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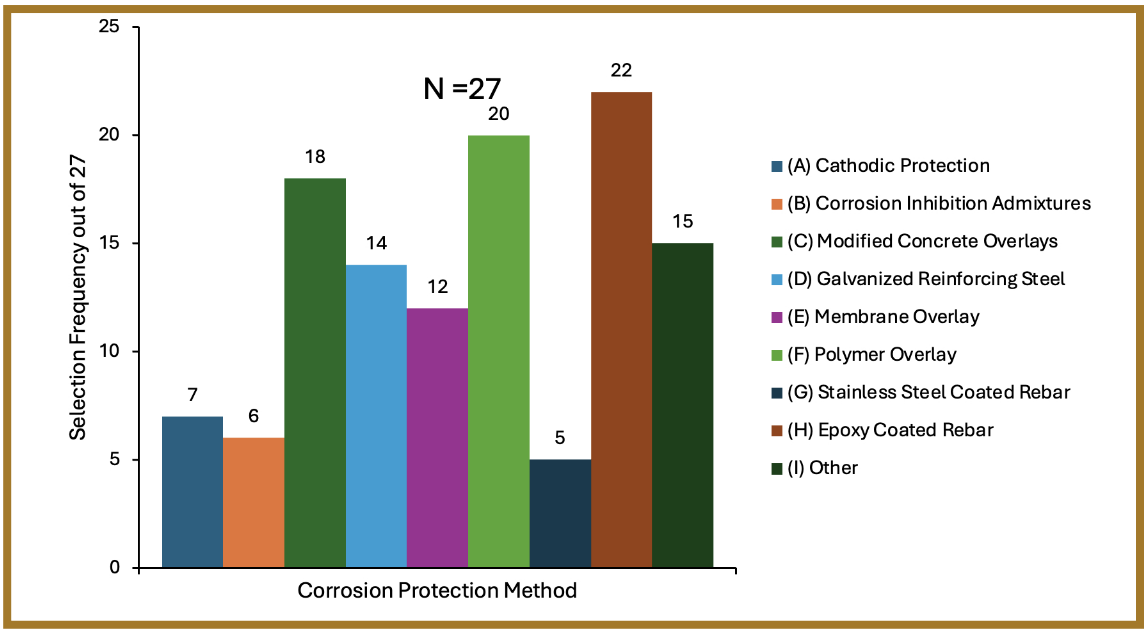
Synthesis Study: Review of Durability and Performance of the Latest Epoxy-Coated Rebar



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The use of de-icing salts on roads during the winter months has caused corrosion damage to bridge reinforcements, which has increased maintenance costs. The corrosion protection system most widely used by various State Departments of Transportation is a combination of quality concrete, adequate cover, and fusion bonded epoxy-coated reinforcing bars. This report contains a summary of the latest developments in the fabrication and use of fusion epoxy-coated and Allium (stainless steel coated) reinforcing steel within concrete bridge decks and one-way solid slab and T-beam bridges. The study findings indicate that although original epoxy materials are still used, significant improvements in the fabrication and handling of the epoxy-coated bars have significantly improved the corrosion protection of reinforcements. Findings from a literature review and survey responses from a questionnaire of state DOTs indicate that although DOTs view epoxy-coated reinforcement as effective, they continue to look for alternatives to improve corrosion protection.</td></tr>
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EXECUTIVE SUMMARY

Introduction

The use of deicing salts on the roads in the winter months has proven to be harmful because of the corrosion damage to the reinforcement that increases maintenance costs. Of the wide variety of corrosion protection systems implemented by the United States' Departments of Transportation, by far the most widely used are quality concrete, adequate cover, and fusion bonded epoxy-coated reinforcing bars. Their ease of implementation, effectiveness of corrosion protection, and economic advantages exceed that of any other method. Epoxy-coated bars were first introduced in Pennsylvania in 1973 and first implemented in Indiana bridges in 1976. This report contains a summary of the state of the art in the fabrication and use of fusion epoxy-coated and Allium (stainless steel coated) reinforcing steel in concrete bridge decks and one-way solid slab and T-beam bridges.

The study findings indicated that although the original epoxy materials were still used, the significant improvements that took place in the fabrication and handling of the epoxy coated bars resulted in improved corrosion protection of the reinforcement. Notably, there is a lack of motivation in the producers of epoxy coatings to produce improved epoxy material. It could be concluded that this lack of motivation may be due to improved performance against corrosion of this reinforcement. The findings from a literature review and the responses to a survey questionnaire of state DOTs indicate that although DOTs view epoxy-coated reinforcement as effective in protecting the steel against corrosion, they continue to look for alternatives to improve corrosion protection.

The higher initial cost of alternate methods of corrosion protection that are deemed more effective, such as stainless steel, is seen as a significant barrier for its full-throated implementation. This calls into question whether life-cycle improvements in concrete bridge deck performance are a result of using corrosion protection methods with higher initial cost that also have the potential to be more effective than epoxy-coated bars. Unfortunately, such alternate methods of corrosion protection often lack the time and prevalence in the field of epoxy-coated bars to make a proper comparative assessment. Considering that other contributing factors impact the long-term performance of concrete bridge decks, it is important to properly assess the benefit of a more costly method, such as stainless steel. In some instances, interventions are carried out due to some other contributing issue(s) not related to corrosion of the reinforcement. Increasing the overall costs of the project could possibly diminish the positive impact from the more expensive initial cost of stainless steel.

Findings

- The most reliable and widely used epoxy-coated reinforcement was Fusion Bonded Epoxy coating (FBE). The coating meets the ASTM A775/A775M (green coating) standard and is manufactured in plants that participate in the CRSI voluntary epoxy coating plant certification program.
- In general, epoxy-coated reinforcement continues to perform well. Departments of Transportation in the U.S. are still using epoxy-coated reinforcement as their go-to method of corrosion protection in the construction and rehabilitation of concrete bridge decks. Out of the surveyed DOTs, only the New Jersey DOT had a negative experience with epoxy-coated reinforcement.
- Construction practices have been identified as one of the main factors contributing to the deficient performance of epoxy-coated reinforcement. Practices such as handling, storage, placing, pouring of concrete, low concrete cover, and patching of damaged areas are keys to the adequate performance of epoxy-coated reinforcement.
- Laboratory and field evidence has identified epoxy-coated reinforcement as an effective method for protecting the steel against corrosion, provided that it meets standards, that fabrication and handling guidelines are followed, and that high quality concrete is used in conjunction with adequate concrete cover.
- State Departments of Transportation continue to explore new corrosion protection methods or combinations of existing corrosion protection methods and construction practices to enhance the performance of concrete bridge decks. Identified methods include improved concrete quality and steel reinforcement. Examples include the use of high-performance concrete in combination with epoxy-coated reinforcement. Other alternatives, such as stainless steel reinforcement, galvanized steel, ChromX ASTM 1035 steel, and fiber reinforced concrete, require more data on their cost effectiveness over the life of the structure.

Implementation

It is recommended that, under the following conditions, INDOT continues to use FBE 413 (green coating) in combination with high quality concrete and specified cover as an effective method of corrosion protection.

1. *Epoxy-Coated Reinforcement:* Epoxy-coated reinforcement should be obtained from coating plants that are participating in the voluntary CRSI program. Epoxy-coated reinforcement should meet standard ASTM A775/A775M. INDOT should continue to implement the method from Samples and Ramirez (1999), which uses a larger coating thickness to mitigate potential damage during handling and casting operations.
2. *Construction Practices:* Adequate concrete cover as determined by relevant standards, should be provided. The use of high-quality concrete with low permeability should be maintained, as well as the practice presented in Section 2.6 regarding the following guidelines.
   - Maintain adequate handling and storage of epoxy-coated reinforcement before and during construction and minimize sun exposure.
   - Monitor and patch any damage to the coating during construction using the patching material specified by the manufacturer.
   - Placement of the reinforcement should adhere to the guidelines in Section 2.6.
   - Minimize foot traffic over the reinforcement and concrete hoses movement during placement of the reinforcement and continue the use of extension on hose during casting operation to mitigate potential damage to the coating.
   - Vibrators should be equipped with non-metallic heads.
3. *Lifecycle Cost Assessment:* To properly assess the impact on the lifecycle of concrete bridge decks, more detailed

inspections, such as those conducted in the Samples and Ramirez (1999) study, should be scheduled to collect data on the bridge condition and on interventions, including economic costs, since 1976. These detailed inspections should take place in addition to regular inspections. This data should be recorded and analyzed to monitor the long-term field performance under Indiana environments and traffic. This information will complement the findings in this study and will provide a better understanding of the actual performance of bridge decks in Indiana; thus, a more informed decision can be made regarding the use of epoxy-coated reinforcement versus other alternatives.

4. *Interventions:* The survey indicated that INDOT is implementing a silane deck sealer at about year 3 and year 7 of a bridge deck's life, and then a polymer overlay is programmed. This practice may serve as an additional protective layer to help prevent the ingress of chloride into the concrete. However, the effects of implementing this method alongside epoxy-coated reinforcement remain unclear. Therefore, it is recommended to evaluate the effectiveness of the silane sealer and polymer overlay by collecting data on the bridges where this intervention was implemented. Furthermore, the survey of DOTs supports the implementation of a bridge cleaning program following the winter season. State DOTs found the cleaning program beneficial for the bridge deck performance at a low cost compared to other alternatives.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. INTRODUCTION

1.1 Background

Deicing salts are widely used in the United States as a mechanism to increase the service level of roads during the winter. However, this practice has been shown to be harmful to structural components, causing considerable damage and raising the maintenance costs. The annual dollar impact caused by corrosion deterioration in concrete bridge decks in the United States was reported to be $8.29 billion (Koch et al., 2002a).

The primary cause of reinforced concrete bridge deterioration is chloride-induced corrosion. The chlorides come from either marine exposure or the use of deicing salts for snow and ice removal (Koch et al., 2002a). The use of deicing salts was incorporated in the late 1950s in the U.S. This practice became a problem in the 1960s and so emerged the need for implementation of corrosion protection systems (Manning, 1996). In contrast, non-corrosive deicing chemicals such as calcium magnesium acetate (CMA) do not represent a viable alternative to corrosive salts because of their elevated cost of a $1,000/ton compared to the most used, sodium chloride (salt), of $30/ton.

Corrosion is a consequence of the penetration of chlorides, oxygen, and moisture into the concrete; therefore, the methods to protect against bridge deck corrosion typically involve reducing the penetration of these agents to the level of reinforcement. Epoxy-coated reinforcement (ECR) began to be implemented as a corrosion protection system in 1973 in Pennsylvania (Kilareski, 1977). This type of coating is intended to prevent the access of chlorides to the level of reinforcement. Additionally, it acts as an electrical insulator between bars, which prevents the electrical connections between anodes and cathodes on separate bars (Farshadfar, 2017). Epoxy-coated reinforcement has been specified in all types of corrosive conditions like in marine environments and in locations with major use of deicing salts. Moreover, ECR has been reported as the second most common corrosion protection method used by Department of Transportations across the U.S., only surpassed by increased concrete cover (Russell, 2004).

Indiana began implementing the first generation of epoxy-coated reinforcing steel in 1976, the combination of epoxy-coated reinforcement and a minimum concrete cover (2.5 in.) of Class C concrete became the leading method for protection against corrosion in concrete structures in the state (Samples & Ramirez, 1999). Epoxy-coated reinforcement is specified through ASTM A775/A775M for steel that is coated and then bent, and ASTM A934/A934M for bars that are fabricated and then coated. The specifications for jobsite practices are described in ASTM D3963/D3963M and in Appendix X1 of ASTM A775/A775M and Appendix X2 of ASTM A934/A934M. A more detailed discussion can be found in Sections 2.3 and 2.6.

There has been uncertainty regarding the performance of ECR and whether other methods can outperform it while remaining economically feasible. Consequently, vast research has been conducted targeting the performance of epoxy-coated rebar as a corrosion protection system; some scholars claim it is the most researched method against steel corrosion in concrete structures (McDonald, 2010a). Nonetheless, several researchers were skeptical about the efficiency of ECR and recommended the use of epoxy-coated rebar only until a superior method becomes available (Darwin & Scantlebury, 2002). A field investigation was conducted on more than 100 bridge decks in Indiana built between 1972 and 1980. The field observation included taking photographs and videos and measurements of concrete cover and area of spalling, delamination or debonding. The investigation included 28 bridge decks built with epoxy-coated reinforcement, in which only around 11% showed problems. The results of the investigation found that an average of 12 defects per foot of bar are being induced on epoxy-coated rebars during casting of concrete. Additionally, it was found that the concrete cover was below the specified design value in 36% of the 114 bridge decks tested (Samples & Ramirez, 1999).

Chapter 2 of this report presents a literature review on the current state of the art of types of coatings in use to protect steel reinforcing bars against corrosion. The most recent investigations on the performance of ECR and stainless steel coated rebar (Allium) as part of corrosion protection systems in concrete bridge decks are also reviewed. This chapter is organized in chronological order, starting with the experience in the Florida Keys in the 1980s, and concludes with the most recent studies in epoxy-coated rebar as well as Allium-, textured epoxy-, and polyol-based coatings.

Chapter 3 presents the detailed information and insights obtained by a survey of DOTs in the U.S. and territories. The survey focused on corrosion protection practices in the Departments of Transportation across the U.S. and territories. This chapter describes the survey questions, the collected responses, the analysis of the responses, and findings. Chapter 4 provides the findings and recommendations for implementation to INDOT from the overall study. The references used in this study are listed in Chapter 5.

1.2 Scope

The work reported herein presents the state of the art in the fabrication and use of fusion epoxy-coated and Allium (stainless steel coated) reinforcing steel in concrete bridge decks and one-way solid slab and T-beam bridges.

1.3 Objectives

This research on the overall synthesis study has the following objectives.

- Summarizing the state of the art on types and use of coated reinforcing steel with focus on flexible fusion bonded epoxy-coatings and Allium technology of cladding steel rebar with stainless steel.
- Providing the Indiana Department of Transportation (INDOT) with an overview of the current research and practice on the durability of epoxy-coated and stainless steel cladding reinforcement.
- Summarizing Department of Transportation practices, across the United States, related to corrosion protection systems.

The previous objectives are pursued to synthesize the latest technology in epoxy-coated reinforcing steel, and Allium rebar. The information should assist Indiana in the evaluation of the use of epoxy-coated rebars versus other more expensive corrosion protection alternatives for use with the current practice of deicing salts and for Indiana's environmental conditions.

1.4 Methodology

Relevant practices and information related to design and construction were collected to help elucidate the state-of-the-art performance of bridge applications of the types of epoxy-coated rebars and latest coating technologies suitable for the use in concrete bridge decks and bridges.

The literature review includes the findings of previous investigations, analysis of the current design methods, foreign and domestic specifications, and field implementation of the relevant corrosion protection systems. Furthermore, the search will compile available performance information in the laboratory and in the field, as well as comparable DOT specifications in the U.S.

A survey was conducted on the U.S. Departments of Transportation practices, specifications, durability, and types of corrosion protection rebar systems most used in concrete bridge decks. Through the survey questions, the experience from the DOTs in the categories of research, field implementation, and specifications are catalogued and the results analyzed and summarized. A proposed implementation plan on possible implementation is also included.

2. LITERATURE REVIEW ON EPOXY-COATED REINFORCING STEEL

2.1 Introduction

The literature review presented in this chapter describes an evaluation of past performance of epoxy-coated reinforcement, helps elucidate the state of the art in industry practice, and summarizes the key findings of the research performed since the introduction of epoxy-coated reinforcement as an integral part of the corrosion protection system in concrete bridges. The information presented includes: (1) history and development of epoxy-coated reinforcement as a corrosion protection method; (2) laboratory performance; (3) bridge case studies including lifecycle and cost analysis; (4) site handling guidelines; and (5) new coating technologies being developed and adopted in the market.

2.2 Initial Experience of Epoxy-Coated Reinforcement

Premature damage to the concrete structure due to steel corrosion such as cracking and spalling in Florida Keys bridge decks, built with epoxy-coated rebar, after only 5–6 years was documented in the 1980s. The damage was attributed to the deficient performance of epoxy-coated steel caused by a large number of coating defects. These defects were attributed to the manufacturing process, specifically bending. It must be noted that the epoxy-coated rebars met the standards at the time (Zayed & Sagues, 1990). In addition, damage to the coating worsened during handling, shipment, and casting of concrete (Farshadfar, 2017). It has been recognized that the bars were also exposed to salt spray, as a consequence of rebar storage in close proximity to the sea, for extended periods of time prior to embedment in the concrete structure (Sagüés et al., 2001). All these factors could be considered as contributors to the deficient performance of ECR experienced by Florida DOT in marine environments. However, it has to be noted that of over 300 bridges built with epoxy-coated reinforcement only a few presented corrosion related problems. Nevertheless, the experience led the Florida Department of Transportation to permanently suspend the use of epoxy-coated reinforcement in 1992. While the Florida Keys case study challenged the effectiveness of epoxy-coated rebar as a corrosion protection system, there are clearly enough other contributing factors that should warrant specifying epoxy-coated reinforcing steel, as extensive research has shown that epoxy-coated rebar can effectively protect against corrosion.

In Indiana, studies funded through the Joint Transportation Research program by Samples and Ramirez in 1999 and 2000 (Samples & Ramirez, 1999) evaluated the performance of concrete bridge decks built in Indiana between 1972 and 1980. It is worth noting that no indication of corrosion had been reported by INDOT prior to the study, but the Indiana Department of Transportation felt the need to evaluate with actual field data the effectiveness of the ECR as part of the corrosion protection system in concrete bridge decks. The study encompassed 123 bridges in which twenty-eight contained epoxy-coated rebar and Class C concrete. The study found that in bridges with comparable age, epoxy-coated reinforcement with Class C concrete provided the most successful corrosion protection method whereas uncoated reinforcement with Class C concrete cover was the least successful method. The major recommendations of that study were related to construction practices and thickness of the coating since it was found that concrete cover was below the specified limits, and severe damage to the coating was caused during construction. Specifically, it was recommended an additional increment of 6 mils to the minimum coating as the evidence suggested that a thicker coating is more resilient to damage caused during transportation and construction practices; and to lower the concrete pump hose to the level of the rebar to minimize concrete impact on the coating as it was found that this would reduce the number of defects to the coating by 50% (Samples et al., 1999).

The studies performed in Indiana and past experience in the Florida Keys put into perspective the significant role both the manufacturing process and the construction practices play in the performance of epoxy-coated reinforcement. The coating process and specifications are discussed in the next section.

2.3 Coating Process and Specifications of Epoxy-Coated Reinforcement

2.3.1 Epoxy Resins

The first commercially used epoxy resins were the products of a chemical reaction between Bisphenol A and Epichlorohydrin and were patented in the 1940s by Greenlee in the United States (Ellis, 1993). Greenlee improved adhesion, hardness, inertness, and thermal resistance into these new epoxy resins with the objective of developing superior surface coatings to those at the time.

Epoxy resins have many applications in several industries such as aircraft and car industries, tool making, fabrication of ships, and civil engineering. In civil engineering, epoxy resins are used in flooring, concrete bonding and repair, and road and bridge coatings. These epoxy resins are available in liquid or solid state (powder) and are applied by dip coats, electrostatic spray, flock spray, and electrostatic fluidized bed (Ellis, 1993).

2.3.2 Standard Specifications

The most common specifications for epoxy-coated reinforcement are ASTM A775/A775M, ASTM A934/A934M, and AASHTO M254. ASTM A775/A775M comprises bars which are first coated and then bent to the desired shape. ASTM A934/A934M covers bars that are prefabricated and then coated with a fusion bonded epoxy coating. Both ASTM A775/A775M and ASTM A934/934M specify electrostatic spray or other suitable methods for applying the fusion bonded epoxy coating. An in-depth analysis of these specifications is presented below.

The Concrete Reinforcing Steel Institute (CRSI) highlighted the comparison between the standard specifications ASTM A775/A775M-07 and A934/934M-07 in a publication titled *Highlights and Guidelines of Specifications Coating, Fabrication and Field Handling of Epoxy-Coated Reinforcing Steel Bars* (CRSI, 2008). This publication reflects the similarities and differences between the standards published in 2007. An updated version is shown in Table 2.1. Table 2.1 presents the comparison of the standards published in 2022, ASTM A775/A775M-22 and ASTM A934/A934M-22. The highlighted items in Table 2.1 indicate differences between the standards. Furthermore, the authors stated that in North America, approximately thirty-five manufacturing plants produce epoxy-coated rebars to ASTM A775/A775M standard on a regular basis, and only one to ASTM A934/A934M standard on a regular basis (EIG, n.d.). This evidences that epoxy-coating bars meeting ASTM A775/A775M are much more available to DOTs, which could explain the reason it is the most commonly used epoxy-coated rebar by agencies.

The major difference between the ASTM A775/A775M and ASTM A934/A934M is that in ASTM A775/A775M the bars are coated first and then bent to design, whereas in ASTM A934/A934M the bars are fabricated first and then coated. The implication of these differences could be that less damage may be induced to the bars due to bending. However, there is no evidence suggesting that one fabrication method is better than the other. Moreover, both standards limit the total repaired coating area to not exceed 2% of total surface area in 1-ft length. Therefore, the allowable damage is the same for both cases.

Manufacturing quality of epoxy-coated reinforcing steel plays a crucial role in the method's performance against corrosion since poor coating quality has been reported to be one of the causes for deficient performance in concrete bridge decks. Consequently, significant work was conducted to improve the manufacturing process in areas such as amount of permitted coating damage, bar cleanliness by avoiding surface contamination, and thickness of the coating. In 1991 the CRSI implemented a Coating Certification Program for Fusion-Bonded Coating Application Plants in North America, and in 2013 the CRSI began certifying plants outside North America. This voluntary-industry-sponsored program has been reported to be effective at improving the quality of epoxy-coated steel rebar (CRSI, 2013). The program evaluates quality control policies and procedures, handling and storage practices, surface preparation, curing, holiday testing, thickness measurement, and adhesion testing. Additionally, coating plants are subject to random inspections on a yearly basis. Certified plants have been reported to be averaging less than 0.20 holidays per foot of bar. ASTM A775/A775M and ASTM A934/A934M limit the number of holidays to 1 holiday per foot of length. Additionally, average backside contamination, including dust, and other contaminants, between the coating and the steel of certified plants has been reported to be 14%. The best estimates for backside contamination prior to 1991 ranged between 40% to 50%. Additionally, thickness variability has been reduced by 23% compared to thickness variability of not certified plants. As of 2013 the CRSI reported that thirty-eight plants in North America and Canada are certified or pending certification (CRSI, 2013).

The Epoxy Interest Group (EIG) of CRSI documented the chronological changes to ASTM A775/A775M in a study titled, *Do Epoxy-Coated Bars Provide Cost-Effective Corrosion Protection?* (McDonald, 2010).

TABLE 2.1
Comparison of Standard Specifications for Epoxy-Coated Reinforcement

Item	ASTM A775/A775M-22	ASTM A934/A934M-22
Description	Coated first and then fabricated	Prefabricated and then coated
Steel	Shall be free of contaminants: oil, grease, or paint Bars with sharp edges or other imperfections should not be coated	
Certifications	Written certification identifying powder lot number, material quantity, date of manufacture, name, and address of the powder manufacturer	
Powder Storage	Shall be stored in a temperature-controlled environment according manufacturer's recommendation Powder shall be used within recommended shelf life	
Patching Material	Shall be inert in concrete and specified by manufacturer	
Surface Preparation	Shall be cleaned by abrasive blast cleaning to near-white metal per SSPC_SP 10, SSPC-VIS 1	
Blast Profile	Roughness depth readings 1.5 to 4 mils by replica tape measurements	
Profilometer	Recommended	
Blasting	Required blasting media with high degree of grit	
Pretreatment	Air knives shall be used after blasting Bars are to be checked for salt contamination Contaminated bars should be cleaned by acid washing prior to blast cleaning	
Cleaning/Coating Interval	No longer than 3 hours	
Temperature	Measured, prior to coating using infrared guns or temperature indicating crayons, every 30 minutes	
Application	Electrostatic spray or other suitable method	
Thickness	After curing, 7 to 12 mils for nos. 3 to 5 bars After curing, 7 to 16 mils for nos. 6 to 18 Measurement is the average of 3 gage readings of 5 recorded measurements No single recorded coating shall be less than 80% of minimum thickness or 120% of maximum thickness Frequency of two bars every two production hours	After curing, 7 to 12 mils on straight sections After curing, on bent sections 7 to 16 mils Measurement is the average of 3 gage readings from 5 recorded measurements No single recorded coating shall be less than 80% of minimum thickness or 120% of maximum thickness Frequency of two straight bars and two bent bars from each production hour
Coating Continuity	No more than one holiday per linear foot	
Coating Flexibility	Test temperature between 68°F and 86°F Bent Angle no. 3–11–180° for no. 14 and 18–90° Frequency of one bar every four production hours	
Coating Adhesion	–	Evaluated by cathodic disbondment testing
Tests	Tests for coating thickness on two bars every two production hours Bend tests on one bar every four production hours Random tests for coating continuity	Tests for coating thickness on two bars of straight section and two bars of bent section each production hour Tests for continuity on two bars each production hour Tests for coating flexibility on one bar each four production hours Test for coating adhesion on two bars from each 8-hour production shift
Retest	Two retests on random samples for each failed test	If any test fails to meet requirements, two new samples shall be evaluated from same lot
Damage	The maximum amount of repaired damaged coating shall not exceed 1% of total surface area in each 1-ft length. Not including sheared or cut ends Bars shall not be flaming cut Total repaired area not to exceed 2%	The maximum amount of repaired damaged coating shall not exceed 1% of the total surface area in each 1-ft length Total repaired area not to exceed 2%
Repair	Repaired area shall have a minimum coating thickness of 7 mils	
Storage	Cover is required if storing coated bars outdoors for more than 2 months Stored off the ground on protective cribbing	

Table 2.2 summarizes the changes to ASTM A775/A775M between 1981 to 2007.

The evidence shows that there has been significant industry improvement in the quality of epoxy-coated reinforcement manufactured. Even though the CRSI certification is not a product quality guarantee, it is recommended that agencies specifying epoxy-coated reinforcement in construction projects, obtain the reinforcement from certified plants because certified plants adhere to strict quality controls and hence produce the highest quality epoxy-coated reinforcing steel.

The performance of epoxy-coated reinforcement is evaluated in the next section. Figure 2.1 is a map showing the CRSI certified plants in the United States.

TABLE 2.2
Chronological Changes to ASTM A775/A775M

Year	Change	Prior Version
1981	First version approved	–
1989	Damage limit reduction to 1% of total surface area for every 1-ft length	Damage limit of 2% of total surface area for every 1-ft length
1989	Introduction of anchor profile of 1.5–4 mil	–
1990	Repair of all damage	Repair of damage >0.1 in.^{2}
1993	Coating thickness 7–12 mils	90% between 5 and 12 mils
1994	Increase bend test to 180°	120°
1995	Reduce allowable holidays to less than 1 per foot	2 per foot
1995	No coating deficiency allowed	0.5%
1997	Coating adhesion CD test	–
1997	Cover bars stored outside if longer than 2 months	–
2004	Coating thickness increased for larger diameter bars, 7–16 mils (nos. 6–18)	7–12 for all bar sizes
2004	Clarified individual thickness measurements. No single measurement <80% of minimum or >120% of maximum	–
2006	Clarification on thickness measurements added	–
2007	Added patching material requirements	–

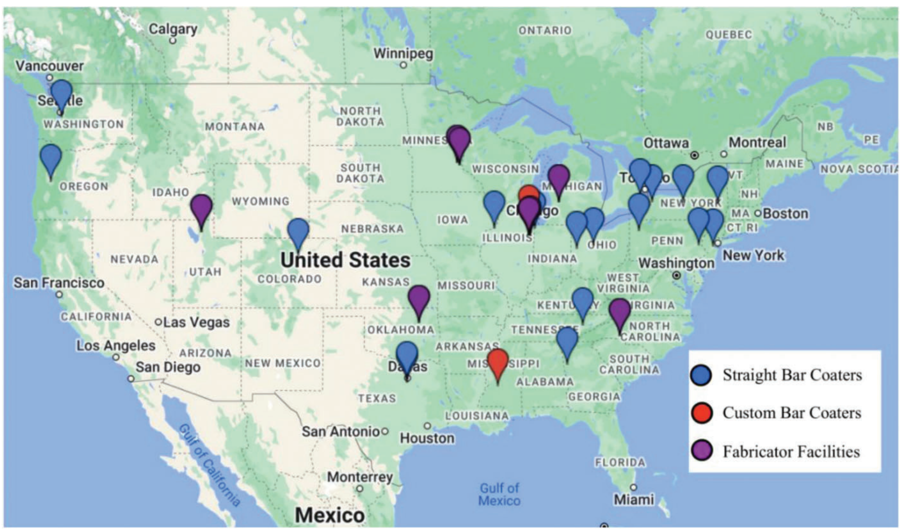


Figure 2.1 Map of certified epoxy bars fabricators plants.

2.3.3 Manufacturing

The manufacturing process of epoxy-coated reinforcement in North America must meet the requirements set by ASTM. The most common manufacturing process in the U.S. is specified by ASTM A775/A775M. These bars are first coated with epoxy and then fabricated to the desired shape. The process typically includes the following steps.

1. *Surface Preparation:* The surface of the steel reinforcing bars to be coated shall be cleaned with abrasive blast cleaning to near-white metal in accordance with SSPC-10 (ASTM A775-6.1). This step reduces impurities and contaminants that can affect the bond between the coating and the steel bar.

2. *Coating Application:* If pretreatment is used in the preparation of the surface, the powder coating shall be applied to the cleaned and pretreated steel reinforcing bar surface as soon as possible after surface treatment have been completed, and before visible oxidation of the surface occurs as discernible to a person with normal or corrected vision. In no case shall application of the coating be delayed more than 3 h after cleaning (ASTM A775/A775M). The coating is applied using a powder-spray booth to the heated steel. The even coating coverage is provided by the interaction between the electrically charged powder particles, which are attracted to the grounded steel surface. Additionally, the heat acts as a catalyst in the chemical reaction that causes the epoxy resins powder to form crosslinked polymers, which gives the desired properties (McDonald, 2010a).

3. *Curing:* The coating hardens during the curing period. Often times the curing is followed by an air or

water quench that reduces the rebar temperature to facilitate handling (McDonald, 2010a).

2.4 Performance

2.4.1 Laboratory Performance

The studies on the laboratory performance of epoxy-coated reinforcement are shown in chronological order by the date of publication of the report.

2.4.1.1 Accelerated testing of plain and epoxy reinforcement in simulated seawater and chloride solution (Erdoğdu et al., 2001). This study simulates a marine environment to evaluate the performance of epoxy-coated reinforcement used in bridge decks subjected to deicing salts and marine conditions. The study focused on corrosion initiation and propagation periods. Plain and epoxy-coated rebars were assessed over a period of 2 years. In laboratory conditions, the epoxy-coated rebars were cast in concrete slabs and exposed to synthetic seawater and 3% chloride solutions, thus simulating deicing salts. The concrete slabs had a water to cement ratio of 0.6 with approximately 1-in. concrete cover. The epoxy-coated reinforcement was evaluated under three conditions: (1) no damage to the coating, (2) 1% damage to the coating, and (3) 2% damage to the coating. The damage was induced by removing square areas using a hand grinder up to the desired damage percentage. Potential measurements were taken in accordance with ASTM C-876, which indicates a 90% probability of corrosion risk. Additionally, corrosion rate was measured using linear polarization readings over the 2-year study. The corrosion current density measured in the reinforcement from the 3% sodium chloride solution and synthetic seawater are shown in Figure 2.2 and Figure 2.3, respectively.

The study reported that in the case of the uncoated reinforcement, corrosion initiated after 5 months of exposure to synthetic seawater. The epoxy-coated rebar with no damage to the coating exhibited no corrosion during the 2-year testing period. On the contrary, the epoxy-coated reinforcement with 1% and 2% coating damage, showed moderate corrosion distress.

The study concluded that the epoxy-coated reinforcement, due to its dielectric characteristics and high resistance to ionic diffusion of the coating, is effective at reducing corrosion activity, even with damage to the coating, compared to the uncoated rebar.

2.4.1.2 Retarding of corrosion processes on reinforcement bar in concrete with an FBE coating (Darwin & Scantlebury, 2002). This study, conducted in the United Kingdom, investigated the performance of fusion bonded epoxy coating on poor-quality concrete subjected to cyclic wet/dry conditions in a corrosive NaCl solution over a total period of 12 months. The reinforcing steel was coated with Akzo Nobel Powder FBE, by electrostatic spray method, with a thickness of approximately 9 mils, and cut to 6 in. (15 cm) length. Holidays of 0.2-in. diameter were intentionally made to some specimens using a flat head drill bit. The concrete was composed of 1 part cement, 2 parts sand, and 4 parts aggregate with water to cement ratio of 0.7, and a 1.3-in. concrete cover.

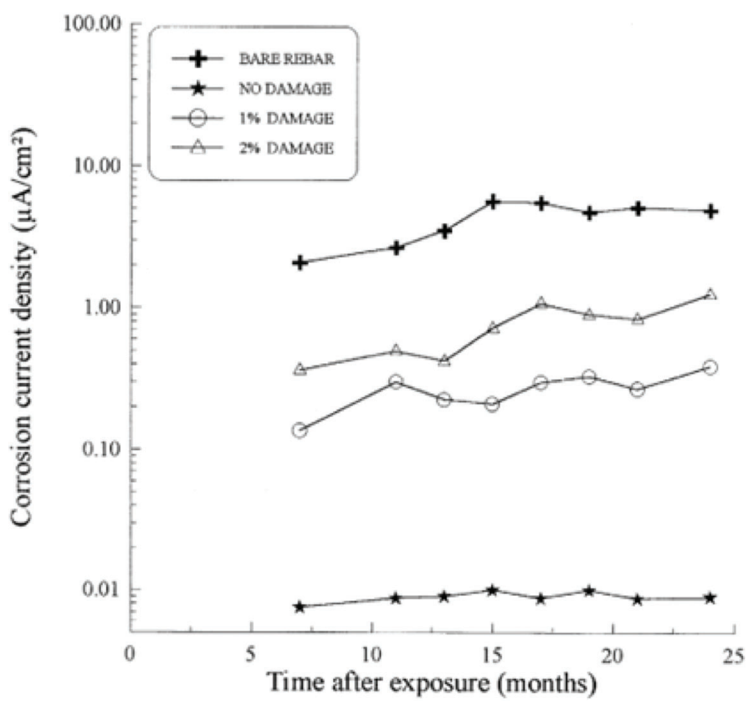


Figure 2.2 Current density of rebar in slabs exposed to 3% sodium chloride (Erdoğdu et al., 2001).

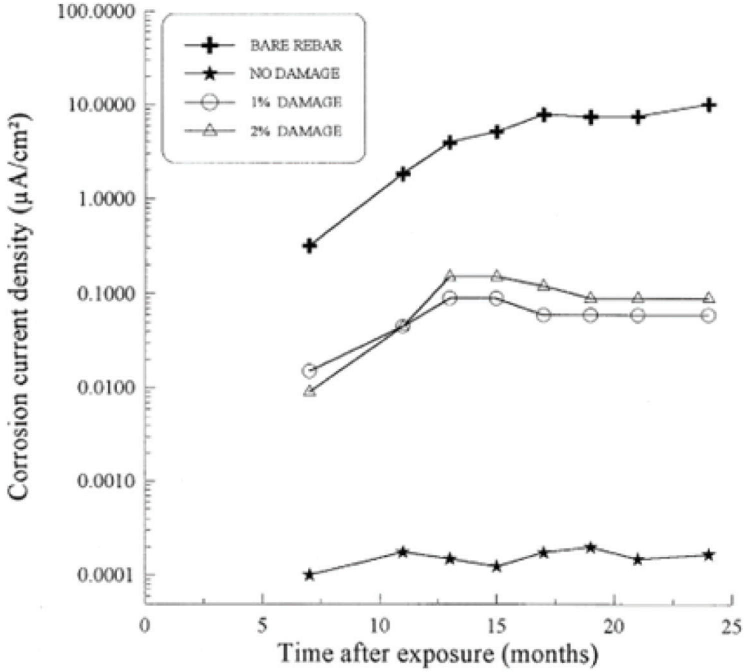


Figure 2.3 Current density of rebar in concrete exposed to synthetic seawater (Erdoğdu et al., 2001).

Specimens were exposed to monthly cycles of wetting and drying in a 3.5% NaCl solution. The test was classified as very severe conditions according to British Standard–BS8110. Periodic visual inspections and weekly half-cell potential measurements were conducted throughout the study. Figure 2.4 and Figure 2.5 show the half-cell potentials of uncoated (black) rebar and FBE-coated rebar.

Figure 2.5 does not include the FBE reinforcement with induced damage because of high impedance preventing measurements. The study concluded that the FBE coating significantly prevents corrosion in concrete reinforced with steel. Furthermore, reinforcement coated with fusion bonded epoxy with chromate conversion did not corrode in the conditions assessed.

Similarly, there was no evidence of corrosion in the reinforcement coated with ordinary FBE, as the measured resistance was of the order of 10^8 Ω cm^2. The authors indicated that concrete typically has a resistance of 10^5 Ω cm^2; however, after 6 months of cyclic exposure, the fusion bonded epoxy-coated reinforcement reached potentials that suggested probable corrosion. Moreover, the authors remain skeptical whether the kind of damage introduced to the coating is representative of the actual damage induced during handling and construction.

2.4.1.3 Evaluation of multiple corrosion protection systems for reinforced concrete bridge decks (O'Reilly et al., 2011). This study evaluates and compares the effectiveness of several corrosion protection systems used in the industry. Specifically, the study considered conventional steel reinforcement, conventional ASTM A775/A775M epoxy-coated steel reinforcement (3M^{TM} Scotchkote 413 Fusion Bonded Epoxy), corrosion inhibitors added to the concrete in combination with conventional steel and conventional epoxy-coated reinforcement, steel coated with 2 mils of epoxy coating of 98% zinc and 2% aluminum underneath the epoxy coating (multiple-coated reinforcement), epoxy-coated with improved adhesion, galvanized reinforcement, and ASTM 2205 pickled stainless steel.

The tests consisted of ponding the field specimens on a 10% rock salt solution every 4 weeks over a period of 250 to 254 weeks. Corrosion activity was monitored using macrocell voltage drop, corrosion potential measurements, and chloride content sampling at end of life. At the end of testing, field specimens were visually inspected, and epoxy-coated reinforcement were subjected to disbondment tests.

Figure 2.6 shows the corrosion rates of conventional (black) reinforcement and epoxy-coated reinforcement over the 250-week testing. The study concluded that amongst all systems assessed, conventional reinforcement (uncoated reinforcement) showed the highest corrosion rates, and that epoxy coating effectively reduced the corrosion rates compared to conventional steel. Corrosion inhibitors are not effective in cracked concrete and exhibit benefit when used in combination with epoxy coating. Epoxy-coated reinforcement with improved adhesion did not exhibit better performance than the conventional epoxy coating. In comparison with multiple-coated reinforcement, conventional epoxy-coated reinforcement exhibited less corrosion losses in bench-scale specimens. Laboratory tests indicated that ASTM 2205 stainless steel is a highly effective system in protecting against corrosion in concrete with elevated chloride content.

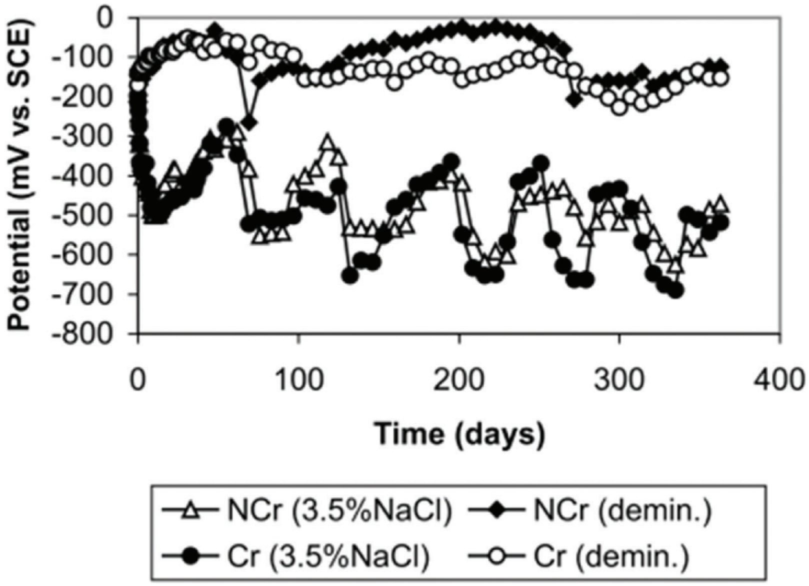


Figure 2.4 Half-cell potentials of uncoated rebar during cyclic immersion (Darwin & Scantlebury, 2002).

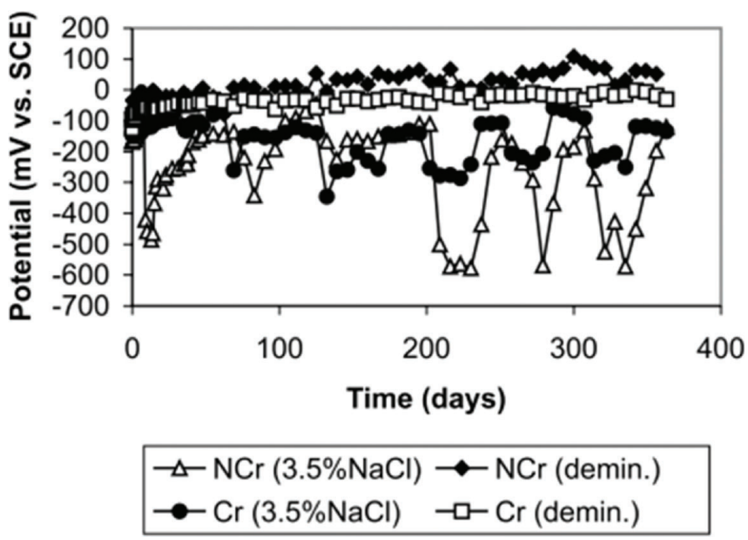


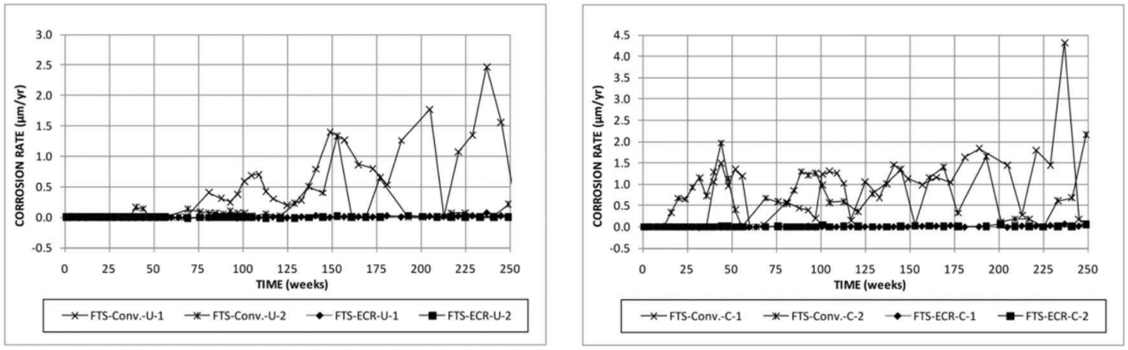
Figure 2.5 Half-cell potentials of FBE-coated rebar during cyclic immersion (Darwin & Scantlebury, 2002).

In the O'Reilly et al. (2011) study a field investigation of bridge decks in Kansas was conducted and a life-cycle comparison between corrosion systems was also conducted. The comparison will be discussed in Section 2.4.2 and 2.5, respectively.

2.4.1.4 Structural and corrosion performance of concrete bridge decks reinforced with corrosion-resistant reinforcing steel (Sim, 2014). An evaluation of the corrosion performance of concrete bridge decks reinforced with eleven different corrosion-resistant steels, shown in Figure 2.7, is presented in this study. Specifically, conventional steel, epoxy-coated, hot dip galvanized, tin-plated zinc-clad, un-plated zinc-clad, Zbar, MMFX II micro-composite, and four types of stainless steel were evaluated. The average epoxy coating thickness was 12.3 mils for #5 rebar and 12.3 mils for #8 rebar. Corrosion performance was measured by electrical current flowing across mats under a 2-week wet cycle followed by a 2-week dry cycle, in accordance with ASTM G109, using a 3% by weight NaCl solution.

The study ranked the corrosion-resistant bars in a 1–10 scale in which number 1 exhibits the best corrosion performance, and number 10 the worst corrosion performance. Epoxy-coated was ranked 8th overall, only outperforming MMFX II, and conventional steel (black bar). Stainless steel (316 LN) was ranked 1st overall, indicating it has the best corrosion performance out of the tested specimens. The ranking was based on tests results and visual examination of cracked specimens with identical mats after a 503-day exposure to the NaCl solution. The corrosion performance ranking is shown in Table 2.3.

The study concluded that epoxy-coated reinforcement can undergo corrosion, and that its performance



(a) Uncracked Concrete (b) Cracked Concrete

Figure 2.6 Individual corrosion rates based on total area for specimens with conventional steel and epoxy-coated reinforcement in (a) uncracked concrete, and (b) cracked concrete (O'Reilly et al., 2011).

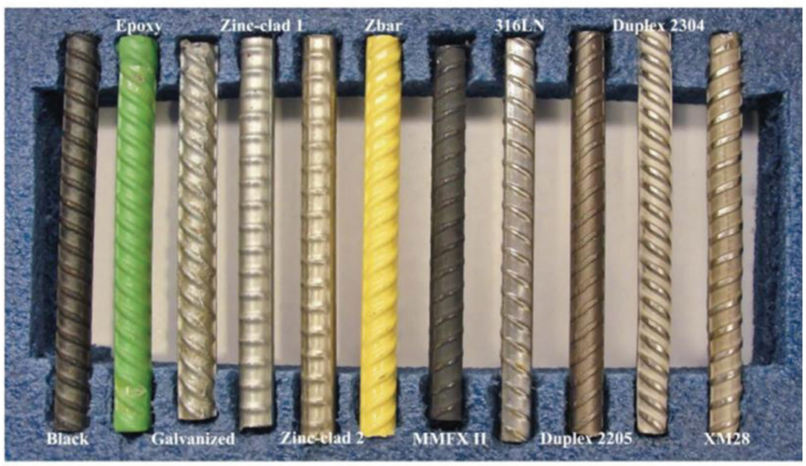


Figure 2.7 Corrosion-resistant steel evaluated (Sim, 2014).

is highly correlated to coating damage. Thus, there is potential for the use of other corrosion protection systems to provide improved performance.

2.4.1.5 Performance evaluation of corrosion protection systems for reinforced concrete (Farshadfar, 2017). This study presented an evaluation and a comparison in the performance of conventional steel and epoxy-coated reinforcement, with galvanized steel, MMFX steel with 9% and 4% chromium ASTM A1035 Type CS and CM steel, and epoxy-coated MMFX steel containing 4% and 2% chromium—epoxy-coated ASTM A1035 Type CM and CL steel. Four tests were conducted to evaluate the corrosion-resistant steel: rapid macrocell test, cracked beam test, southern exposure, and modified southern exposure—beam specimen. MMFX and conventional epoxy-coated rebars were evaluated in accelerated laboratory conditions according to ASTM G109 standard for 40 weeks. Intentional damage was induced to epoxy-coated reinforcement prior to testing. Additionally, the study evaluated the performance of reinforced concrete, reinforced with conventional rebar and epoxy-coated rebar, with replacement of cement by percentages of fly ash (20% and 40%), silica fume (5% and 10%), and slag cement (20% and 40%). All concrete mixes had a water-to-cement ratio of 0.45. The tests were conducted on prismatic concrete specimens.

TABLE 2.3
Performance of Corrosion-Resistant Reinforcement (Sim, 2014)

Rank	Bar Type	Corrosion Performance
1	316LN	Best
2	Duplex 2304	↑
3	Duplex 2205	
4	Zinc-clad	
5	Galvanized	
6	XM-28	
7	Zbar	
8	Epoxy	↓
9	MMFX II	
10	Black	Worst

The study showed that the critical chloride threshold of epoxy-coated MMFX reinforcement at 2% chromium was 4.11 lb/yd^3 and at 4% chromium was 5.16 lb/yd^3. Epoxy-coated MMFX bars containing 4% chromium exhibited greater corrosion resistance compared to 2% chromium, and conventional epoxy-coated bars. The critical chloride threshold is shown in Table 2.4.

TABLE 2.4
Critical Chloride Threshold (lb/yd³) of MMFX Bars

Specimen	Water Soluble Chloride Threshold (lb/yd³) 1	2	3	4	5	6	7	8	Average	Std. Dev.
MMFX-ECR (2%)	4.44	5.41	3.93	4.26	3.69	2.96	–	–	4.11	0.63
MMFX-ECR (4%)	5.11	3.42	6.67	5.16	4.15	6.42	–	–	5.16	1.66
MMFX (4%)	3.05	3.46	5.51	3.03	3.78	2.34	5.35	7.46	4.25	1.81
MMFX (9%)	4.24	5.59	2.76	4.12	1.87	1.59	5.45	10.7	4.54	1.47

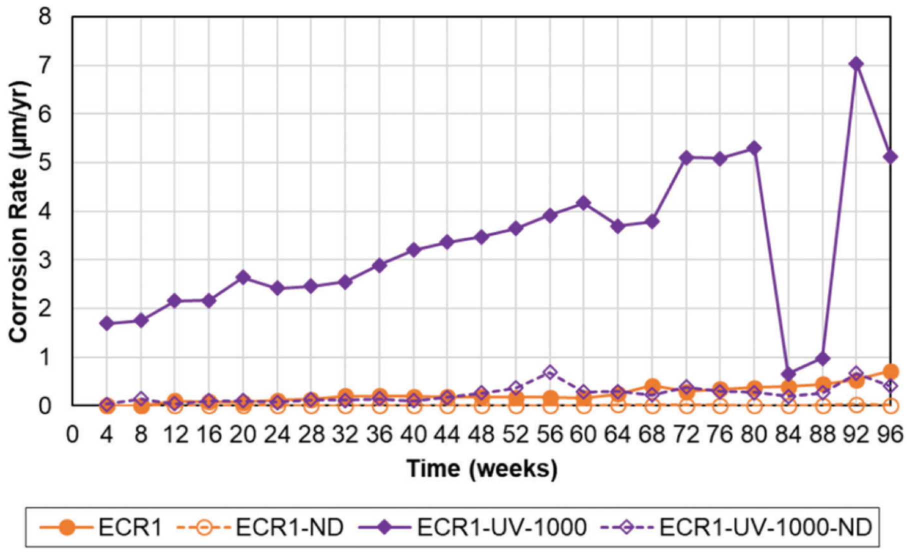


Figure 2.8 Average LPR corrosion rate (µm/yr) of damaged and undamaged ECR without and with 1,000 hours of UV exposure in the cracked beam test (Grayli, 2022).

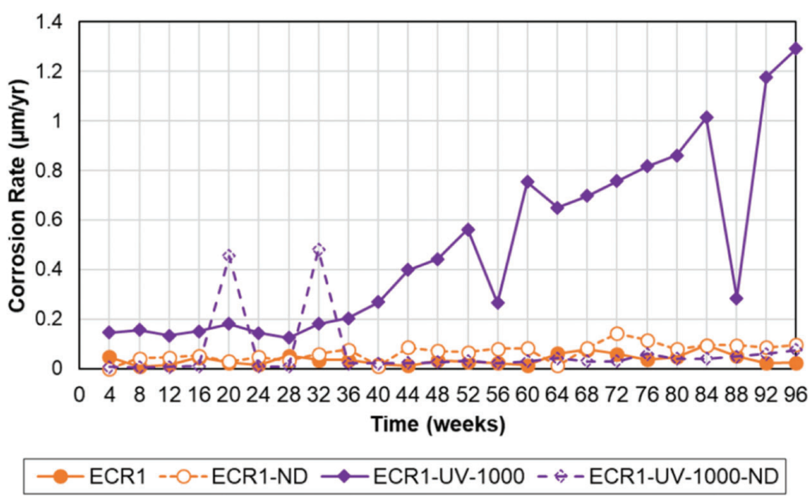


Figure 2.9 Average LPR corrosion rate (µm/yr) of damaged and undamaged ECR without and with 1,000 hours of UV exposure in the southern exposure test (Grayli, 2022).

The report noted that in specimens containing epoxy-coated reinforcement in combination with 40% fly ash, 40% slag, and 10% silica fume, corrosion loss was approximately 10% of for mixes containing Portland cement only. The study concluded that the use of epoxy-coated reinforcement in combination with supplementary cementitious material like fly ash and slag improves corrosion resistance of concrete compared to conventional bars and 100% Portland cement as binder.

2.4.1.6 Evaluation of multiple corrosion protection systems for reinforced concrete bridge decks (Grayli, 2022). The study evaluated the performance of conventional epoxy-coated steel (ASTM A775/A775M), hot-dip galvanized (ASTM A767), continuous galvanized (ASTM A1094), conventional reinforcement (ASTM A615), and ChromX reinforcement (ASTM A1035 Type CS) (see Figures 2.8 and 2.9). The specimens were subjected to rapid macrocell, cracked beam test, and southern exposure. Epoxy-coated reinforcement was assessed under several conditions to simulate any damage that can be caused during handling, placing, and storage (ultraviolet exposure conditions). The study also performed a cost-benefit comparison between alternatives by implementing a 100-year life cost analysis, which will be discussed in Section 2.5.

The study showed that green coated reinforcement (ASTM A775/A775M) with no ultraviolet exposure had lower corrosion loss than conventional reinforcement. Moreover, epoxy-coated reinforcement with no damaged to the coating, in the "as-received" from the plant condition, showed approximately zero corrosion losses, indicating that under the performed tests if the coating remains undamaged, there will be no significant corrosion activity. The study reported that UV exposure has a significant effect on the corrosion resistance efficiency of epoxy-coated reinforcement; an equivalent of 1.2 months of outdoor exposure increased total corrosion loss by approximately 30% in Rapid Macrocell Test. This study outlines the importance that proper handling and storage practices have over the effectiveness in corrosion protection of epoxy-coated reinforcement.

2.4.1.7 Summary of laboratory performance

1. In 2001, accelerated testing of plain and epoxy-coated coated reinforcement in simulated seawater and chloride solutions demonstrated that epoxy-coated rebar with no damage to the coating exhibited no corrosion during the 2-year testing period. Epoxy-coated with induced coating damage showed moderate corrosion. The conclusion of the study indicated that epoxy-coated reinforcement is effective at reducing corrosion activity, even with damage to the coating (Erdoğdu et al., 2001). Another important lesson was to protect that coating from damage to extend its usefulness as a corrosion protection system.
2. In 2002, the investigation on fusion bonded epoxy coating (FBE) in poor quality concrete subjected to a corrosive NaCl solution concluded that FBE significantly prevents corrosion in concrete reinforced with steel even in poor quality concrete (Darwin & Scantlebury, 2002).
3. In 2011, an evaluation of multiple corrosion protection systems for reinforced concrete bridge decks concluded that amongst all systems evaluated, conventional reinforcement showed the highest corrosion rates, and epoxy-coating effectively reduced the corrosion rates compared to conventional steel (O'Reilly et al., 2011). Additionally, the study demonstrated that corrosion inhibitors are not effective in cracked concrete; epoxy-coated reinforcement with improved adhesion did not exhibit better performance than conventional epoxy coating; and stainless steel is a highly effective corrosion protection system in concrete with elevated chloride content (O'Reilly et al., 2011).
4. In 2014, a study on the structural and corrosion performance of concrete bridge decks reinforced with corrosion-resistant reinforcing steel, ranked epoxy-coated 8th best corrosion resistant bar whereas stainless steel was ranked the best corrosion resistant bar out of 10 distinct types. The study concluded that the performance of epoxy-coated reinforcement is highly correlated to coating damage (Sim, 2014).
5. A study on the evaluation of corrosion protection systems for reinforced concrete in 2017, concluded that the use of epoxy-coated reinforcement in combination with supplementary cementitious material like fly ash and slag improves corrosion resistance of concrete compared to conventional bars and 100% Portland cement as binder (Farshadfar, 2017).
6. In 2022, the evaluation of multiple corrosion protection systems of reinforced concrete bridge decks demonstrated that UV exposure has a significant effect on the efficiency of epoxy-coated reinforcement, further highlighting the importance in proper handling and storage practices in epoxy-coated reinforcement (Grayli, 2022).

2.4.2 Field Performance

Figure 2.10 depicts the geographical location of the studies presented herein.

2.4.2.1 Minnesota, 2008. The corrosion performance of epoxy-coated reinforcement was assessed in four bridge decks (19015, 27812, 27815, and 27062) built between 1973 and 1978 in Minnesota. The investigation included visual inspections—looking for signs of corrosion, delaminated concrete, half-cell potential measurements, electrochemical spectroscopy, and ground penetrating radar. Concrete cores were evaluated in the laboratory for chloride content, carbonation depth, and concrete density. The result showed light cracking, few delamination areas, and modest corrosion. Overall, the four bridge decks were in good condition. It was found that corrosion occurred primarily around the joints over the bridge piers. The researchers recommended that these locations be sealed to reduce humidity and chloride concentration from deicing salts.

Minnesota DOT used to require only the upper mat of reinforcement to be epoxy-coated as it was closer to the surface; however, current practice requires both upper and lower mats to be epoxy-coated. The researchers reported that current MnDOT practices were found to be effective and recommended to be continued (Pincheira, 2008).

2.4.2.2 New York, 2009. In New York state an ordinal integer value rating was used in 2009 to indicate the health of bridge elements. This rating is based on the general condition of bridge elements and not on specific type of deterioration (Agrawal et al., 2009).

Table 2.5 shows the rating based on the *NYDOT Bridge Inspection Manual* of 2017. The study aimed to develop a computerized model to determine deterioration rates for bridge elements and reported that bridge decks reinforced with epoxy-coated rebar performed

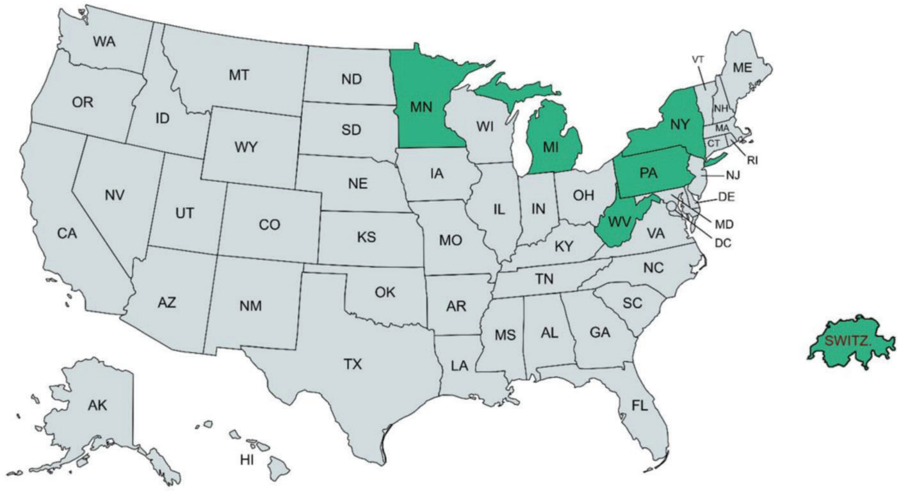


Figure 2.10 Geographical location of field studies.

TABLE 2.5
Bridge Inventory Rating Scale (NYDOT, 2017)

Code	Description
N	*Not Applicable*
9	*Excellent Condition*
8	*Very Good Condition:* No problems noted
7	*Good Condition:* Some minor problems
6	*Satisfactory Condition:* Structural elements show some minor deterioration.
5	*Fair Condition:* All primary structural elements are sound, but may have minor section loss, cracking, spalling or scour.
4	*Poor Condition:* Advance section loss, deterioration, spalling or scour.
3	*Serious Condition:* Loss of section, deterioration, spalling, or scour have seriously affected primary structural components. Local failures are possible. Fatigue cracks in steel or shear cracks in concrete may be present.
2	*Critical Condition:* Advanced deterioration of primary structural elements. Fatigue cracks in steel or shear cracks in concrete may be present or scour may have removed substructure support. Unless closely monitored it may be necessary to close the bridge until collective action is taken.
1	*Imminent Failure Condition:* Major deterioration or section loss present in critical structural components, or obvious vertical or horizontal movement affecting structure stability. Bridge is closed to traffic, but corrective action may put the bridge back in light service.
0	*Failed Condition:* Out of service beyond corrective action.

significantly better than bridge decks with uncoated steel. The investigation predicted that it would take around 32 years for a bridge deck built with uncoated steel to drop from a rating of 7 (new condition, no deterioration) to a rating of 5 (minor deterioration, but functioning as originally designed), and 49 years to drop from a rating of 7 to 4 (used to shade between ratings 3 and 5), whereas it would take 38 for a bridge deck built with epoxy-coated reinforcement to drop from a rating of 7 to 5, and 62 years to drop from a rating of 7 to 4 (poor condition) (Agrawal et al., 2009). It has to be noted that the rating scale used in this study corresponds to NYDOT bridge inspection manual of 1997 in which the scale ranges from 1 (failed condition)–7 (no deterioration). Ratings 8 and 9 described condition "N" of the current NYDOT bridge inspection manual of 2017.

2.4.2.3 West Virginia, 2009. In 2009, a study in West Virginia assessed the condition of six bridge decks built with epoxy-coated reinforcing steel. Visual inspections, crack mapping, delamination survey, continuity testing, concrete cover measurements, and core sampling and laboratory testing were conducted. The age of the bridge decks ranged from 33 to 35 years.

Table 2.6 summarizes the observations of the study. The study concluded that corrosion in epoxy-coated bars was correlated to high chloride concentration, low coating thickness, and extended exposure to chloride concentrations; however, no major deteriorations were observed (McDonald, 2010b).

2.4.2.4 Michigan, 2015. Michigan DOT implemented the use of epoxy-coated reinforcement in the construction of bridge decks in both the bottom and top

TABLE 2.6
Field Observations of Bridge Decks in West Virginia (McDonald, 2010b)

Bridge No.	Description	Observations
2668 N	Seven spans, supported on steel girders Epoxy-coated reinforcement in top and bottom mats Topped with anti-icing and anti-skid epoxy-based overlay in 2008	Few delamination away from expansion joints Extensive transverse cracking No corrosion-related deterioration visible on decks soffit Epoxy thickness between 9 to 15 mils Chloride values at bar depth range from 0.009% to 0.0117% by weight of concrete
2672 N	Three spans on concrete girders Epoxy-coated rebar in top and bottom mats	Visible transverse cracks Visible spalling Visible staining Chloride values at bar depth ranged from 0.009% to 0.039% by weight of concrete
2676 S		Indication of active corrosion Chloride values at bar length ranged from 0.182% to 0.222% by weight of concrete Coating thickness less than 7 mils
2673	Five spans on steel girders Epoxy-coated reinforcement in top mat Uncoated reinforcement in bottom mat	Largest delamination of all decks tested Transverse cracking Signs of corrosion stains at construction joints Chloride values at bar depth ranged from 0.079% to 0.165% by weight of concrete
2930	Six spans on steel girders Spans 5 and 6 with uncoated reinforcement in top and bottom mats Spans 1 to 4 with epoxy-coated reinforcement in top and bottom mats	Higher frequency of cracking No corrosion-related deterioration in spans 1 trough 4 Deterioration detected in spans 5 and 6 No cracks were found in spans containing epoxy-coated reinforcement Coating thickness between 8 to 15.8 mils Chloride values at bar depth ranged from 0.041% to 0.165% by weight of concrete
2953	Three spans on steel girders Epoxy-coated reinforcement in top and bottom mats	No corrosion related deterioration observed Chloride values at bar depth ranged from 0.082% to 0.165% by weight of concrete None of the epoxy-coated bars exhibit sighs of corrosion

mats in 1982. Epoxy-coated reinforcement has been the most common rebar used by MDOT; however, there have been instances where MDOT implemented stainless steel reinforcement in 2000, fiber reinforced polymer (FRP) in 2000, and carbon fiber reinforced polymer (CFRP) in 2010 (Valentine, 2015).

A study titled *Expected Service Life of Michigan Department of Transportation Reinforced Concrete Bridge Decks* (Valentine, 2015), estimated the service life of bridge decks containing epoxy-coated reinforcement and evaluated the early performance of bridge decks built with stainless steel rebar and FRP. The study used the National Bridge Inventory (NBI) condition rating scale to show the performance of the aforementioned corrosion protection systems. The rating scale ranges from 0 (failed condition) to 9 (excellent) condition. A rating of 4 typically corresponds to a bridge that requires rehabilitation. A similar rating scale is shown in Table 2.5.

The researchers reported that for epoxy-coated reinforcement, it takes around 53 years for a bridge deck to reach a rating of 5. The bridges studied that were built with epoxy-coated reinforcement had an age of 33 years. The deterioration curve implemented in the study could only estimate a bridge classification beyond 5 due to the lack of data of bridges that attained a rating below 4.

A bridge built with stainless steel was estimated to reach a rating of 7 in 19 years. Researchers conclude that stainless steel reinforcement is performing better than epoxy-coated reinforcement in the early stage. On the other hand, bridge decks with fiber reinforced polymer are estimated to reach a rating of 7 in 7 years, which indicates that FRP is not performing well in the early stages (Valentine, 2015). Table 2.7 summarizes the expected life of bridge decks as per this study.

The results show that epoxy-coated reinforcement is performing well. Since MDOT began implementing stainless steel, and FRP in 2000, and this study was conducted in 2015, only the early performance of these two methods could be studied in this limited sample. This raises questions about the impact of other parameters, such as traffic, and assumes standard construction practices.

TABLE 2.7
Expected Bridge Service Life in Michigan

Corrosion Protection System	Results
Epoxy-Coated Reinforcement	Estimated Service Life 86 years
Stainless Steel Reinforcement	19 years to reach rating of 7
Fiber Reinforced Polymer	7 years to reach rating of 7

2.4.2.5 Pennsylvania, 2012, 2016. A total of 954 bridge decks built between 1973 to 1983 were analyzed in Pennsylvania in 2012. The analysis included review and evaluation of their 2012 NBI data. The results showed that 32% of bridge decks built with uncoated reinforcement, around 23% bridge decks built with galvanized reinforcement, and around 9% of bridge decks built with epoxy-coated reinforcement exhibited ratings lower than 5, which many agencies used as the rating to begin rehabilitation of bridge decks. The implication of these results is that a bridge deck built with epoxy-coated reinforcement is 2.5 times less likely to require repair than those with galvanized steel in a period of 30 to 40 years (EIG, 2013).

In 2016, a study performed in Pennsylvania evaluated the factors that reduce early-age cracking in concrete bridge decks and assessed the effect of cracks on long-term durability in concrete bridge decks. The investigation analyzed inspection data from 203 bridge decks in Pennsylvania, in which 40 bridges were considered "old bridges," and 163 were newly constructed bridge decks (Manafpour et al., 2016). Field inspection of concrete bridge decks and material testing were performed to identify early-age cracking. It is not clear the age difference between the old and new bridges, nor the difference between construction practices. The data included bridge decks built with different concrete types (AAA, AAAP, and HPS) as well as different reinforcement types (epoxy-coated rebar, galvanized rebar, and black steel).

The data evidenced that premature cracking has a significant effect on early deterioration of bridge decks as cracks allow the access of chlorides that lead to an early initiation time of the corrosion in the reinforcement. However, it was found that epoxy-coated reinforcement, even with damaged coating, was effective in protecting the steel against corrosion at the location of the crack. In addition, epoxy-coated reinforcement was found to perform better than galvanized steel in bridges with the same age (Manafpour et al., 2016).

2.4.2.6 Switzerland, 2016. Epoxy-coated reinforcement has also been employed in corrosion protection systems abroad, where it has been implemented in European countries. The study, *Epoxy-Coated Reinforcement in Concrete Structures: Results of a Swiss Pilot Project After 24 Years of Field Exposure*, documented inspection data of bridge decks built with uncoated and with epoxy-coated reinforcement in Switzerland. The epoxy-coated reinforcement was implemented in prestressed concrete parapets in 1988 (Keßler et al., 2016). The results showed that after 24 years of exposure, the parts where the epoxy coating was not damaged during construction were in excellent condition. On the other hand, when damage to the coating was induced during construction, cathodic disbondment occurred. This information was obtained from a comprehensive bridge inspection that included visual inspection, measurements of concrete cover, chloride profiles, half-cell potential mapping, and the extraction of concrete cores containing segments of epoxy-coated reinforcement. The researchers stated that the chloride content and time of exposure were not sufficient to accurately draw conclusions regarding the corrosion behavior of damaged epoxy-coated reinforcement (Keßler et al., 2016).

2.4.2.7 Summary of field performance

1. Minnesota DOT in 2008 used to require only the top mat of reinforcement to be epoxy-coated; however, current practice requires both top and bottom mats to be epoxy-coated. Researchers reported that the current MnDOT practices were found to be effective and recommended to continued (Pincheira, 2008).
2. An ordinal integer value rating was used in New York 2009 to indicate the health of bridge elements (0-failed condition, 9-excellent condition) (Agrawal et al., 2009). The study predicted that it would take around 32 years for a bridge deck built with uncoated steed to drop from a rating of 7 (no deterioration) to a rating of 5 (minor deterioration), and 49 years to drop from a rating of 7 to 4 (poor condition), whereas it would take 38 years for a bridge deck built with epoxy-coated reinforcement to drop from a rating of 7 to 5, and 62 years to drop from a rating of 7 to 4 (Agrawal et al., 2009).
3. An assessment of six bridge decks built with epoxy-coated reinforcement in West Virginia, in 2009 concluded that corrosion in epoxy-coated bars was correlated to high chloride concentration, low coating thickness, and extended exposure to chloride concentrations. No major deteriorations were observed (McDonald, 2010b).
4. In Michigan in 2015, a study titled *Expected Service Life of Michigan Department of Transportation Reinforced Concrete Bridge Decks* estimated the expected service life of a bridge built with epoxy-coated reinforcement to be 86 years (Valentine, 2015). Additionally, the researchers concluded that stainless steel reinforcement is performing better than epoxy-coated reinforcement in the initial stages, and bridge decks with fiber reinforced polymer are not performing well in the early stages (Valentine, 2015).
5. In Pennsylvania, out of the 954 analyzed bridge decks, 32% of bridge decks built with uncoated reinforcement, 23% of bridge decks built with galvanized reinforcement, and around 9% of bridge decks built with epoxy-coated reinforcement exhibited bridge ratings indicating the need to begin bridge rehabilitation. The researchers indicated that a bridge deck built with epoxy-coated reinforcement is 2.5 times less likely to require repair than those with galvanized steel in a period of 30 to 40 years (EIG, 2013).

6. In Pennsylvania, the investigation of 203 bridge decks in 2016 found that epoxy-coated reinforcement, even with damaged coating, was effective in protecting the steel from corrosion (Manafpour et al., 2016). Additionally, the researchers indicated that epoxy-coated reinforcement was found to perform better than galvanized steel in bridge decks of similar age (Manafpour et al., 2016).
7. In 2016 the results of a Swiss pilot project indicated that after 24 years of exposure, the parts where the epoxy coating was not damaged during construction were in excellent condition. However, when damage to the coating was present, cathodic disbondment occurred. The researchers concluded that the chloride content and time of exposure were not sufficient to accurately draw conclusions regarding the corrosion behavior of damaged epoxy-coated reinforcement (Keßler et al., 2016).

2.5 Lifecycle and Cost Assessment

2.5.1 Evaluation of Multiple Corrosion Protection Systems for Reinforced Concrete Bridge Decks (O'Reilly et al., 2011)

In 2011, a study evaluating the cost effectiveness of several corrosion protection systems, including epoxy-coated reinforcement, was conducted at the University of Kansas. Specifically, uncoated conventional reinforcing steel, conventional epoxy-coated reinforcement, epoxy-coated reinforcement with increased adhesion, pickled ASTM 2205 stainless steel (pickling is a pre-passivation process that can improve the corrosion resistance of stainless steel), and others were evaluated over an assumed 75-year design life. Table 2.8 shows the material costs used in the study. In order to determine the service life of each corrosion method, the researchers estimated an average corrosion rate for each type of corrosion protection system and then determined the duration for which repair was required.

The analysis assumed a 22-cm (8.5-in.) thick bridge deck in which 0.215 m^3 of concrete (\$735.75/m^3) per 1 m^2 deck area and 35.2 kg/m^2 of steel are required. The repair cost was assumed to be \$349/m^2 for all corrosion protection systems and was based on bridges with uncoated conventional reinforcement as bridges with epoxy-coated reinforcement had yet not required repairs (O'Reilly et al., 2011).

The study concluded that epoxy-coated reinforcement is the most cost-effective system, uncoated conventional reinforcement is the least cost-effective method on total costs over a 75-year design life, and ASTM 2205 stainless steel had a higher present cost than epoxy-coated reinforcement, around 16% higher for a discount rate, "i", of 2%. However, the time to first repair in a bridge deck with ASTM 2205 is higher than 75 years. In the case of epoxy-coated reinforcement, the time for first repair was reported as 67-years; however, the corrosion rates used in the study exhibit a large standard deviation, thus it could be possible that bridge decks with epoxy-coated reinforcement reach 75-years design-life (O'Reilly et al., 2011).

2.5.2 Performance Evaluation of Corrosion Protection Systems for Reinforced Concrete (Farshadfar, 2017)

In 2017, a similar cost-benefit analysis was presented in a study titled *Performance Evaluation of Corrosion Protection systems for Reinforced Concrete* (Farshadfar, 2017). The study estimated the total cost over 75-year design life of bridge decks reinforced with conventional rebar, galvanized steel, MMFX steel, epoxy-coated reinforcement, and conventional steel and epoxy-coated reinforcement in combination with replacement of cement with fly-ash, silica fume, and slag. Table 2.9 shows the construction cost of conventional steel, epoxy-coated rebar, and galvanized reinforcement obtained from bids on bridge projects in Kansas between 2015 and 2016 (Farshadfar, 2017).

Similarly to O'Reilly et al. (2011), an assumed 22 cm (8.5 in.) thick concrete deck was used to estimate the concrete costs (\$725.20/m^3), and the present value was obtained for 2%, 4%, and 6% discount rates over a 75-year design life. The study found that a bridge deck reinforced with conventional steel and 100% Portland cement had the highest total cost, galvanized steel was among costliest methods tested, epoxy-coated reinforcement was the most cost-effective system of rebar, and the systems containing supplementary cementitious material are the most cost-effective systems studied (Farshadfar, 2017).

2.5.3 Evaluation of Multiple Corrosion Protection Systems for Reinforced Concrete Bridge Decks (Grayli, 2022)

This study developed a cost estimation analysis that includes the construction and repair costs necessary to achieve a 100-year service life. The study considered conventional steel, epoxy-coated reinforcement, ChromX reinforcement, galvanized steel, and continuous galvanized steel. Material costs were based on bids for new bridge decks and deck replacements in the

TABLE 2.8
Material Cost (O'Reilly et al., 2011)

Type	Cost (\$/kg)
Conventional Reinforcement	0.77
Epoxy-Coated Reinforcement	0.99
ASTM 2205 Stainless Steel	5.19

TABLE 2.9
Material Cost (Farshadfar, 2017)

Type	Cost (\$/kg)
Conventional Reinforcement	0.73
Epoxy-Coated Reinforcement	0.94
Galvanized Steel	1.94

TABLE 2.10
Material Cost (Grayli, 2022)

Type	In-Place Cost ($/yd^2)
Conventional Reinforcement	52.5
Epoxy-Coated Reinforcement	68
Galvanized Steel	75.9
ChromX	93.3
Concrete	113

states of Oklahoma and Kansas in 2020 (Grayli, 2022). Two scenarios were evaluated; the first scenario considered a full deck replacement (new bridge deck construction); the second scenario considered partial deck repair. The present value cost was based on an 8-in. bridge deck at a 2% discount rate. The material costs are shown in Table 2.10.

The study concluded that over a 100-year design life, epoxy-coated reinforcement, galvanized steel, and ChromX reinforcement were cost-effective corrosion protection systems as the difference in costs between them are not significantly high. Furthermore, epoxy-coated reinforcement should be protected from UV exposure as improper storage was found to increase its life-cycle cost (Grayli, 2022).

2.5.4 Summary of Lifecycle and Cost Assessment

1. The study titled *Evaluation of Multiple Corrosion Protection Systems for Reinforced Concrete Bridge Decks* (O'Reilly et al., 2011) concluded that epoxy-coated reinforcement is the most cost-effective system, conventional reinforcement is the least cost-effective method on total costs over a 75-year design life.
2. In 2017, it was found that a bridge deck reinforced with conventional steel and 100% Portland cement had the highest total cost, epoxy-coated reinforcement was the most cost-effective system of rebar, and that the systems containing supplementary cementitious material are the most cost-effective systems studied (Farshadfar, 2017).
3. In 2022, it was concluded that over a 100-year design life, epoxy-coated reinforcement, galvanized steel, and ChromX were cost-effective corrosion protection systems (Grayli, 2022).

2.6 Jobsite Guidelines and Recommendations

The information obtained from the literature review suggests that one key factor in the performance of epoxy-coated reinforcement is maintaining the integrity of the coating. The coating plants in North America are able to produce epoxy-coated reinforcement with less than 0.2 holidays per foot of bar, which is significantly lower than the limit of 1 holiday per foot imposed by ASTM standards; however, additional damage can be introduced during transportation and at the jobsite. The following section highlights the guidelines and recommendations regarding operating practices of epoxy-coated reinforcement at the jobsite. Handling and storage requirements for epoxy-coated reinforcement are included in ASTM A775/A775M, ASTM A934/A934M, ASTM D3963/D3963M, ACI 301. Table 2.11 describes the guidelines for implementing these standards.

CRSI strongly recommends additional guidelines for the inspection of epoxy-coated reinforcement prior to concrete placement as it is the final opportunity to verify that the coated reinforcement is installed according to design, thus ensuring that the coating will provide adequate protection.

1. Bar spacing, size and type should be in accordance with the required specifications. Customary practice includes photographic documentation.
2. In the field, coating bends should be done only if approved by the structural engineer. Bends should not show cracks or fractures.
3. Lap lengths should be approved by the structural engineer and should be measured and documented.
4. Mechanical splices should be epoxy-coated.
5. Concrete cover should be measured, and necessary action should be taken if inadequate concrete cover is found.
6. All damage should be repaired with appropriate patching material specified by the epoxy-coated reinforcement manufacturer. If damage exceeds 2% in any foot length it should be rejected.
7. Agencies are encouraged to collect samples at the jobsite for laboratory testing.
8. Welding should be approved by the engineer. Any welds should be cleaned and repaired with patching material.
9. Bars that are partially cast in concrete, and exposed to prolonged periods, should be protected against UV, salts, and condensation.

2.7 Coating Technologies for Reinforcing Steel

2.7.1 Epoxy Coating Technology

2.7.1.1 Fusion Bonded Epoxy Rebar Coating 413. Recognized by the green color, Scotchkote Fusion-Bonded Epoxy Coating 413 is a one-part, heat curable, thermosetting epoxy coating designed for corrosion protection of reinforcing steel. The epoxy resists cathodic disbondement, deicing salts, airborne salt spray, sea water, harsh chemicals, acid rain, carbonation, contaminated aggregate, and concrete additives. Coating 413 has improved UV resistance, provides excellent adhesion and coverage on concrete reinforcing steel bar of any size or shape, and meets ASTM A775/A775M, ASTM A1078, type 1 and ASTM 1055, AASHTO M284 (AASHTO, 2009; ASTM, 2022, 2025).

Epoxy-coated reinforcement ASTM A775/A775M has been the most common method of epoxy-coated reinforcement used by agencies as it can be bent after the reinforcement has been coated.

2.7.1.2 Fusion Bonded Epoxy Rebar Coating 426. Type 426 Skotchkote Fusion-Bonded Epoxy Rebar coating, recognized by the purple or grey color, is advertised to provide superior resistance from disbondment

TABLE 2.11
Guidelines for the Field Handling of Epoxy-Coated Reinforcement

Item	Guideline
Handling	When handling, avoid bundle-to-bundle or bar-to-bar abrasion. Coated steel should be offloaded as close as possible to their points of placement. Equipment for handling should have protected contact areas. Coated bars should be lifted and not dragged. Hoisting should be done using nylon or padded slings.
Storage	Coated and uncoated steel should be stored separately. Stored off ground on protective cribbing, and timbers placed between bundles when stacking is necessary. When long-term (over 2 months) outdoor storage is needed, protect from sunlight, salt spray, and weather exposure.
Placing	All wire bar supports, spacers, and tying wire should be coated with dielectric material. After placing, walking on coated reinforcement should be minimized. Placed coated steel should be inspected for damaged coating prior to placing concrete. Coated steel should not be flame cut. When damage does not exceed 2% of surface area, it should be repaired using patching material.
Casting	Vibrators should be equipped with nonmetallic heads such as plastic-headed vibrator. Minimize traffic and concrete hoses on coated reinforcement.

without pretreatments, meets ASTM A934/A934M, and meets ASTM A775/A775M and AASHTO M284 except flexibility. Fusion-Bonded Epoxy Coating 426 is a one-part, heat curable, thermosetting epoxy coating with improved corrosion protection for after-fabrication application. Coating 426 is resistant to cathodic disbondment, deicing salts, airborne spray, sea water, harsh chemicals, acid rain, carbonation, contaminated aggregate, and concrete additives (3M, 2024).

Fusion bonded epoxy-coated 426 reinforcement has been implemented in states such as Minnesota, Wisconsin, and Oklahoma. Lexington Ave. Bridge (Project MN-01-01) in Minnesota used prefabricated fusion bonded epoxy-coated reinforcement in a bridge deck slab (De Rojas, 2001).

2.7.1.3 Textured epoxy-coated reinforcement. Epoxy-coated reinforcement's smooth surface is a factor that makes bridge decks more susceptible to cracking because the smooth surface reduces the bond between the reinforcement and the concrete, thus increasing radial force-transferring mechanism, and inducing transverse cracks. The Illinois Department of Transportation developed a new epoxy coating with improved bond between the epoxy-coated reinforcement and the concrete. This new coating is called textured epoxy-coated reinforcement (Pérez-Claros & Andrawes, 2023).

The manufacturing process of this new coating includes the application of an additional layer of polymeric powder of varied sizes and densities over the traditional epoxy coating. As a result of this layer, friction at the rib faces is increased and the bond-slip interaction is improved.

The results of this study suggest that textured epoxy increases initial slip resistance; however, there was no evidence of an improvement in the peak strength in the pullout test. The authors reported that the textured epoxy-coated reinforcement exhibits the same level of corrosion protection as compared to conventional epoxy-coated reinforcement.

Up to the date of this report, there is no evidence suggesting that textured epoxy-coated reinforcement is being used in new construction or rehabilitation projects by agencies in the U.S., or that textured epoxy-coated reinforcement is being manufactured in large scale by fabrication plants in North America. Furthermore, it is not clear if textured epoxy-coated reinforcement meets ASTM A775/A775M or ASTM A934/A934M or other standard specifications. Further testing has to be performed to determine the effects the roughened surface of the coating has on corrosion resistance and flexibility properties.

2.7.2 Stainless Steel Coatings

Section 2.4 of the literature review not only covered the performance of epoxy-coated reinforcement but also highlights the results of studies which compared several corrosion resistant steel alternatives, including stainless steel. Evidence shows that compared to epoxy-coated reinforcement, stainless steel is the only type of corrosion resistant steel that provides better protection against corrosion. However, the high cost of solid stainless steel, described in Section 2.5, poses a significant challenge to the implementation of stainless steel as a corrosion protection method in concrete bridge decks. One way to overcome this challenge has been to apply a stainless steel coating to the conventional black rebar. Nuovinox, stainless steel cladding, and the newest approach of the NCHRP-240 IDEA program, stainless steel coating, are analyzed in this section.

2.7.2.1 Stainless steel-clad (Nuovinox, Stelax.UK). Stelax is a specialized plant in the United Kingdom that manufactures NUOVINOX steel. The hot bar mill includes a scrap processing plant that converts highgrade raw carbon steel into NUOVINOX's carbon steel core. Stainless steel coil is converted into walled stainless steel pipes which become the metallurgically bonded stainless steel cladding of the finished product (https://www.stellaind.com/).

NUOVINOX is composed of a carbon steel core that is clad with stainless steel. This composite material has identical properties to stainless steel and at a price 40% to 50% lower than hot-rolled stainless steel. NUOVINOX provides an elevated level of corrosion resistance, can be bent up to 180 degrees without causing damage to the cladding, and has superior strength and ductility compared to mild steel (https://www.stellaind.com/).

Stainless steel clad has been reported to behave the same as solid stainless steel and has potential to become a cost-effective solution to the corrosion of reinforcement; however, there have been concerns regarding NUOVINOX quality and availability (De Rojas, 2001).

2.7.2.2 stainless steel cladding reinforcement NCHRP 240. An NCHRP IDEA 240 project developed a new stainless steel coated reinforcement that is intended to replace conventional black rebar and epoxy-coated reinforcing steel. The innovative solution consists of forming a metallic multilayer composite steel reinforcement bar with a stainless steel outer layer. The initial manufacturing process consisted of a cold spray application of stainless steel to the finish rebar; however, the coated bar could not be bent without showing considerable damage to the coating. In the final approach, the stainless steel coating is applied to the steel billet using laser cladding, and then the coated billet is reheated and hot rolled. With this approach, the bars were able to be bent around a 2-in. diameter mandrel (Mcalpine, 2023).

Figure 2.11 shows the results of the macrocell corrosion rates comparison of the conventional reinforcement with the initial cold spray and the final cladded approach using 316 stainless steel coating. There is a significant reduction in corrosion loss per year when implementing the NCHRP 240 approach compared to black reinforcement which indicates the feasibility of this new type of reinforcement.

The researchers were able, in partnership with Allium Engineering, Inc., to produce a spool of #5 rebar containing around 1,500 lbs. of clad reinforcement. One of the concerns regarding this manufacturing process was the potential to damages to the coating induced by the hot-rolling process, which was evidenced when testing the spool of #5 rebars in the form of uneven coating, which the researchers indicated that this problem would not be an issue since sufficient cover was provided; however, it is not clear what coating thickness is required or recommended for the stainless steel cladding reinforcement to provide adequate corrosion protection to the conventional reinforcement core. Additionally, microcracks were discovered within the coating, which was attributed to the hot-rolling process; further investigation on the effect these microcracks might have on the behavior of the coating in bond strength between the coating and the reinforcement and on the reinforcement behavior due to applied loads needs to be addressed. Similarly, the effects of the hot-rolling process on several stainless steel clad rebar diameters need to be evaluated.

The study reported that the pullout failure of the stainless steel coated rebar was between 1,300 to 1,500 psi, compared to black rebar pullout failure of 1,500 psi, and epoxy-coated reinforcement pullout failure ranging from 1,100 to 1,200 psi. Moreover, impact damage testing showed that stainless steel coated rebar exhibited less visible damage than epoxy-coated rebars (Mcalpine, 2023). However, the impact test was performed on the initial cold-spray approach and not on the hot-rolled final approach.

It was also stated that this new product initially can be specified through AASHTO M329 and later will be

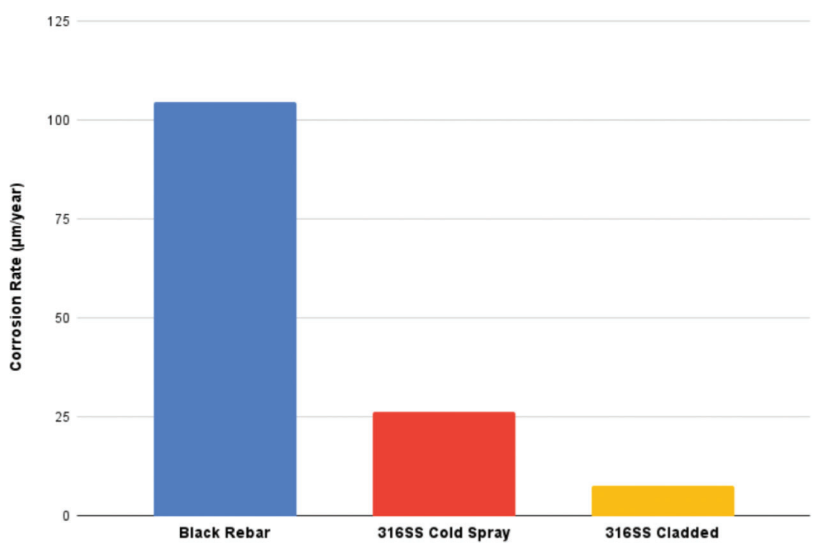


Figure 2.11 Rapid macrocell corrosion rates (Mcalpine, 2023).

included in ASTM standards. This method is expected to increase the life cycle of infrastructure to 100 to 200 years, but initial project costs are expected to be from 1% to 2% higher. The cost of this alternative is expected to compete with methods like galvanized steel. But it is more expensive than epoxy-coated bars. It is unclear how the researchers determined the life cycle range of 100 to 200 years, which is notably broad, as well as the increase in initial project costs. Further evaluation is needed to estimate the life cycle based on prototype testing, corrosion rate measurements, and models, as well as to understand the increases in initial project costs.

There is no evidence that this method is being used in the field; however, support from several Departments of Transportation, including Virginia DOT, Florida DOT, Rhode Island DOT, and California DOT has been sought. Once Allium can manufacture 10 to 15 tons of this stainless steel coated reinforcement meeting AASHTO M329, then a pilot precast component can be built which can be subject to field-type testing (Mcalpine, 2023). The author's conclusion that this reinforcement is expected to increase upfront costs only 1% to 2% remains to be independently corroborated. This alternative appears promising, as stainless steel has demonstrated greater effectiveness in corrosion protection compared to epoxy-coated reinforcement, and it is expected to be more cost-effective than solid stainless steel reinforcement. This is because only an external layer of stainless steel is applied to the conventional reinforcement. However, further testing is required to determine whether this approach could be viable for future reinforced concrete bridge decks or other infrastructure.

2.7.3 Other Experimental Coatings

2.7.3.1 Soy-protein and corn-derived polyol-based coatings. Proposed soy-protein coating materials can be an alternative to epoxy-coated reinforcement or can be used for repairs of damage coatings in corrosive environments**.** These products are synthesized using denatured soy protein isolate (SPI) and corn derived sorbitol plasticizers (Sajid et al., 2022).

Corrosion performance was determined by rapid macrocell tests. The study concluded that soy protein coatings in combination with corn-derived sorbitol have adequate anticorrosion properties. The addition of sorbitol enhanced the abrasion resistance. These authors claim that the results demonstrated that soy protein coatings have adequate characteristics for use as a supplementary protective coating material (Sajid et al., 2022).

This is an experimental study with no evidence of field implementation. Damage to the coating is one of the concerns in epoxy-coated reinforcement, which can be expected to be a concern in soy-protein and corn-derived polyol-based coatings. Furthermore, construction projects require significant amounts of reinforcement, which pose manufacturing challenges to these types of coatings. A more practical application of soy-protein and corn-derived polyol-based coatings might be in repairing damage to other coatings such as epoxy-coated reinforcement rather than serving as a standalone coating.

2.8 Summary and Conclusions

In this section, a summary of the findings and conclusions derived from the literature review is presented.

2.8.1 Summary of Findings

2.8.1.1 Standard specifications and manufacturing process

1. Epoxy-coated reinforcement is most commonly specified through ASTM A775/A775M and ASTM A934/A934M. The main difference between these two specifications is that in ASTM A775/A77M the bar is coated and then bent to the desired shape, on the contrary, ASTM A934/A934M requires that bars be bent prior to the application of the coating. The most typically employed epoxy-coated reinforcement, characterized by the green color of the coating, meets standard ASTM A775/A775M.
2. Performance of epoxy-coated reinforcement has been enhanced throughout the years by improvements in the manufacturing process, and changes to ASTM A775/A775. For instance, prior to 1989, the standard had the damage limit of 2% of the total surface area for every 1-ft length, current standard limits this damage to 1%. Additionally, coating plants in the U.S. that participate in the CRSI certification program are able to produce epoxy-coated bars with as little as 0.2 holidays per foot of bar. ASTM A775/A775M has a limit of 1 holiday per ft of bar. Another improvement in the manufacturing process has been the reduction in the coating thickness variability.

2.8.1.2 Laboratory performance

1. Epoxy-coated reinforcement subjected to simulated seawater and chloride solutions is effective at reducing corrosion activity, even with induced damage to the coating (Erdoğdu et al., 2001). The corrosion rates of epoxy-coated reinforcement compared to the corrosion rates of conventional reinforcement indicate that epoxy-coated reinforcement has higher resistance to corrosion (O'Reilly et al., 2011).
2. Epoxy-coated reinforcement with improved adhesion does not have better corrosion performance than conventional epoxy-coated reinforcement. However, this type of reinforcement improves the bond between the reinforcement and the concrete (O'Reilly et al., 2011).
3. Coating damage is highly correlated to the corrosion performance of epoxy-coated reinforcement and should be minimized (Sim, 2014).
4. Ultraviolet exposure has a deleterious effect on the performance of epoxy-coated reinforcement (Grayli, 2022).
5. Stainless steel is a highly effective corrosion protection system in concrete with elevated chloride content and

is the only corrosion resistant steel that has consistently demonstrated better corrosion performance compared to epoxy-coated reinforcement (O'Reilly et al., 2011).

2.8.1.3 Field performance and cost-effectiveness

1. Epoxy-coated reinforcement implemented in both top and bottom mats provides adequate corrosion protection in bridge decks (Pincheira, 2008).
2. Integer value ratings is a tool used by DOTs to estimate the health of bridge decks and to predict the time it would take a bridge deck to require rehabilitation (NYDOT, 2017).
3. High chloride concentrations, low coating thickness, inadequate concrete cover, and extended exposure to chloride concentrations have been identified to have a deleterious effect on the performance of epoxy-coated reinforcement (McDonald, 2010b).
4. Field performance investigations indicated that epoxy-coated reinforcement is performing better than galvanized steel in bridge decks of similar age (Manafpour et al., 2016).
5. Epoxy-coated reinforcement is a cost-effective corrosion protection alternative. This method is described as the most cost-effective system on total costs over a 75-year design life (O'Reilly et al., 2011).

2.8.1.4 Jobsite guidelines. The performance of epoxy-coated reinforcement is highly correlated with the integrity of the coating during transportation, handling, and construction. Adhering to adequate guidelines enhances the performance of epoxy-coated reinforcement.

2.8.1.5 Coating technologies for reinforcing steel

1. Fusion Bonded Epoxy Rebar Coating 413 coating meets standard ASTM A775/A775M, is characterized by the green color and resists cathodic disbondment, deicing salts, harsh chemicals, and carbonation.
2. Fusion Bonded Epoxy Rebar Coating 426, characterized by the grey or purple color, does not meet flexibility requirement in standards. FBE rebar 426 cannot be bent after being coated.
3. Textured epoxy-coated reinforcement provides improved bond between the reinforcement and the concrete (Pérez-Claros & Andrawes, 2023); however, there is no evidence that this type of reinforcement exhibits better performance than conventional epoxy-coated reinforcement.
4. Stainless steel is a highly effective corrosion resistant steel; however, costs represent a significant drawback to this alternative. Nonetheless, project NCHRP 240 presented a modern approach by applying stainless steel coating using laser cladding. This method could increase the lifecycle of bridge decks to 100–200 years with an initial estimated costs of 1%–2% higher than traditional methods (Mcalpine, 2023). These conclusions remain to be independently corroborated.
5. Soy-protein and corn-derived polyol-based coatings have adequate anticorrosion properties. However, similarly to epoxy-coated reinforcement, damage to the coating is expected to be a concern (Sajid et al., 2022).

2.8.2 Conclusions

The conclusions presented herein are based on the findings summarized in Section 2.8.1 in the categories of laboratory performance, field performance, lifecycle and cost assessment, jobsite guidelines, and coating technologies.

1. Improvements in the quality of manufacturing process, and rigorous standards have progressed the quality and enhanced the corrosion performance of epoxy-coated reinforcement. These changes enable the DOTs to obtain the highest quality of epoxy-coated reinforcement available in the market.
2. Under laboratory testing, epoxy coating is effective at reducing corrosion activity of the steel reinforcement in concrete bridge decks.
3. Damage to the coating is highly correlated with the corrosion protection provided by the coating.
4. In laboratory testing, there is a concern that the amount of damage intentionally created might not be representative of the damage induced during construction.
5. Epoxy-coated reinforcement should be protected from UV exposure.
6. Stainless steel is a highly effective corrosion resistant steel, which outperforms epoxy-coated reinforcement.
7. Epoxy-coated reinforcement should be employed in both top and bottom mats to provide adequate corrosion protection in concrete bridge decks.
8. Bridge inspection and tools like the integer value ratings are beneficial to estimate the lifecycle and maintenance requirements of concrete bridge decks.
9. Chloride content at the level of reinforcement and time of exposure should be minimized for a proper performance of epoxy-coated reinforcement.
10. Epoxy-coated reinforcement is a cost-effective corrosion protection alternative.
11. Maintaining adequate guidelines like the ones shown in Table 2.11 and inspection prior to concrete placement are strongly recommended practices to ensure that epoxy-coated reinforcement will provide adequate corrosion performance.
12. Fusion Bonded Epoxy Coating 413 and 426 present resistance to cathodic disbondement, deicing salts, airborne salt sprays, sea water, harsh chemicals, acid rain, carbonation, contaminated aggregate, and concrete additives.
13. Fusion Bonded Epoxy Coating 426 does not meet flexibility requirements of standards. This type of coating cannot be bent after the application of the coating.
14. Epoxy-coated reinforcement with improved adhesion does not have better corrosion performance than conventional epoxy-coated reinforcement.
15. Project NCHRP 240, stainless steel-clad reinforcement, is a promising alternative to the use of solid stainless steel in bridge deck construction. Further investigation needs to be implemented to corroborate the conclusion in estimated costs, manufacturing

guidelines, coating thickness, and corrosion performance described in the study.
16. A practical application of polyol-based coating is in repairing damage to other coating like epoxy-coated reinforcement, rather than serving as a standalone coating.

3. SURVEY OF STATE DEPARTMENTS OF TRANSPORTATION

3.1 Introduction

Twenty-seven state DOTs responded to the survey. The DOTs responding are listed in Table 3.1 and the geographic distribution is shown in Figure 3.1. The states that present similar climate and environmental conditions to those found in Indiana are bolded in Table 3.1.

The survey is intended to establish the extent and type of epoxy-coated reinforcement used as a key component of corrosion protection systems in concrete bridges. Additionally, the survey queries the DOTs on the various experiences in the categories of research, field implementations, durability, and types of corrosion methods.

The survey is composed of ten questions that focus on three distinct groups of data. The first section inquires about the kind of corrosion method the agency uses and the criteria by which that certain method was chosen. The second section seeks information on the performance of the chosen corrosion protection systems that are currently in use. The last section aims to determine the lessons learned and plans to deploy a new corrosion method in future projects.

3.2 Survey Questions

This section describes in detail the survey questions in the order presented.

1. What methods of corrosion protection are currently used in bridge decks in your region? Please check all methods that apply. In the space provided beside each method, please specify whether the method is used only in new construction or rehabilitation of existing bridge decks or both.
   a. Cathodic Protection
   b. Corrosion Inhibition Admixtures
   c. Modified Concrete Overlays (please specify type)
   d. Galvanized Reinforcing Steel
   e. Membrane Overlay
   f. Polymer Overlay
   g. Stainless Steel Coated Rebar
   h. Epoxy-Coated Rebar
   i. Others (Please specify, include combination of the above, too.)
2. Which of the methods checked above are currently in your specifications or standard drawings?
3. What are the main concerns when selecting corrosion methods?

TABLE 3.1
DOTs Response Breakdown by State

Delaware	South Carolina	**Missouri**	**New Jersey**	**Indiana**
Alaska	Vermont	**South Dakota**	Arizona	**Pennsylvania**
Kentucky	**West Virginia**	**Utah**	**Kansas**	**Ohio**
Rhode Island	**Nevada**	**Colorado**	**New York**	–
North Dakota	Mississippi	Texas	Oklahoma	–
Georgia	Maine	Virginia	**Iowa**	–

Note: States that present similar climate and environmental conditions to those found in Indiana are bolded.

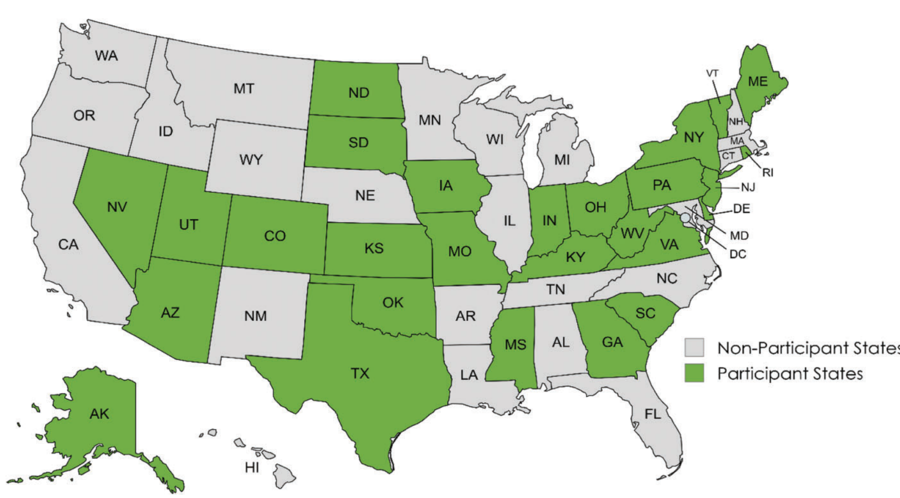


Figure 3.1 DOTs response map.

4. Is there a plan to implement new corrosion systems in future projects? Please specify.
5. What criteria have you used in your choice of all corrosion protection methods? Please check the criteria that apply and make comments in the space provided.

   a. Economic
   b. Performance in the Lab
   c. Previous Research/Finding
   d. Manufacturer's Information
   e. Site Selection
   f. State Experience
   g. Purpose of Rehab
   h. Other (please specify)

6. How well are all the corrosion protection methods performing and how long have they been in place?
7. What criteria are used to evaluate the performance of all the corrosion protection systems?
8. Can you state a few of the main deteriorations observed during bridge deck inspection?
9. What strategies are used by your agency to prevent, delay, or reduce deterioration of bridge decks?
10. Of all the strategies and corrosion protection systems used by your agency, describe which ones have been the most effective and least effective. Please explain.

3.3 Survey Responses

Herein the responses received are summarized and presented in the same order as in the survey. The questions are shown in Italics with the summary of the responses immediately following the question. The total number of responses received, "N" is shown next followed by the summary of the responses in table or graph form (Table 3.2 and Figure 3.2) or both as needed.

What methods of corrosion protection are currently used in bridge decks in your region? Please check all methods that apply.

Please specify whether the method is used only in new construction or rehabilitation of existing bridge decks.

Cathodic Protection: Four DOTs stated that cathodic protection is used in both rehabilitation projects and new construction projects. Ohio DOT have used galvanic anodes in some rehabilitation projects. However, they are not used in new construction.

Corrosion Inhibition Admixtures: Three DOTs stated that corrosion inhibition admixtures are used in both rehabilitation projects and new construction projects. Oklahoma DOT declared only using corrosion inhibition admixtures in rehabilitation projects. Ohio DOT mentioned that corrosion inhibition admixtures are required in all new prestressed beams, precast reinforced concrete arch sections, and three sided flat top culverts unless epoxy-coated steel is used.

Modified Concrete Overlays: Fourteen DOTs stated that the main use of modified concrete overlays is in rehabilitation projects. Additionally, four states mentioned the use of modified concrete overlays in new construction projects. Ohio DOT declared the extensive use of modified concrete overlays, with the purpose of establishing a new wearing surface, restoring ride quality, and protecting the underlying deck. Iowa DOT specified the use of high-performance concrete with low permeability, low slump concrete, and ultra-high-performance concrete (UHPC).

Galvanized Reinforcing Steel: Five DOTs mentioned the use of galvanized reinforcing steel in new construction projects.

Membrane Overlay: Five DOTs stated that membrane overlay is used in both rehabilitation projects and new construction projects. Four DOTs mentioned the use of membrane overlay only in rehabilitation projects.

Polymer Overlay: Ten DOTs use polymer overlay for rehabilitation projects only. Six DOTs use polymer overlay for both rehabilitation projects and new

TABLE 3.2
Selection of Corrosion Protection Method by State

	Method										Method								
State	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**State**	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**
Delaware			×	×		×		×		Alaska			×		×			×	×
Kentucky			×	×	×		×	×		Rhode Island				×	×				
North Dakota		×				×		×	×	Georgia								×	
South Carolina			×	×		×			×	Vermont	×			×	×			×	×
West Virginia	×		×	×				×		Nevada					×	×		×	
Mississippi						×				Maine	×	×		×	×	×	×		×
Missouri			×			×		×	×	South Dakota			×			×		×	×
Utah				×		×		×	×	Colorado	×	×			×	×	×	×	
Texas		×	×	×		×		×	×	Virginia	×		×		×	×			×
New Jersey			×	×			×	×		Arizona			×			×		×	
Kansas	×		×			×		×	×	New York			×	×		×		×	×
Oklahoma		×	×	×	×	×		×	×	Iowa			×			×		×	×
Indiana			×		×	×		×		Pennsylvania			×	×	×	×		×	
Ohio	×	×	×	×	×	×	×	×	×	—									

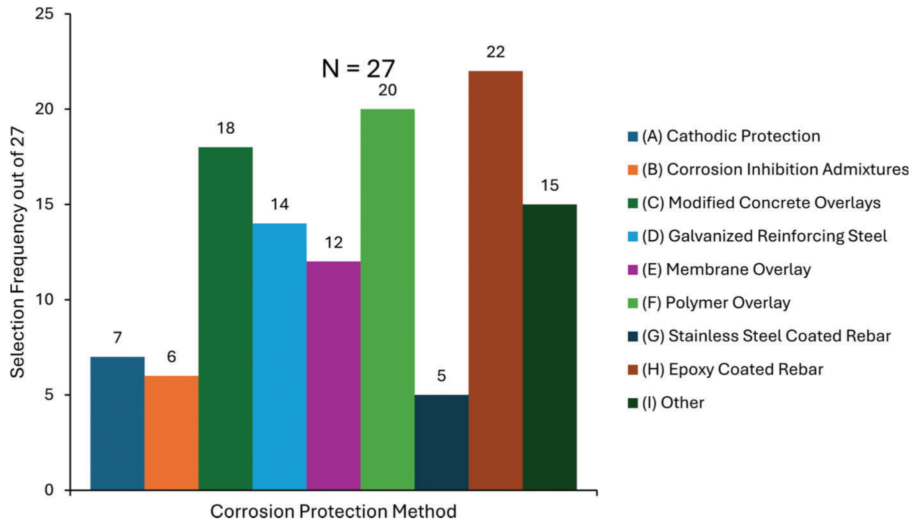


Figure 3.2 Selection frequency corrosion protection method.

construction projects but mentioned that it is mainly used in rehabilitation projects.

Stainless Steel Coated Rebar: Three DOTs use stainless steel coated rebar in new construction projects. Iowa DOT uses solid stainless steel rebar for deck to rail connections and in larger decks where an increased service life is desired but declared that have not use stainless steel coated reinforcement.

Epoxy-Coated Rebar: Ten DOTs use epoxy-coated rebar both in rehabilitation projects and new construction projects. Four DOTs use epoxy-coated rebar only in new construction projects. Pennsylvania DOT mentioned that epoxy-coated reinforcement is the standard choice of most contractors.

Other (Please Specify): Fifteen DOTs use other types of corrosion systems such as magnesium alumino liquid phosphate (MALP), high chromium rebar, solid stainless rebar, chromium alloy, GFRP, FRP, low dosage of steel fibers, low slump dense concrete overlays, stainless steel rebar, polymer fiber reinforced concrete to control cracking, ¾ minimum polyester overlay, and methyl methacrylate. These additional types of corrosion methods are shown in Table 3.3.

Which of the methods checked above are currently in your specifications or standard drawings? What are the main concerns when selectin corrosion methods?

Table 3.4 lists the methods currently in state specifications. Figure 3.3 indicates that the top two concerns throughout the twenty-seven collected responses are the *economic aspect* and *effectiveness* of the corrosion system. The Texas Department of Transportation reported the following concerns: damage to the epoxy coating during construction and contractor leaving it unrepaired; and variation in the performance being reported for galvanized reinforcing steel.

Is there a plan to implement new corrosion systems in future projects? Please specify.

The responses indicated that while most of the states are using epoxy-coated reinforcement, there is the desire to continue looking for improved methods of corrosion protection in concrete bridge decks. The state implementation plan of new corrosion systems is shown in Table 3.5.

What criteria have you used in your choice of all corrosion protection methods? Please check all criteria that apply and make comments in the space provided.

In their practice, agencies implement several methods of corrosion protection. The response regarding the criteria used by each DOT to determine the choice of the corrosion protection system is shown in Table 3.6. Similarly, Figure 3.4 shows the selection frequency of each of the alternatives provided in the survey.

How well are all the corrosion protection methods performing, and how long have they been in place?

The most common response was that in general all methods are performing as expected with some minor issues. However, some of these methods have been used only in the last 10–15 years making it difficult to assess their long-term performance. Below is a description of the state's responses by method of corrosion protection.

Cathodic Protection: Virginia DOT reported that projects with cathodic protection over the last 10 years, which have been passive systems, appear to indicate satisfactory performance. However, VDOT had limited use of cathodic protection, mostly limited to impressed current, which performed well early but were difficult to maintain due to thermal expansion and contraction that resulted in a loss of current.

Modified Concrete Overlays: South Carolina DOT has been using modified concrete overlays since 2007 with reliable performance. West Virginia DOT reported

TABLE 3.3
Other Types of Corrosion Methods Identified by State

State	Corrosion Method Type: Other	State	Corrosion Method Type: Other
Alaska	ASTM A1035 high chromium bars When using epoxy, we usually still install a membrane prior to pavement. With A1035 and paving, no membrane is used	Vermont	We use other types of reinforcing steel: solid stainless, chromium alloy, GFRP
Maine	Heavily use GFRP for concrete decks	Missouri	Low dosage of steel fibers–15 pounds per yard jointless decks where possible Silane sealer on new decks, then retreat on a cycle
South Dakota	Low Slump Dense Concrete Overlays	Utah	Polymer fiber reinforced concrete to control cracking. New construction combines fiber reinforced concrete with coated reinforcing and a polymer overlay
Texas	The use of ¾″ min polyester overlays has increased in the last 4 years	Virginia	Low cracking deck concrete for new construction High carbon chromium rebar
Kansas	Methyl methacrylate in rehabs	New York	High performance internal curing concrete with low permeability and reduced cracking Concrete sealer is applied to new bridges
Oklahoma	Magnesium Alumino Liquid Phosphate (MALP) on a few projects	Ohio	Experimenting with internal curing to aid in extending the life of concrete bridge decks by reducing cracking

Figure 3.3 Main concerns when selecting corrosion protection methods.

that latex modified overlays appear to perform better over micro-silica overlays, which are less forgiving of poor bonding interface and weather conditions. Iowa DOT have found no issues with ultra-high-performance concrete overlays; however, they have only been in service for a few years. Iowa DOT mentioned that the majority concrete overlays have been installed in older bridge decks reinforced with black rebar, and only 7% on decks with epoxy-coated reinforcement. Indiana DOT reported that silica fume modified concrete

TABLE 3.4
Methods in Specifications or Standard Drawings by State

State	Methods in Specifications or Standard Drawings	State	Methods in Specifications or Standard Drawings
Delaware	Modified concrete overlay Polymer overlay Galvanized reinforcing steel	Alaska	No standard drawings. Membranes and epoxy rebar are in standard specifications. Polyester concrete and A1035 rebar are special provisions
Kentucky	Epoxy-coated rebar	Rhode Island	Membrane overlay Galvanized reinforcing steel
North Dakota	Epoxy-coated rebar	Georgia	Epoxy-coated rebar
South Carolina	Galvanized reinforcing steel Modified concrete overlay	Vermont	Cathodic protection Membrane overlay Galvanized reinforcing steel Epoxy-coated rebar Other (solid stainless, chromium alloy, GFRP)
West Virginia	Cathodic protection Modified concrete overlay Epoxy-coated rebar	Mississippi	Hybrid polymer concrete overlay
Missouri	Epoxy-coated rebar Silane sealer Steel fiber RC	South Dakota	Modified concrete overlay Polymer overlay Epoxy-coated rebar Stainless steel rebar
Utah	Epoxy-coated rebar Galvanized reinforcing steel Polymer overlay	Maine	Membrane overlay Polymer overlay Stainless steel coated rebar Galvanized reinforcing steel FRP rebar
Colorado	Stainless steel rebar Polyester concrete overlay Asphaltic membranes	Texas	Corrosion inhibition admixtures Galvanized reinforcing steel Polymer overlay Epoxy-coated rebar Modified concrete overlay
Virginia	Specifications contain: Rigid concrete bridge deck overlay (425)[1], concrete penetrant sealer (428)[1], Waterproofing membrane systems (429)[1], epoxy bridge deck overlays (431)[1]	New Jersey	Galvanized reinforcing steel Epoxy-coated rebar
Arizona	Epoxy-coated rebar	Kansas	Epoxy-coated rebar Methyl methacrylate Polymer overlay
New York	Modified concrete overlay Galvanized reinforcing steel Polymer overlay Epoxy-coated rebar High AADT Solid stainless steel	Oklahoma	Corrosion inhibition admixtures Modified concrete overlay Galvanized reinforcing steel Membrane overlay Polymer overlay Epoxy-coated rebar
Iowa	Epoxy-coated rebar and concrete overlays UHPC overlays, high-performance concrete and thin polymer overlays have special provisions	Indiana	Silica fume modified concrete overlay Polymer overlays Epoxy-coated reinforcement
Pennsylvania	All methods mentioned in question 1 Stainless steel is within the standard, but it is not used Cathodic protection is in standard but only use in substructure	Ohio	All methods in question 1 are covered in ODOT'S specification, supplemental specifications, or plan notes

[1]Virginia specifications section.

overlay have mixed results, because the material is susceptible to cracking during initial construction.

Galvanized Reinforcing Steel: VDOT implemented the use of galvanized reinforcing steel in limited projects over the last 5 years and stated that it is performing well. South Carolina DOT recently began using galvanized steel and is awaiting its performance evaluation.

Polymer Overlay: SDDOT reported the use of polymer chips seal overlays beginning in the 1990's with satisfactory performance and only occasional

TABLE 3.5
Implementation Plan of New Corrosion Strategies by State

State	Description	State	Description
Delaware	Nothing new	Alaska	Polyester overlays and A1035 Alaska uses spray-applied membranes
North Dakota	Structural decks are treated with silane	Georgia	Vetting other options besides epoxy-coated reinforcement
South Carolina	Looking into the use of GFRP bar in bridge decks	Vermont	Looking for new, better, and more economical
West Virginia	May start requiring galvanized reinforcing steel in all concrete bridge decks and barriers on interstates and expressways	Mississippi	UHPC for bridge deck overlays
Missouri	Low dosage of steel fibers	South Dakota	Just started requiring stainless steel in bridge decks
Utah	Looking into the use of ChromX 4100	Maine	Use of composite structures
Colorado	Evaluated on a case-by-case basis	Texas	GFRP reinforcement in bridge decks in selected areas
Virginia	Polymer modified concrete Considering fiber reinforced latex and polyethylene overlays	New Jersey	Would like to implement a cathodic protection system plan for rehabilitation, replacement, and repairs of concrete bridge decks for future projects. Looking into the use of multiple galvanic anode systems
Kansas	Currently implementing methyl methacrylate in rehab projects	New York	Galvanizing will continue to be an option in addition to systems in use now
Oklahoma	Starting to use galvanized steel rebar	Iowa	Considering introducing sacrificial galvanic anodes into deck repair areas prior to placing concrete overlays
Indiana	No	Pennsylvania	Cathodic protection is under further consideration
Ohio	All methods are given consideration for each new project or rehabilitation. Ohio preferred reinforcing type is epoxy-coated reinforcement; however, there seems to be something shifting to galvanized reinforcement		

TABLE 3.6
Criteria Used for Selection of Corrosion Methods by State

	Criteria									Criteria							
State	A	B	C	D	E	F	G	H	State	A	B	C	D	E	F	G	H
Delaware	×	×	×		×	×			Alaska	×		×		×	×	×	
Kentucky	×					×	×	×	Rhode Island	×		×	×	×	×	×	
North Dakota	×		×			×			Georgia	×	×	×	×	×	×		
South Carolina	×		×	×	×	×	×		Vermont	×	×	×	×	×	×	×	×
West Virginia	×		×		×	×	×		Nevada					×	×		
Mississippi	×						×		Maine	×		×		×	×	×	
Missouri	×	×	×	×	×	×	×		South Dakota	×		×		×	×		
Utah	×		×			×	×		Colorado	×	×	×	×		×	×	
Texas	×		×		×	×	×		Virginia	×		×			×	×	
New Jersey	×				×	×	×		Arizona	×		×			×	×	
Kansas	×	×			×	×	×		New York	×		×			×	×	
Oklahoma	×		×	×					Iowa	×	×	×		×	×		
Indiana	×	×	×		×	×	×		Pennsylvania	×		×		×	×		×
Ohio	×	×	×		×	×	×		—								

failures. UDOT has been using polymer overlays since 2002 and stated that the overall performance is good; however, when placed with new construction, cracking from deck shrinkage tends to crack the overlay. Iowa DOT have used polymer overlays with satisfactory performance. Pennsylvania mentioned that polyester polymer concrete (PPC) was first used in 2019 for bridge decks and has been performing well. Moreover, latex has been the go-to overlay for a longer period and has performed well when installed well.

Epoxy-Coated Reinforcing Steel: Alaska reported that epoxy-coated reinforcing steel has been in use since the 1980's and has performed well particularly in

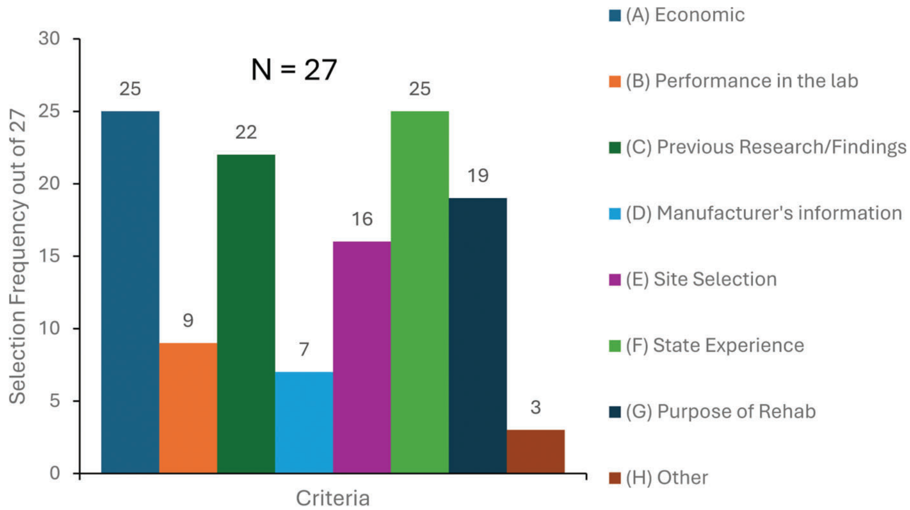


Figure 3.4 Number of instances out of 27 responses.

Figure 3.5 Criteria used to evaluate the performance of corrosion protection systems.

combination with a membrane. Missouri DOT and Oklahoma DOT reported that epoxy-coated rebar has been in use for over 40 years with good success. Similarly, New York DOT has been using epoxy-coated reinforcement since 1976 with no failures attributed to failure of epoxy coating. South Dakota DOT implemented epoxy coating in the 1980's and reported that it has been performing well. Additionally, North Dakota DOT claimed that epoxy rebar and silane applications have been performing well for over a decade. Utah DOT began using epoxy-coated reinforcing in 1978 with a satisfactory performance overall; however, damage to epoxy coating led to occasional corrosion issues. Vermont DOT stated that epoxy coating has been used for about 40 years and has had some service issues. Similarly, the Texas DOT has found the earliest epoxy-coated rebar to be problematic and has attributed that to the bad formulation of the coating. Iowa DOT observed increased bridge deck corrosion of the bottom mats in bridges built in the late 1970's as only the top mat was reinforced with epoxy-coated rebar. However, in the 1980s, Iowa DOT implemented the use of epoxy-coated reinforcement in top and bottom mats, and since then, no significant issues have been noted. Indiana DOT, which has been using epoxy-coated reinforcement for about 30 years, reported that they do not often encounter bridge deck spalling when epoxy-coated reinforcement has been used.

Other Methods: New Jersey DOT stated that the UHPC overlays for the pilot project have been in service for 4 years. The existing decks and overlays show no signs of deterioration or corrosion. Typically, a 25 to 35-year service life is expected for a newly constructed bridge deck. NYDOT reported that ultra-high-performance concrete overlays have been performing well. Maine DOT has been using GFRP since 2010 and has put over two million linear feet in bridge decks with satisfactory performance.

What criteria are used to evaluate the performance of all the corrosion protection systems?

Can you state a few of the main deteriorations observed during bridge deck inspections?

The most common deterioration signs observed during bridge deck inspection are shown in Figure 3.6. Table 3.7 shows the criteria used to evaluate the performance of all corrosion protection systems. According to the Texas Department of Transportation, for bridge decks placed in the last 30 years, cracking is the most common deterioration found. It is followed by shallow spalls related to low clear cover to the reinforcement, a construction defect. On older decks, over 40 years old, the observed deteriorations are concrete delamination above top mat reinforcement. TXDOT reported concrete overlay delamination at various stages, over 20-year performance, as well as thin polymer overlay failure within 5 to 10 years. The Colorado Department of Transportation reported efflorescence and orange rust stains on bridges without stay-in-place forms prior to the 1980's. The Rhode Island Department of Transportation stated that the

TABLE 3.7
Criteria Used to Evaluate the Performance of Corrosion Protection Systems by State

State	Criteria	State	Criteria
Delaware	Long-term performance	Alaska	Signs of efflorescence, delamination/spalls in the deck
Kentucky	Number of deck issues	Rhode Island	Bridge inspection reports
North Dakota	Deck testing for chlorides pre rehab	South Carolina	Lifespan of bridge deck. Deck cracking has been an issue, it is believed corrosion of rebar is the cause
Vermont	Concrete spalling and pop-outs due to corrosion of rebar	West Virginia	Findings during NBI bridge safety inspections
Maine	Cost/performance vs. importance of structure, i.e., is it on a National Highway System (NHS) road vs. rural remote?	Missouri	Cost, effectiveness, maintenance
Utah	Performance based on physical evidence of corrosion	Colorado	Historical data and manufacturer's literature and performance
Virginia	Deterioration analyses by element or bridge type on ad hoc basis by tracking performance data stored in BrM	New Jersey	Bi-annual bridge re-evaluation survey report
Arizona	Compare to control bridge. Similar bridges without protection	Kansas	Spalling, wear, cores (special investigation)
New York	Bi-annual inspection reports and in-depth bridge deck evaluation for rehabilitations	Oklahoma	Durability, life span, corrosion resistance
Iowa	Primarily inspection reports to keep track of performance	Indiana	Bridge inspection data and maintenance needs
Pennsylvania	Visual inspection	Ohio	Does not have a quantitative approach to evaluating performance of the corrosion practices. Systems performance is based upon subjective outcomes of the bridge element over time and inspection data

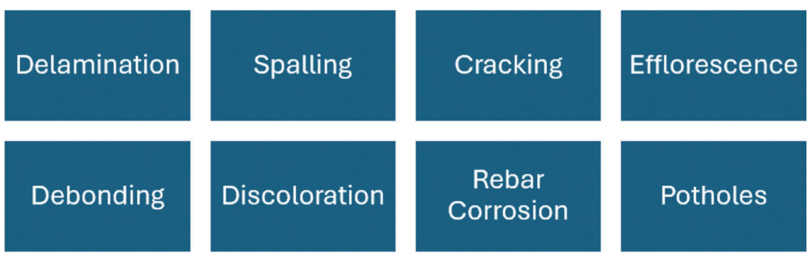


Figure 3.6 Main deterioration observed during bridge deck inspection.

most common deteriorations, cracking, spalling, and efflorescence, are observed on bridge decks where no protection system was incorporated. Table 3.8 shows the responses by state and Figure 3.7 shows states that were specifically identified as given similar conditions to Indiana by region.

What strategies are used by your agency to prevent, delay, or reduce deterioration of bridge decks? Of all the strategies and corrosion protection systems used by your agency, describe which ones have been the most effective and least effective. Please explain.

Table 3.9 summarizes the responses to the questions of strategies used by each state. This followed by comments from individual states regarding the effectiveness of the strategies used.

Delaware: Polyester polymer concrete (PPC) overlays seem to have a better finish than modified concrete; however, it is tough to determine the in-service life of the PPC overlay vs. the modified concrete overlay since it has only been in use within the last 15 years. There are concerns regarding the effectiveness of galvanized rebar.

Alaska: Introduced new CIP bridge decks, primarily used decked bulb-tees with longitudinal keyways. This configuration provides a net compressive force in the decks limiting crack widths. The A1035, ChromX—chromium alloy reinforcing steel rebar—has been effective in recent projects. Contractors appreciate not having to protect and repair the A1035 rebar compared to epoxy-coated rebar.

Kentucky: All implemented methods have been effective. Premature failure of overlays during construction has been observed. No early failures of coated or corrosion resistant reinforcement have occurred.

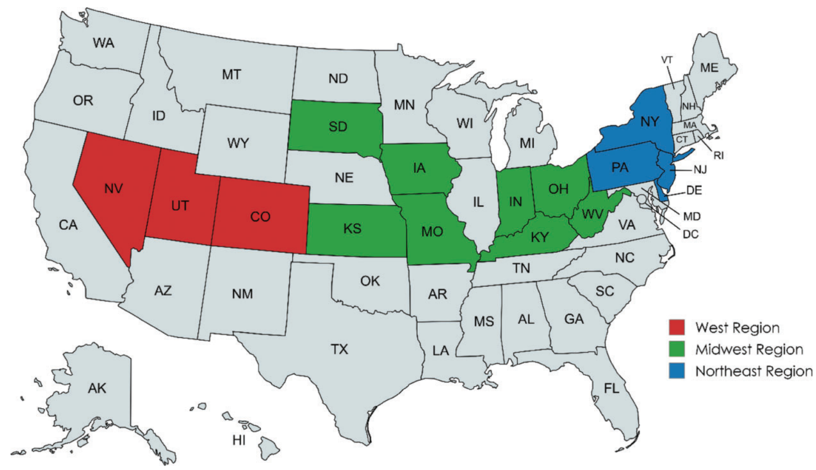


Figure 3.7 Target states division by region.

TABLE 3.8
Deterioration Observed During Bridge Deck Inspection

State	Observation	State	Observation
Delaware	Minor cracking of overlays, particularly modified concrete. Also rare, bus has happened—delamination between the concrete and overlay	Alaska	Signs of efflorescence on soffit, delamination/ spalls in the deck
Kentucky	Potholes. Failure of overlays	Rhode Island	Spalling, efflorescence, cracking. However, these observations are on older bridge decks that protection systems were not incorporated
North Dakota	Overlay delamination and localized spalling	Georgia	Cracking, spalling, punch throughs
South Carolina	Deck cracking, rebar corrosion	Vermont	Concrete spalling and pop-outs due to expansion of the reinforcing steel during corrosion
West Virginia	Cracking, spalled, and delaminated concrete, exposed reinforcement with corrosion	Nevada	Delamination of concrete and corrosion of rebar
Mississippi	Delamination and spalling of concrete	Maine	Cracking and delamination are the significant issues for non-corrosion resistant decks
Missouri	Cracks, spalls, delamination, efflorescence, saturation, deck edge deterioration, scaling, and rebar exposed with section loss	South Dakota	Just the normal deck cracking, spalls, and delamination. Some areas with ASR in concrete.
Utah	Potholes or spalling in concrete elements. Delamination and deterioration of polymer overlays	Colorado	Map cracking or spalling on the bottom surface. Some efflorescence and orange rust stains on bridges
Texas	Recent decks, cracking is most common. Shallow spalls related to low clear cover is next. On older decks, concrete delamination	Virginia	Cracks, spalls, and delamination
New Jersey	Spalls/ potholes throughout the bridge deck, cracking on the deck surface, cracking on the underside of the deck, efflorescence is on the underside due to exposed rusted reinforcement and chloride contamination	Arizona	Cracking, spalling, and delamination
Kansas	Spalling, rust, debonding	New York	Cracking and spalling due to corroded bar
Oklahoma	Spalls and potholes, discoloration, and efflorescence	Iowa	Full depth transverse cracks in new concrete decks, random cracking in new concrete overlays, and spalling and delamination of concrete overlays
Indiana	Spalling due to corrosion of reinforcing bars is the main source of deterioration. Also observed somewhat frequent instances of overlays delaminating from the original concrete deck	Pennsylvania	Delaminations, potholes, cracking
Ohio	Time has to be accounted for in any inspection observations with respect to deterioration		

TABLE 3.9
Strategies Used to Prevent Bridge Deck Deterioration by State

State	Description	State	Description
Delaware	Silane sealing every 5 years, crack sealing	Alaska	Belt and suspenders of using a membrane in conjunction with other corrosion protection systems
Kentucky	Concrete sealing on new structures	Rhode Island	Low permeability concrete mix designs, galvanized rebar, polymer asphalt waterproofing membranes, and polymer modified hot mix asphalt overlays
North Dakota	Silane treatment, epoxy patching and sealing, bridge deck overlays, polymer modified overlays	Georgia	Preservation with copolymer overlays and rehabs with latex modified overlays or concrete overlays
South Carolina	Latex modified concrete overlays on deck rehab Polyester concrete overlays Galvanized reinforcing steel	Vermont	High performance concrete and corrosion resistant reinforcing steel waterproofing membranes (spray or torch applied) asphalt overlay
West Virginia	Bridge deck washing program, deck sealing program, concrete overlay projects, use of cathodic protection	Nevada	Epoxy-coated rebar and deck overlays as part of initial construction
Mississippi	½″ hybrid polymer concrete overlay before needing hydro demolition or full deck replacement	Missouri	Epoxy-coated rebar, wearing surfaces—low slump, latex modified, and silica fume concrete
South Dakota	Bridge deck washing and cleaning in spring following winter. Sealing and silane treatment	Utah	Combination of polymer fiber RC with coated reinforcement and polymer overlays
Maine	Membrane and corrosion resistant rebar	Colorado	Taking chloride samples to remove contaminated portions the place overlays on service life left
Texas	Silane sealers, epoxy crack sealers, thin multi-layer polymer overlays, and polyester overlays	Virginia	Bridge deck cleaning. Taking appropriate action at time of rehab. Epoxy bridge deck overlay and rigid overlay
New Jersey	Type B or Type C bridge deck repairs	Arizona	Deck washing after winter
Kansas	Deck patching, overlays, mill and overlays, epoxy rebar, methyl methacrylate flood coast, asphalt overlays with waterproofing material, galvanic anodes	New York	Use of high-performance internal curing concrete with corrosion protected rebar Impervious overlays on rehabilitation projects Concrete sealing in all new bridge decks Crack sealing with methyl methacrylate
Oklahoma	Provide 2 ½″ of cover. Use epoxy-coated rebar and apply silane sealant	Iowa	Recently added micro and macro fibers into bridge decks and overlay mixes Started to use high molecular weight methacrylate to seal cracks in decks and overlays The district bridge repair crews will epoxy inject delaminated areas in concrete overlays to re-establish bond between deck and overlay
Indiana	The maintenance department applies a silane deck sealer at about year 3 and 7 of a bridge deck's life, then a polymer overlay is programmed for construction	Pennsylvania	Requirement of a dual-protection system on all new interstate bridge decks
Ohio	Implemented a statewide sealing and cleaning program on the priority system. Use of different concrete reinforcement options. Wearing surface overlays. Conversion to semi-integral superstructures to eliminate joints		

Rhode Island: The polymer modified asphalt waterproofing membrane. Since the implementation of chloride content in bridge deck concrete was dramatically reduced. The readings were taken from older decks that used waterproofing membranes that were not as sophisticated as currently used systems. Additionally, waterproofing membranes have a much better cost benefit ratio than all of the other protection systems currently being used.

North Dakota: Treating new decks and existing decks with silane, using natural deicing chemicals in moderation have been effective.

Vermont: High performance concrete with corrosion resistant reinforcing seems to require the least maintenance. Waterproof membranes work well but have caused pot holing in the pavement, creating a maintenance problem, if not installed correctly. Membrane and pavement systems have worked well if installed properly but do not provide the same service life as the rest of the structure and must be removed and reinstalled to remain effective.

West Virginia: All systems have been effective. Routinely washing and sealing bridge decks will be the most effective when considering cost to benefit. In some cases, micro-silica overlays have been the least effective due to their expense and possibility of not achieving a proper bond to the substrate concrete. However, some micro-silica overlays have performed very well but with mixed results and a high application cost.

Nevada: Overlays tend to work well.

Maine: Non-corrosive reinforcement has been the best while galvanic protection has been the least.

Missouri: Epoxy-coated rebar has been shown to be the most effective method. Cathodic protection was used in the past, but it was difficult to maintain and easily damaged by vandals and maintenance activities.

South Dakota: LSDC overlays have been the most effective to existing bridge decks and slabs for extending the service life. Epoxy bars have been the most effective for new bridges. High expectations for stainless steel for future bridges. Polymer chips seals, in existing bridges, are the least effective methods compared to LSDC overlays, but they work.

Utah: Coated reinforcement seems to be the most effective. However, with about 50 years of continuous use, it is difficult to make a definitive comparison to the levels of deterioration from before the switch to coated steel was made. Utah has started to use polymer fiber reinforced concrete decks. So far it has not resulted in crack-free decks as hoped.

Colorado: Waterproof membranes with asphalt overlays have proved effective for up to 20 years. CDOT is implementing a strategy to replace these membranes every 20 years when the time is due for replacing asphalt overlay cycles (5–7 years).

Texas: Overall good deck performance is observed. A good performance is considered 50 years without issue. The vast majority meet that criteria but there are some (especially in the Texas Panhandle) that do not. Preventing measures are aimed at extending that 50-year target to 75 and 100 years.

Virginia: New construction materials and hydro mill prior to rigid overlay have been the two most effective.

New Jersey: The most effective corrosion protection systems have been UHPC overlays and the use of stainless steel reinforcement. The least effective protection systems used have been the use of epoxy-coated rebar. However, there are significant cost savings when using epoxy-coated rebar in lieu of stainless steel reinforcement and UHPC.

Arizona: Hydro-demolition with LMC overlay. This rehab can make a substantial difference to the deck surface.

Kansas: The most effective systems have been epoxy-coated rebar, concrete overlays, galvanic anodes (when used for long term repairs). The least effective have been fume overlays due to maintenance concerns with mixed results on polyester overlays.

New York: New performance concrete mixes with the use of corrosion protected rebar have been the most effective. New polymer overlays and UHPC overlays have proven effective for rehabilitation.

Oklahoma: Silane epoxy rebar combination. Some success with corrosion inhibitors. Using epoxy rebar on the top of the deck and black steel on the bottom layer has led to corrosion problems.

Iowa: Fiber reinforcement seems to be helping with the early-age cracking. Concrete overlays have been effective. A first concrete overlay on a bridge typically lasts 25 to 35 years before requiring replacement. Good outcomes are expected with ultra-high-performance concrete overlay and the use of solid stainless steel rebar in decks.

Indiana: It is too early to determine the effectiveness of the bridge decks sealing program. Epoxy-coated reinforcement appears to provide much better service life than uncoated bars.

Pennsylvania: Epoxy-coated reinforcement has been highly successful but frequently presents cracking. The state experience with latex overlays has been variable and is highly dependent on the quality of the installation. PPC has been highly effective for corrosion prevention but may present minor rutting. Hybrid composite synthetic concrete (HCSC) is currently in the experimental stage but shows promise.

Ohio: Rehabilitated columns exposed to the use of deicing salts in the splash zones are patched, galvanic anodes placed, wrapped with composite fiber, and epoxy sealed applied. This system the ODOT uses has shown really good results.

3.4 General Discussion of Survey Results

Epoxy-coated reinforcement was identified as the most utilized corrosion protection method in the survey of Departments of Transportation in the United States. The results show that 22 states, out of the 27 participant states, implement epoxy-coated reinforcement in construction of new bridges and in rehabilitation projects. The only states that did not mention the use of epoxy-coated rebar are South Carolina, Mississippi, Maine, Rhode Island, and Virginia. Additionally, it was found that epoxy-coated reinforcement is present in the standard specifications of many of the states, including the ones that did not incorporate epoxy-coated reinforcement in the agency's practice. The second most utilized method is polymer overlays, which is mainly implemented in rehabilitation projects. The responses indicate that 20 agencies are implementing this corrosion protection alternative. Moreover, modified concrete overlays, which are mainly used in rehabilitation projects, is the third most used corrosion protection method. All other methods are utilized on less frequent occasions compared to these three methods mentioned. The least implemented corrosion protection method was identified to be stainless steel reinforcement (coated stainless steel rebar or solid stainless steel rebar) with only five responses. However, there is an indication that agencies are looking into the possibility of using stainless steel reinforcement in new construction to increase the service life of bridge decks. Similarly, galvanized steel is used only in new construction.

The survey results show that more states are implementing other methods than the alternatives included in the survey questionnaire. These other methods are mainly related to concrete quality such as high-performance internal curing concrete, polymer reinforced concrete, low slump dense concrete, and fiber reinforced concrete; sealers such as silane sealer; and only a few responses indicated the implementation of other types of reinforcing steel like chromium ASTM A 1035 bars.

Several factors were identified as contributing to the corrosion protection method selection process. Throughout the survey, most of the responses collected were related to cost and effectiveness. However, it was identified that other factors such as the bridge type, environmental exposure, and historical performance are also major factors considered by the agencies. Additionally, there is a concern regarding the field implementation of epoxy-coated reinforcement, as several states indicated that considerable damage may be induced to the coating during construction, and in some cases is left unrepaired. Furthermore, the results obtained in Question 5 indicate that the state experience and economic aspect are the main criteria agencies consider when selecting a corrosion protection system. These two alternatives were selected as the criteria in the choice of corrosion protection system by 93% of the participating states. Kansas DOT and Nevada DOT were the only two states that did not select the economic aspect as a concern. The next two closest alternatives were previous research/findings and purpose of rehab, with 82% selection and 70% selection, respectively.

These results put into evidence the need for a corrosion protection system that can effectively protect the steel against corrosion while also being economically viable. Additionally, the "state experience" was identified as a main criterion used by agencies when selecting a specific corrosion protection method. This finding might indicate that even if a corrosion protection system is proven to be effective at protecting against corrosion and economically viable, agencies may still decide to choose an alternative which is more familiar to the previous state practices. Mississippi DOT and Oklahoma DOT were the only states that did not select state experience as a criterion to consider in the corrosion protection method selection process.

The survey responses indicate that while most of the agencies implement epoxy-coated reinforcement, there is a desire to continue looking for improved methods of corrosion protection in concrete bridge decks. Indiana DOT and Delaware DOT were the only two surveyed DOTs that declared they did not have a plan to implement new corrosion systems in future projects. The new implementation methods identified by the agencies are shown below and were categorized into concrete-related and reinforcement-related.

1. Concrete-Related: These methods include polymer overlays, concrete sealers, and improved concrete alternatives. The agencies are considering the implementation of silane as a concrete sealer, glass fiber reinforced polymer, methyl methacrylate, polyester overlays, polymer modified reinforced concrete, latex modified reinforced concrete, and ultra-high-performance reinforced concrete. The application of concrete sealers, overlays, and the implementation of improved concrete prevents the ingress of agents such as chlorides, moisture, and oxygen, which are required for the corrosion process, thus protecting the reinforcing steel from damage related to corrosion.

2. Reinforcement-Related: These methods include the implementation of diverse types of rebars. The agencies stated plans for implementing galvanized reinforcing steel, glass fiber reinforced polymer bars, and ChromX-ASTM A 1035-reinforcing steel.

Additionally, agencies indicated the interest of implementing cathodic protection as well as a combination of the alternatives.

Amongst the criteria used to evaluate the performance of corrosion protection systems, agencies declared to consider historical data, maintenance data, bridge deck inspection, and deck chloride testing. The responses suggest that agencies strongly rely on inspection reports to evaluate bridge deck performance. These inspection reports clearly indicate that damages such as delamination, spalling, cracking, efflorescence, debonding, discoloration rebar corrosion, and potholes are the most common deteriorations present in bridge deck inspections. It is important to note that time must be accounted for in observations regarding deterioration. Additionally, it has been reported by several DOTs that these deteriorations are primarily observed in old bridge decks, where, in many instances, no corrosion protection system has been incorporated.

Agencies have experienced several strategies to prevent bridge deck deterioration. Sealers, membranes, overlays, polymers, and the implementation of a bridge deck cleaning program are amongst the most common strategies that were identified in the survey responses. Moreover, epoxy-coated reinforcement as part of initial construction was reported by several DOTs as an effective strategy to prevent, delay, or reduce deterioration.

Additionally, agencies seem to be exploring the alternatives of a combination of different corrosion protection systems, for instance, increased concrete cover in combination with epoxy-coated reinforcement and application of silane sealer; dual protection systems on new bridges; membranes in combination with corrosion resistant rebar; corrosion resistant rebar in combination with polymer fiber reinforced concrete; and others were identified. All these strategies may increase the service life of bridge decks; however, it is too early to determine what strategy is most effective.

In general, it was identified that the current corrosion practices throughout the surveyed states are performing well. Specifically, agencies have had good results with ChromX rebar, for example, Alaska DOT stated that contractors like not having to protect or repair the coating; Delaware DOT express concerns regarding the effectiveness of galvanized steel; however, other DOTs stated that they are experimenting and even will require the use of galvanized reinforcement in their projects; epoxy-coated reinforcement was reported to provide much better service life than uncoated reinforcement, for instance, Oklahoma DOT reported not having any issues after the agency began coating both top and bottom mats, and was identified as the most effective corrosion practice by many DOTs; South Dakota DOT expressed high expectations for stainless steel. Polymer modified asphalt waterproof membranes showed satisfactory results in Rhode Island. However, some of the methods have been in place only in the last 10–15 years making it difficult to assess their long-term performance. It may be too early to determine the long-term performance of most of these methods. The only method agencies have significant field data is epoxy-coated reinforcement.

Epoxy-coated reinforcement has been in use the longest compared to the other systems with over 50 years of implementation in bridge deck construction. Some DOTs like Ohio stated that epoxy-coated reinforcement is the preferred method by contractors. Utah DOT reported some occasional corrosion issues that were caused by damage to the coating. Similarly, early corrosion issues were reported by Texas DOT, which were attributed to the bad formulation of the coating. Iowa DOT reported that bottom mats presented corrosion problems in bridges built in the 1970s; however, when the practice of epoxy coating both top and bottom was introduced in the 1980s, there have been no major corrosion issues. New Jersey DOT was the only agency that stated that epoxy-coated reinforcement has been the least effective method in their experience. Even though there was an indication of some corrosion issues with epoxy-coated reinforcement, the agencies did not report major adverse performance of epoxy-coated reinforcement. On the contrary, experience has proven that epoxy-coated reinforcement improved throughout the years and is an effective corrosion protection alternative.

3.5 Discussion of Survey Results in States with Similar Latitude to Indiana

In this section, the results of the following states are discussed in detail. The states shown in Table 3.10 are considered to have similar environmental conditions and use of deicing salts to the state of Indiana.

Epoxy-coated reinforcement was selected as a corrosion protection method implemented by the Department of Transportation in all the 15 states shown in Table 3.10. Epoxy-coated rebar is the preferred method by contractors in Pennsylvania. Modified concrete overlays and polymer overlays were the second most common response. These two alternatives were selected by 12 of the 15 target agencies. Nevada DOT, Utah DOT, and Colorado DOT did not report the use of modified concrete overlays. Kentucky DOT, West Virginia DOT, and New Jersey DOT did not mention polymer overlays as a corrosion method in their agency's practice. The least frequent method identified was corrosion inhibition admixture which only Colorado DOT and Ohio DOT reported using this method. Ohio DOT was the only agency who mentioned the use of all the alternatives presented in the survey. Additionally, Ohio DOT mentioned the use of galvanic anodes in rehabilitation projects; the requirement of corrosion inhibition admixtures in all new prestressed beams; the extensive use of modified concrete overlays in rehabs; and the use of internal curing concrete to extend the life of bridge decks. Iowa DOT uses solid stainless steel rebar for decks to rail connection and in larger decks. South Dakota DOT is experimenting with low slump dense concrete overlays. Kansas DOT mentioned the use of methyl methacrylate in rehabs. Missouri DOT reported the use of low dosage of steel fibers (15 lb/yd) and silane sealers on new decks. Utah DOT controls cracking with polymer fiber reinforced concrete and mentioned that new construction combines fiber reinforced concrete with coated reinforcement and a polymer overlay. New York DOT applies concrete sealers to new bridges and uses high performance internal curing concrete with low permeability and reduced cracking.

These agencies are considering introducing several methods in the department's practice. The following alternatives were identified according to the responses from the target states. Galvanized steel reinforcement, ChromX rebar, steel fiber reinforced concrete, stainless steel, and cathodic protection. West Virginia DOT may start requiring galvanized reinforcing steel in all

TABLE 3.10
Target States

Delaware	South Dakota	New York
Kentucky	Utah	Iowa
West Virginia	Colorado	Indiana
Nevada	New Jersey	Pennsylvania
Missouri	Kansas	Ohio

concrete bridge decks and barriers on interstates and expressways, similarly, New York DOT mentioned that galvanizing will continue to be an option in addition to systems in use. Utah DOT is considering the use of ChromX reinforcement. Missouri DOT is experimenting with low dosage of steel fibers. South Dakota DOT just started to require stainless steel in bridge decks. New Jersey DOT and Iowa DOT are looking into introducing sacrificial galvanic anodes into deck repair for future projects.

These departments are looking into improved methods of corrosion protection. However, from the literature review, it can be inferred that stainless steel reinforcement has been the only type of steel reinforcement that performs better than epoxy-coated reinforcement. Studies have shown that epoxy-coated reinforcement performs similarly or even better than both galvanized steel and ChromX. It is also worth noting that galvanized steel reinforcement and stainless steel reinforcement are much more expensive alternatives compared to epoxy-coated reinforcement; New Jersey DOT stated that there is a significant cost saving when using epoxy-coated rebar in lieu of stainless steel reinforcement.

The target DOTs rely on bridge deck inspections to evaluate the performance of corrosion protection systems. The reports aid in finding physical evidence of corrosion and maintenance needs of concrete bridge decks. These reports are being done bi-annually in New Jersey and New York and are based on the guidelines and data from the NBI. Additionally, Colorado DOT indicated that manufacturer's literature and performance data is considered when evaluating corrosion performance.

Spalling due to corrosion of reinforcing steel has been identified as the main source of deterioration observed in Indiana. Cracking, delamination, and potholes were reported to be observed during bridge deck inspections by most of the target agencies. These deteriorations are attributed to corrosion of the steel reinforcement. Additionally, it was identified that delamination of concrete overlays is being observed in several agencies, including Delaware DOT, Utah DOT, Iowa DOT, and Indiana DOT.

To prevent bridge deck deterioration, target agencies are implementing several strategies such as application of silane sealers by Delaware DOT, Kentucky DOT, and Indiana DOT; combination of epoxy-coated reinforcement and overlays or modified concrete by Nevada DOT, Missouri DOT, Utah DOT, Kansas DOT, New York DOT, and Iowa DOT; and implementation of a bridge deck washing and cleaning program by South Dakota DOT. These responses indicate that agencies are looking into combine systems and not rely only on one specific corrosion protection method. It seems that sealers, and overlays in combination with epoxy-coated reinforcement is the main strategy being used to prevent bridge deck deterioration in these agencies.

The responses obtained from the target DOTs indicate that overall, the implemented corrosion protection methods are performing as expected. Epoxy-coated reinforcement was identified as the most effective corrosion protection system by many of the target DOTs. New Jersey DOT was the only agency (out of the total 27 responses) that described epoxy-coated reinforcement as the least effective method; however, it was mentioned that there are significant cost savings when using epoxy-coated reinforcement. New York DOT declared that new Performance concrete mixes with the use of corrosion protected rebar have been the most effective. Routinely washing and sealing bridge decks was identified as the most effective practice by West Virginia DOT. There are mixed results regarding the effectiveness of overlays, some agencies indicated that the overlays implemented within their district are performing well but other agencies express adverse performance. The long-term performance of some of these methods remains to be determined at this time. Moreover, comparing them with epoxy-coated reinforcement, which has been in use for over 50 years, is challenging. This could lead to erroneous conclusions, as some alternatives have been used for less than 15 years.

There is indication of satisfactory performance of most of the alternatives the Departments of Transportation in the U.S. are considering and implementing. Furthermore, epoxy-coated reinforcement is shown to be an effective corrosion protection method. It is worth mentioning that methods effective in one location may not work in another, even if environmental conditions and the use of deicing salts are similar. Factors such as agency's experience, contractors' familiarity with the method, and material availability play a role in determining which method should be considered. However, there is great value in examining what other agencies are evaluating and implementing.

3.6 Summary of Survey Discussion

1. *Method:* Epoxy-coated reinforcement was identified as the most utilized corrosion protection method by the surveyed Departments of Transportation in the United States. The second most utilized method is polymer overlays. The least implemented method was identified to be stainless steel reinforcement.
2. *Factors in the Selection:* Cost/effectiveness, previous research/findings, purpose of rehab, and state experience were identified as the major factors contributing to the selection of corrosion protection systems.
3. *Alternatives:* The survey results indicated the desire to continue looking for improved methods of corrosion protection in concrete bridge decks. The new corrosion protection systems being considered are mainly related to concrete quality, steel reinforcement selection, and a combination of methods. Several agencies are implementing methods such as high-performance internal curing concrete, polymer reinforced concrete, low slump dense concrete, fiber reinforced concrete, silane sealer, and chromium ASTM A1035 bars.

4. *Performance:* The DOTs indicated that in general all methods are performing as expected with some minor issues. However, it may be too early to determine the long-term performance of most of these methods. Epoxy-coated reinforcement has been implemented by agencies for over 50 years. Even though there have been instances that indicate some corrosion issues of epoxy-coated reinforcement, experience has shown that epoxy-coated reinforcement has improved throughout the years and so has its effectiveness in a corrosion protection system. Comparison of other systems with epoxy-coated reinforcement could lead to erroneous conclusions, as some alternatives have been used for less than 15 years.

4. FINDINGS, RECOMMENDATIONS, AND PROPOSED IMPLEMENTATION

4.1 Findings

The findings presented in this chapter are based on the work summarized in Chapters 2 and 3. The findings from the work in Chapter 2 are presented in Sections 4.1.1 to 4.1.5 in the categories of laboratory performance, field performance, lifecycle and cost assessment, jobsite guidelines, and coating technologies. Section 4.1.6 presents the findings from a survey conducted on state DOTs on corrosion protection of steel in reinforced concrete bridge decks.

4.1.1 Laboratory Performance

1. Epoxy-coated reinforcement under laboratory conditions subjected to simulated seawater and chloride solutions is effective at reducing corrosion activity, even with induced damage to the coating (Erdoğdu et al., 2001). Conventional uncoated (black) reinforcement presents the highest corrosion rates (O'Reilly et al., 2011).
2. Data showed that epoxy-coated reinforcement with improved adhesion through the use of sand does not have better performance than conventional epoxy-coated reinforcement (O'Reilly et al., 2011).
3. Stainless steel is a highly effective corrosion protection method in concrete in the presence of chloride concentrations (O'Reilly et al., 2011). It is the only method that laboratory experiments have shown to perform better than epoxy-coated reinforcement under accelerate corrosion.
4. The combination of epoxy-coated reinforcement with supplementary cementitious materials like fly ash, and slag improved the corrosion resistance compared to the use of 100% Portland cement binder (Farshadfar, 2017).
5. Coating damage is highly correlated to the corrosion performance of epoxy-coated reinforcement and should be minimized (Samples et al., 1999). Additionally, ultraviolet (UV) exposure has a deleterious effect on the performance of ECR against corrosion (Grayli, 2022).

4.1.2 Field Performance

1. After the fabrication and handling practices were improved in 1990s with the implementation of the CRSI program and continued modifications to ASTM A775/A775M, no evidence of adverse performance of epoxy-coated reinforcement has been identified from the field performance described in Section 2.4.2. There is evidence of minor corrosion issues related to high chloride concentration, thinner coating thickness, and extended exposure to chloride concentrations.
2. In the construction of concrete bridge decks, the use of epoxy-coated bars on the top and bottom mats was shown to improve performance against corrosion when compared to the alternative of only using coated bars in the top mat (Pincheira, 2008). This practice by Minnesota DOT is now a requirement similar to Indiana that requires all reinforcement used in the concrete deck to be epoxy-coated.
3. The health of bridge decks has been estimated using the integer value rating. Reports using this prediction methods based on the rating number indicated that a bridge deck assuming nominal construction containing epoxy-coated reinforcement would present minor deteriorations in 38 years and would take 62 years to present advance section loss in the reinforcing bars, accompanied by concrete deck deterioration, and spalling (Agrawal et al., 2009).
4. In a Michigan study, the expected service life of a bridge deck with epoxy-coated reinforcement was estimated to be around 86 years (Valentine, 2015).
5. Evidence shows that stainless steel reinforcement is performing better than epoxy-coated reinforcement at least in the early stages of service (Sim, 2014). Here it must be noted that none of the alternate methods of corrosion protection including stainless steel have been in service as long as epoxy-coated reinforcement in service since the mid-1970s.
6. Epoxy-coated reinforcement has been shown to perform better than galvanized steel in bridge decks of similar age (Manafpour et al., 2016).

4.1.3 Lifecycle and Costs Assessment

1. The studies presented in Section 2.5 evaluating the lifecycle and cost of methods of corrosion protection put into evidence that epoxy-coated reinforcement is a cost-effective method on total cost over a design service life of 75-years (O'Reilly et al., 2011) and 100-years. Additionally, galvanized steel, and ChromX are cost-effective corrosion protection methods over a 100-years design life (Grayli, 2022).
2. The study titled *Evaluation of Multiple Corrosion Protection Systems for Reinforced Concrete Bridge Decks* reported that stainless steel represents around 16% higher present cost compared to epoxy-coated reinforcement at a discount rate of 2% over a 75-year design life. However, the time for first repair in a bridge with solid stainless steel is expected to be higher than 75 years (O'Reilly et al., 2011). There is a need to collect more data regarding the long-term performance of solid

stainless steel to further evaluate if in the long-term it can be a cost-effective alternative to epoxy-coated reinforcement.

4.1.4 Jobsite Guidelines

1. Evidence indicates that maintaining the integrity of the coating during construction is a key factor in the performance of epoxy-coated reinforcement. Damage to the coating as well as high chlorides induced by deicing salts are one of the main causes of the adverse performance of epoxy-coated reinforcement.
2. It was identified that the manufacturing practices of epoxy-coated reinforcement improved significantly over the years, and this has resulted in better performance. Coating plants in North America are able to manufacture epoxy-coated reinforcement with as little as 0.2 holidays per foot of bar; ASTM standards limit the damage to 1 holiday per foot.
3. The main guidelines that need to be considered to maintain the integrity of the coating include handling, storage, placing, and casting of concrete. Following adequate guidelines (see Section 2.6), will improve the performance of epoxy-coated reinforcement.
4. Inspection of epoxy-coated reinforcement prior to concrete placement has been identified as an important practice to warrant that the coating is installed according to design and to ensure the coating will provide adequate protection.

4.1.5 Coating Technologies

1. The new technologies, other than NUVINOX, FBE 413 (green) and FBE 426 (purple), presented in this study are in the testing stages, and are not being implemented by DOTs.
2. Fusion Bonded Epoxy Rebar 413, and 426 are the most common methods of epoxy-coated reinforcement.
3. Fusion Bonded Epoxy Rebar 426 although advertised to provide superior resistance to disbondement without pretreatment, does not meet flexibility requirements of standards.
4. There is no evidence suggesting that textured epoxy reinforcement will improve corrosion performance compared to conventional epoxy-coated reinforcement while it improves some of its bond strength.
5. Stainless steel Allium appears to be a promising method for corrosion protection and is expected to compete with the costs of galvanized steel once it is produced on a large scale and made available for industry (Mcalpine, 2023). However, there is no evidence that this product will be available for DOTs to implement in their practice soon nor estimates on actual cost.
6. Based on the information collected, there is no evidence that supports that polyol-based coating can be an alternative to epoxy coating. These experimental coatings can contribute as patching materials but not as a total substitution to epoxy. Similarly to epoxy, coating damage of polyol-based alternatives represents a significant concern.

4.1.6 States Departments of Transportation Survey

The findings of the state's Department of Transportation survey correspond to the responses obtained from the 27 participating states and U.S. territories presented in Chapter 3.

1. Deteriorations including delamination, cracking, and potholes are being reported by agencies during bridge deck inspections and are attributed to corrosion of the steel reinforcement.
2. It was identified that agencies desire to continue looking for improved methods of corrosion in concrete bridge decks. Departments of Transportation are experimenting with several techniques aimed at increasing the service life of concrete bridge decks while being economically viable.
3. The alternative approaches being evaluated by DOTS aim to enhance the quality and permeability of concrete, along with selecting corrosion-resistant steel. For instance, high-performance internal curing concrete, polymer reinforced concrete, low slump dense concrete, fiber reinforced concrete, silane sealers, galvanized steel, solid stainless steel, epoxy-coated reinforcement, and chromium ASTM A1035 bars are agencies' evaluating types and combination of alternatives. However, there is no one technique that has gained traction for more general implementation.
4. Agencies are relying on the combination of several corrosion protection systems rather than one specific corrosion method. For instance, states in comparable geographic location to Indiana are using silane sealers, combination of epoxy-coated reinforcement and overlays or modified concrete. More of these agencies are considering the use of solid stainless steel in their practice.
5. Most of the strategies implemented by agencies have been in place for a relatively short period of time (10–15 years); therefore, it is not possible to reach a definitive conclusion regarding the long-term performance of these modern technologies or the combination of alternatives. However, results indicate that all alternatives employed by DOTs show a satisfactory performance regarding protection in the short term.
6. Epoxy-coated reinforcement is the most popular corrosion protection alternative being implemented by DOTs in the United States, with only New Jersey DOT reporting an adverse experience. The other 21 states' responses indicated satisfaction with the use of epoxy-coated reinforcement with some minor deterioration observed in some instances.
7. Epoxy-coated reinforcement was identified as the most effective corrosion protection system by the majority of the states located in similar latitude to Indiana. Only one state responding (New Jersey) identified epoxy-coated reinforcement as the least effective corrosion protection method but indicated that it is the cheapest alternative to use.
8. DOTs identified the following as the major factors influencing the selection of corrosion protection systems:
   - cost/effectiveness,
   - previous research/findings,
   - purpose of rehab, and
   - a state's own past experience.

9. Bridge deck cleaning program has been a cost-effective alternative to maintaining the integrity of bridge decks.
10. Bi-annual bridge deck inspections based on the NBI are used to find physical evidence of corrosion and maintenance needs. This evidence is used by DOTs to evaluate the performance of corrosion protection systems.

4.1.7 Summary of Findings

1. The most reliable and widely used epoxy-coated reinforcement was identified as the Fusion Bonded Epoxy coating (FBE) meeting ASTM A775/A775M (green coating) and manufactured in plants that participate in the CRSI voluntary epoxy coating plant certification program.
2. In general, epoxy-coated reinforcement is performing well. Departments of Transportation in the U.S. are still implementing epoxy-coated reinforcement as the go-to method of corrosion protection in the construction of new concrete bridge decks and in rehabilitation. Out of the surveyed DOTs, responses indicated only New Jersey DOT as having a non-positive experience with epoxy-coated reinforcement.
3. Construction practices have been identified as one of the main factors contributing to the deficient performance of epoxy-coated reinforcement. Practices such as handling, storage, placing, pouring of concrete, low concrete cover, and patching of damaged areas are key to an adequate performance of epoxy-coated reinforcement.
4. Laboratory and field evidence has identified epoxy-coated reinforcement as an effective method of protecting the steel against corrosion provided it meets standards, and fabrication and handling guidelines are followed used in conjunction with high quality concrete is used in conjunction with adequate concrete cover.
5. DOTs practices such as bridge deck cleaning plans and constant bridge inspections are measures implemented by DOTs that contribute to the performance of bridge decks. The implementation of a cleaning plan reduces the chloride concentration in bridge decks after the use of deicing salts during winter.
6. U.S. Departments of Transportation continue to explore new or combinations of existing corrosion protection methods and construction practices to enhance the performance of concrete bridge decks. The identified methods include improved concrete quality and steel reinforcement. Examples are the use of high-performance concrete in combination with epoxy-coated reinforcement. Other alternatives such stainless steel reinforcement; galvanized steel; ChromX ASTM 1035 steel; and fiber reinforced concrete, while considered in general require more data on cost effectiveness over the life of the structure.

4.2 Recommendations and Proposed Implementation

The following plan based on the findings from this project represents the views of the authors.

4.2.1 Corrosion Protection for Indiana Concrete Bridge Decks

It is recommended that INDOT continues to use FBE 413 (green coating) in combination with high quality concrete with specified cover as an effective method of corrosion protection under the following conditions.

- *Epoxy-Coated Reinforcement:* Epoxy-coated reinforcement should be obtained from coating plants participating in the voluntary CRSI program. Epoxy-coated reinforcement should meet standard ASTM A775/A775M. Continue the implementation of the findings by Samples and Ramirez (1999) using a larger coating thickness to mitigate potential damage during handling and casting operations.
- *Construction Practices:* Maintain the use of high-quality concrete with low permeability. Provide adequate concrete cover as determined by relevant standards. Maintain practice as presented in Section 2.6 regarding the following guidelines.
- Adequate handling and storage of epoxy-coated reinforcement before and during construction and minimize sun exposure.
- Monitor and patch any damage to the coating during construction, using patching material specified by the manufacturer.
- Placement of the reinforcement should adhere to the guidelines in Section 2.6. Minimize foot traffic over the reinforcement and concrete hoses movement during placement of the reinforcement and continue the use of extension on hose during casting operation to mitigate potential damage to the coating. Vibrators should be equipped with non-metallic heads.

4.2.2 Lifecycle Cost Assessment

To properly assess the impact on the lifecycle of concrete bridge decks, in addition to regular inspection, more detailed inspections such as those conducted in the Samples and Ramirez (1999) study should be scheduled to collect data both on the bridge condition as well as on interventions, including economic costs since 1976. Those data should be recorded and analyzed to monitor the long-term performance in the field under Indiana environments and traffic. This information will complement the findings in this study and will provide a better understanding of the actual performance of bridge decks in Indiana; thus, a more informed decision can be made regarding the use of epoxy-coated reinforcement versus other alternatives such as stainless steel, silane sealers, polymer overlays, galvanized steel, and others.

4.2.3 Interventions

The survey indicated that INDOT is implementing a silane deck sealer at about year 3 and year 7 of a bridge deck's life, and then a polymer overlay is programmed. This practice may serve as an additional protective layer to help prevent the ingress of chloride into the concrete. However, the effects of implementing this method alongside epoxy-coated reinforcement remain unclear. Therefore, it is recommended to evaluate the effectiveness of the silane sealer and polymer overlay by collecting data on the bridges where this intervention was implemented. Furthermore, the survey of DOTs supports the implementation of a bridge cleaning program following the winter season, is recommended. U.S. DOTs found the cleaning program beneficial for the bridge deck performance at a low cost compared to other alternatives.

4.3 Additional Work

Following this synthesis study the researchers recommend consideration of the additional work proposed below.

1. An ongoing long-term evaluation of corrosion performance alternatives is recommended. The majority of the alternatives DOTs indicated in the Survey that are under consideration have been in place for about 10–15 years which gives an indication of the initial performance only; therefore, an ongoing assessment to establish long-term performance and a proper comparison to epoxy-coated reinforcement can be obtained.
2. Solid stainless steel has been shown to be more effective than epoxy-coated reinforcement against corrosion. However, it brings with it a substantial increase in the initial cost over the use of epoxy-coated bars. More research targeted at establishing the actual life-cycle cost of a concrete bridge reinforced with solid stainless steel would address whether the initial increment in cost is justified by the long-term benefits.
3. Project NCHRP 240 on stainless steel coated reinforcing bars offers an alternative to reduce the initial cost of solid stainless steel bars. However, there is a need for more investigation and corroboration of the results presented in the study. Furthermore, in addition to the lack of information on the life cycle performance, standards and manufacturing guidelines for the stainless steel-clad reinforcement presented in project NCHRP 240 are not available.

The survey responses indicated that agencies have been implementing a combination of different alternatives. However, there is a lack of field and laboratory research regarding the corrosion performance of the combination of the alternatives.

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About the Joint Transportation Research Program (JTRP)

On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,600 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at http://docs.lib.purdue.edu/jtrp.

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