When a silver nitrate solution is sprayed on a concrete containing chloride ions, a chemical reaction occurs. The chlorides combine with the silver to produce silver chloride, a whitish substance. In the absence of chlorides, the silver instead bonds with the hydroxides present in the concrete, creating a brownish color. This method was first investigated by Collepari, et al., 1970. Work done by Otsuki, et al., 1992 to determine the optimum concentration of silver nitrate solution to be used indicates that a 0.1N solution is suitable and that the color change border corresponds to the location of a soluble chloride concentration of 0.15% by weight of cement.

In this study, a number of the cores from each bridge were sprayed with a 0.1N solution of silver nitrate and allowed to sit for at least 24 hours. Typical results are shown in Figure 9.



Figure 9. Results of Core Testing with Silver Nitrate Solution for Chlorides

Figure 9 clearly shows the brown coloration caused by the application of the silver nitrate solution. This result was typical of all the cores tested, suggesting that there was no chloride penetration on either deck of the two bridges tested.

b. Conclusions

1. The depth to steel for the bridge on KY 32 over Scrubgrass Creek averaged 4.08 inches and had a coefficient of variation of 14.0 percent.
2. The depth to steel for the Old Sonora Road Bridge, Hardin County, averaged 2.12 inches and had a coefficient of variation of 13.8 percent.
3. The results of the Rapid Migration Test indicated there was no chloride penetration on either bridge deck.
4. A small amount of corrosion was present in approximately two places on the Old Sonora Road Bridge. However, each location was associated with a crack in the concrete that ran from the surface of the deck down to the level of the steel. This tends to confirm the idea that cracks on a bridge deck will allow water to penetrate to the level of the steel, which will initiate and promote the corrosion of steel.
5. No difference was noted in the performance of the steel when comparing one bridge with the other.

4. National Cooperative Highway Research Program Recommendations and Guidelines

Improved bridge deck performance has also been a focus for the National Cooperative Highway Research Program (NCHRP). In 2004, NCHRP Synthesis 333, *Concrete Bridge Deck Performance*, comprehensively analyzed past and current practices used to improve concrete bridge deck performance (2). Information was obtained through a literature review and surveys completed by highway agencies throughout the United States and Canada. This synthesis report found epoxy-coated reinforcements used in both layers of deck reinforcement to be effective in protecting against corrosion, although wet or chloride environments significantly diminished their protective effect. LMC overlays and low-slump dense concrete overlays were recommended as the best choice for bridge deck protection. The use of membranes as part of a waterproofing system have produced mixed results. Some highway agencies view membranes as a successful and cost-effective measure for new construction and rehabilitation, while others report poor performance and short service life. A shorter-than-expected service life is likely due to weathering and exposure to traffic that leads to debonding and stripping of an asphalt riding surface. The performance of sealers is difficult to assess due to inconsistencies between laboratory and field tests. Attempts to use cathodic protection are costly; and most have proven unreliable and required extensive maintenance.

NCHRP Synthesis 333 also detailed several design and construction practices to improve concrete bridge deck performance. Concrete constituent materials such as fly ash, silica fume, ground-granulated blast furnace slag, and high-range, water-reducing admixtures are suitable for decreasing the permeability of concrete overlays. Design practices to improve bridge deck performance include maintaining a minimum concrete cover of 64 mm or 2.5 inches, wet curing immediately and for at least seven days, use of a curing compound, and using smaller reinforcing bars at closer spacings. Additionally, environmental and weather conditions should always be taken into consideration during placement of any bridge deck protective system.

NCHRP Synthesis 425, *Waterproofing Membranes for Concrete Bridge Decks*, used results from surveys sent to transportation departments in both the United States and Canada to provide an overview of waterproofing membranes as an option for concrete bridge deck protection (18). While reviews of waterproofing membranes were generally favorable, such membranes are only one part of a waterproofing system. Accordingly, the success of the system is not wholly dependent on the membrane itself. The life of a waterproofing membrane also depends on the asphalt riding surface and can be extended through proper maintenance of that surface. Another important factor to consider is how well the membrane bonds to the bridge deck. To improve bonding, a primer is recommended between the bridge deck and membrane, and a tack coat is recommended between the membrane and the asphalt riding surface. Problems associated with waterproofing membranes, such as lack of adhesion between layers, are more common on existing bridge decks as opposed to new bridge decks. However, more states use them to rehabilitate existing bridge decks rather than having them as a requirement for new construction. Out of the 31 states that currently use waterproofing membranes, only four specify membranes exclusively for new bridge decks, while 11 specify membranes exclusively for existing bridge decks and 16 specify them for both new and existing bridge decks. This synthesis found that research on waterproofing membranes since 1995 is severely lacking, and thus suggested more investigations on existing waterproofing membranes.

The synthesis also recommended developing test standards to more accurately assess the usefulness of waterproofing membrane systems.

In 2009, NCHRP *Guidelines for Selection of Bridge Deck Overlays, Sealers, and Treatments* used responses from surveys sent to transportation departments throughout the United States, Canada, and Puerto Rico, to construct a set of guidelines for use in selecting the most appropriate bridge deck rehabilitation option (19). The guidelines outlined two basic steps: (1) deck characterization and (2) selection of repair option. The first step involves determining the extent of rehabilitation necessary through an assessment of the bridge deck's current condition. There are four important factors to consider in this assessment process: deck distress (e.g., spalling or delamination), time-to-corrosion of deck reinforcements, deck surface conditions (e.g., drainage problems or abrasion loss), and the concrete quality of the deck. Once the current state of the deck is known, a decision can be made as to whether the deck requires action, minor maintenance, installation of an overlay, or structural rehabilitation.

Step 2 involves selecting a repair option based on the extent of rehabilitation determined in Step 1. If a bridge deck does not require any repair action, regular assessment intervals should be assigned based on the bridge's condition. Maintenance of a bridge deck can take the form of patching, crack repair, or sealers. These maintenance options are appropriate when the deck shows minor distress. If the deck shows moderate distress but is still structurally sound, an overlay may be installed or replaced. Structural rehabilitation is the most extensive repair option, may be partial or full depth, and should be reserved for bridge decks in serious distress. When making a final decision on a specific rehabilitation effort, it is important to remember several other factors as well, such as traffic constraints, cost, and future expectations of the bridge deck.

NCHRP Report 566, *Guidelines for Concrete Mixtures Containing Supplementary Cementitious Materials to Enhance Durability of Bridge Decks*, provides detailed guidelines for selecting an optimum concrete mixture for bridge deck construction using locally sourced materials (3). Discrepancies among concrete materials from different locales can result in mixtures with very different properties. Thus, the quality of local materials is the best deciding factor when selecting an optimum concrete mixture. The process for selecting an optimum concrete mixture is organized into six steps:

1. The concrete performance requirements for the specific location must be determined through analysis of the local environment as well as through test methods.
2. The most suitable raw materials for use in the concrete mixture are logically selected after careful consideration of all available materials and possible sources.
3. An experimental matrix is designed for testing different combinations of the raw materials selected in Step 2.
4. This experimental matrix is employed to conduct actual testing of the proposed concrete mixtures.
5. The results obtained in Step 4 are analyzed with the desirability function to identify both the best tested concrete (BTC) and best predicted concrete (BPC).
6. Final testing and analysis is performed on the BTC and BPC to confirm the optimum concrete mixture.

5. State Standard Specifications

This chapter reviews KYTC's current policies regarding bridge deck construction and overlays, as well as those from several states surrounding Kentucky, to gain a better understanding of available overlay options. The types of overlays used in each state are charted in Appendix B.

a. Kentucky

The KYTC Structural Design Guidance Manual requires the use of Class AA concrete for bridge deck construction. However, section 601.03.04 of the current edition of the Kentucky Standard Specifications for Road and Bridge Construction mandates the use of Class AAA concrete in bridge decks. The strength requirement for Class AAA is 5,500 psi at 28 days. Conversely, the strength requirement for Class AA is 3,500 psi. There are differences in the water-to-cement ratio, minimum cement factor, and slump. Class AAA concrete has a minimum cement factor of 686 pounds per cubic yard (lbs./yd³) compared to 620 lbs./yd³ for the Class AA concrete. While a four (4) inch slump is permitted for Class AA concrete, Class AAA concrete is allowed a maximum slump of seven (7) inches. A table differentiating between these two classes of concrete, as well as the concrete classes specified by the other states in this section, can be found Appendix B. The Structural Design Guidance Manual further states that bridge deck slabs should be at least eight (8) inches thick, include epoxy-coated reinforcements in the top and bottom layer, and have a minimum cover of 2.5 inches for those reinforcements. Additional corrosion protection on newly constructed bridge decks, such as exotic overlay materials or corrosion inhibiting admixtures, should be considered only for critical structures that are unable to undergo extensive maintenance repairs that require long periods of closure. Typically, surface texture on bridge slabs is created through the formation of transverse grooves after the concrete has been placed, compacted, struck off, and screeded. If no texture is required, a surface is finished with a burlap drag. Wet curing is then applied using a Type II membrane-forming curing compound in combination with wet burlap. Wet curing of the fresh concrete continues for at least seven days. However, if a new bridge deck is to receive a special surface course or a waterproofing membrane, the curing compound is not used in the wet curing process.

Bridges are routinely inspected to maintain proper conditions. The KYTC 2017 Bridge Inspection Procedures Manual requires initial inspections (within 90 days of completion of work for all on-system bridges and within 180 days for all off-system bridges) to establish a baseline for future inspections. All bridges undergo routine inspections at least once every 24 months; sub-standard bridges are inspected once per year. Interim inspections are used to monitor specific deficiencies. They are scheduled depending on a bridge's age, traffic characteristics, and structural deficiencies.

Once it has been determined that a bridge deck requires restoration, construction of an LMC overlay or waterproofing membrane is typically specified. The KYTC Standard Specifications state that a Type I or Type III cement is used for an LMC overlay and must include both a water-reducing admixture and a Styrene-Butadiene latex admixture. LMC overlays are placed during nighttime hours when ambient temperatures are less than 85°F. At least 0.25 inch of an existing deck surface must be removed using mechanical scarifiers or grinders. If any epoxy, asphalt, foreign substances, or unsound patches remain, these materials should be removed using hammers or other small equipment if depth exceeds 0.25 inch. Repairing a deck surface includes repairing or replacing damaged steel reinforcements, restoring sections of spalled or deteriorated concrete,

patching holes in the deck, and then blast cleaning the surface. The deck surface is wetted at least an hour prior to placement of the overlay. Immediately before placement of the LMC overlay, a thin layer of the LMC mixture is brushed and scrubbed onto the wetted deck surface as a grout-bond coat. The LMC overlay is placed at a thickness of at least one (1) inch, or 1.25 inches if the overlay requires a textured finish. The overlay is consolidated using vibration and finished using a finishing machine. If a textured finish is required, it is obtained by performing a broom finish transversely across the surface. A LMC overlay is cured using wet burlap and polyethylene (PE) film four mils thick for 24 hours. After the initial 24-hour period, the burlap and PE film are removed, and the surface of the deck is air cured for an additional 48 hours if a Type I cement is used; an additional 24 hours is necessary if using Type III cement. A thin coat of epoxy-sand slurry is applied to the deck after it has been cured and dry at least 24 hours.

The Kentucky Standard Specifications also describe a fiberglass waterproofing membrane that is a one-step waterproofing and reflective-crack suppression system for bridge decks. The system is made up of a fiberglass-reinforced factory coating with an asphalt polymer and a strongly bonding contact adhesive on one side that bonds to the surface being treated. The material must conform to various ASTM tests for tensile strength, pliability, percent moisture, and permeability.

KYTC specifications do not include instructions for installing any type of waterproofing membrane.

b. Indiana

The INDOT 2013 Design Manual states that newly constructed bridge decks are to be made of Class C concrete at least eight (8) inches thick, with a 28-day compressive strength of at least 4,000 psi. All reinforcements are epoxy-coated. The top cover must be at least 2.5 inches. Maximum bar spacing is eight (8) inches. Regarding protection of newly constructed bridge decks, the 2016 Standard Specifications state that new bridge decks should be heavily broom-textured if they are to receive an LMC overlay to ensure maximum bonding.

Indiana's *Bridge and Culvert Preservation Initiative* (BCPI) program has the goal of more efficiently maintaining its bridge inventory. The program includes recommendations for both preventative and corrective maintenance actions. Bridges are inspected on a two-year cycle and given a condition rating. The bridge condition rating is then used to determine the depth and course of action necessary to maintain the integrity of the bridge. Corrective maintenance treatments specific to the bridge deck are more fully discussed in the INDOT 2013 Design Manual. Partial- or full-depth patching is used as a temporary solution to improve the riding surface of a bridge deck if a more-permanent technique cannot be used at the time. LMC overlays are the most commonly used rehabilitation technique, with an average service life of 15 years. Polymeric overlays (a flexible overlay consisting of an epoxy polymer combined with a special aggregate) are also used and have an average service life of 10 years. MSC overlays have been used since the early 1990s to provide a low diffusivity concrete overlay but are still considered experimental and must be approved before use. Indiana still observes the moratorium on waterproofing membrane systems due to their low reliability. Low-slump concrete overlays are not recommended because their performance is comparable to LMC overlays but are more expensive. Overlays may be replaced only if the existing overlay is removed first. INDOT also recommends the use of epoxy or silane sealants to prevent the ingress of chloride ions into the concrete bridge deck. The service

life of sealants is typically one to three years but results may vary; the cost-benefit ratio favors the use of sealants to extend the life of the bridge deck concrete.

Indiana Standard Specifications provide detailed installation instructions for a LMC overlay. Ambient temperature must be at least 45°F and rising, but no higher than 85°F. A power-operated mechanical milling machine is used to remove 0.25 inch of the existing deck surface. Some hand-chipping is permitted if necessary. Any remaining unsound concrete is removed through hand-chipping or hydro-demolition. The entire surface of the bridge deck is sandblasted before completing any necessary patching. The deck surface is pre-wetted and kept moist for at least an hour prior to placing the LMC overlay. Immediately before placing the overlay, a thin layer of the LMC overlay mixture is brush applied onto the wetted deck surface as a bond coat. The LMC overlay is placed to an elevation approximately 0.5 inch above the final grade, then consolidated with a vibrating mechanism and machine finished to the required grade. The surface of the LMC overlay is textured with transverse grooves. Curing of the finished concrete deck is accomplished using one layer of wet burlap, followed by either a second layer of wet burlap or a PE film placed approximately one hour after placing the first layer. The deck is wet cured for at least 24 hours, then all covering materials are removed and dry curing continues for an additional 72 hours.

c. Ohio

The Ohio DOT 2004 Bridge Design Manual states that bridge decks are to be made of Class QC 2 concrete at least 8.5 inches thick, with a 28-day compressive strength of 4,500psi. All reinforcements are epoxy-coated for protection against corrosion and have a minimum covering of 2.5 inches. Other types of protection for new bridge decks include drip strips, Type 3 waterproofing (a primer coat and waterproofing membrane consisting of a high-density asphalt mastic between two layers of polymeric fabric), or an asphaltic concrete wearing surface. Overlays are not placed on new bridge decks. The 2013 Ohio DOT Standard Specifications require that concrete bridge decks be cured with wet burlap for at least seven days, then sprayed with a membrane curing material.

Ohio DOT's bridge inventory preservation strategy is included in the Bridge Design Manual. Estimation of bridge deck repair quantity is done through in-depth field inspections that include visual inspections, sounding for deterioration, and core evaluation. After evaluation and testing, the unsound area of the bridge deck is estimated as a percentage of the total deck area. When this is greater than or equal to 60%, replacement of the bridge deck instead of rehabilitation is warranted.

The Ohio DOT bridge maintenance manual outlines repair options for bridge decks. Sealing with a silane sealer is recommended to repair minor scaling, aggregate popouts, or seal minor cracking. The life expectancy for sealing a concrete bridge deck with silane is about five years. Scaling may also be repaired with a concrete bridge deck overlay. The Bridge Design Manual states microsilica modified concrete (MSC) is state of the art for use in bridge deck overlays, but the manual also specifies LMC and superplasticized dense concrete (SDC) overlays. A Type 3 waterproofing membrane is only suggested for protection of newly constructed bridge decks, and not bridge deck restoration. An epoxy waterproofing membrane may only be allowed for bridge deck restoration on bridges that cannot support the extra load induced by a concrete overlay.

Ohio DOT Supplemental Specifications 847 and 848 provide detailed instructions for concrete bridge deck overlay installations. The existing concrete overlay is removed if applicable. For bridge decks without an existing concrete overlay, 0.25 inch of the existing deck surface is removed, unless there is unsound concrete, in which case the depth removed may exceed 0.25 inch. Any concrete removal is accomplished by either scarification and chipping or hydro-demolition. After the necessary portion of the existing concrete surface is removed, all surfaces and exposed steel are blast cleaned. The deck surface is wetted and kept wet for at least an hour prior to placing the overlay. MSC and LMC overlays are placed at a minimum of 1.25 inches thick, and SDC overlays are placed at a minimum of 1.75 inches thick. The fresh concrete overlay is finished using a self-propelled finishing machine within 10 minutes of overlay's placement. The surface of the concrete overlay is textured with a random pattern of transverse grooves. Curing operations depend on the type of concrete overlay installed. LMC overlays are wet cured with a single layer of burlap and either four mils of white opaque polyethylene film or a wet burlap-white opaque polyethylene sheet for 48 hours. The covering is removed after 48 hours and the overlay is air-cured for another two days. MSC and SDC overlays are wet cured with a single layer of burlap and either four mils of white opaque polyethylene film or a wet burlap-white opaque polyethylene sheet for 72 hours.

d. West Virginia

The West Virginia Division of Highways (WVDOH) 2010 Standard Specifications state that bridge decks are to be constructed using Class K concrete unless plans specify Class H concrete, which is also allowed. The WVDOH 2014 Bridge Design Manual states that monolithic bridge decks are at least eight (8) inches thick and include epoxy-coated reinforcements in both layers, with a minimum top cover of 2.5 inches. If a concrete bridge deck has a design ADT greater than 3,500 vehicles per day or is a National Highway System bridge, it receives a dual protection deck system which depends on the maximum span length. In these cases, bridges with a span length of less than or equal to 350 feet receive a Class H full depth concrete deck, and bridges spanning more than 350 feet receive a specialized concrete overlay in combination with a Class K concrete deck. Concrete bridge decks are wet cured for at least seven days using wet burlap. A membrane-forming curing compound may be used as well, but only on bridge decks constructed from Class K concrete.

Bridge inspection intervals are determined based on condition. Generally, bridges are inspected once every two to four years. Inspections are performed according to the 1990 WVDOH *Bridge Inspection Manual*, which also references various national standards for bridge inspection. The extent and type of rehabilitation needed for a bridge is determined based on its current condition, future travel demand estimates, and anticipated capital and maintenance investments. Basic repairs are temporary and include crack repair or minor patching. Repairs are typically considered temporary with the intention of eventually constructing either a bridge deck overlay or a full deck replacement.

For concrete deck overlays, the WVDOH Standard Specifications require the use of either LMC or MSC overlays. The concrete used in LMC overlays must include an approved styrene-butadiene admixture, and the concrete used in MSC overlays must include both an approved microsilica admixture and a high range water-reducing admixture. The existing deck surface is removed down to the top mat of rebar using roto-milling or hydro-demolition. Any unsound or other delaminated

areas are also removed. The surface and any exposed steel are blast cleaned. Prior to placing the concrete overlay, the surface of the deck is thoroughly wetted. The minimum thickness of concrete overlay allowed is 1.25 inches. After compaction and finishing, the fresh concrete is textured with a wet burlap drag. Curing begins using wet burlap. LMC overlays receive an additional four mils of PE film over the burlap to assist curing. Both types of concrete overlays are wet cured for 96 hours. The burlap remains saturated throughout the 96-hour period. After the wet-cure period, the PE film and burlap layers are removed. An LMC overlay is air cured for an additional 48 hours.

e. Virginia

The Virginia Department of Transportation's (VDOT) Road and Bridge Specifications state that all bridge superstructure concrete is to be Class A4 and all steel reinforcements in bridge decks are to be epoxy-coated. Concrete in new bridge decks is consolidated by mechanical vibration, screeded, and textured with grooves sawed transversely to the centerline. Additionally, a multi-ply damp fabric is dragged over the deck surface to complete the finish. Deck tolerances of 0.25 inch in 10 feet are required if a bridge deck is to receive an asphalt concrete overlay of one inch or more. Concrete for new decks is wet cured for at least seven days using white PE sheeting, or until 70% of the maximum required concrete strength has been achieved. Wet burlap may also be used, but it is not required for curing the concrete. Following the wet-cure period, a white pigmented curing compound is spray applied to the deck surface.

VDOT Road and Bridge Specifications indicate that LMC and MSC overlays and waterproofing membranes are used to repair concrete bridge decks. PMC overlays are only allowed under special provisions. When preparing to place a concrete overlay, VDOT requires milling of 0.5 inch of the existing deck surface. Any patching or other repairs must be completed as necessary to ensure a proper bond between the deck and the overlay. The surface of the deck is thoroughly cleaned within 24 hours of placing the overlay. The deck surface is wetted and kept wet for at least an hour prior to placing the concrete overlay. When the overlay is placed, the ambient temperature must be at least 50°F and rising but not above 85°F. A thin layer of the concrete mixture is brushed onto the deck surface immediately before placement of the overlay. The minimum thickness of the overlay is limited to 1.25 inches. The fresh concrete is wet cured with burlap immediately after finishing. LMC overlays require a 48-hour wet cure, followed by a 48-hour dry cure. MSC overlays require a 72-hour wet cure, followed by the application of a liquid membrane-forming curing compound.

Waterproofing membranes used in Virginia are one of the following five types:

1. A primer and prefabricated membrane consisting of a laminate formed with suitable plasticized coal tar and reinforced with nonwoven synthetic fibers or glass fibers;
2. A primer, mastic, and prefabricated membrane consisting of a laminate formed of rubberized asphalt and reinforced with synthetic fibers or mesh;
3. A primer and prefabricated membrane consisting of a laminate formed with suitably plasticized asphalt, reinforced with open-weave fiber glass mesh, and having a thin polyester top surface film;
4. A hot-poured liquid elastomeric membrane with protective covering; or
5. A surface conditioner and a hot-applied rubberized asphalt membrane with protective covering.

When waterproofing membranes are installed on concrete bridge decks, the deck is thoroughly cleaned and dried prior to installation. A primer is first applied to the surface of the deck in accordance with the membrane manufacturer's installation instructions. Placement of the membrane begins at the lowest point of the deck to facilitate drainage. Preformed membrane strips are overlapped at least four inches during installation. A wide-tipped torch, an adhesive, or rollers are used to ensure that the membrane strips are well-sealed. Liquid membranes are heated per the manufacturer's instructions, sprayed onto deck surface, and then worked in with squeegees until a uniform thickness is achieved. Immediately afterwards, a protective covering is placed over the liquid membrane to ensure adhesion. Waterproofing membranes are overlain with an asphalt riding surface within 24 hours of the membrane being applied. The asphalt riding surface must be at least 1.5 inches thick after compaction. VDOT requires electrical resistance tests after installation to determine the system's effectiveness. Any areas reading less than 500,000 ohms are evaluated and replaced if deemed detrimental to the system.

Virginia specifications also outline instructions for the application of waterproofing epoxy-resin compounds to seal bridge decks. The surface of the deck is sandblasted and cleaned. Two coats of the epoxy-resin compound are applied. The first coat is applied at a rate of 1 gallon/75ft², and the second coat is applied at a rate of 1 gallon/50ft². Sufficient sand is used to completely cover each coat of epoxy while it is still wet. Curing instructions are left up to the manufacturer.

f. Tennessee

The Tennessee Standard Specifications for Road and Bridge Construction require bridge decks to be constructed of Class D concrete, be at least eight (8) inches thick, and have a 28-day compressive strength of at least 4,000 psi. All reinforcements used in the bridge construction are epoxy-coated. Bridge decks are cured for at least seven days using a membrane-curing compound in combination with a damp layer of burlap or other approved material.

PMC overlays are used on both new and existing bridges. Either Type I or Type III Portland cement may be used, which must contain a polymer admixture. Overlays are placed when the ambient temperature is between 55° and 75°F, wind velocity is low, and relative humidity is normal to high. Any unsound concrete is removed using hydro-demolition (or by hand around areas of spalling or exposed reinforcements) to a depth specified on the plans. After hydro-demolition, the entire deck is power washed to clean it and remove remaining debris. After placement, the fresh concrete is consolidated and finished using a self-propelled, vibrating screed-type finishing machine. Mechanical means are employed to achieve texture, forming transverse grooves across the overlay surface. A layer of wet burlap covered by a sheet of white plastic to retain moisture is used to cure the freshly placed concrete. Type I cement requires a 24-hour wet cure, followed by 24-hour dry cure. Type III cement requires a 12-hour wet cure, followed by 12-hour dry cure. Both Type I and Type III cement must reach a compressive strength of 3,000 psi before traffic loading is allowed.

Waterproofing membranes may also be used on concrete bridge deck surfaces. These membranes may be one of two types: either a membrane laminate formed with suitable plasticized coal tar and reinforced with non-woven synthetic fibers or glass fibers, or a laminate of rubberized asphalt reinforced with synthetic fibers or mesh. Before applying either type of waterproofing membrane system, the deck's surface is cleaned and dried. The manufacturer's instructions are followed regarding the use of a tack coat or primer. Installation of the waterproofing membrane system

begins by placing the first membrane strip adjacent to the curb and forming a butt joint. Then each membrane strip is added so that it overlaps the previous one. It is important to begin at the lowest point to facilitate drainage, with water running over the laps. A wide-tipped torch, an adhesive, or rollers are used if necessary to ensure that the membrane strips are well-sealed. An asphalt overlay is placed immediately after the waterproof membrane is sufficiently in place. An adhesive bond coat between the membrane and the asphalt overlay may be used to ensure a good bond between the waterproofing membrane system and the asphalt overlay.

g. Washington

Washington State DOT (WSDOT) has a comprehensive Bridge Deck Program aimed at rehabilitating bridge decks to prevent costly total deck replacements. Bridges are designated as in need of an overlay once the amount of minor repairs and/or patching exceeds 2% of the total deck area (20). WSDOT currently chooses from among three types of modified concrete overlays: LMC, MSC, or fly-ash modified concrete (FAMC). Both low-slump, dense modified concrete (LSDMC) and rapid-set, latex modified concrete (RSLMC) for use in concrete overlays have been discontinued due to poor performance.

Before placing the overlay, a hydro-milling machine with at least 7,000 psi of water pressure is used to remove 0.5 inch of good concrete and any previous patches. Any areas below the top mat of reinforcing steel are repaired using 4,000 psi concrete. The repaired areas cure for at least 24 hours before additional work continues. Once these preparation steps have been completed and the temperature of the existing deck is between 45° and 75°F, the concrete overlay is placed at a thickness of 1.5 inches using a finishing machine. The overlay is wet cured with burlap for at least 42 hours. Only after the concrete has reached at least 3,000 psi and has been strength tested per ASTM C805 may it be opened to traffic.

WSDOT's use of concrete bridge deck overlays to preserve the integrity of its bridge inventory has been very successful. Only 14 bridge deck replacements (1.3% of total statewide deck area) have been necessary between 1986 and 2009 as result of its comprehensive Bridge Deck Program (21).

6. American Society of Civil Engineers Infrastructure Report Card

The American Society of Civil Engineers (ASCE) publishes a report card every four years that grades different aspects of America's infrastructure as well as the infrastructure of individual states. In this section, grades given to an individual state's bridges are compared to that state's specifications for bridge deck overlay methods. States were chosen from the Wet Freeze climate zone (Figure 10) to expand the state comparisons begun in the previous section. As Kentucky is located in this zone, the similar climate conditions of the other states in this zone will provide the best backdrop for comparing bridge deck overlay methods intended to prevent chloride and moisture penetration. The entire list of states and their grades that were compared for this section can be found in Appendix C.



Figure 10. Climate Zone Map (22).

Grades were assigned based on the following criteria: capacity, condition, funding, future need, operation and maintenance, public safety, resilience, and innovation. On the 2017 report card, the United States received a C+ for its bridges. A C grade is a mediocre rating and indicates that assets within that category requires attention. Kentucky received a D for its bridges, which is a poor rating that indicates assets within that category are at risk. The D grade was the lowest grade given to any state — Kentucky was only one of two states to receive this grade. Overall, there was not a correlation between a specific type of overlay method used and the grade given to a state's bridges. The two highest grades awarded by ASCE to any state in a bridge category were C+ and B-. A grade of B is a good rating, indicating that the bridges are adequate for now. Out of the states KTC selected, the following received these highest grades: Indiana (C+), Illinois (C+), Tennessee (B-), and Maryland (B-).

Because there was no correlation between highly rated bridges and specific overlay types used, Kentucky's specifications for overlay placement were next compared to the specifications from the states in which bridges earned the highest grades (Indiana, Illinois, Tennessee, and Maryland).

Kentucky's preferred methods for bridge deck overlay are LMC overlays and waterproofing membranes with asphalt overlay. Indiana and Maryland also use LMC overlays, and overall the methods used by the three states when placing these overlays are the same. Recommended curing time is the most noticeable difference. Wet curing methods and durations are consistent across the three states, but Indiana and Maryland specify an additional 72 hours of dry curing time. Indiana Standard Specifications do not state a type of cement to use in its LMC overlays, but Maryland specifies Type I cement. Kentucky, however, only specifies an additional 48 hours for Type I cement, and 24 hours for Type III cement. Furthermore, although Kentucky requires that curing time should not occur when temperatures are less than 50°F, both Indiana and Maryland further specify that any day temperatures dip below 50°F will not count towards the curing period. Maryland also has the following restrictions in place: the LMC shall not be placed adjacent to another LMC surface course that is less than 96 hours old. Grinding or chipping an existing concrete pavement within six feet of a LMC surface course is not permitted until the LMC has cured for at least 48 hours. If delays of less than one hour occur during placement, wetted burlap is placed over the ends of the concrete to prevent drying. If placement delays exceed one hour, bulkheads or dams are installed and placement cannot proceed until 12 hours have passed.

In addition to Kentucky, Illinois and Tennessee specify the use of waterproofing membranes with asphalt overlays. Each state specifies a different type of waterproofing membrane system, yet all systems have some sort of fiberglass component in common. Kentucky specifies a high-strength, fiberglass-reinforced factory coating with an asphalt polymer and a strongly bonding contact adhesive on one side that bonds to the surface being treated. Illinois specifies a waterproofing membrane system that consists of a penetrating primer, a built-up coal tar pitch emulsion membrane with two plies of coated glass fabric, and a 0.5 inch-thick asphalt sand seal protection layer. Tennessee specifies two types, either a pre-formed membrane laminate formed with suitable plasticized coal tar and reinforced with non-woven synthetic fibers or glass fibers; or a pre-formed laminate of rubberized asphalt, reinforced with synthetic fibers or mesh. The waterproofing membrane systems used by Illinois and Tennessee differ significantly in terms of both components and installation. The systems used by Tennessee are similar to waterproofing membrane systems encountered in the research conducted for this report. The system Illinois uses, however, is similar to the methods used by Tennessee to waterproof Portland cement concrete masonry surfaces, as described in Section 605 of the Tennessee Standard Specifications. The most noteworthy difference among the specifications for each state is that Kentucky provides performance specification but without any guidance on installation procedures, while both Illinois and Tennessee provide detailed method specifications.

ASCE included funding as one criteria to evaluate bridges, so a comparison was performed between the amount of funding allocated towards a state's bridges and the condition of those bridges. Only funding data from the Federal Highway Bridge Fund was readily available, and more funding from the Federal Highway Bridge fund (per bridge) did not necessarily correlate to a higher grade received, as seen in Appendix C.

7. Discussion

State standard specifications for new bridge deck construction are consistent across all the states reviewed for this study. Based on this observation and a comparison to NCHRP recommendations to improve new bridge deck performance, it appears that Kentucky is up to date on best practices for new bridge deck construction.

An investigation into bridge deck overlay practices used across various states has made evident the wide range of available options for bridge deck rehabilitation. Appendix B contains a table that compares bridge deck overlay practices across various states. Included in the table are bridge deck overlay methods described in state standard specifications, bridge design manuals, and/or bridge repair manuals from each state.

Of the states reviewed for this study, waterproofing membranes and LMC overlays are the most commonly used methods for bridge deck rehabilitation. Out of 23 states assessed, 16 states employ waterproofing membranes and 15 states employ LMC overlays. Widespread LMC overlay use is an expected outcome based on the research reviewed regarding bridge deck rehabilitation. In addition to their proven performance, LMC overlays provide the longest service life and the NCHRP recommends them as one of the best choices for bridge deck protection.

Waterproofing membranes have attained mixed results, most likely due to difficulty achieving a sufficient bond between the layers that make up a waterproofing system, or other construction or installation-related issues. Despite these difficulties, the use of waterproofing membranes is widespread in the Wet Freeze climate zone, and research shows they may serve as an effective bridge deck rehabilitation option. For instance, a report published by Purdue University in 2013, reviewed previously in this report, recommended that Indiana lift its moratorium on waterproofing membranes due to the potential for waterproofing membranes to be the most effective protective system as long as they are installed correctly. The importance of proper installation is emphasized both in this Purdue University report and by the NCHRP. The Purdue University report further recommended that INDOT develop standard specifications for using waterproofing membrane systems to ensure successful installation. The NCHRP specifically recommends the use of a primer between the bridge deck and waterproofing membrane, and a tack coat between the membrane and asphalt riding surface to improve bonding between all layers. Although Kentucky currently allows waterproofing membranes, KYTC standard specifications for their use is limited to stating that a fiberglass waterproofing membrane system is allowed, but they do not include any guidelines for application. Other states that allow waterproofing membranes, particularly states which have earned high grades for their bridges, provide detailed instructions regarding their installation. Further use of waterproofing membranes in Kentucky should be considered and monitored for performance, and instructions for their installation subsequently developed.

MSC overlays follow as the next most commonly used method, although with more limited use — only 7 of the 23 states assessed permit this type of overlay. Indiana considers it to be in an experimental phase, allowing for its use only in certain circumstances, but Ohio considers microsilica concrete to be state of the art for use in bridge deck overlays because it is less permeable than other options. It is highly recommended that Kentucky begin to investigate the possible advantages of using MSC overlays based on these observations.

Other types of modified concrete overlays include superplasticized dense concrete (SDC), fly-ash modified concrete (FAMC), and polymer modified concrete (PMC). The use of these options is not particularly widespread throughout the states reviewed for this report, but some states allow for their use. Minnesota and Missouri allow PMC as one option for overlays, and Tennessee mandates PMC exclusively for overlays. As one of the concrete choices available for overlays in Washington, FAMC overlays play an effective role in WSDOT's efforts to preserve their bridge inventory (20).

Silane and/or epoxy sealers are used more as a preventative approach than rehabilitation. Only two of the states investigated here make use of them. Ohio uses sealers to repair minor defects in bridge decks, and Indiana applies them to bridge decks in an effort to block the ingress of chloride ions. However, according to Indiana DOT, the service life of either type of sealer is short (less than three years) and their success rate has also been disappointing. Nevertheless, the low initial cost of sealers justifies them as a possible option for mitigating concrete bridge deck deterioration.

Rosphalt is a polymer-modified asphalt possessing negligible permeability when mixed according to the manufacturer's directions. It requires little curing time and eliminates the need for an additional waterproofing membrane when applied on bridge decks as a protective overlay. The use of Rosphalt is not currently accepted as a standard practice but it has been applied experimentally. The majority of studies reviewed here found the performance of Rosphalt to be favorable. Despite the proven advantages of using Rosphalt overlays instead of traditional overlays (e.g., minimized traffic disruption due to shorter installation periods, and greater durability), some studies have found Rosphalt to be too expensive to serve as a viable alternative to traditional overlays. However, a cost comparison study conducted for KYTC found that installing traditional LMC overlay over three bridges would be costlier than Rosphalt overlays for a rehabilitation project of the I-64 Riverside Expressway in Louisville, Kentucky (11). Based on the generally favorable performance of Rosphalt, as well as the contradictory results regarding its costs, it is recommended that KYTC adopt the experimental use of Rosphalt to conduct a more definitive cost-benefit analysis.

There is a wide range of available bridge deck overlay options, each with its advantages and disadvantages. It is important to use a comprehensive approach when selecting the best option for a given circumstance because there is no one best overlay option that applies universally to every situation. For instance, the NCHRP-published guidelines for selecting the most appropriate bridge deck rehabilitation option — *Guidelines for Selection of Bridge Deck Overlays, Sealers, and Treatments* — and the Indiana DOT's Bridge and Culvert Preservation Initiative describes a range of available options to better maintain the state's bridge inventory. Currently, KYTC only approves LMC overlays and waterproofing membranes as standard practice. This study recommends experimentally using alternative methods, monitoring their performance, and developing proper installation instructions.

It is vital that all installation instructions for any bridge deck rehabilitation method are adhered to strictly. Instructions for installing LMC overlays are provided in Kentucky Standard Specifications and must be closely followed to ensure the LMC overlay has a long service life. Instructions for the installation of waterproofing membranes, however, are severely lacking. The Cabinet should develop more specific instructions for the installation of waterproofing membranes to ensure the

success of this method. Additionally, the development of detailed installation instructions for any new bridge deck rehabilitation method adopted in the future is important for ensuring its successful implementation.

8. Summary and Recommendations

The search for an effective bridge deck protective system has been a research topic since concrete bridge deck deterioration was first identified as a critical problem in the 1970s. The two most commonly used methods of bridge deck protection or rehabilitation are concrete overlays and waterproofing membrane systems. Concrete overlays can be supplemented with admixtures and are divided into the following types: latex modified concrete (LMC), microsilica concrete (MSC), superplasticized dense concrete (SDC), fly-ash modified concrete (FAMC), and polymer modified concrete (PMC). Waterproofing membrane systems consist of either preformed membrane strips or a constructed-in-place liquid membrane that is overlaid with an asphalt riding surface. The research reviewed for this report, as well as various state standard specifications, have provided several insights into which methods may provide longer lasting bridge deck overlays. All of the methods mentioned above are used in at least one state, but LMC overlays are the most commonly used, followed by MSC overlays.

The two most critical findings of this research are: (1) the importance of a comprehensive approach when selecting a bridge deck rehabilitation method, and (2) it being imperative to properly follow instructions when installing overlays. Failure to follow instructions could lead to an ineffective overlay with a shortened life span. Based on the literature reviewed for this study, the following recommendations are made to develop longer lasting bridge deck overlays:

- Continue the use of LMC overlays.
- Consider the further use of waterproofing membranes while documenting installation procedures and long-term performance characteristics.
- Begin experimental use of the following alternative methods — MSC, SDC, FAMC, PMC, and Rosphalt overlays — to expand the number of options KYTC has to choose from when conducting a bridge rehabilitation project.
- Develop guidelines for selecting the most suitable method for bridge deck protection or rehabilitation for any given project.
- Ensure clear and detailed installation instructions are available for all approved bridge deck rehabilitation methods.
- Stress the importance of strict adherence to all installation instructions.

References

1. Havens, J. H., Hopwood, T., and Courtney, E. E., **Bridge Decks and Overlays**, Research Report UKTRP 87-1, Kentucky Transportation Research Program, University of Kentucky, College of Engineering, January, 1987.
2. Russell, Henry G, NCHRP Synthesis Report 333, **Concrete Bridge Deck Performance** National Cooperative Highway Research Program, Transportation Research Board, Washington, D.C., 2004.
3. **Guidelines for Concrete Mixtures Containing Supplementary Cementitious Materials to Enhance Durability of Bridge Decks**, NCHRP Report 566, Transportation Research Board, Washington D.C., 2007.
4. Rahal, A.S., **Bridge Decks Constructed for Increased Durability**, Research Report 402 KYP-71-25, Kentucky Bureau of Highways, Division of Research, October, 1974.
5. Hopwood, Theodore II, James H. Havens, and Edgar E. Courtney, **Summary of Experimental Bridge Features**, Research Report UKTRP-87-5, Kentucky Transportation Research Program, University of Kentucky, College of Engineering, March, 1987.
6. Hunsucker, David Q., and Michael D. Stone, **Performance of Pyrament Cement Concrete in a Highway Bridge Deck**, Research Report KTC 95-9, Kentucky Transportation Center, University of Kentucky, College of Engineering, May, 1995.
7. Hunsucker, David Q., and Michael D. Stone, **Performance of Shrinkage Compensating Bridge Deck Concrete (Class S) I-75, Kenton County**, Research Report KTC 95-8, Kentucky Transportation Center, University of Kentucky, College of Engineering, May, 1995.
8. Hunsucker, David Q., and Michael D. Stone, **Use of Class AA Concrete Modified with a High-Range Water Reducing Admixture in a Full-Depth Bridge Deck Slab US 127, Lincoln County**, Research Report KTC 95-21, Kentucky Transportation Center, University of Kentucky, College of Engineering, September, 1995.
9. Sprinkel, Michael M., and Alex K. Apeageyi, **Evaluation of the Installation and Initial Condition of Rosphalt Overlays on Bridge Decks**, Final Report FHWA/VCTIR 13-R5, Virginia Center for Transportation Innovation and Research, June, 2013.
10. Ventry, William F., **Value Engineering Study of I-64 Riverside Rehabilitation**, VE Group, L.L.C. with Kentucky Transportation Cabinet, February, 2007.
11. **Bridge Deck Resurfacing using Rosphalt 50**, Technical Report 03-1, Maine Department of Transportation, Transportation Research Division, December, 2004.

12. Rowe, Geoffrey M., Phillip Blankenship, and Doug Zuberer, **Evaluation of Rheology and Engineering Properties of a Bridge Deck Thermo-Plastic Waterproofing Material**, 2010 FHWA Bridge Engineering Conference, April 2010.
13. Griffin, James J., Issam E. Harik, and Ching Chiaw Choo, **Performance Evaluation of Bridges with Structural Bridge Deck Overlays (SBDO)**, Research Report KTC-06-05/FRT81-82-97-1F, Kentucky Transportation Center, University of Kentucky, College of Engineering, March, 2006.
14. Chiaw, Choo Ching, and Issam E. Harik, **Performance Evaluation of Concrete Bridge Decks Reinforced with MMFX and SSC Rebars**, Research Report KTC-06-02/FRT113-01-1F, Kentucky Transportation Center, University of Kentucky, College of Engineering, January, 2006.
15. Frosch, Robert J., Michael E. Kreger, and Brad V. Strandquist, **Implementation of Performance-Based Bridge Deck Protective Systems**, Publication FHWA/IN/JTRP-2013/12, Joint Transportation Research Program, Indiana Department of Transportation and Purdue University, West Lafayette, Indiana, June, 2013.
16. Stanish, K.D., Hooton, R.D. and Thomas M.D.A., **Testing the Chloride Penetration Resistance of Concrete: A Literature Review**, FHWA Contract DTFH61-97-R-00022, University of Toronto, Department of Civil Engineering, Toronto, Canada, 1997.
17. Thomas, M.D.A., Pantazopoulou, S.J., and Martin-Perez, B., **Service Life Modelling of Reinforced concrete Structures Exposed to Chlorides – A Literature Review**, Ontario Ministry of Transportation, University of Toronto, 1995.
18. **Waterproofing Membranes for Concrete Bridge Decks**, NCHRP Synthesis Report 425, National Cooperative Highway Research Program, Transportation Research Board, Washington D.C., 2012.
19. Krauss, Paul D., John S. Lawler, and Kimberly A. Steiner, **Guidelines for Selection of Bridge Deck Overlays, Sealers, and Treatments**, National Cooperative Highway Research Program, Transportation Research Board, Washington, D.C., May, 2009.
20. Wilson, DeWayne, **Washington State DOT's use of Modified Concrete Overlays to preserve bridge decks**, Concrete Bridge Views, Federal Highway Administration and National Concrete Bridge Council, Issue 75, March/April 2014.
21. **Bridge Deck Preservation Program**, Washington State Department of Transportation, 2012, Web. https://pavementvideo.s3.amazonaws.com/2012_WBPP/PDF/9%20-%20Bridge%20Deck%20Preservation%20Program%20-%20DeWayne%20Wilson.pdf

22. Zhang, Weiguang, Shihui Shen, Prasanta Basak, Haifang Wen, Shenghua Wu, Ahmed Faheem, and Louay N. Mohammad, **Development of Predictive Models for Initiation and Propagation of Field Transverse Cracking**, Transportation Research Record: Journal of the Transportation Research Board, No. 2524, Transportation Research Board, Washington D.C., 2015.

Appendix A

Structure Inventory and Appraisal Sheet (English Units)

Bridge Key: 10964 Agency ID: 091B00008N SR: 39.7 SD/FO: SD

IDENTIFICATION

State 1: 21 Kentucky Struc Num 8: 091B00008N
 Facility Carried 7: KY-32 Location 9: 4.2 MI NE OF JCT KY 1455
 Rte. (On/Under) 5A: Route On Structure Rte. Signing Prefix 5B: 3 State Hwy
 Level of Service 5C: 1 Mainline Route Number 5D: 00032
 Directional Suffix 5E: 0 N/A (NBI) % Responsibility: Unknown
 SHD District 2: District 9 County Code 3: Nicholas (091)
 Place Code 4: FIPS 0000 Mile Post 11: 13.896 mi
 Feature Intersected 6: TTI RR & SCRUBGRASS CREEE
 Latitude 16: 38° 20' 32" Longitude 17: 083° 57' 47"
 Border Bridge Code 98: Unknown (P)
 Border Bridge Number 99

INSPECTION

Frequency 91: 24 months Inspection Date 90: 8/27/2014 Next Inspection: 8/27/2016
 FC Frequency 92A: 24 months FC Inspection Date 93A: 8/27/2014 Next FC Inspection: 8/27/2016
 UW Frequency 92B: NA UW Inspection Date 93B: NA Next UW Inspection: NA
 SI Frequency 92C: NA SI Date 93C: NA Next SI: NA
 Element Frequency: 24 months Element Insp. Date: 8/27/2014 Next Elem. Insp.: 8/27/2016

CLASSIFICATION

Defense Highway 100: 0 Not a STRAHNET hwy Parallel Structure 101: No || bridge exists
 Direction of Traffic 102: 2-2-way traffic Temporary Structure 103: Not Applicable (P)
 Highway System 104: 0 Not on NHS NBIS Length 112: Long Enough
 Toll Facility 20: 3 On free road Functional Class 26: 07 Rural Mjr Collector
 Defense Hwy 110: 0 Not a STRAHNET hwy Historical Significance 37: 5 Not eligible for NRHP
 Owner 22: 01 State Highway Agency
 Custodian 21: 01 State Highway Agency

STRUCTURE TYPE AND MATERIALS

Number of Approach Spans 46: 4 Number of Spans Main Unit 45: 1
 Main Span Material Design 43 A/B:
 3 Steel 10 Truss-Thru
 Deck Type 107: 1 Concrete-Cast-in-Place
 Wearing Surface 108A: 3 Latex Concrete/Similar
 Membrane 108B: 0 None
 Deck protection 108C: None

CONDITION

Deck 58: 5 Fair Super 59: 5 Fair Sub 60: 4 Poor
 Culvert 62: N N/A (NBI) Channel/Channel Protection 61: 7 Minor Damage

AGE AND SERVICE

Year Built 27: 1932 Year Reconstructed 106: 0
 Type of Service on 42A: 1 Highway
 Type of Service under 42B: 7 Railroad-waterway
 Lanes on 28A: 2 Lanes under 28B: 0 Detour Length 19: 9.9 mi
 ADT 29: 732 Truck ADT 109: 8% Year of ADT 30: 2015

LOAD RATING AND POSTING

Inventory Rating Method 65: 2 ASR tons Operating Rating Method 63: 2 ASR tons
 Inventory Rating 66: HS14.4 Operating Rating 64: HS22.7
 Design Load 31: 2 M 13.5 (H 15) Posting 70: 5 A/Above Legal Loads
 Posting Status 41: A Open, no restriction

GEOMETRIC DATA

Length Max Span 48: 100.07 ft Structure Length 49: 250.00 ft
 Curb/Sdwk Width L 50A: 0.50 ft Curb/Sidewalk Width R 50B: 0.50 ft
 Width Curb to Curb 51: 20.01 ft Width Out to Out 52: 21.00 ft
 Approach Roadway width 32: (w/ shoulders) 23.95 ft Median 33: 0 No median
 Deck Area: 5,249.34 sq. ft
 Skew 34: 0.00° Structure Flared 35: 0 No flare
 Vertical Clearance 10: 328.05 ft Horizontal Clearance 47: 20.01 ft
 Minimum Vertical Clearance Over Bridge 53: 328.05 ft
 Minimum Vertical Underclearance Reference 54A: R Railroad beneath struc
 Minimum Vertical Underclearance 54B: 21.76 ft
 Minimum Lateral Underclearance Reference R 55A: R Railroad beneath struc
 Minimum Lateral Underclearance R 55: 18.25 ft
 Minimum Lateral Underclearance L 56: 0.00 ft

APPRAISAL

Bridge Rail 36A: 0 Substandard Approach Rail 36C: 0 Substandard
 Transition 36B: 0 Substandard Approach Rail Ends 36D: 0 Substandard
 Str Evaluation 67: 4 Minimum Tolerable Deck Geometry 68: 3 Intolerable - Correct
 Underclearance, Vertical and Horizontal 69: 5 Above Tolerable
 Waterway Adequacy 71: 8 Equal Desirable Approach Alignment 72: 4 Minimum Tolerable
 Scour Critical 113: 8 Stable Above Footing

PROPOSED IMPROVEMENTS

Bridge Cost 94: \$788,000 Type of Work 75: 31 Repl-Load Capacity
 Roadway Cost 95: \$250,000 Length of Improvement 76: 24.9 ft
 Total Cost 96: \$1,037,000 Future ADT 114: 805
 Year of Cost Estimate 9: 1994 Year of Future ADT 115: 2035

NAVIGATION DATA

Navigation Control 38: Permit Not Required
 Vertical Clearance 39: 0.0 ft Horizontal Clearance 40: 0.0 ft
 Pier Protection 111: Not Applicable (P) Lift Bridge Vertical Clearance 116

Structure Inventory and Appraisal Sheet (English Units)

Str Unit	Elm/Env	Description	Element Notes
1	22/1	Concrete Deck - Protected w/ Rigid Overlay	The wearing surface has minor sized transverse, longitudinal, and random cracks with some areas of delamination throughout. Patches are present in the wearing surface at the abutments and along the transverse joints. A large patched area is present in the east bound lane at abutment 1. A smaller patched area and minor spalling is also present in this patching near the roadway centerline at abutment 1. This area of the deck has surrounding cracks that are beginning to open up. Deck patching is present along the joint over pier 2 with the downstream end (north end) having some minor to moderate spalling along the patches. Concrete patching is present in the wearing surface at piers 3 and 4. Within the truss span is patching is approximately 30"-36" in length x the full width of both lanes. Several patches are also present in the wearing surfaces of the approach spans near piers 3 and 4. Concrete and some cold mix asphalt patching is present along the transverse joint over pier 5 (minor spalling is present at the north end). Abutment 6 has a large 4' x 16' patch across the end of the deck with some surrounding random cracking. See photos.
1	110/1	Reinforced Conc Open Girder/Beam	The outside faces of the outside beam's ends over piers have areas of cracking and spalling with some disintegration and section loss of the concrete. A few of these areas have rebar exposed. The upstream face of the upstream beam (south) has a couple feet of light longitudinal cracking near abutment 1 and several shallow spalls with exposed steel in the underside of the beam near abutment 1. Beam 3 from upstream in span 1 has minor sized longitudinal cracking in the underside of the beam for ~ 20'. The downstream (north) exterior span 1 beam over pier 2 has moderate spalling with exposed steel. The bearing area of the upstream exterior span 2 beam has heavy spalling with exposed steel over pier 2. This along with the heavy spalling in the pier cap below are reducing the beam's bearing area at this location. This area should be monitored. The exterior haunches of the beams over piers 3 and 4 have cracking with seepage with some minor to moderate spalling. The exterior face of the downstream beam over pier 3 has some light diagonal shear cracking. The upstream span 4 beam at pier 5 has light to moderate vertical and longitudinal cracking with seepage. This beam also has a couple of shallow spalls with exposed steel in the underside. See photos.
1	113/1	Painted Steel Stringer	The exterior stringers have rusting corrosion along the length of the top flanges. Below the joint locations the exterior stringers have some measurable (moderate) section loss along top flanges and at clip angles connections. The upstream exterior stringer on the L-0 side of floor beam 1 has approximately 6" of rust through in the web along the top flange/web interface. Otherwise, the interior stringers have only minor amounts of light rusting at this time. See photos.
1	121/1	Painted Steel Bottom Chord Thru Truss	The majority of the lower chord has surface rusting throughout. Several of the lower chords baton plates have areas of corrosion with rust through. Some minor to moderate corrosion and pack rust are present along the top of the bottom chord just below the baton plate connections. Minor rusting corrosion is present in some of the vertical gusset plates at the interfaces with the vertical and diagonal members. The lower lateral gusset plate at the upstream L0 connection has moderate to heavy corrosion that is creating measurable section loss along the downstream edge of the plate. The interior vertical gusset plate at the upstream L-3 connection has a small area of rust through in the lower portion of the plate. The lower lateral gusset plate at the upstream L-5 connection has a small area of rust through near the lateral cross bracing connection. Pack rust is causing some minor bulging at a spliced location in the lower chord near the downstream L2 connection. The lower lateral gusset plate connection at downstream L-6 has heavy rusting corrosion and area along the upstream edge (approximately 8' x 5') has rusted away. See photos.
1	126/1	Painted Steel Thru Truss (excl. bottom chord)	The paint system on the exterior faces of the upper chord has areas of flaking painted with the exposed steel being rusted. The top face of the upper chord has some light surface rusting. The lattice work on the undersides of the endposts have some moderate to heavy deterioration with several pieces being rusted in two and/or missing. See photos.
1	152/1	Painted Steel Floor Beam	For the majority of their length, the floor beams that are over piers 3 and 4 (L-0 and L-6) are rusted throughout with corrosion and minor-moderate section loss along the top and bottom flanges. The lower portions of the webs also have some flaking rust and corrosion. The most advanced deterioration (moderate) is along the top flanges where they contact the deck, especially the exterior ends. Pack rust is present at several of the stringer clip angle connections to the webs of the floorbeams, especially the end floorbeams at L-0 and L-6. See photos.
1	205/1	Reinforced Conc Column or Pile Extension	This bridge has four piers with two round concrete columns in each. All of these columns have some light to minor cracking with some seepage below the pier caps. Minor to moderate spalling is present at the top of the pier 2's downstream column.
1	215/1	Reinforced Conc Abutment	Abutment 1 has approximately 8' of minor cracking at the south end of the cap. The upstream concrete pile also has some minor cracking. There is a minor full height vertical crack with seepage near the center of abutment 6. Both abutments have some erosion that is exposing the concrete piles and has undermined the caps 1.5' - 2' horizontally. See photos.
1	234/1	Reinforced Conc Cap	The south (upstream) face of pier cap 2 has heavy spalling with disintegration and exposed steel. This spalling along of the cap is reducing the bearing of the span 2 beam and should be monitored. The north (downstream) end of pier cap 2 has some moderate spalling at the end. The upstream end of pier cap 3 also has heavy spalling with exposed steel that is encroaching on the tuss bearing. The ends of pier cap 4 have been patched since the last inspection and the repairs appear to be satisfactory. Pier cap 5 has some moderate spalling with exposed steel at the upstream end of the cap. The caps that the approach span's beams bear on at piers 3 and 4 have some minor to moderate spalling along their length. See photos.
1	301/1	Pourable Joint Seal	The joint seal over pier 2 has areas that have lost adhesion, have debris and vegetation growth. The joint seal over pier 5 has areas that have lost adhesion and with adjacent areas in the deck patched with concrete and cold mix asphalt. See photos.
1	304/3	Open Expansion Joint	The open expansion joints are at the ends of the truss span over piers 3 and 4. These are sliding plate joints that are rusted with no seals and allow significant leakage on to members below. See photos.
1	311/3	Moveable Bearing (roller, sliding, etc.)	The moveable bearings at pier 4 have some areas of rusting with mostly minor corrosion. The interior anchor bolts have corrosion with some moderate section loss.

Structure Inventory and Appraisal Sheet (English Units)

Bridge Key: 5383 Agency ID: 047B00064N SR: 85.0 SD/FO: ND

IDENTIFICATION

State 1: 21 Kentucky Struc Num 8: 047B00064N
 Facility Carried 7: OLD SONORA RD Location 9: .1 MI W OF JCT US 31W
 Rte. (On/Under) 5A: Route On Structure Rte. Signing Prefix 5B: 4 County Hwy
 Level of Service 5C: 1 Mainline Route Number 5D: 01189
 Directional Suffix 5E: 0 N/A (NBI) % Responsibility:
 SHD District 2: District 4 County Code 3: Hardin (047)
 Place Code 4: FIPS 0000 Mile Post 11: 0.239 mi
 Feature Intersected 6: I 65
 Latitude 16: 37° 32' 20" Longitude 17: 085° 52' 52"
 Border Bridge Code 98: Unknown (P)
 Border Bridge Number 99

INSPECTION

Frequency 91: 24 months Inspection Date 90: 11/10/2014 Next Inspection: 11/10/2016
 FC Frequency 92A: NA FC Inspection Date 93A: NA Next FC Inspection: NA
 UW Frequency 92B: NA UW Inspection Date 93B: NA Next UW Inspection: NA
 SI Frequency 92C: NA SI Date 93C: NA Next SI: NA
 Element Frequency: 24 months Element Insp. Date: 11/10/2014 Next Elem. Insp.: 11/10/2016

CLASSIFICATION

Defense Highway 100: 0 Not a STRAHNET hwy Parallel Structure 101: No || bridge exists
 Direction of Traffic 102: 2 2-way traffic Temporary Structure 103: Not Applicable (P)
 Highway System 104: 0 Not on NHS NBIS Length 112: Long Enough
 Toll Facility 20: 3 On free road Functional Class 26: 09 Rural Local
 Defense Hwy 110: 0 Not a STRAHNET hwy Historical Significance 37: 5 Not eligible for NRHP
 Owner 22: 01 State Highway Agency
 Custodian 21: 01 State Highway Agency

STRUCTURE TYPE AND MATERIALS

Number of Approach Spans 46: 0 Number of Spans Main Unit 45: 4
 Main Span Material Design 43 A/B:
 2 Concrete Continuous 04 Tee Beam
 Deck Type 107: 1 Concrete-Cast-in-Place
 Wearing Surface 108A: 1 Monolithic Concrete
 Membrane 108B: 0 None
 Deck protection 108C: None

CONDITION

Deck 58: 5 Fair Super 59: 7 Good Sub 60: 8 Very Good
 Culvert 62: N N/A (NBI) Channel/Channel Protection 61: N N/A (NBI)

AGE AND SERVICE

Year Built 27: 1959 Year Reconstructed 106: 0
 Type of Service on 42A: 1 Highway
 Type of Service under 42B: 1 Highway
 Lanes on 28A: 2 Lanes under 28B: 4 Detour Length 19: 1.2 mi
 ADT 29: 292 Truck ADT 109: 0% Year of ADT 30: 2014

LOAD RATING AND POSTING

Inventory Rating Method 65: 2 ASR tons Operating Rating Method 63: 2 ASR tons
 Inventory Rating 66: HS20.0 Operating Rating 64: HS26.6
 Design Load 31: 2 M 13.5 (H 15) Posting 70: 5 A/Above Legal Loads
 Posting Status 41: A Open, no restriction

GEOMETRIC DATA

Length Max Span 48: 75.13 ft Structure Length 49: 253.94 ft
 Curb/Sdwik Width L 50A: 2.50 ft Curb/Sidewalk Width R 50B: 2.50 ft
 Width Curb to Curb 51: 23.95 ft Width Out to Out 52: 29.00 ft
 Approach Roadway width 32: (w/ shoulders) 16.08 ft Median 33: 2 Closed Med v
 Deck Area: 7,364.01 sq. ft
 Skew 34: 5.00° Structure Flared 35: 0 No flare
 Vertical Clearance 10: 328.05 ft Horizontal Clearance 47: 23.95 ft
 Minimum Vertical Clearance Over Bridge 53: 328.05 ft
 Minimum Vertical Underclearance Reference 54A: H Hwy beneath struct
 Minimum Vertical Underclearance 54B: 16.08 ft
 Minimum Lateral Underclearance Reference R 55A: H Hwy beneath struct
 Minimum Lateral Underclearance R 55: 11.15 ft
 Minimum Lateral Underclearance L 56: 22.97 ft

APPRAISAL

Bridge Rail 36A: 0 Substandard Approach Rail 36C: 0 Substandard
 Transition 36B: 0 Substandard Approach Rail Ends 36D: 0 Substandard
 Str Evaluation 67: 7 Above Min Criteria Deck Geometry 68: 5 Above Tolerable
 Underclearance, Vertical and Horizontal 69: 5 Above Tolerable
 Waterway Adequacy 71: N Not applicable Approach Alignment 72: 7 Above Min Criteria
 Scour Critical 113: N Not Over Waterway

PROPOSED IMPROVEMENTS

Bridge Cost 94: \$0 Type of Work 75: Unknown (P)
 Roadway Cost 95: \$0 Length of Improvement 76: 0.0 ft
 Total Cost 96: \$0 Future ADT 114: 292
 Year of Cost Estimate 9: Unknown Year of Future ADT 115: 2034

NAVIGATION DATA

Navigation Control 38: Permit Not Required
 Vertical Clearance 39: 0.0 ft Horizontal Clearance 40: 0.0 ft
 Pier Protection 111: Not Applicable (P) Lift Bridge Vertical Clearance 116

ELEMENT CONDITION STATE DATA

Str Unit	Elm/Env	Description	Units	Total Qty	% in 1	Qty. St. 1	% in 2	Qty. St. 2	% in 3	Qty. St. 3	% in 4	Qty. St. 4	% in 5	Qty. St. 5
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Structure Inventory and Appraisal Sheet (English Units)

INSPECTOR WORK CANDIDATES

Work Candidate ID	Action	Object	Agency Status	Agency Priority	Assigned to a Project	Rec. Date
A-KYTC-0EF3B34B-0000003 D	Ovly Deck	Bare Concrete Deck	Approved	High	No	12/07/2007

Appendix B

Type of overlay or other bridge deck protection method used by state.									
	ASCE Bridge Rating	Latex Modified Concrete (LMC)	Microsilica Concrete (MSC)	Superplasticized Dense Concrete (SDC)	Fly-Ash Modified Concrete (FAMC)	Polymer Modified Concrete (PMC)	Silane Sealer	Epoxy Sealer	Waterproofing Membrane
Connecticut	N/A	X*							X
Delaware	N/A	X					X	X	X
Illinois	C+								X
Indiana	C+	X	X			X	X	X	
Iowa	D+								
Kentucky	D	X							X
Maine	C-								X
Maryland	B-	X							
Massachusetts	N/A	X							X
Michigan	D*	X	X						X
Minnesota	N/A	X				X**			
Missouri	C-	X				X**			X
New Hampshire^	C								X
New Jersey	N/A								
New York	D+								
Ohio	N/A	X	X	X			X		
Pennsylvania	D+	X							X
Rhode Island	N/A								
Tennessee	B-					X			X
Vermont	C						X		X
Virginia	C	X	X						X
Washington	C-	X	X		X				
West Virginia	N/A	X	X						
Wisconsin	N/A								

*Rating is for Roads category, which includes bridges

**Polyester concrete overlay

^Uses concrete overlays, but type of concrete is not specified

Concrete Mix Design Requirements by State						
	Class of Concrete	Maximum Free Water by W/C Ratio (lb/lb)	28-Day Compressive Strength (psi)	Slump (inches)	Minimum Cement Factor (lb/yd³)	Air Content (%)
Kentucky	AA	0.42	4,000	2-4	620	6 +/- 2
	AAA	0.4	5,500	3-7	686	6 +/- 2
Indiana	C	0.443	4,000		658	
Ohio	QC 2		4,500		520 (lbs)	
West Virginia	K	0.44	4,000		658	7
Virginia	A4	0.45	4,000	2-4	635	6.5 +/- 1.5
Tennessee	D	0.4	4,000	8 max	620	7

Appendix C

ASCE Bridge Ratings and Federal Bridge Funding				
	ASCE Bridge Rating	Number of Bridges	Funding from Federal Highway Bridge Fund	Federal Funding per Bridge
Wisconsin	N/A	14,088	\$18,338,315	\$1,302
Iowa	D+	24,398	\$55,992,439	\$2,295
Minnesota	N/A	13,137	\$31,503,007	\$2,398
Tennessee	B-	20,058	\$48,225,560	\$2,404
Indiana	C+	18,953	\$57,935,376	\$3,057
Kentucky	D	14,116	\$60,070,229	\$4,255
Illinois	C+	26,621	\$115,836,622	\$4,351
Missouri	C-	24,350	\$110,423,034	\$4,535
Ohio	N/A	27,015	\$150,832,751	\$5,583
West Virginia	N/A	7,125	\$49,652,743	\$6,969
Virginia	C	13,765	\$96,325,080	\$6,998
New Hampshire	C	2,438	\$21,333,507	\$8,750
Michigan	D*	11,022	\$101,565,876	\$9,215
Vermont	C	2,731	\$29,215,167	\$10,698
Maine	C-	2,402	\$28,991,777	\$12,070
Delaware	N/A	864	\$10,731,416	\$12,421
Washington	C-	7,902	\$146,002,200	\$18,477
Pennsylvania	D+	22,660	\$429,256,634	\$18,943
Maryland	B-	5,291	\$105,117,894	\$19,867
New York	D+	17,442	\$429,256,634	\$24,611
New Jersey	N/A	6,566	\$172,163,924	\$26,221
Connecticut	N/A	4,218	\$127,691,078	\$30,273
Massachusetts	N/A	5,136	\$182,654,222	\$35,564
Rhode Island	N/A	766	\$71,488,933	\$93,328

*Rating is for Roads category, which includes bridges.