



# Long-Term Corrosion Protection of Bridge Element Reinforcing Materials in Concrete

Kentucky Transportation Center Research Report – KTC-17-03/SPR16-513-1F

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**Research Report**  
KTC-17-03/SPR16-513-1F

**Long-Term Corrosion Protection of Bridge Element Reinforcing Materials in Concrete**

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<b>16. Abstract</b> Preventing or mitigating the corrosion of reinforcing steel in bridge decks is a major challenge for state transportation agencies. With agency budgets stretched thinner every year, they must implement strategies to extend the service lives of bridges and other critical structures. As such, it is imperative for them to adopt cost effective materials and maintenance practices to delay the onset of bridge corrosion. To assist the Kentucky Transportation Cabinet (KYTC) in its efforts to improve the condition of its bridges as well as its construction and maintenance practices, researchers at the Kentucky Transportation Center (KTC) investigated the use and performance of different reinforcing materials, supplementary cementitious materials, and concrete sealers. This document extensively reviews field and laboratory studies of these materials and draws general conclusions about their effectiveness. A survey administered to transportation agencies around the United States revealed that corrosion prevention and mitigation practices vary widely, but that the use of multiple corrosion-inhibition systems is growing. Based on our literature review and analysis of practices used by other state transportation agencies, we recommend the use of multiple corrosion-inhibition methods to defend against bridge corrosion. For the construction of new reinforced concrete structures, a multiple approach to corrosion resistance could prove highly beneficial and offer a cost-effective strategy to prolong the service lives of bridges. Recommended actions are proposed for KYTC, which are geared toward strengthening its bridge construction and maintenance program.			
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## Executive Summary

Preventing bridge corrosion is one of the most challenging maintenance issues state transportation agencies face. Corrosion of reinforcing steel is problematic because it leads to the spalling and deterioration of concrete cover. The corrosion of reinforced concrete bridges first emerged as a serious problem in the United States in the late-1960s and early-1970s after state and local transportation agencies increased their use of deicing salts to keep roads and bridges free of ice and snow during the winter months. Deicing salts and deicing chemicals are effective in keeping roads clear, however, they permeate the concrete of bridge decks, barrier walls, and foundations, and accelerate the corrosion of the reinforcing steel. Chloride penetration shortens bridge service lives and drives up expenses for agencies with already-tight budgets. The Kentucky Transportation Cabinet (KYTC) has increased its use of deicing chemicals in recent years. From 2004 to 2011, KYTC tripled the amount of deicing chemicals it applied to its roadways. Much of this increase came from expanding the use of liquid salts. Widespread use of deicing materials has increased the chloride levels of KYTC's bridges. To identify the most effective strategies of inhibiting or mitigating bridge corrosion, the Cabinet asked Kentucky Transportation Center (KTC) researchers to identify current best construction and maintenance practices. To accomplish this goal, researchers investigated the use and performance of various reinforcing materials, supplementary cementitious materials (i.e., admixtures), and concrete sealers. Along with this literature review, KTC administered a survey to state transportation agencies around the United States focused on what strategies are currently used to prevent bridge corrosion.

All steel eventually corrodes, but different types corrode at different rates. Since the 1970s, state transportation agencies have routinely turned to epoxy-coated reinforcing steel (ECR) as a cost-effective option for delaying the onset of corrosion, especially in severe environments. Most research studies confirm that ECR inhibits corrosion. Some researchers have questioned its durability, citing epoxy's propensity to debond after prolonged exposure to moisture. Over time, epoxies inevitably break down, and moist and humid environments can accelerate this process. Accordingly, ECR may not be the best option in these settings. Solid stainless steel is recommended if agencies want to attain a service life up to 100 years, but it is very costly and generally reserved for critical projects (e.g., interstate bridges). Other options, such as galvanized steel or stainless clad rebar, may enhance corrosion resistance, but they are not immune from problems. Small holidays (gaps) in the coatings and imperfectly sealed end caps facilitate the entry of chlorides and moisture, potentially accelerating corrosion. Chrome steels, because they are price competitive with black steel, appear promising, however, there are limited data on its field performance. Some agencies (e.g., Virginia) are opting for chrome steels over ECR. Fiber reinforced polymer reinforcing material eliminates corrosion, but testing has been limited. It is unclear if they will perform well under a variety of environmental conditions, or if degradation will be problematic.

Supplementary cementitious materials are also used to inhibit corrosion. Admixtures reduce the permeability of concrete, improve concrete density, and increase the electrical resistivity of concrete — all of which delays the onset of corrosion. The most frequently used admixtures include fly ash, silica fume, ground granulated blast furnace slag, and calcium nitrite. Most of the studies in the literature review confirmed the benefits to using admixtures, as they limit the penetration of chlorides. One potential downside of using an admixture is the slight loss of compressive strength, although no studies indicated the loss of compressive strength would be sufficient to negatively impact bridge performance. Nonetheless, ongoing and future studies examining the utility of admixtures should be attentive to the issue of compressive strength and determine whether there are tradeoffs involved in their use. Transportation

agencies interested in using admixtures should explore ternary concrete formulations that contain at least two admixtures in addition to cement because some research has indicated they outperform binary mixtures.

Surface treatments (i.e., sealants) are organic and inorganic materials that are applied to deck surfaces to prevent the ingress of moisture and chloride. The most commonly used surface treatments are silanes and siloxanes. These have generally proven more effective than silicates and epoxies. Some research indicates that surface treatments reduce corrosion and the infiltration of contaminants, however, their performance is strongly tied to the environmental setting, concrete formulation, the condition and structure of concrete, and traffic levels. A positive correlation exists between the depth of sealant penetration and overall performance. Although some sealers may increase carbonation, this will not necessarily translate into more significant corrosion if excessive moisture is not present. Most sealers need to be reapplied every 5 to 20 years. Transportation agencies should carefully weigh the costs and benefits of repeated applications to decide whether alternative methods of protection will be more cost-effective.

The survey of state transportation agencies found that most continue to use ECR for many of its projects. Stainless steel reinforcement is most common on high-profile projects. Most agencies use high performance concrete for bridge construction, while cover thickness of 2.5 inches is most common. The use of sealants is widespread. The most popular are silanes and siloxanes, epoxies, and methacrylates. Agencies typically apply sealants during construction and maintenance activities, although there is more variability among agencies with respect to frequency of reapplication. While some agencies lack a fixed schedule, others reapply sealants at 4-10 year intervals. All but one agency applies crack sealants to bridge decks. The most frequently used crack sealants are methacrylate and epoxies. Approximately half the agencies use multiple methods to prevent or minimize corrosion. These agencies stated that different combinations of materials are used depending on the project context (e.g., frequency of deicing chemical use, traffic levels).

Based on the literature review and analysis of practices used by other state transportation agencies, this study recommends the use of multiple corrosion-inhibition methods to defend against bridge corrosion. For the construction of new reinforced concrete structures, a multiple approach to corrosion resistance could prove highly beneficial. This approach blends high performance concrete, which establishes an effective barrier that limits the rates of chloride penetration and carbonation, with reinforcing bar materials that are more resistant to corrosion (e.g. MMFX® ChromX, or in more critical/severe applications stainless steel). As the survey of the literature indicated, there is disagreement over the effectiveness of various treatments. But researchers were practically unanimous in their endorsement of using a sufficient cover of high-quality concrete to slow the progression of corrosion. Other treatments are supplemental and cannot serve as a replacement for high-quality concrete. The findings lead to the following recommended actions for KYTC:

- Develop specifications for high-performance concrete for use on bridge decks.
- Continue to monitor the performance of current bridge decks that have been constructed with experimental reinforcing steel as well as conventional decks treated with protective sealants.
- Evaluate corrosion activity of painted structural concrete.
- Conduct further evaluations of sealant types and determine which work best with specific concretes.
- Perform a cost-benefit analysis to evaluate the anticipated benefits of using various protection methods/treatments.
- Identify and implement experimental maintenance activities related to sealing bridge decks/cracks.
- Experiment with multiple corrosion-protection systems on newly constructed bridges and apply one or more of those routinely for new bridges and deck replacement projects.

## Chapter 1 Introduction

Preventing bridge corrosion is one of the most challenging maintenance issues state transportation agencies face. The corrosion of reinforced concrete bridges emerged as a serious problem in the late-1960s and early-1970s after state and local transportation agencies increased their use of deicing salts to keep roads and bridges free of ice and snow during the winter months. Deicing salts and deicing chemicals are effective in keeping roads clear, however, they permeate the concrete of bridge decks, barrier walls, and foundations, and accelerate the corrosion of the reinforcing steel. Chloride penetration shortens bridge service lives and drives up expenses for agencies with already-tight budgets. Like many state transportation agencies, the Kentucky Transportation Cabinet (KYTC) has increased its use of deicing chemicals. From 2004 to 2011, the Cabinet tripled the quantity of deicing chemicals applied. Much of this increase came from ramping up the use of liquid salts. As the use of deicing materials has become more widespread and intense, chloride levels have increased in KYTC's bridges. Higher chloride concentrations have and will continue to corrode reinforcing steel, which leads to the spalling of concrete cover.

Given the expanding use of deicing chemicals, it is critical for KYTC and other state transportation agencies to develop and implement proactive strategies and building activities that delay the onset of corrosion in reinforced concrete bridges. There are numerous options available to mitigate corrosion and extend the service lives of bridges. The objective of this study is to discuss corrosion protection methods that have been used over the past 40 years, determine which have proven the most successful and are therefore the most promising, and make recommendations for Cabinet staff to consider when selecting materials and treatments for use in new construction, rehabilitation, and maintenance activities. The remainder of this first chapter addresses project objective and provides a high-level discussion of bridge corrosion, including a review of the processes which drive corrosion as well as the materials and protective treatments that have been devised to slow its onset and progression. Later chapters deal with reinforcing materials, concrete and follow-on treatments, covering both field and laboratory evaluations. We restrict our focus to different types of reinforcement (e.g., epoxy-coated reinforcing steel, stainless steel, galvanized steel), concrete admixtures (e.g., pozzolans such as fly ash and silica fume), concrete sealers (e.g., siloxanes and silanes), and multiple corrosion-inhibition systems (which combine two or more of the solutions listed — for example, epoxy-coated rebar and admixtures). Previously, the Kentucky Transportation Center (KTC) investigated protecting reinforced concrete, other than bridge decks, with thin film coatings (Palle et al. 2005 and Meade et al. 2016) and penetrating sealers (Wells et al. 2014). KTC is also investigating bridge deck waterproofing materials (e.g., membranes and impermeable asphalts) under a separate project, KYSPR 17-531 *Waterproofing Options for Bridge Decks*. It is anticipated that work will be completed and reported on in 2019.

### 1.1 Project Objectives

The objective of this research was to identify current industry practices and materials specified in bridge design and used in construction, maintenance, and rehabilitation activities to extend bridge service lives by cost effectively enhancing the corrosion resistance of reinforced concrete bridge elements.

To achieve those goals, KTC researchers addressed the following tasks:

- 1) Perform a literature search and summary of recent publications to identify current options/practices for improving corrosion resistance of concrete reinforcing materials, concrete materials, and deck maintenance practices.
- 2) Perform a survey of DOTs to identify current uses of various types of concrete reinforcements/costs/performance along with deck maintenance actions to prevent corrosion including costs/durability.

- 3) Conduct directed inquiries (by telephone) to researchers, material suppliers, construction companies, and DOT representatives to resolve conflicting information and elicit specific details not addressed in Tasks 1 and 2.
- 4) Prepare this report summarizing the results of Tasks 1-3 and develop recommendations for practices related to bridge design and maintenance.

One of the challenges confronted during this study was making direct comparisons between different studies. This was problematic because of the large number of treatments that are used to mitigate corrosion as well as the varied methodologies used to evaluate them in the laboratory and field. For this reason, the goal of this report is to derive from the literature general rules of thumb that accurately characterize the performance of various corrosion mitigation techniques. Also compared are the first costs of different materials and treatments. In concert with the performance studies, they can help officials select appropriate, cost-effective options for future bridge projects. Life-cycle costs for some materials and treatments were difficult to estimate as the service lives of some materials and durability of some treatments have not been firmly established despite the many reports and papers addressing their use. That is especially true of Kentucky where most of the materials and treatments have seen only limited research or field use. Chapter four discusses a survey of state highway agencies to determine their current practices. The report closes with a summary of key conclusions and a short list of recommendations.

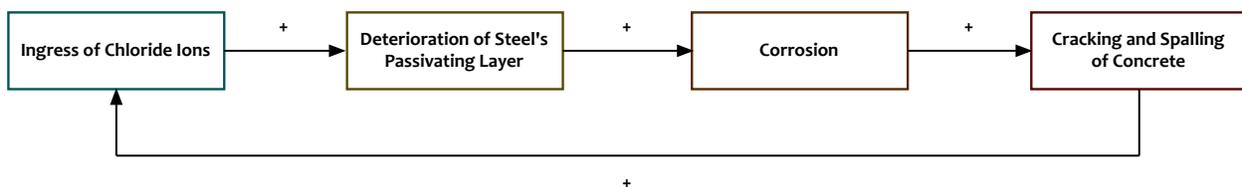
## Chapter 2 Literature Review Summary

### 2.1 The Problem of Bridge Corrosion

The primary problem with reinforced concrete is the corrosion of the reinforcing steel. Historically, the most common material used for reinforcement has been conventional black steel reinforcing bars (rebars)<sup>1</sup>. Although conventional rebar bolsters the compressive and tensile strength of concrete, there is a problem — over time steel begins to corrode, which leads to gradual deterioration of the concrete. Corrosion is not immediate because freshly poured concrete has a high pH (approximately 13). The high pH helps form a passivating layer on the steel that is in direct contact with the concrete. This layer protects steel by suppressing electrochemical corrosion. As concrete ages, however, the concrete's pH begins to fall (to about 11), which typically results from either the introduction of chloride ions or carbonation. While carbonation can promote corrosion, the primary driver of corrosion on most bridges is the ingress of chloride ions. As chloride ions penetrate concrete they lower concrete's pH, which in turn foments the breakdown of the steel's passivating layer, thus facilitating corrosion. This process begins at steel grains that become anodes, where iron ions form and release electrons. These electrons flow through the steel to steel grains that act as cathodes, where water and oxygen combine with electrons to form hydroxide. In response, iron ions and hydroxide flow through the concrete pore solution to balance the charges. When iron ions react with oxygen, rust formation begins. Because the volume of rust is three to six times that of the original steel, the corroding steel exerts significant tensile forces that exceed the concrete's tensile capacity. This causes cracking, delamination, and spalling of the concrete.

On bridges with thick layers of concrete cover, the migration of chloride ions toward the reinforcing steel is the most significant contributor to corrosion. Figure 1 summarizes this process. Introducing chloride ions generally produces more localized corrosion than carbonation. When chloride ions react with steel they are not consumed, which exacerbates corrosion. And since chlorides remain present, it leads to corrosive pitting. Over time, pits deepen and the acid formed during the reaction accelerates corrosion and further deepens the pits (contributing to the positive feedback loop in which corrosion, once it begins, stimulates more corrosion).

Concrete cracking presents problems because the cracks open new pathways through which chloride-laden water can travel directly to the reinforcing steel. Repeated freeze-thaw cycles acting on concrete expand cracks as well. Once cracking begins, a positive feedback loop begins whereby cracking introduces more corrosion-inducing water and chemicals to the concrete (Figure 1). Infiltrating chloride ions penetrate concrete and eventually reach the reinforcing steel and break down its passivating layer. Eventually this leads to corrosion. As corrosion products build up, the concrete spalls and cracks. Cracking opens new pathways through which chloride ions enter, aggravating the corrosion process through a positive feedback loop. Dissolved minerals remain after water evaporates, increasing concrete's vulnerability to the future ingress of water and chlorides.



**Figure 1 Simplified Representation of the Chloride-Induced Corrosion Process**

<sup>1</sup> Much of the material in this section was taken from NACE (2012). To avoid excessive in-text citations, this footnote should be viewed as the controlling reference for this section.

A host of internal and extrinsic (i.e., environmental variables) factors impact corrosion rates and the pace of concrete deterioration. Table 1 summarizes how different aspects of the ambient environment affect corrosion. Temperature, moisture availability, freeze-thaw cycles, and chloride (irrespective of its source) all factor into corrosion. Some of the key concrete properties that influence the rate of deterioration include: 1) magnitude and extent of chloride permeation, 2) sensitivity of the passivating layer to chloride attack, 3) the rate of corrosion reactions once corrosion has begun, and 4) the rate at which concrete cracks and spalls once it has been exposed to expansive tensile forces.

**Table 1 Factors Influencing Corrosion Rate**

<b>Factor</b>	<b>Explanation</b>
<b>Temperature</b>	<ul style="list-style-type: none"> <li>• Warmer temperatures promote corrosion</li> <li>• With every 10-degree increase in air temperature, the corrosion rate doubles</li> </ul>
<b>Freeze-Thaw Cycles</b>	<ul style="list-style-type: none"> <li>• More frequent and numerous freeze-thaw cycles accelerate weather and encourage the formation of cracks</li> <li>• Chloride-laden water infiltrates cracks, penetrating toward reinforcing steel</li> </ul>
<b>Humidity</b>	<ul style="list-style-type: none"> <li>• Higher relative humidity speeds corrosion</li> </ul>
<b>Atmospheric Contaminants and Debris</b>	<ul style="list-style-type: none"> <li>• Pollutants, sulfur and nitrous oxides, carbon dioxide, and airborne chloride ions facilitate corrosion</li> </ul>
<b>Marine Environments</b>	<ul style="list-style-type: none"> <li>• Airborne chlorides (generated from, e.g., salt spray) foster corrosion</li> </ul>
<b>Soils</b>	<ul style="list-style-type: none"> <li>• Chloride ions and sulfates contained in soils can stimulate the corrosion of reinforcement in bridge foundations</li> </ul>
<b>Drainage</b>	<ul style="list-style-type: none"> <li>• Configuration of bridge drains influence water runoff</li> <li>• Drains that are improperly configured (i.e., fail to convey water away from the bridge deck) facilitate corrosion</li> </ul>

All steel eventually corrodes, however, there are many treatments and strategies bridge owners can use to slow down the corrosion process and achieve a service life of 75-100 years. Most transportation agencies now aim for a 75- to 100-year service life for new bridges — especially for highly trafficked bridges. These methods are briefly introduced here.

Using a high-performance concrete, which is manufactured by lowering the water-to-cement ratio and incorporating supplementary cementitious materials (admixtures) into the formulation, reduces the speed of chloride ingress and therefore reduces corrosion. Silica fume and fly ash are the most commonly used admixtures. Admixtures reduce concrete permeability and increase the threshold at which corrosion begins. Once corrosion is initiated, admixtures can help slow its rate of progression. In the presence of admixtures, more cumulative corrosion can occur before concrete begins to crack. Admixtures also positively influence concrete electric resistance, which helps to minimize macro-cell corrosion. With sufficiently thick concrete cover, the use of admixtures can extend a bridge’s service life by 20 to 25 years.

Another option for mitigating corrosion is to either modify conventional rebar (by using epoxy coatings or metallic coatings or cladding) or select alternative materials to manufacture them (e.g., stainless steel, fiber reinforced polymer). Epoxy-coated rebar (ECR) has been the most popular choice among state highway agencies to mitigate corrosion. Epoxy powder is sprayed over preheated rebar and fuses, which forms a coating. The resultant coatings form protective barriers between the steel rebar and the chloride ions and moisture in the concrete thereby preventing corrosion of the rebar. Under ideal conditions, ECR may extend a bridge's service life up to 30 years. In field applications, the performance of ECR has been uneven. Over time, prolonged moisture exposure works to disbond epoxy from the underlying steel. Small imperfections in epoxy coatings also let chloride ions penetrate to the surface of the steel, leading to corrosion. Several conditions undermine the ability of ECR to mitigate corrosion: significant cracking in the concrete, shallow concrete cover, high concrete permeability, and high chloride concentrations.

A second option for protecting plain steel rebar is to envelop it with a metallic coating or to clad it with corrosion-resisting metal. The most common coating is zinc and the most common cladding is stainless steel. Research on the comparative performance of hot-dipped galvanized reinforcing steel with other types of rebar has produced contradictory results. Although cladding rebar extends its life, the return on investment that transportation agencies can expect is unclear, especially for bridges in chloride-saturated environments. There has been limited use of cladded rebars compared to other alternatives.

A third option is to use a combination of a polymer (epoxy) coating over a metallic coating (zinc) on steel rebar (Z-bar). This product has been tested with some good results, but experimental results and service experience with the material are not extensive.

Fabricating rebar out of alternative materials such as stainless steel, fiber reinforced polymers, and chrome steel (e.g. MMFX® ChromX) has shown promise, however, they have downsides. While stainless steel resists corrosion and virtually assures a 75- to 100-year service life, it is also much more expensive than conventional black steel. Accordingly, its use is typically restricted to bridges with high traffic volumes (e.g., interstate bridges) or locations near marine (salt) exposures where it is possible to justify the higher costs. Fiber reinforced polymers will not corrode, however, their expense and the durability issues they encounter under some circumstances makes them a less attractive option. MMFX® ChromX is a proprietary steel that has been recommended by several researchers due to its high corrosion resistance, however, extensive long-term field and laboratory studies are lacking and there are questions over whether it may prove too brittle to attain the durability necessary for long-term use on bridges.

The final category of corrosion prevention measures is treatments using concrete sealants. Included among these are silanes, siloxanes, and other organic and inorganic materials. Surface treatments prevent chloride ions from entering the concrete substrate. Many surface treatments also mitigate carbonation (although siloxanes and silanes do not). Sealants are applied by brush or roller, or in some cases the deck is flooded with them. Often, they are not applied until several years after construction, although there is no definitive guidance on the optimal time to begin their application (noting that the concrete must be cured if a sealant is to be applied at/just after construction). Some sealants (e.g., high-molecular-weight methacrylates) can be used after cracking develops to heal them and inhibit the further ingress of contaminants. To maintain their effectiveness, sealants should be applied at regular intervals (every 5-20 years depending on location). However, exposure to vehicular traffic and the ambient environment can degrade their performance. As many sealants don't penetrate deeply into concrete, their use on bridge decks typically requires more frequent applications due concrete wear in wheel paths.

Once corrosion begins, several additional rehabilitation strategies are available to reduce chloride levels. Some methods, like cathodic protection and electrochemical chloride removal and re-passivation are quite

expensive, while other solutions are more affordable (e.g., using overlays). Cathodic protection introduces external voltage to the surface of reinforcing steel, which transitions it to a cathodic state. This increases the number of reduction reactions while reducing the number of anodic reactions (anodic reactions are responsible for steel deterioration). Cathodic protection is not typically installed upon bridge construction because even in severe environments it takes upwards of 10 to 20 years for corrosion to begin in most cases. Installing cathodic protection systems on newly constructed bridges is also problematic because transportation agencies must pay for their maintenance, and it is possible the system's design life will have lapsed by the time corrosion begins. The use of overlays is a viable and commonly implemented technique to rehabilitate bridge decks. Overlays, such as latex-modified concrete, low-slump concrete, high-density concrete, and polymer concrete, can extend the life of a bridge deck by 15-20 years in many cases.

The remainder of this report examines different corrosion prevention measures in greater detail as well as the survey results. The end of each chapter includes a bulleted list of key takeaway messages that summarize key findings.

## **2.2 Reinforcement Materials**

This section describes the manufacturing processes of different types of reinforcing materials and presents the findings of selected research studies that have investigated their corrosion resistance. The following kinds of reinforcing materials are covered:

- Epoxy-coated reinforcing steel
- Stainless steel
- Stainless steel clad reinforcing steel
- Galvanized reinforcing steel
- Continuous galvanized reinforcing steel
- Chrome (MMFX® ChromX) reinforcing steel
- Multi-coating reinforcing steel
- Fiber reinforced polymers

The goal of this section is not to exhaustively review all available research literature (there is simply too much). It provides a high-level overview with the goal of identifying the strengths and weaknesses of each rebar material. Generally, there are few long-term field-based studies of these materials. The one exception is epoxy-coated reinforcing steel. The reason for this is that epoxy-coated reinforcing steel has been in widespread usage for the longest amount of time, while the other materials have only been used over the past 30 years. Since the projected service lives of these materials can range from 75 to 100 years, the limited field data is understandable. In more favorable environments traditional carbon steels may not experience corrosion in the first 20 years following their placement. Although every effort has been made to include as many long-term field studies as possible in this section, many of the studies discussed are either based on laboratory experiments or they report on the short-term performance of demonstration projects, both of which may not accurately capture a material's long-term corrosion resistance. Laboratory studies attempt to replicate real-world conditions by accelerating concrete's exposure to harsh environmental conditions (e.g., application of deicing salts, temperature fluctuations). These experiments do not perfectly replicate the actual environments materials are placed in, however. Thus, laboratory experiments may not capture how materials will respond once they are exposed real-world environmental stresses.

### **2.2.1 Epoxy-Coated Reinforcing Steel**

In the late-1960s and early-1970s, once transportation officials and engineers recognized that environmental agents such as deicing salts were to blame for the rapid corrosion of bridge decks, a search began for a

technique that would protect steel reinforcements from deterioration. Epoxy-coated reinforcing steel (ECR) was initially used in the 1970s, and today is probably the most commonly used material to inhibit bridge corrosion. Over 65,000 bridges throughout the United States have been constructed with ECR. It is also used throughout the world, from the Middle East, where it protects bridges and other concrete structures from the deleterious effects of marine- and salt-contaminated soils, to Europe and Asia, where it has been the preferred material for bridge construction in coastal and marine settings (McDonald, 2016). The manufacturing process is straightforward. Mill scale and oxidation are first removed from steel bars with grit blasting. The bars are then heated to approximately 450° F before undergoing an electrostatic powder-coating process. The heat of the bars melts the powder on contact, which produces a polymer coating. The most widely used standards for ECR are ASTM A775 *Standard Specification for Epoxy-Coated Steel Reinforcing Bars* and ASTM A934 *Standard Specification for Epoxy-Coated Prefabricated Steel Reinforcing Bars*, while ASTM D3963 *Standard Specification for Fabrication and Jobsite Handling of Epoxy-Coated Steel Reinforcing Bars* provides direction on the handling of finished bars. ECR should not be exposed to direct sunlight because ultraviolet radiation degrades the coating. Bars coated with epoxy must be stored separately from reinforcing steel not coated with epoxy. If protected and non-protected bars are stored together, the epoxy layer of ECR may be damaged by the rougher surfaces of uncoated steel. Any damage to epoxy coatings should be repaired before ECR is used for construction.

Conventional straight ECR meeting ASTM A775 is pigmented green and termed *green bar*. It may need to be formed by bending, which can fracture the epoxy. If fractured, the epoxy is repaired, typically with a liquid-applied coating. Repairs (or the lack thereof) with this type of ECR can result in poor field performance. The ASTM A934 rebar is preformed prior to epoxy coating. It is termed *purple bar*. The cost of purple bar is greater than green bar but avoids coating damage encountered in rebar bending operations.

Epoxy coatings have proven a relatively effective means of guarding reinforcing steel against the worst effects of corrosion. Numerous studies have indicated that epoxy helps prevent spalling and delamination of concrete, but at the same time, research also indicates epoxy coatings degrade over time (NACE, 2012). Epoxy coatings offer the most robust protection of underlying steel when concrete is uncracked. However, prolonged exposure to moisture softens the coating. Moisture also compromises the adhesive bond between epoxies and steel reinforcement, which gradually exposes the steel to the ambient environment. Defects introduced during the manufacturing process can be problematic. Holidays — small imperfections and openings in epoxy coatings — let moisture and deicing fluids seep into the area surrounding the reinforcing steel, eventually resulting in corrosion. The following paragraphs discuss studies that have endorsed ECR as a viable way of impeding corrosion as well as studies that have questioned its long-term benefits.

Smith and Virmani (1996) authored perhaps the first large-scale study of ECR performance in bridge decks. They inspected 92 bridge decks constructed with ECR throughout the United States and Canada. At the time of the study, all the bridges had been in service for periods of between three and 20 years. Delamination was observed on ten bridge decks, although 81 percent of the ECR segments showed no signs of corrosion. Just two percent of the samples indicated significant corrosion. Where corrosion occurred, it was generally associated with shallow concrete cover and high chloride concentrations. Chloride levels for most bridges exceeded the threshold required to initiate corrosion on unprotected steel. Commonly accepted guidelines specify the thresholds for different magnitudes of steel corrosion as follows:

- 0.03 percent chloride to weight of concrete ( $\approx 1.2 \text{ lb./yd}^3$ ) = initiation of corrosion
- 0.08 percent chloride to weight of concrete ( $\approx 2.4 \text{ lb./yd}^3$ ) = accelerated corrosion
- 0.18 percent chloride to weight of concrete ( $\approx 7.2 \text{ lb./yd}^3$ ) = major section loss of steel (Morse, 2009)

The best performing decks had ECR installed in both the top and bottom rebar mats. Despite the positive evaluation, Smith and Virmani (1996) noted that the adhesive strength of epoxy decreased over time, and that ECR in the study's oldest bridges exhibited the most significant loss of adhesion. Despite its limitations the researchers concluded ECR is effectively defends against corrosion when paired with sufficiently thick concrete cover and regular inspections.

Pincheira et al. (2008, 2015) discussed the long-term performance of four Minnesota bridge decks constructed using ECR in the 1970s. Overall, the study decks were in good condition, with only a small percentage of deck area experiencing delamination (less than 1.1% for all bridges). Researchers did, however, observe significant corrosion activity near expansion joints, cracks, and areas where delamination and spalling had occurred — ECR corrosion was most severe at expansion joints and longitudinal or transverse cracks. Researchers noted the presence of light rust on bars with bar-level chloride content as low as 0.40 lb./yd<sup>3</sup> (0.24 kg/m<sup>3</sup>) and widespread rust where chloride content reached 5.05 lb./yd<sup>3</sup> (3 kg/m<sup>3</sup>). Beneath unbroken concrete surfaces, corrosion damage was minimal. Changes in coating adherence were not correlated with either corrosion or chloride ion concentrations — loss of coating adherence took place on both corroded and non-corroded bars as well as in the presence of high and low chloride concentrations. Pincheira et al. (2015) recommended the following procedures to guard against future corrosion: sealing cracks and expansion joints to prevent the infiltration of chloride ions, using a bar cover of at least 3.0 inches (7.62 cm), and using concrete admixtures to reduce its permeability.

Lawler et al. (2011) presented the results of a study examining the long-term performance of ECR on bridge decks in West Virginia exposed to aggressive environmental conditions (i.e., significant applications of deicing salts, repeated freeze-thaw cycles). Thirty-three bridge decks were included — 14 had ECR and 19 were fabricated with uncoated black steel. Among the bridges sampled, corrosion and deterioration were observed on all the decks reinforced with uncoated steel bars. Only three of the decks built using ECR had deteriorated. Corrosion occurred on just four out of the 45 ECR segments extracted from bridge decks. Decks that contained ECR in the top and bottom mats experienced no deterioration, whereas decks with a top mat fabricated out of ECR and bottom mat made with uncoated steel increased a bridge's vulnerability to corrosion. Most of the deterioration witnessed by the researchers occurred around construction joints, which funnel chlorides into the deck. Lawler et al. concluded that epoxy coatings conferred a significant degree of protection to reinforcing steel. The lowest chloride concentration where ECR corroded was 0.132 percent by weight of concrete (~528 lb./yd<sup>3</sup>), but there were also areas where concentrations up to 0.263 percent by weight of concrete (~1,052 lb./yd<sup>3</sup>) did not result in corrosion.

The Iowa Department of Transportation currently uses ECR in the top and bottom mats of all bridges. Fanous and Wu (2005) described the long-term performance of bridges constructed with ECR. The oldest deck included in their sample was built 20 years prior to study. Researchers found no evidence of delamination or spalling on bridge decks constructed with ECR. All rebar embedded in uncracked concrete evinced no signs of corrosion, even where chloride contents exceeded 1.23 lb./yd<sup>3</sup> (0.73 kg/m<sup>3</sup>), a threshold commonly associated with the onset of corrosion. Where corrosion impacted ECR, it was due to cracking in the bridge deck. However, there were some potentially worrying signs. The adhesive bonds between the epoxy and steel bars had weakened with age. Moisture and high chloride concentrations had also degraded the coating adhesion. Fanous and Wu (2005) argued that having sufficiently thick concrete cover will delay the onset of corrosion, and is something transportation agencies should consider. In a separate project, Wiss, Janney, Elstner Associates, Inc. (2011) surveyed the condition of eight Iowa bridges — four with ECR in only the top mat and four in which ECR was used in the top and bottom mats. They found corrosion-related damage on five of the eight bridges. Four bridges exhibited damage on less than four percent of the deck area. The lowest chloride concentration associated with corrosion of an undamaged ECR bar segment was

0.179 percent by weight of concrete (~716 lb./yd<sup>3</sup>), five times the amount required to instigate corrosion on unprotected steel. In some locations where chloride concentrations were as high as 0.304 percent by weight of concrete (~1,216 lb./yd<sup>3</sup>) ECR presented no signs of corrosion. Corrosion-related damage was most common in areas with transverse cracks positioned directly atop the reinforcing bars. Researchers concluded that installing ECR prolongs bridge service life. However, defects and holidays in epoxy coating undermine its performance, and no coating creates an impenetrable barrier against moisture, chlorides, and electrical currents.

Examining two bridges in Switzerland and Germany, Zintel et al. (2014; see also Keßler et al., 2016) concluded that ECR offered an effective means of deterring corrosion activity. The two bridges were constructed in 1989 and 1991, and so the study speaks to bridge conditions after 20+ years of service. Epoxy coatings on both bridges remained in good condition. There was high average coating resistance, suggesting that the ECR had not been damaged by ambient environmental conditions and is a dependable option for safeguarding bridges against corrosion even in severe environments.

Sagüés et al.'s (1991) investigation of bridges in Florida was one of the first to cast doubt on the effectiveness of ECR. After identifying several bridges in the Florida Keys where ECR had significantly corroded due to the harsh marine environment and defects in epoxy coatings, Sagüés et al. (1994) examined 30 additional bridges throughout Florida to investigate the performance of epoxy coatings. None of the other ECR bridges in this study exhibited corrosion, however, the level of chloride penetration had not yet exceeded the threshold necessary to initiate corrosion. Despite the lack of corrosion, Sagüés et al. (1994) observed that nearly all the epoxy coatings displayed a significant reduction in the adhesive bond between the epoxy and underlying reinforcing steel. This was observed on all structures over five years of age, irrespective of chloride content. Laboratory tests conducted as part of the study demonstrated that the likelihood of corrosion goes up significantly when disbonding occurs, because it exposes tiny portions of the steel to the concrete matrix. Simulation models developed using empirical observations indicated the best performing bridges are constructed with modern concrete formulations — high-performance varieties that incorporate admixtures such as fly ash. Ultimately, Sagüés et al. (1994) contended that concrete quality and the depth of concrete cover are likely to have the most significant impact on bridge performance, as the failure of ECR in the Florida Keys revealed the limitations of epoxy coatings.

Brown et al. (2003) reported on a comparative study in the state of Virginia that examined whether ECR outperformed conventional black steel in terms of durability and corrosion resistance. A particular focus was on determining if the extra cost of ECR could be justified based on its performance. Under 25% of bridge decks constructed since 1981, they concluded, were likely to experience sufficient corrosion within 100 years to necessitate rehabilitation, regardless of the type of reinforcing material that had been used. Based on its performance, they observed that ECR is not a cost-effective technique for mitigating corrosion (cf. Sagüés et al., 1994) because it only extends the service life of a bridge deck — on average — by five years over what is expected with carbon steel, and that in harsh environments state DOTs can expect the highest returns on investment with stainless steel reinforcement (316LN). Where exposure to severe environmental conditions is not a problem, Brown et al. (2003) argued the optimal technique to prolong bridge lives the use of low-permeability concrete, which inhibits the passage of chloride ions to the reinforcing bars.

In a follow-up study, Weyers et al. (2006), summarized the findings of a 14-year research project that investigated the performance of ECR on Virginia bridges. Mirroring other studies, they found that epoxy coatings naturally degrade when exposed to highly alkaline and moist environments. Holidays introduced during the manufacturing process undermined ECR's performance and led to epoxy disbondment, with disbonding occurring in as little as four years. Echoing Brown et al., (2003), Weyers et al. (2006) stated

that the average service life benefit of ECR (over carbon steel) is 3-6 years. Because of the limited benefits conferred by ECR, they did not regard it as the most cost-effective treatment option. As such, they proposed guidelines for minimizing corrosion. For non-critical decks, beams, and substructure elements that are not exposed to severe marine environments or large quantities of deicing salts, they recommended pairing low-permeability (i.e., high-performance) concrete with conventional steel. For bridge segments less than 500 feet long on major routes — but which are not part of the National Highway System — corrosion-resistant metallic reinforcing bars (MMFX® ChromX), they contended, would offer the necessary performance and longevity. On highly trafficked bridges that are exposed to severe environmental conditions, Weyers et al. (2006) advised using stainless steel.

Ramniceanu et al. (2008) also studied the performance of Virginia bridge decks (following up on the work of Brown et al. [2003] and Weyers et al. [2006]). Their findings generally align with those previous studies. They found that defects introduced during the manufacturing process can seriously undermine the field performance of ECR. On many ECR samples they assessed, the epoxy coatings had not been allowed to fully cure. These bars were unevenly heated and did not reach a high enough temperature. Samples that were not fully cured exhibited a larger number of holidays and increased moisture absorption due their increased porosity. Like other studies that have questioned the utility of ECR, Ramnicanu et al. (2008) observed significant declines in adhesion, and many samples had little or no epoxy coatings remaining on the surface. This is problematic because once the epoxy is no longer affixed to the surface it leaves the reinforcing steel exposed to the ambient environment, and corrosion can proceed unimpeded.

Covino et al. (2000) reported on ECR performance following the rehabilitation of the Perley Bridge in Ottawa, Ontario, Canada. To extend the service life of one span, ECR was installed in both directions, however, the concrete cover thickness varied. Within six years, ECR on the bridge's southbound lane had begun to corrode, but no signs of corrosion appeared on the northbound lane. The key difference between the two lanes was that the concrete cover thickness on the northbound lane was approximately twice that of the southbound lane. Insufficient cover depth promoted more rapid corrosion on the southbound lane. Covino et al. (2000) estimated that ECR only added one to four years to the bridge's service life. Another issue that may have contributed to the ECR's faulty performance was the less restrictive manufacturing standards acceptable in the 1970s. At the time, up to two percent of the epoxy surface could be flawed and still meet standards. The presence of these flaws, even across a small area, likely contributed to the poor performance of ECR on the southbound lane (see Pfeiffer et al., 1993 on the implications of changing manufacturing standards). Covino et al. (2000) argued the two factors which appeared to most significantly influence corrosion were cover depth and the level of chloride contamination. The marginal benefits conferred by ECR were — presumably — not sufficient to justify its added expense.

### **2.2.2 Galvanized and Continuously Galvanized Reinforcing Steel**

Galvanizing traditional carbon steels with a zinc coating improves their corrosion resistance. The outer zinc coating functions as a sacrificial anode by establishing cathodic protection and protects underlying steel from corrosive agents by creating a physical barrier (Dallin et al., 2015). It also resists the de-passivating effects of carbonation. Key factors influencing the speed of corrosion in galvanized rebar are the source and abundance of chloride ions, the condition of the galvanized coating, and concrete cover thickness. Unprotected carbon steel embedded in ordinary concrete depassivates once the pH falls below 11.5. In concretes contaminated with chlorides, this critical pH for corrosion may be higher. Steel galvanized with zinc, on the other hand, remains passivated until the pH drops below 9.5 (Yeomans, 2004). The chloride threshold at which corrosion initiates on galvanized rebar is typically at least 2-4 times that of unprotected carbon steel, and the onset of corrosion may be 4-5 times longer when zinc galvanization is present. Unlike other coating materials (e.g., ECR, paints), the galvanized zinc is metallurgically bonded to the underlying

steel (Yeomans, 2004). Compared to ECR, galvanized rebar can better tolerate damage that occurs during transportation and handling (Pianca and Schell, 2005). In the United States, ASTM A767 *Standard Specification for Zinc-Coated (Galvanized) Steel Bars for Concrete Reinforcement*, applies to the manufacture of zinc-coated steel bars. Field observations of structures built over the past 70 years presents a mixed picture on its performance. Some studies have cited benefits from using galvanized rebar, demonstrating that it effectively keeps corrosion in check. Other research (e.g., Pianca and Schell, 2005) has questioned the utility of galvanization, noting that galvanized rebar may be more vulnerable to the effects of chloride ions. In 1979, the FHWA recommended against using galvanized reinforcement after a series of laboratory experiments questioned its ability to deter corrosion. However, the agency rescinded this recommendation in 1983 (Maki, 2010).

Historically, the hot-dip method has been the technique most widely used to galvanize steel. During this process, cleaned steel bars are immersed in molten zinc that has been heated to 450° C. This produces a series of zinc-iron alloy layers and an outer surface coating of almost pure zinc. The pure zinc is more completely passivated than zinc-iron alloy layers, corroding uniformly at a rate less than 10 percent of untreated carbon steels. Some of the zinc-iron layers created during conventional hot-dipping are brittle and will crack if deformed. Therefore, reinforcing bars must be bent to size before they are galvanized. When zinc eventually corrodes, corrosion products (principally zinc oxide and zinc hydroxide) migrate from the site of corrosion, densifying the surrounding concrete in the process while filling voids and micro-cracks (Yeomans, 1998). This decelerates corrosion and increases the bond strength between the reinforcing steel and concrete. As such, galvanization offers strong adherence and produces a surface that is resistant to abrasion. To prevent galvanized reinforcement from creating gas bubbles when in contact with wet cement, chromate quenching is sometimes specified for galvanized reinforcing bars as a safeguard, though it is not always employed.

More recently, a new type of reinforcing steel has become commercially available — continuously galvanized rebar. It is produced using a method comparable to the hot-dip method, although the specifics of the process differ slightly. Small amounts of aluminum are added to the zinc bath, and a shorter immersion time is used to prevent formation of the zinc-iron alloy layers. Aluminum impedes zinc-iron reactions and produces a very flexible zinc coating. After steel bars are preheated, they are dipped into molten zinc for 4-5 seconds. Preheating the steel bars reduces the potential for embrittlement and improves the final product's ductility. Continuously galvanized rebar may also be covered with an epoxy coating to improve its corrosion resistance. Though the continuously galvanized rebar zinc coating is thinner than typically found on conventional hot-dipped rebar, manufacturers claim that it has a potential service life of 100 years.

In 2009, the International Federation of Structural Concrete (Yeomans, 2009) released a study that discussed numerous examples of galvanized reinforcement's real-world performance. Bermuda was the first country to use galvanized rebar on a widespread basis, with applications dating to at least the 1930s (see also Maki, 2010). Officials chose galvanized steel because of the island's harsh marine environment and the nature of local aggregates, which have high chloride concentrations. After its initial application on a dock project, the country's Department of Public Works recommended galvanized reinforcements for all structures (its use is legally mandated today). Following World War II, many structures — docks, jetties, bridges — were constructed with galvanized steel. Surveys in 1991 found little evidence of corrosion in these structures despite their exposure to high chloride levels well above the threshold for initiating corrosion in unprotected steel. In 1981 and 1991, the Portland Cement Association commissioned studies to document the performance of galvanized reinforcement in six bridge decks (including one in Florida that was exposed to seawater). After 24 years, the galvanized bars exhibited superficial corrosion in sound,

uncracked concrete even in the presence of extremely high chloride levels. In Pennsylvania, inspections of 237 bridge decks constructed with galvanized steel revealed that just one bridge displayed significant deterioration due to corrosion. But the damaged bridge was also hampered by defective concrete, which led to chloride infiltration and corrosion. None of the bridges constructed with galvanized steel that had decks in conformance with standard concrete specifications exhibited failures of the steel or deck.

Pianca and Schell (2005) reported on the condition of galvanized reinforcement that was used in three Ontario, Canada, bridges after 30 years of use. Since each bridge performed in a slightly different manner, brief summaries are presented here. Bridge 1 was constructed in 1975 and was inspected in 1995 and 2004. By 1995, chloride concentrations at the level of reinforcement had reached the threshold generally required to initiate corrosion in black steel. There was no evidence of significant corrosion. By 2004, chloride concentrations at the level of reinforcement were six times the threshold. The bridge continued to perform well, with only minor delaminations. Researchers estimated that galvanization added at least three years to the steel's service life. Bridge 2 was originally built early in the 20<sup>th</sup> century; it was rehabilitated with galvanized steel in 1976. Twenty years later, the deck remained in fair condition, with approximately 10% of the deck exhibiting corrosion-induced deterioration. By 2004, 15% of the bridge's deck either showed signs of deterioration or had undergone rehabilitation to fix corrosion-related defects. The third bridge was constructed in 1975. In the years immediately following construction, a waterproof membrane was applied to the concrete surface, which enhanced its corrosion resistance. In 2004, the deck remained in good condition and presented no signs of corrosion-induced damage. Overall, corrosion affected approximately one percent of the deck surface. Pianca and Schell (2005) speculated that the waterproofing membrane effectively blocked chloride ions in the years immediately following construction, although by 2004 chloride concentrations at the level of reinforcement had passed the corrosion-initiation threshold. In comparison, a sidewalk next to the road that was also built with galvanized steel but lacked waterproof membrane experienced delaminations across 12.3 percent of its area. Pianca and Schell advised against relying on galvanized reinforcement as either the primary or sole method of corrosion protection. They argued for applying waterproofing membranes and the use of concrete of adequate thickness and quality to slow the ingress of chloride ions.

In another study of the long-term performance of galvanized reinforcement, Helene et al. (2004) presented their findings after investigating a 40-year-old bridge on the Uruguay coast, which is an environmentally harsh setting due to its seawater exposure. Constructed in 1966, the bridge was fabricated out of pre-stressed concrete and galvanized rebar. Several problems arose during the bridge's construction that could have undermined its performance — concrete segregation, concrete formulations of varying quality, and the application of concrete cover that was too thin. Despite these issues, the bridge exhibited good overall performance. On galvanized strands that had been exposed to the atmosphere, corrosion was significant. Elsewhere, corrosion was scarce or not present. Helene et al. concluded that using galvanized steel is an effective option to protect against corrosion; there was no evidence of fractures due to hydrogen embrittlement (as opposed to the findings of other researchers). The results suggested that galvanized steel can have a service life up to twice that of ordinary black steel. However, state DOTs should remain attentive to two issues when considering the use of galvanized steel. First, the manufacturing process may create imperfections in the zinc surface layer that can shorten the duration of its protective capacity. Second, corrosion can occur unevenly, even while some portions of the zinc layer remain protective.

### **2.2.3 Stainless Steel**

Stainless steel has emerged as a popular option for reinforcement, particularly in environments that are extremely harsh. Stainless steels are defined as iron-based alloys with a minimum chromium content of 11 percent. Alloying elements, including nickel, molybdenum, copper, and nitrogen, are added to achieve the

necessary mechanical, fabrication, and corrosion resistant-characteristics (Hansson, 2016). Stainless steel resists corrosion due to a passive protective film that develops on its surface. The protective film is a very thin layer of chromium-rich oxide. Stainless steel is also exceptionally adherent, inert, and self-repairing. Higher chromium content facilitates greater corrosion resistance. Stainless steels have many advantages over more traditional carbon steels. They have good ductility (meaning they can be readily worked), excellent weldability, and a homogeneous microstructure. Also, the cut ends of stainless steel bars do not require protection (cf. stainless clad rebar). Four types of stainless steel are available for use in commercial applications: martensitic, ferritic, austenitic, and duplex (ferritic-austenitic). Austenitic stainless steels have 16-26 percent chromium, while their nickel content is between 6 and 22 percent. The chromium content of duplex stainless steels is between 18 and 29 percent, and typically have a nickel content of 4-9 percent. Molybdenum enhances pitting resistance, however, adding this element can significantly increase costs. Manufacturers have experimented with new formulations to reduce their price. Common strategies have been to replace some nickel with manganese and reduce or eliminate molybdenum.

Like any steel, however, stainless steel eventually corrodes. Six types of corrosion may impact stainless steel: uniform, pitting, crevice, galvanic, intergranular, and stress corrosion cracking. Uniform corrosion is quite rare because environments are not generally aggressive enough to produce it. Pitting begins in extremely small surface irregularities or at the location of non-metallic inclusions. This type of corrosion spreads via electrochemical reaction. Factors which influence the pitting include temperature, chloride concentration, and the amount of alloying elements present in the steel. Crevice corrosion affects small, confined spaces such as gaps, where two components meet, under gaskets and seals, inside cracks and seams, beneath sludge piles, and in spaces filled with deposits. Galvanic corrosion occurs when two metals with divergent galvanic potentials are brought into contact. Under this scenario, the most anodic metal is attacked. Avoiding the use of dissimilar metals wards off galvanic corrosion. Intergranular corrosion is caused when chromium carbides form at grain boundaries. This reduces the passive layer's chromium content and stability, leading to corrosion. Lastly, stress cracking corrosion is the result of a component suddenly cracking and failing without deformation. This may occur when a component is stressed by an applied load or by residual stress. Highly aggressive environments can also promote stress cracking corrosion. While many research studies discussed here have found that stainless steel, when used as a reinforcing material, performs well and resists corrosion, its expense is a serious obstacle. Because of this, state DOTs have generally reserved stainless steel for bridge projects in severe environments and heavily trafficked routes. Readers should bear in mind the difficulty of proposing sweeping generalizations about the performance of stainless steels, as many grades of stainless steel have been used for bridge construction and rehabilitation. Different grades, which are distinguished according to their metal composition, resist corrosion to varying degrees (see Hansson, 2016).

The use of stainless steel has expanded mostly over the past 20-30 years, however, there are several examples of stainless steel being used for bridge construction as many as 80 years ago. A 1999 Arminox study reported on a concrete pier located in the Port of Progreso, Yucatan, Mexico, that was originally built with stainless steel reinforcement. The pier was completed in 1941, and designers chose stainless steel due to the severe marine environment and the use of extremely porous concrete. Petrographic analysis suggested a high water-to-cement ratio for the concrete of 0.55 to 0.60. Optical emission spectroscopy analysis of the steel indicated it was comparable to AISI 304-grade (18-8 grade). Visual inspections of the pier revealed it to be in good condition. Four spalled areas exposed significant corrosion of the reinforcement that lacked cover. On covered reinforcement, only light surface corrosion was present on over 5-20 percent of its surface area. Chloride analysis indicated very high concentrations, generally averaging from 0.6 percent to 1.0 percent by weight of concrete (~24 to 40 lb./yd<sup>3</sup>) with some readings as high as 1.9 percent by weight of concrete (~76 lb./yd<sup>3</sup>). The condition of the pier built with stainless steel

was particularly notable given that a nearby pier approximately 200 meters (~220 yd.) away constructed in the 1960s with plain carbon reinforcement steel exhibited significant deterioration in the columns and decks. In another study that assessed the long-term corrosion resistance of stainless steel, MacGregor (1998) documented the performance of AISI 316 stainless steel reinforcement in exterior precast cladding panels. After 20 years, no corrosion was visible despite the marine environment and less than one inch of concrete cover (about 20 mm).

An investigation by Garcia-Alonso et al. (2007) examined the corrosion properties of several steels including reinforcing carbon steel, AISI 304 and 316L stainless steels, and HSS1 and HSS2, two relatively novel stainless steels that replace a significant fraction of nickel with manganese. Steel bars were embedded in two types of concrete (normal and high-performance) and exposed to varying levels of chlorides over the course of approximately two years. Although the carbon steel corroded, there was no evidence of pitting corrosion in steel exposed to chloride concentrations of 2 percent and 4 percent (~40 to 80 lb./yd<sup>3</sup>) by weight of concrete. Two of the steels tested — AISI 304 and HSS2 —repassivated after pitting initiated. These results are consistent with other studies that have found austenitic and duplex stainless steels are most resistant to corrosion. The critical chloride concentration threshold for corrosion of austenitic stainless steels is at least 10 times higher than for traditional carbon steels.

Serdar et al. (2013) studied the long-term corrosion behavior of six different stainless steels that were embedded in mortar and exposed to a simulated marine environment over the course of two years. The steels evaluated were AISI types 410, 204Cu, 2101, 304, 2304, and 316 (see Table 1 of Serdar et al. [2013] for the chemical composition of each steel grade). The steels' surfaces did not undergo preparation before they were embedded in a mortar. Usually, stainless steel rebars are abrasive blasted or pickled prior to use to remove surface oxides. After curing, the specimens were partially submerged in a sodium chloride (NaCl) solution for a period of two years. AISI type 2304 displayed the best performance, which researchers attributed to robust protection established by a passive layer that contained chromium, nickel, and molybdenum. Two other steel types with a small amount of nickel but large amounts of nitrogen and manganese — AISI 204Cu and 2101 — displayed good long-term performance, however, they were more vulnerable to corrosion than common austenitic steels (e.g., AISI types 304 and 316).

Van Niejenhuis et al. (2016) conducted laboratory experiments to understand the corrosion resistance of six grades of austenitic and duplex stainless steel at lower price points than the grades that have typically been used for transportation applications. Included among the steel types were S31653, S32205, S32101, S30403, S24100, and S32302 (UNS designations; see Van Niejenhuis et al., 2016, Table 1, p. 363 for the chemical makeup of each steel). Each specimen had one inch (25 mm) of concrete cover, significantly less than the 63.5-76.2 mm (2.5-3.0 in) of concrete cover mandated by most state DOTs. The performance of stainless steel in cracked and uncracked concrete was examined. All samples were exposed to salt brines continuously for two years, with ambient temperatures in the 68-70° F (20-25° C) range. Except for S32205, all specimens housed in the cracked concrete exhibited signs of corrosion. Corrosion in the cracked specimens was localized and restricted to locations near the intersection of the crack and steel reinforcement. Observations indicated that corrosion began at the root of cracks and then spread along the reinforcement's surface. Corrosion current densities over the bar surface did not increase in a consistent manner, impeding efforts to accurately estimate time to corrosion. No bars embedded in unbroken concrete exhibited corrosion. Duplex stainless steels had slightly better corrosion resistance than austenitic steels, most likely because they contain higher levels of chromium. Van Niejenhuis et al.'s (2016) ranked the performance of each steel, noting their results were the inverse of those in Bertolini and Gastaldi (2011), which they attributed to different preparation methods — Van Niejenhuis et al. did not pickle bars prior to testing, a practice which eliminates some imperfections.

Hansson (2016) provides the most thorough review of different stainless steels, their corrosion-resistant properties, chloride thresholds, and methodological approaches to evaluating their performance. Along with ranking the different alloys currently available on the market (see below), Hansson described some of the factors which affect post-initiation corrosion rates in stainless steel:

- Distribution and magnitude of localized attacks
  - This influences the lateral growth of a corrosion pit and the spread of corrosion products.
- How effectively non-corroding areas function as a cathode affects the rate of corrosion
  - Stainless steels are less effective as a cathode than black steel. Once the passive film deteriorates locally and anodic areas form, corrosion pits expand slowly because the adjacent steel surface is an inefficient cathode.
- The composition, solubility, and specific volume of corrosion products
- How effectively corrosion products protect underlying steel from rapid corrosion rates
  - When corrosion begins, the current density is extremely high, however, it decreases over time. As such, the progressive development of corrosion products may eventually moderate corrosion.
- Whether corrosion products block or partially block pre-existing cracks
  - As other studies (see above) demonstrated, corrosion occurs preferentially where the concrete's structural cracks adjoin reinforcing steel. Van Niejenhuis et al. (2016) observed that corrosion was localized proximate to cracks and that corrosion products deposited near cracks may create a sort of blocking effect.

Reviewing several studies, Hansson ranked the performance of different alloys (Figure 2, see p. 78 of Hansson [2016]). This table, reproduced here, summarized the findings of 11 studies. While not exhaustive and limited to six alloys, it could inform the selection of reinforcing materials for bridge construction. For each reference, the table should be read from left to right. For example, Bertolini and Gastaldi (2011), found that 316LN performed the best, followed by ASIS 2304 and ASIS 2101.

2205	Alloy					References
	316LN	2304	2101	304LN	XM28	
—	1	2	3	1304 equivalent	—	Bertolini and Gastaldi (2011)
—	1	—	—	2	—	Castro et al. (2003)
—	—	—	—	—	High Mn, low Ni	Elsener et al. (2011)
—	2	3	1	—	—	Randström et al. (2010)
—	3 (316)	1	2	4 (304L)	—	Schönning and Randström (2011)
1 pre-cracked concrete	4 pre-cracked concrete	3 pre-cracked concrete	2 pre-cracked concrete	5 pre-cracked concrete	6 pre-cracked concrete	Van Niejenhuis et al. (2016)
2 as-rolled	1 clad, pickled	3 pickled	4 as-rolled	—	—	Hart (2009)
1	—	2	—	3	—	Alvarez et al. (2011)
—	1 (316) no corrosion	1 no corrosion	3 (crevice corrosion at seal)	2 (304)	—	Serdar et al. (2013)
1	—	—	2	—	—	Ji et al. (2005)
—	1	—	2	—	—	Scully and Hurley (2007)

**Figure 2** Rankings of Common Stainless Steel Alloys Used as Reinforcement Material

Consistent with some researchers who have studied the performance of ECR, Hansson (2016) argued that while stainless steels are effective at reducing corrosion, designers should invest their energies in eliminating or reducing the number of cracks in concrete because the roots of cracks are where corrosion is most likely to begin. Hansson presented two options to reduce the number of cracks. The first is to reduce the thickness of concrete cover. Because stainless steels are more corrosion resistant than other materials, using less concrete should not be problematic. Reducing the thickness may diminish the number of load-induced cracks and the widths of shrinkage cracks. The second option is using prestressed concrete, as this approach has showed promise in earlier studies.

#### 2.2.4 Stainless Clad Rebar

Solid stainless steel reinforcement is remarkably effective at resisting corrosion, however, as noted in the previous section, it is very costly and because of its expense is used for only the most critical infrastructure projects. To obtain the benefits of stainless steel without its high price, manufacturers developed stainless steel clad rebar, which is conventional black steel that is clad with 316LN stainless steel during the manufacturing process. It is much less expensive than solid stainless steel rebar, although it is a bit more expensive than ECR. However, the long-term costs of stainless clad rebar are less than ECR, and it is expected to prolong the service life of bridge decks. Most studies confirm the effectiveness of stainless clad rebar, and yet it is not without problems. For instance, imperfect bonding between the stainless steel and underlying carbon steel can make the latter vulnerable to corrosion.

Rasheeduzzafar et al. (1992) in an early study of stainless clad rebar compared its performance to ECR, galvanized, and untreated steels. Specimens were embedded in mortar with a water-to-cement ratio of 0.45 and then exposed to three levels of chloride concentration — 4, 8, and 32 lb./yd<sup>3</sup> (2.37, 4.74 and 18.96 kg/m<sup>3</sup>) — for seven years. Severe corrosion afflicted the untreated steel while the galvanized steel delayed

the onset of corrosion. Galvanized steel exhibited significant corrosion at higher chloride exposures, particularly in areas near cracks in concrete. At low chloride levels, the ECR performed well, although at higher chloride concentrations significant corrosion took place. The stainless clad reinforcing steel performed the best. After seven years, even at the highest chloride levels, there was no evidence of corrosion or cracking.

Through a series of laboratory experiments, Cross et al. (2001) estimated that stainless clad rebar with end coatings has a service life of between 50 and 60 years before the onset of concrete damage. However, flaws or imperfections in the surface or coating of stainless clad rebar can dramatically reduce its service life. Holes in the cladding reduce its service life by 15-40 years. Occasionally gaps may form between the cladding and underlying steel. If this occurs it can promote cracking and significantly diminish service life. Cross et al. (2001) enumerated several problems that DOTs should factor into their decision making about stainless clad rebar. If a proper metallurgical bond does not form between the steel and cladding, voids may develop where the underlying steel and cladding adjoin. Cross et al. witnessed this in many of their specimens, with continuous voids emerging at the core-cladding interface. Premature cracking results from this. Another potential issue is internal corrosion. This occurs when the underlying black steel corrodes despite there being no visible evidence of corrosion on the cladding. Kahrs et al. (2001) echoed some of the concerns of Cross et al. (2001), observing that while stainless clad rebar is more resistant to corrosion than conventional types of reinforcing steel, its cut ends require protection because the underlying black steel is exposed to ambient conditions. While Cross et al. (2001) estimated that stainless clad rebar can have a service life of up to 75 years, imperfect bonding between the cladding and underlying steel must be resolved to achieve this level of durability.

Cui and Sagüés (2003) examined the corrosion behavior of stainless clad rebar under a variety of test conditions: no cladding breaks, purposefully introduced cladding breaks, different simulated concrete pore solutions, and concretes with varying levels of chloride. Stainless clad rebar fabricated with isolated ends, which had their ends protected with a stainless steel cap or welding overlay, were very resistant to corrosion, even when exposed to a liquid solution with extremely high chloride levels. One year after exposure, the stainless clad rebar still exhibited no corrosion when embedded in concrete with chloride concentrations of up to 8 percent by weight of concrete. Stainless clad rebar that was placed in a saturated  $\text{Ca}(\text{OH})_2$  (calcium hydroxide) solution at  $104^\circ\text{F}$  ( $40^\circ\text{C}$ ) for six months remained passive. After being moved into a chamber with a relative humidity of 100 percent corrosion did not occur on these samples. Specimens with 1-mm holes drilled into the cladding did, however, display signs of corrosion after being placed in a  $\text{Ca}(\text{OH})_2$  solution for 100 days. Using observation data, Cui and Sagüés (2003) developed simulation models that demonstrated the rate of corrosion for carbon steel enveloped by stainless steel cladding is influenced by the concrete's resistivity and the size of clad breaks. High-performance concretes and no (or very small) imperfections in the cladding should result in less corrosion. Cui et al. (2003) reaffirmed many of the findings of Cui and Sagüés (2003), noting that stainless clad reinforcing steel without imperfections or holidays is extremely resistant corrosion when immersed in  $\text{Ca}(\text{OH})_2$  solutions with chloride concentrations of up to 5 percent by weight of concrete. Specimens with breaks in their cladding underwent localized corrosion in a  $\text{Ca}(\text{OH})_2$  solution with a chloride concentration of 1 percent by weight of concrete.

### **2.2.5 Chrome Reinforcing Steel**

Beginning in the early 1990s, the FHWA, American Iron and Steel Institute, and the U.S. Navy embarked on a project to develop low carbon, high-performance steels for use in bridge construction. Out of this research, several commercially available alloys emerged, one of which was MMFX® ChromX, which is a nanostructure modified steel (Rana et al., 2009). Its microstructure differs from conventional steel, having a laminated lath structure that is often described as resembling plywood. This confers greater strength,

ductility, toughness, and corrosion resistance than black steel. Proponents claim that its corrosion resistance is on par with stainless steel despite it being much less expensive. Some states have begun to use MMFX® ChromX and phase out ECR. Weyers et al (2006) reported that the Virginia DOT planned to use MMFX® ChromX along with stainless steel and stainless clad rebar for structural elements in highly corrosive environments. At the time, the price of MMFX® ChromX was comparable to black steel and less than ECR. Mirmiran et al. (2009) also recommended the use of MMFX® ChromX in the state of Florida, concluding that it has the potential to serve as an alternative means of reinforcement, although they suggested further testing (e.g., pull-out tests to evaluate bond length and the effectiveness of hooks and mechanical anchorages, assessment of fatigue performance). Barr and Wixom (2009) discussed a pilot project in Utah that incorporated MMFX® ChromX steel and suggested that bridge decks likely to be exposed to high traffic volumes or significant quantities of deicing salts would benefit from using MMFX® ChromX, stainless clad rebar, or stainless steel reinforcement for construction. Although it has received mostly favorable notices, research focused on MMFX® ChromX steel remains scarce, although early results appear promising. Indeed, the chloride concentration threshold at which corrosion will initiate in MMFX® ChromX is approximately four times that of conventional black steels (Barr and Wixom, 2009).

Rizkalla et al. (2005) discussed an experiment that compared the performance of Grade 60 steel and MMFX® ChromX steel. The experiment investigated three concrete bridge decks with span-to-depth ratios of 12.5 and tested them until they failed using concentrated loads (i.e., simulated truck wheel loadings). Three test conditions were examined: Grade 60 steel, MMFX® ChromX steel, and 33 percent less MMFX® ChromX steel. For the latter condition, MMFX® ChromX steel was used, however there was one-third the amount used as reinforcement than in the MMFX® ChromX base scenario to determine the benefits of its high-strength properties. The simulated deck with one third MMFX® ChromX steel attained the same ultimate load-carrying capacity and deflection at service load as decks reinforced with Grade 60 steel. Disbonding of MMFX® ChromX steel bars lowered the ultimate strength 6 percent. Overall, the MMFX® ChromX steel displayed good performance and Rizkalla et al. (2005) endorsed the claims of higher corrosion resistance.

Chajes et al. (2005) performed several laboratory simulations in preparation for the use of MMFX® ChromX on the reconstruction of a bridge in Newark, Delaware. Based on laboratory results, they observed that MMFX® ChromX has a yield strength approximately twice that of regular steel. But they cautioned that designers must be careful not to produce designs in which beams are over-reinforced. They also observed that the steel does not have a clear yield point and that it is less ductile than black steel. The strength of MMFX® ChromX was comparable to standard black steel, however, they warned that beams reinforced with MMFX® ChromX could potentially develop larger cracks than beams constructed using black steel.

Chiaw and Harik (2005) wrote about a KYTC bridge along CR5128 in Scott County, Kentucky, that was constructed with both stainless clad rebar and MMFX® ChromX steel (one span was built with each material). During testing, they found that MMFX® ChromX had a nonlinear moment-curvature response, and that decks constructed with MMFX® ChromX steel exhibited higher ultimate strengths than decks fabricated with stainless clad rebar — 57 percent higher in the positive moment region and 85 percent in the negative moment region. MMFX® ChromX also had a nonlinear stress-strain relationship. The area underneath the moment-curvature curves was smaller for MMFX® ChromX than stainless clad rebar. As of their writing, field investigations had been conducted over a limited period (one year). The decks remained in excellent overall condition with only very minor cracks detected — so small they could not be measured. The study established a long-term monitoring program, however, no additional published results have been made available.

DeJong et al. (2009) studied the fatigue performance of MMFX® ChromX and 316LN stainless steel in corrosive environments. They compared the performance of both materials under variable amplitude fatigue, applied in both an ambient laboratory setting and corrosive conditions. Corrosive conditions were simulated through an impressed current or by ponding a NaCl solution on test specimens. The 316LN stainless steel and MMFX® ChromX steel were less vulnerable to corrosion fatigue than black reinforcing steel. Both materials also retained their intrinsic fatigue limits under corrosive conditions, which indicated that their resistance to corrosion fatigue at low stresses was significantly better than black steel. Under ambient environmental conditions, the MMFX® ChromX fatigue limit was 1,150 MPa. This fell to 900 MPa when the material was exposed to corrosive surroundings. Both materials also performed worse in corrosive environments when overloads were applied, with their lifespans being 50-85% shorter than in ambient conditions, however, this performance far outpaced that of conventional black steel. Although the stainless steel did not develop rust in corrosive conditions, some light surface rusting emerged on the MMFX® ChromX. While DeJong et al. did not offer a recommendation, their conclusions appear to suggest that both materials are viable replacements for conventional black steel in bridge construction.

### **2.2.6 Multi-Coating Reinforcing Steel**

Several reinforcing steel types are available or coming available that combine a polymer (e.g., epoxy) coating over zinc coated steel. One product, Z-bar, uses thermally bonded zinc (probably a powder) over black bars with a thermally bonded epoxy layer (yellow in color to distinguish it from green rebar). Continuous galvanized rebar can also be coated with a polymer. In both cases, if the polymer coating is breached, the zinc layer will protect the steel rebar from corrosion. In both cases, since the zinc coating is ductile, the coated bars can be bent. Tremblay et al. (2012) performed laboratory tests of eight metallic rebar materials including: black, MMFX® ChromX, epoxy coated, Z-Bar, stainless clad, high-nickel stainless, high-manganese stainless and duplex stainless steel. Rebars were subjected to a 3 percent sodium chloride solution bath three days a week for 8 hours. The samples were removed from the bath and dried under ambient conditions. This procedure was repeated for 260 cycles, thought to be equivalent to 10 years' exposure under Vermont's climatic conditions. Z-bar, stainless clad and solid stainless steel rebars all showed low corrosion compared to the other materials.

### **2.2.7 Fiber Reinforced Polymers**

The application of fiber reinforced polymers (FRPs) to civil engineering projects has increased over the past 30 years. The first application of FRP (glass) on a U.S. bridge occurred in 1996. Project designers and engineers have increasingly turned to FRPs because they are lightweight, ductile, and durable (Keller, 2001). Wanting a reinforcement solution for bridges that does not corrode when subjected to harsh environmental conditions, state DOTs have experimented with various forms of FRPs as a replacement for more conventional reinforcement methods (e.g., carbon steel, ECR). While the American Concrete Institute (ACI) has only issued non-mandatory design guidance for FRPs, it has authored mandatory specifications for using carbon FRP and glass FRP to reinforce concrete (ACI 440.5-08 *Specification for Construction with Fiber-Reinforced Polymer Reinforcing Bars* and ACI 440.6-08 *Specification for Carbon and Glass Fiber-Reinforce Polymer Bar Materials for Concrete Reinforcement*). The American Association of State Highway Transportation Officials has also released guidance on the use of FRP.

FRPs have two components — a fiber, which is made from a material, such as carbon, glass, aramid, and recently, basalt, and a resin (polymer) — and come in a variety of forms including shot, chopped, long, and woven (Busel, 2012). Glass FRP is typically the least expensive (Benmokrane et al., 2002) and has found the most widespread use. Although basalt FRP has received greater attention because it is environmentally friendly (Dhand et al., 2015). Fibers are the source of strength and stiffness whereas the polymer protects and transfers the load between fibers. Resins fall into two categories. Thermoset resins, which are most

commonly used for structural purposes, are liquid at room temperature. Once they have been heated and cured they attain a solid state, after which they cannot revert to liquid or be reformed. The most common thermoset resins are polyester, vinyl ester, polyurethane, and epoxy. Each of these come with advantages and disadvantages (Busel, 2012). The other class of resins is thermoplastic resins, which are solid at room temperature and liquefy upon heating. Once they have been heated, they are cooled under pressure, re-attaining a solid form. Because FRP is anisotropic, it possesses high strength in the direction of fibers and enhances shear strength, dowel action, and bond performance. FRP does not exhibit yielding and remains linear elastic until failure.

Many researchers have discussed the benefits and downsides of FRPs in a civil engineering context (e.g., Keller, 2001; Bakis et al., 2002; Hastak et al., 2004; Alampalli and Ettouney, 2006; Böer et al., 2013). From a structural perspective, FRPs display high strength-to-weight ratios, high stiffness-to-weight ratios, good ductility, and are lightweight, which can lead to a quicker and smoother installation once construction crews become accustomed to assembling them. The tensile strength of FRPs is better than steel despite being one-quarter of the weight. Other benefits of FRPs include greater durability and more reliable performance, lower lifecycle costs compared to traditional methods of reinforcement, high corrosion and fatigue resistance, and a high live load capacity. Additionally, FRPs minimize the use of heavy equipment and provide a good option for extending the lives of superstructures needing repairs.

Understandably, state DOTs have been intrigued by a reinforcing material that is seemingly impervious to chloride-induced deterioration. Although promising, researchers have also reported on the negative qualities of FRPs. As Böer et al. (2013) observed, FRPs are not immune from deterioration when exposed to harsh environmental conditions. Subjecting FRPs to salts and freeze-thaw cycles may accelerate their degradation, the latter owing to the expansion and contraction of salt deposits. Using FRPs as a reinforcing material is also much more expensive than conventional steels. Nystrom et al. (2003) argued on the basis of two demonstration bridge projects that the improvements in performance FRPs offer does not justify their much higher costs, and they would not be cost competitive with traditional reinforced-concrete bridges. However, they suggested FRPs might be a viable option for standard short-span bridges. Other challenges associated with the use of FRPs include the restricted number of design figurations they can be fabricated into, structural engineers having little experience with them, and possible failures of the wearing surface (e.g., Alampalli and Ettouney, 2006). Because their adoption for civil engineering application is recent, there are no long-term performance data for FRPs (see below). Another potential drawback of FRPs is they often require a deflection-driven design because they have a low modulus of elasticity. Evidence also suggests that FRPs are more sensitive to thermal changes than steel or concrete.

The short-term performance of FRP reinforcement is somewhat mixed, however, several studies have concluded it is an effective approach and resists deterioration better than steel reinforcement. Mufti et al. (2005) examined concrete cores of bridges constructed with glass FRP (composed of E-glass and vinyl ester) over a 5-8 year period against control specimens. Although laboratory tests have shown that alkali has a propensity to attack and undermine glass FRP, Mufti et al. did not observe gaps between the glass FRPs and concrete. There were no outward signs of degradation on the matrix or glass fibers either. This is critical because degradation at the glass fiber-polymer interface can impair the stability of glass FRP and lead to debonding. No hydrolysis reaction occurred in the glass FRP exposed to natural environments, nor were there significant changes in the glass transition temperature. Phillips et al. (2005) reviewed a demonstration project in Virginia that involved construction of a three-span bridge. Two spans were reinforced entirely with ECR while on the third span glass FRP in the top mat was paired with ECR in the bottom mat. The researchers instrumented the bridge and monitored its performance over the course of two years. They found that glass FRP bars distributed the transverse load in the same manner as the spans

reinforced just with ECR. Impact factors were less than design values in the first year, but rose above the design values during the second year. However, researchers did not find evidence of cracking or anomalous structural behaviors. The measured stress in the glass FRP bars were less than the design allowable stress. Gooranorimi et al. (2016) evaluated GFRP rebar from a TXDOT bridge after 15 years of service and found the rebar to be in good physical and structural condition.

Trejo et al. (2005), based on a series of laboratory experiments, observed that glass FRPs exposed to water and alkaline solutions could have a lower capacity than the design tensile strength. However, these experiments did not replicate field conditions (i.e., direct exposure to water and alkaline solutions). Reinforcement embedded in concrete does not encounter these conditions because concrete does not have saturated pores. Following this research, the samples of glass FRP-reinforced concrete samples were stored outside with the aim of testing them later. Trejo et al. (2009) reported on this follow-up testing. Glass FRP bars were removed from concrete specimens and tested for residual tensile capacity and modulus of elasticity. After determining the glass FRP exhibited reduced capacities, they developed a numerical model to simulate the behavior of glass FRP reinforcement in concrete. The model indicated that during the first several years the loss of mean stress capacity occurs rapidly but wanes over time. This decay is likely to be more severe in smaller bars. The model anticipated that the probability of bars not meeting ACI 440 requirements was 0.44 for #3 bars, 0.25 for #5 bars, and 0.2 for #6 bars. While this should not necessarily preclude the use of FRPs for bridge construction, Trejo et al. (2009) cautioned that additional research is needed, especially given that the specimens they examined were not exposed to the loads generally expected of real-world situations.

### **Key Takeaways**

- No steel is immune to corrosion. All steel types eventually corrode, although the timetable varies according to the type of preventative actions taken.
- ECR has been the most popular choice among transportation agencies to deal with the problem of premature bridge corrosion. Research studies from the past 25 years present a mixed (although mostly favorable) picture. Some have endorsed the utility of ECR, while others have questioned its protective capacity, citing instances where epoxy coatings failed to arrest corrosion, disbonded from the underlying steel, or disintegrated themselves. Epoxy coatings break down over time, and this may occur more quickly in moist and humid environments.
- Galvanized steels have seen limited use compared to ECR and other materials. Its proliferation was likely hobbled in the 1970s by an FHWA statement discouraging its use (although this was later withdrawn). Field studies indicate that decks engineered with galvanized rebar have generally performed well. Like stainless clad rebar, imperfections in zinc surfaces can expose the underlying steel to corrosive agents.
- Solid stainless steel is probably the material recommended most often to achieve a 75-100 year service life. It is much more expensive than alternative options and typically reserved for the most corrosive and high-traffic environments.
- Stainless clad rebar carries many of the benefits of solid stainless steel but at a lower price point. There are several potential issues with stainless clad rebar — holidays and other imperfections in the cladding can allow the infiltration of chlorides and moisture; imperfectly sealed end caps can also let in moisture and chlorides. Both these issues may accelerate corrosion.
- There is still little field research available on FRPs. Their installation on demonstration projects is quite recent, and therefore there are no long-term performance data. Laboratory experiments have indicated additional work is necessary to understand how severe environmental conditions affect the degradation of FRPs as well as how their stress capacities change over time.

- Numerous authors observe that merely protecting a bridge deck’s reinforcing steel is not sufficient to delay the onset of corrosion. Establishing a thick cover with high-performance concrete is at least as important for extending the service life of a bridge. Preventing the development of cracks is also critical for delaying corrosion.

### 2.3 Supplementary Cementitious Materials

In the 1970s state DOTs began to incorporate supplementary cementitious materials (i.e., admixtures), into concrete formulations to improve their durability and delay the onset of corrosion. Common admixtures are silica fume, fly ash, ground granulated blast furnace slag, calcium nitrite, sodium monofluorophosphate, and hydroxyalkylamines (see below for a description of each; often the blanket term *pozzolans* is applied to these materials). A less widely used supplementary cementitious materials is disodium tetrapropenyl succinate. The logic underpinning the use of these materials is straightforward. They produce a denser concrete, reduce its permeability, constrain the flow of ions, increase electrical resistivity and slow down the corrosion current (McDonald, 2011; Hornbostel et al., 2013). Numerous researchers have demonstrated that supplementary cementitious materials decrease porosity and limit chloride infiltration (Dhir and Jones, 1999). Along with these benefits, Rupnow (2012) observed that using admixtures improves the workability and finishability of concrete; produces a higher ultimate strength than Portland cement concrete; reduces the early rate of heat generation; and creates a final concrete whose freeze-thaw resistance, modulus of elasticity, and resistance to deicing salts is roughly equivalent to those of Portland cement concrete. Incorporating materials, such as fly ash, into a concrete mixture reduces the concrete’s capillary pore system and diminishes its permeation properties, making it harder for chloride-infused water to reach the level of steel reinforcement (Dhir and Jones, 1999). Because most supplementary cementitious materials are industrial waste, reusing them in concrete can have an environmentally positive impact. Table 2 summarizes the characteristics of several materials typically used as admixtures.

Hansson et al. (2012) noted that some admixtures are termed corrosion inhibitors. Corrosion inhibitors are defined as chemical compounds that reduce the corrosion rate by affecting the anodic or cathodic half-cell reactions, or both. Materials that affect the transport mechanism of the aggressive species to the reinforcing steel bars are not considered inhibitors such as pozzolans (e.g., microsilica) or sealants. Hansson noted that corrosion-inhibiting admixtures in concrete function by:

- Increasing the resistance of the passive film on the steel to breakdown by chlorides;
- Creating a barrier film on the steel;
- Increasing the degree of chloride binding in the concrete;
- Scavenging the oxygen dissolved in the pore solution; and
- Blocking the ingress of oxygen.

There are many questions about the efficiency of the inhibitors in steel reinforced concrete structures. Lack of understanding about the mechanistic, environmental, and safety aspects are some of the major limitations of using inhibitors in reinforced concrete structures. For example, the use of calcium nitrite is allowed in many jurisdictions but not permitted in others. Corrosion inhibitors should conform to ASTM C 1582, *Standard Specification for Admixtures to Inhibit Chloride-Induced Corrosion of Reinforcing Steel in Concrete*.

Concrete mixtures that blend cement and one supplementary cementitious material (i.e., fly ash) are termed binary concrete mixtures, while a formulation that contains cement plus two supplementary cementitious materials are classified as ternary mixtures. Researchers have begun to investigate whether including two or more supplementary cementitious materials produces significant benefits (e.g., Civjan et al., 2005; Nidiffer et al., 2014). While there is no consensus on whether ternary formulations are more effective at

limiting corrosion than binary mixtures, there is evidence to suggest this is the case. Ternary formulations do have several downsides: increased setting times, unpredictable changes in the time between the initial and final set, a slower gain in strength compared to other concrete blends, and a prolonged curing time, which discourages its use in very cold settings.

**Table 2** Key Types of Supplementary Cementitious Materials

Material	Notable Properties and Features
<b>Fly Ash</b>	<ul style="list-style-type: none"> <li>Derived from the burning of coal, the most frequently used supplementary cementitious material</li> <li>Consists primarily of silicate glass, it contains silica, alumina, iron, calcium, and a number of minor constituents</li> <li>There are two classes of fly ash:               <ul style="list-style-type: none"> <li>Class F fly ash (most commonly used in the US) has a low calcium content (&lt; 10% CaO) and is less than 5% carbon</li> <li>Class C fly ash has a much higher calcium content (between 10% and 30% CaO), and is less than 2% carbon</li> </ul> </li> </ul>
<b>Ground Granulated Blast Furnace Slag</b>	<ul style="list-style-type: none"> <li>A byproduct of iron production, it is passed through a granulator and ground prior to its incorporation into concrete</li> <li>Three grades are available: Grades 80, 100, and 120</li> <li>Grades 100 and 120 are most often used in concrete structures because they gain strength more quickly than Grade 80</li> </ul>
<b>Silica Fume</b>	<ul style="list-style-type: none"> <li>A byproduct produced when coal is burned</li> <li>A noncrystalline form of silicon dioxide (typically &gt; 85%)</li> <li>Available in powder and liquid forms</li> </ul>
<b>Calcium Nitrite</b>	<ul style="list-style-type: none"> <li>A powder manufactured by reacting hydrated lime with NO<sub>x</sub> gas</li> <li>Used to inhibit corrosion and accelerate the setting of concrete</li> <li>Converts to nitrate in the environment, which has a lower toxicity</li> </ul>

Thomas and Bamforth (1999) discussed the results of a long-term study that examined the field performance of concretes formulated with slag and fly ash in a variety of settings — laboratory, sea walls, hydraulic dams, and the splash zone of sea fronts. To test concrete performance for the latter condition, the researchers cast and cured reinforced concrete blocks using three distinct concrete formulations — one contained only Portland cement (control condition), one contained Portland cement and 30% fly ash, and the final mixture contained Portland cement and 70% slag. Models for chloride diffusivity were developed based on the performance of the concrete blocks and data collected from the other field sites mentioned. Observations revealed that after two years the diffusivity of concrete mixed with fly ash was one order of magnitude lower than the mixture containing only Portland cement. The model anticipated this to be two orders of magnitude lower after 100 years. Concrete formulated with slag exhibited significantly higher diffusivity than other mixtures the first month after it was cast, however, this quickly declined with the passage of time. After 30 years of exposure in a marine environment, the chloride concentrations at a depth of about 2 inches (50 mm) in fly ash and slag concrete should be negligible. Their modeling indicated that

approximately 200 years would need to elapse before chloride concentrations hit threshold levels in the fly ash concrete mixture and that transport rates fall as concrete ages. Both points underscore the importance of using adequate concrete cover over reinforcing steel. Thomas and Bamforth recommended the use of fly ash or slag to prolong the service lives of concrete structures, especially in environments saturated with chlorides.

In a far-reaching study, Civjan et al. (2005) investigated the effects of different combinations of admixtures on corrosion resistance. They studied 14 concrete formulations, which contained varying amounts of Portland cement, calcium nitrite, silica fume, fly ash, ground granulated blast furnace slag, and disodium tetrapropenyl succinate (DSS) (see Table 1, Civjan et al, 2005, p. 690 for exact formulations). Each formulation contained from one to three admixtures. Researchers mixed and placed the concrete pursuant to ASTM C 192-02. Blocks then went through testing cycles in which they were exposed to a ponded NaCl solution, dried, and then exposed to the solution again. Testing lasted for approximately two years. The researchers found that calcium nitrite, when used by itself, established reliable protection against corrosion in uncracked concrete. However, if cracking was present, it was less effective, and the chloride threshold was quickly exceeded. DSS exhibited the best performance when used by itself or in combination with calcium nitrite. It significantly reduced the permeability of concrete and warded off corrosion even in the presence of cracking. One tradeoff involved in the use of DSS, however, is its negative impact on the compressive strength of concrete. Concrete formulations that contained only silica fume, or silica fume and calcium nitrite, were more prone to micro-cracking. To achieve maximum protection, Civjan et al. recommended using a ternary mixture consisting of calcium nitrite, silica fume, and fly ash (all in moderate amounts), or a combination of calcium nitrite and blast furnace slag. Except for the formulations with DSS, all the mixtures had a higher compressive strength and displayed better performance and higher quality than a formulation that contained only Portland cement.

Although their findings mostly reaffirmed the conclusions of earlier work, Montemor et al.'s (2002) investigation of how binary concrete mixtures perform in environments with high levels of carbon dioxide offers a useful starting point for understanding conditions where admixtures actually degrade the resistivity of concrete. Their study looked at the effects of fly ash in concrete with high chloride levels and exposure to an atmosphere with high CO<sub>2</sub> concentrations — 5 percent. In the high-CO<sub>2</sub> environment, the presence of fly ash during the setting process facilitated carbonation, which increased concrete porosity and reduced concrete resistance. This reaction was exacerbated by chlorides. In environments with natural levels of CO<sub>2</sub>, carbonation proceeded slowly, consumption of Ca(OH)<sub>2</sub> was insignificant, and the inclusion of fly ash helped to bind chloride and block pores, which in turn diminished the rate at which chlorides penetrated concrete. In the CO<sub>2</sub>-rich environment, fly ash increased the corrosion rate by an order of magnitude. There were complex competition effects among the carbonation rate, pozzolanic reactions, and chloride diffusion that influenced chloride concentrations. While the level of CO<sub>2</sub> in the experiments was well above natural atmospheric levels, Montemor et al. cautioned against using fly ash in extremely polluted environments.

Although its use is uncommon today, volcanic ash was one of the first natural pozzolans used to densify concrete. Fajardo et al. (2009) investigated the use of volcanic ash (composed of andesite) from Mexico to measure how well it enhances corrosion resistance. Three different concrete formulations were studied — a control mixture that only contained Portland cement and two additional formulations whose proportions of natural pozzolans were 10 percent and 20 percent, respectively. All testing occurred in a laboratory setting. During each testing cycle, specimens were exposed to chlorides through a partial immersion in a NaCl solution for three days and then allowed to dry for four days. Fajardo et al. observed that the inclusion of natural pozzolans lowered the porosity of the mortar matrix and increased the specimens' electrical resistivity. The best performing concrete contained 20 percent natural pozzolans. It had the highest

resistivity, which significantly increased induction time and lowered the corrosion rate by an order of magnitude. Although including pozzolans at this level decreased the concrete's compressive strength, the authors argued this loss in strength was a reasonable tradeoff given its better corrosion protection and the concrete's ability to stymie the passage of chlorides. If users are unwilling to compromise in this area, they recommended the addition of superplasticizers during mortar preparation, as they can replace some of the lost compressive strength.

Cracking that occurs soon after the placement of concrete influences the rate and magnitude of chloride penetration. As such, limiting early-age cracking helps delay the onset of corrosion. Bayard et al. (2010) investigated the influence of supplementary cementitious materials, water-to-cement ratio, and placement and curing temperatures on the development of stresses and early-age cracking in concrete. They tested five concrete mixtures at various temperatures to simulate placement during the four seasons. Three of the formulations included supplementary cementitious materials — Classes C and F fly ash and ground granulated blast furnace slag. After casting the concrete, rigid cracking frame testing and free shrinkage testing were performed to evaluate shrinkage and cracking. Lowering the placement and curing temperatures postponed and reduced the temperature peak, reduced stresses, and delayed cracking. Higher amounts of admixtures, through their effects on hydration rate, temperature, and stiffness development were associated with increased time to cracking. The cracking times for the formulations with admixtures were significantly less than those for the control condition (a mixture that contained only Portland cement). The combination of a reduced rate of heat generation and modulus of elasticity development were the primary factors that improved cracking resistance. Tensile stresses developed more slowly in formulations with admixtures that were placed during hot summer temperatures. Overall, Bayard et al. concluded that supplementary cementitious materials were effective in delaying cracking when concrete was poured during hot weather. Whiting et al (2000) found that the addition of silica fume likely does not have much of an impact on early-age cracking. However, Alaskar and Hooton (2016), based on laboratory experiments, argued that concretes with supplementary cementitious materials may be more susceptible to autogenous and thermal shrinkage, and therefore more vulnerable to early-age cracking. Given the inconsistency in research findings, practitioners should identify the potential benefits and drawbacks of particular admixtures. Because cracking provides an entry point for chlorides, transportation agencies wanting to minimize the penetration of chlorides early in the lifecycle of concrete decks should thoroughly investigate the performance of the supplementary cementitious materials they plan to use, and recognize there may be uncertainty over how specific concrete formulations will perform.

Given their study area's proximity to Kentucky, Nidiffer et al.'s (2014) investigation of Tennessee bridges warrants extended discussion. This research combined analysis of field specimens with laboratory experimentation to determine the most effective concrete formulations for inhibiting chloride penetration. Rapid chloride penetration tests and surface resistivity tests were used to characterize the performance of different concrete mixes. The state currently uses binary concrete formulations, and all samples obtained from the field were Class D mixtures, which contained cement, Class F fly ash, limestone, and natural sand. All samples collected from the field had a below average ability to resist the penetration of chloride ions. Twenty-eight days after casting, the binary mixtures displayed moderate to high chloride ion penetrability characteristics; 56 days following casting, the penetrability characteristics had improved modestly. However, Nidiffer et al. remarked that achieving sufficient durability with binary mixes is unlikely, and that over time concrete deterioration is likely due to poor resistivity. Based on laboratory work, they proposed a ternary concrete mixture to improve concrete durability and resistivity. Their formulation contains 50 percent cement, 30 percent slag, and 20 percent Class F fly ash, along with quantities of coarse and fine aggregates similar to the Class D mixtures they examined. Laboratory analysis indicated that ternary mixtures exhibited very low chloride ion penetrability within 28 days of casting and a higher

compressive strength than binary mixtures. No evident shrinkage cracking was visible in the ternary-formulation concrete a month following casting. The laboratory observations encompassed a relatively short period (56 days), however, the authors proposed a ternary blend specification (see Table 6 in Nidiffer et al., 2014) for use by the state in bridge construction. The blend contains less cementitious material than binary mixes. Because of this and the use of less water during mixing, it should undergo less shrinkage than binary concrete blends. Nidiffer et al. commented that other states could benefit from the use of ternary blends as they yield a finished concrete with greater durability that more effectively resists the chloride ion penetration. This finding meshes with an earlier analysis from Smith et al. (2004), who also observed that supplementary cementitious materials, and more specifically ternary mixtures, successfully reduced the infiltration of chloride and prolonged the corrosion initiation period. A key benefit of using a ternary mixture was the higher resistivity it conferred to the concrete — resistivity values were higher for ternary mixtures than for binary mixtures.

Several other studies are worth quickly highlighting, although not in the same level of detail as those presented above, given that they largely corroborate other researchers' findings. Sideris and Savva (2005) investigated how the addition of calcium nitrite impacts corrosion resistance and concrete durability, finding that addition improved the corrosion resistance of all the concrete formulations they tested, most of which contained additional supplementary cementitious materials, such as fly ash and natural pozzolans. Carbonation depth fell or remained unchanged, while it did not appear that it significantly affected concrete permeability. Choi et al (2006), based on laboratory experiments, confirmed that fly ash improves the corrosion resistance of concrete and reduces the corrosion rate. Fly ash decreased the permeability of concrete, which contributed to the improved resistance. Different admixtures affect concretes in sometimes disparate ways, making it imperative for practitioners to thoroughly research what the most likely effects are of their chosen admixture(s).

### **Key Takeaways**

- Research studies have confirmed that supplementary cementitious materials improve the density of concrete, reduce its porosity, and increase electrical resistivity.
- These properties delay the onset of corrosion, prolonging the service life of the bridge decks in which they are used.
- The use of some admixtures may slightly reduce the compressive strength of concrete. Decisions regarding which admixture to use should account for potential tradeoffs between increased corrosion protection and loss of compressive strength.
- Recent work on ternary concrete formulations, which contain cement plus two supplementary cementitious materials, indicate better performance than binary mixtures as they are less prone to cracking and more effectively block the passage of chloride ions. Engineers should investigate the blend of materials that is mostly likely to achieve the best performance in Kentucky's varied environmental conditions.

### **2.4 Surface and Crack Treatments**

This section reviews the performance of concrete sealants<sup>2</sup>, which are applied to the surface of concrete, or cracks within concrete, to slow the ingress of water and chloride ions. Although concrete formulations used for bridge decks should adequately protect against vehicle traffic and environmental conditions, sealants offer more uniform protection, safeguarding vulnerable portions of the bridge deck against corrosive agents (Attanayake et al., 2006). The American Concrete Institute recommends applying sealants to cracks greater than .007 inches (0.18 mm) in width or protecting them with a system designed to prevent the ingress of

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<sup>2</sup> Throughout this section, *sealant*, *sealer*, and *surface treatment* will be used interchangeably.

chloride ions. Accordingly, there are many situations in which concrete decks can benefit from the use of sealants.

The first portion of the review briefly discusses various sealants and how they work. Much of this discussion draws heavily from several recent articles and reports that provide useful overviews of sealant types and their long-term field performance (Freitag and Bruce, 2010; Johnson et al., 2009; Giannini et al., 2015; Pan et al., 2017a, 2017b)<sup>3</sup>. After covering the basic properties of sealants, the report discusses studies that have attempted to determine which sealants excel at slowing the ingress of chloride ions — and therefore the corrosion of reinforcing steel — in various environments. As in other sections, field studies are included as much as possible. Because the number of field studies is limited, several laboratory studies are discussed; despite imperfectly replicating field conditions, they are nonetheless instructive. Some reports and articles, in their assessments, explicitly mention the names of commercially available products, whereas others refer to generic types of sealants (e.g., siloxanes) and enumerate their chemical properties. If a piece mentioned brand names, they are included here.

Broadly, there are two categories of concrete surface treatments — organic and inorganic. Although organic treatments are used most frequently (e.g., linseed oil) they can have poor fire resistance, easily crack and detach from the underlying concrete, have a limited service life, and may be challenging to remove once their protective capacity diminish. Inorganic treatments have greater durability than organic materials, however, they have not been researched as thoroughly as organic sealants. Common inorganic surface treatments include sodium silicate, potassium silicates, lithium silicate, and fluosilicates. Pan et al. (2017a) grouped surface treatments into four categories based on their mode of operation: surface coatings, materials that produce a hydrophobic effect, pore-blocking treatments, and multifunctional surface treatments. Giannini et al. (2015) include a fifth category, which are thick surface treatments produced by combining mortar and a polymer matrix.

Once applied, surface coatings form a continuous polymer film that blocks substances from entering the concrete substrate. Examples of surface coatings include traditional polymer coatings (epoxy resins, acrylic, polyurethane, and linseed oil), polymer/-clay nanocomposite coatings, and cementitious coatings. Generally, the protective films formed by surface coatings are less than 1 mm thick and do not penetrate concrete pores. These treatments are often used for repair work and for preventing the ingress of additional moisture once water ingress begins. Concrete surfaces treated with polymers resist water due to the barrier effect produced by the coating. Polymer nanocomposite coatings are stronger than traditional polymers, and have greater tensile modulus, abrasion and heat resistance, and thermal stability. Adding nanoparticles to a coating may reduce gas permeability on its surface and lower flammability. Incorporating nanoparticles increases the length of diffusion pathways, with the result being that the rate of polymer degradation may decline. A frequently used type of concrete protection is cementitious coatings. Polymer modified coatings are manufactured using a blend of polymer, cement, and aggregate. Although their use for transportation structures has been limited, geopolymers have shown promise in terms of enhancing the durability of concrete.

Sealers that produce a hydrophobic effect (Giannini et al., 2015 refers to these as penetrant pore liners) penetrate the pores of concrete substrate. As they penetrate, they enlarge the contact angle. Without treatment, the contact angle can be small. Smaller contact angles produce a stronger molecular attraction between the water and concrete (de Vries and Polder, 1997). Once the angle exceeds 90 degrees, the surface becomes hydrophobic and inhibits water penetration. The treatments do not create a continuous membrane,

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<sup>3</sup> This is mentioned here to avoid numerous in-text citations, which would quickly become repetitive and distracting to the reader.

and thus water vapor can generally enter or exit the pores, letting the concrete breathe. Several factors influence the depth of penetration: 1) the type of sealant, 2) the concrete's water-to-cement ratio, 3) the concrete's initial moisture content, and 4) surface preparation of the concrete substrate (Dai et al., 2010). The most common penetrant pore liners are silane and siloxane, which are derived from silicone. Many commercial sealers contain a combination of silane and siloxane; combining them produces a sealant that has the most desirable features of both materials — silane increases penetration depth, improves water repellency, and enhances durability, while the siloxane component blocks pores and diminishes the sealant's volatility (Freitag and Bruce, 2010). Johnson et al. (2009) found that the most commonly used deck treatment in the Midwest US is silane, with solvent-based silanes being a more popular choice than water-based silanes because of their deeper penetration into the concrete substrate. While transportation agencies generally prefer solvent-based silanes because they release volatile organic compounds, environmental regulations can limit their use of the material. When selecting a formulation, transportation agencies should be attentive to the project context and the type and quality of concrete being used. Freitag and Bruce (2010) observed that silanes/siloxanes with small molecules offer reliable protection for high-quality concrete with a fine pore structure, whereas siloxanes with larger molecules may prove to be a sounder option for highly porous concrete.

Pore-blocking surface treatments include lithium silicate, calcium silicate, and sodium silicate. After they are applied, they work by blocking capillary pores in the concrete surface. This increases the hardness of the surface and reduces its permeability. Blocking pores reduces the movement of air, water vapor, and other liquids in concrete, which may reduce the infiltration of chloride and carbon dioxide (thereby delaying corrosion caused by chlorides or carbonation). Some research has indicated that silicate-based solutions, like those listed above, are the most effective treatments. The most widely used pore-blocking sealant is likely sodium silicate. One downside of silicate solutions, according to Freitag and Bruce (2010) is that they may not perform well in concretes made with supplementary cementitious materials (e.g., slag, fly ash, amorphous silica) because these materials reduce the amount of calcium hydroxide in the concrete's pore solution. They also warned against using silicate-forming treatments on cracked concrete (and uncracked concrete that may crack) because they may not penetrate sufficiently to protect the concrete that has been exposed by cracking.

The final category of sealants is multifunctional surface treatments, which are named as such because they offer at least two modes of protection. Most of the products in this category have been developed in recent years and do not fit into the other classifications discussed. Treatments included in this group are silane-clay nanocomposites (SCN), ethyl silicate, and super-hydrophobic paper sludge ash coating. SCNs produce a hydrophobic effect while modifying the microstructure of the underlying concrete, lowering the concrete's permeability and reducing the infiltration of liquids and gasses. The clay reduces surface roughness, which means less surface area is directly exposed to ambient environmental conditions and to potentially severe conditions. Another multifunctional treatment, ethyl silicate, is an alkoxy silane compound that, when applied, forms a silica gel that fills the concrete's pore networks. It potentially offers an environmentally friendly method of protecting concrete, however, it has several downsides — a slow reactive rate, potential cracking during shrinkage and drying, and limited ability to deter the effects of carbonation.

Many factors influence the performance of surface treatments. The first is air permeability. Greater air permeability increases the carbonation rate, which can precipitate corrosion. However, it is important that a completely impermeable layer not sit atop the concrete. Lacking permeability, concrete is unable to breathe, which may lead to a build-up of water beneath the surface and intensify the damage and cracking that results from freeze-thaw cycles. For many polymer coatings, air permeability is near zero, which is one

of their principal drawbacks. Pan et al. (2017a) noted that studies have demonstrated silane and siloxane do not significantly affect air permeability and therefore are not resistant to the ingress of carbon dioxide. Bonding strength is the second factor that affects performance. To achieve their intended effect, surface treatments must adhere well to the concrete substrate — the bonding strength should not be less than 203-254 psi (1.4–1.75 MPa). The strength of adhesion is the result of the chemical properties of the coating and primer, method of application, the quality and condition of the substrate, and the surface roughness of the substrate. The next variables to consider are penetration depth and coating thickness. Pore penetrating sealers must penetrate as deeply as possible to offer long-term protection and durability. Some of the factors which influence the penetration depth of sealants are molecular size and viscosity, solvent type, properties of the concrete substrate such as porosity and saturation degree, reaction time, reaction rate, and the thickness of the application. Table 3 contains a full list, which is reproduced from Attanayake et al. (2006).

**Table 3** Influences on the Depth of Sealant Penetration

<b>Concrete</b>	<ul style="list-style-type: none"> <li>• Pore size</li> <li>• Pore distribution</li> <li>• Moisture</li> <li>• Crack width and density</li> <li>• Tortuosity of pore structure</li> <li>• Pore surface topology</li> </ul>
<b>Penetrating Sealants</b>	<ul style="list-style-type: none"> <li>• Viscosity</li> <li>• Contact angle</li> <li>• Surface tension</li> <li>• Molecular size</li> <li>• Molecular weight</li> </ul>
<b>Environment</b>	<ul style="list-style-type: none"> <li>• Temperature</li> <li>• Relative humidity</li> <li>• Application pressure</li> <li>• Sealant reactivity with substrate</li> </ul>

For coatings that do not penetrate the surface, the overriding consideration should be coating thickness. The fourth performance factor to examine is cracking resistance. If a treatment cannot heal cracks or provide sufficient resistance against cracking, its ability to function as a barrier will be compromised quickly. Lastly, the substrate properties and methods used to apply a sealer impact its performance. The effectiveness of any treatment will be influenced by characteristics such as the age and water content of the concrete substrate, treatment method (e.g., spraying, brushing, flooding), and the amount of sealer applied. A positive relationship between the performance of the surface treatment and concrete porosity has been detected, as concrete with higher porosity encourages the deeper penetration of sealers (Baltazar et al., 2014).

Before discussing individual studies, the report briefly summarizes the findings of several review articles that have attempted to document the performance of various sealers and draw general conclusions. Some of these pieces refer to individual research articles and reports. To avoid confusion over questions of attribution, the original articles are cited during the discussion of their content.

Pan et al. (2017b) offer extensive commentary on sealant performance. As they note (and which should be kept in mind moving forward), it is unwise to directly compare the results from different research studies because of the wide variety of testing methods that are in use. Overall, it appears that surface treatments are effective in limiting chloride penetration, however, the effectiveness of individual products is contingent on the sealant type and the environment it is applied in. Generally, except for silane and siloxane, all surface treatments can reduce the rate of carbonation. Silane and siloxane control the moisture content of concrete

substrate, however, they do not reduce the air permeability, and therefore the diffusivity of carbon dioxide. Organic polymer coatings are generally the most effective at inhibiting carbonation. Many surface treatments increase the ability of concrete to resist abrasion. Epoxies confer the greatest protection in this regard while silanes offer more modest protection. Similarly, most surface treatments can mitigate the effects of freeze-thaw cycles, particularly in very cold environments. For example, if silane is used, two primary factors influence its effect on resistance to freeze-thaw cycles — the concrete's initial moisture content (if initially dry, silane bolsters resistance) and whether the water pressure produced by freezing and thawing exceeds the hydrophobic forces inherent to the silane. Silane also offers additional protection if deicing agents are in use. Just as surface treatments reduce carbonation and the effects of abrasion, they have a relatively good track record of extending the service lives of reinforced concrete. However, the results have been uneven; several researchers have demonstrated that the application of silane reduces the corrosion current and delays the onset of corrosion in uncracked concrete. Other researchers have shown that silane may accelerate corrosion in cracked concrete (Tittarelli and Moriconi, 2010). Indeed, hydrophobic treatments are not the best choice if cracks are present because they may promote additional cracking by increasing the corrosion current. The additional cracking is a consequence of oxygen diffusing more quickly than it otherwise would through unsaturated pores, which are created by the hydrophobic effect. Pan et al. (2017b) cautioned readers about the potential issues that arise with surface treatments as they age and degrade. As degradation takes place, there is a tendency for the diffusion rate of chloride ions to exceed the rate of diffusion in untreated concrete. There are two reasons for this. First, significant amounts of chloride ions accumulate on the protected surface. As this protection breaks down, it opens pathways for the chloride ions, which may quickly descend into the concrete substrate. Second, before coatings begin to fail, they trap water, which leaves the concrete matrix saturated and potentially more vulnerable to chloride ingress.

Johnson et al. (2009) authored a comprehensive review of sealants, summarizing several previous studies, both laboratory and field investigations, which we discuss in turn.

Whiting (1992) studied the performance of three treatments in a laboratory — 1) a water-based silane with 40 percent solids, 2) a solvent-based silane with 40 percent solids, and 3) a solvent-based siloxane with 20 percent solids. Under dry conditions, the siloxane was the best performer, while silanes were more effective on moist concrete specimens. Concrete treated with the solvent-based silane (40 percent solids) displayed chloride contents between 9 and 36 percent lower than the water-based silane.

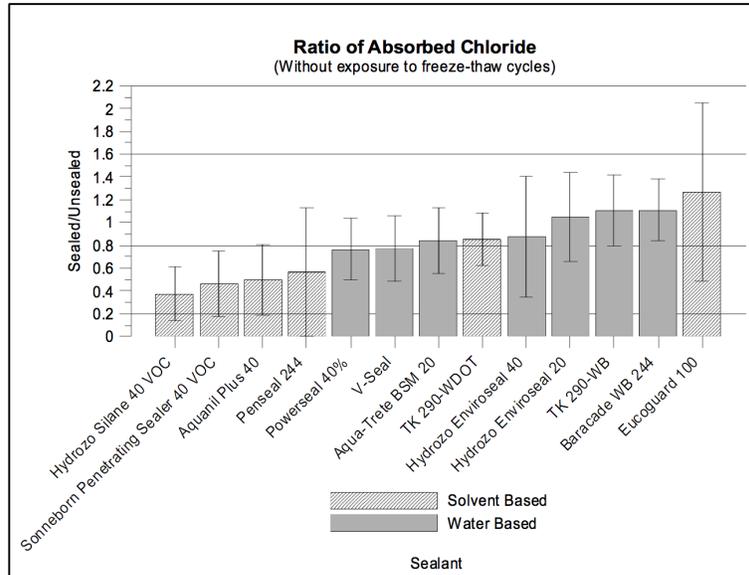
Wright et al. (1993) established that siloxane and linseed oil are more effective at reducing chloride infiltration than silane. And specimens treated with just linseed oil significantly outperformed siloxane. Ultraviolet radiation exposure, however, can undermine the protective capacity of linseed oil. Weyers (1995) found that siloxane and silane performed better than epoxies in blocking chloride ions. On the other hand, Hagen (1995) found that epoxy coatings reduced chloride ingress more effectively than most of the silanes and siloxanes included in the study. In the field component of his investigation, Wright et al. (1993) found that portions of a bridge treated with linseed oil contained less chloride than sections protected by silane and siloxane. The study also indicated that siloxane protected highway surfaces more effectively than silane, whereas silane outperformed siloxane on local roadways. Although there was no clear reason for the difference, Wright speculated that it may have been due to the siloxane having shallower penetration on highway applications.

Hagen (1995) noticed there was little correlation between lab and field results. The reductions in chloride observed in field settings were considerably less than those documented in the lab. Also, there were clear year-over-year declines in the field performance of all sealants. Based on this observation, Hagen concluded that exposure to freeze-thaw cycles and vehicle-induced abrasion negatively impacted sealant performance,

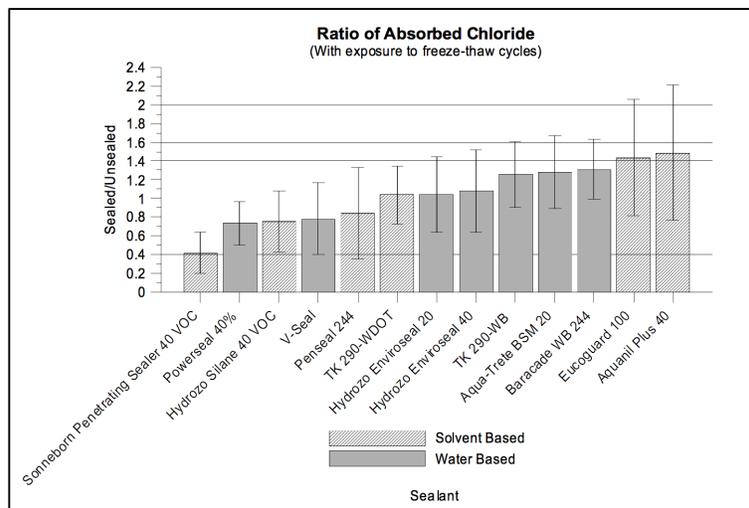
and therefore explained the discrepancy between laboratory and field results. There were also no clear performance trends with respect to silanes versus siloxanes, solvent-based versus water-based sealers, or the solids content. Silanes and siloxanes were clearly better performers than thermoplastic emulsions and sodium-silicate surface coatings. Epoxies did not exhibit good performance. Hagen ordered the best performing sealants as follows: 1) water-based silane with 40 percent solids, 2) siloxane/silane mixture with 40 percent solids, and 3) solvent-based siloxane with 15 percent solids. Smutzer (1993), like Hagen (1995) noted a large discrepancy between the field and laboratory performance of sealants. In the field, silanes were associated with the most significant chloride reductions, followed by epoxies and siloxanes. However, the performance of the epoxies and siloxanes were not statistically distinguishable from one another. As Wright (1993) observed, Smutzer (1993) found that a sealant's ability to protect against chloride ingress waned over time. These results underscore an important point that should be kept in mind when comparing field and laboratory studies — laboratory studies tend to indicate much larger reductions in chloride ingress than do field studies because they are unable to simulate the ambient environment bridges are located in.

As part of an exhaustive discussion of surface treatments, Freitag and Bruce (2010), based on previous research, commented on the performance of silanes, siloxanes, and sodium silicate-based sealants. Laboratory and field studies alike have repeatedly found that silanes can reduce water absorption while not diminishing the breathability of concrete. Conversely, there is more of a mixed picture with respect to carbonation, with silanes reducing the amount of carbonation in some cases, but being associated with increases in others. Sodium silicate-based sealants appear to have a positive effect on carbonation, routinely reducing it, however, they are less effective at preventing the ingress of chloride and the occurrence of corrosion. Many studies have demonstrated the efficacy of silane and silane-siloxane treatments at significantly reducing the infiltration of chlorides. Although these products can withstand intermittent exposure to chlorides (e.g., salt spray in marine environments, deicing materials), they are less resistant when continuously immersed in water with high chloride levels. While this is probably irrelevant for most bridge structures, it may be a salient consideration for structures located in particularly harsh environments. Consistent with findings that silane and silane-siloxane treatments limit the ingress of water and chloride ions, they also dampen corrosion rates. However, the moisture content of concrete and the amount of cracking may offset the effects of sealants. While silane and silane-siloxane surface treatments are generally quite durable, they must be reapplied eventually. Studies quote a wide range of reapplication intervals, from 5 to 20 years. Reapplication intervals are contingent on the exposure conditions and product selected.

Pincheira and Dorshorst (2005) used laboratory tests to understand the performance of bridge deck and crack sealers. Ponding and chloride ion tests were used to evaluate sealants' performance when exposed to chlorides. They studied 13 commercially available deck products, encompassing both water- and solvent-based sealants. For specimens not subjected to freeze-thaw cycles, in general solvent-based products outperformed water-based sealants. Figure 3 summarizes the ratio of absorbed chloride for specimens not exposed to freeze-thaw conditions. The ratio compares the performance of sealed concrete to unsealed concrete. As the chloride ratio values approach one, the chloride protection from the sealant decreases. Figure 4 summarizes the chloride ratio values for specimens exposed to freeze-thaw cycles. Depth penetration tests showed that the average penetration for sealants ranged between 0.06 and 0.15 inches (1.4 mm and 3.8 mm). A critical point to note, however, is that on any deck the penetration depth will have considerable spatial variability.



**Figure 3** Ratio of Absorbed Chlorides for Tested Sealants Not Exposed to Freeze-Thaw Cycles (Pincheira and Dorshorst, 2005)



**Figure 4** Ratio of Absorbed Chlorides for Tested Sealants Exposed to Freeze-Thaw Cycles (Pincheira and Dorshorst, 2005)

Overall, silanes tended to penetrate more deeply than other materials. None of the sealers tested penetrated to the depths claimed by their manufacturers. Consistent with research conducted elsewhere, there was a positive correlation between penetration depth and the chloride absorption ratio. Based on their observations, Pincheira and Dorshorst grouped the tested sealers into three groups. Group I showed the best performance, Group II sealers exhibited moderate performance, while Group III displayed the worst performance. Figure 5 shows their rankings.

Sealant	Ratio of Absorbed Chloride		$CI_{content}^{WisDOT}$		Average Depth of Penetration (mm)	Performance Group Category
	Not Exposed to F/T Cycles	Exposed to F/T Cycles	Not Exposed to F/T Cycles	Exposed to F/T Cycles		
Sonneborn Penetrating Sealer 40 VOC (6)*	0.46	0.42	0.46	0.42	3.1	I
Hydrozo Silane 40 VOC (9)	0.37	0.75	0.42	0.58	3.8	
Powerseal 40% (11)	0.77	0.74	0.66	0.58	1.9	II
V-Seal (2)	0.77	0.78	0.65	0.74	1.7	
Penseal 244 (8)	0.57	0.85	0.54	0.78	2.7	
TK 290-WDOT (4)	0.86	1.04	0.75	0.83	1.8	
Hydrozo Enviroseal 40 (12)	0.88	1.08	0.73	0.82	2.1	
Aqua-Trete BSM 20 (3)	0.84	1.28	0.74	0.98	2	
TK 290-WB (5)	1.11	1.26	0.89	0.96	1.5	III
Hydrozo Enviroseal 20 (10)	1.05	1.04	0.84	0.8	1.4	
Baracade WB 244 (7)	1.11	1.31	0.89	0.99	2.1	
Eucoguard 100 (13)	1.27	1.44	0.88	1.09	1.8	
Aquanil Plus 40 (1)	0.5	1.49	0.5	1.12	2.5	

Figure 5 Rankings of Tested Sealers from Pincheira and Dorshorst (2005)

During a wide-ranging laboratory investigation, Almusallam et al. (2003) studied the performance of five coating types — acrylic, polymer emulsion, epoxy resin, polyurethane, and chlorinated rubber. For each coating type, the researchers obtained samples from two manufacturers for testing. Following the procedures specified by ASTM C 1202, sealants were applied to concrete discs and allowed to set. Specimens were then immersed in a solution of 5 percent NaCl for three months. While the chloride permeability of all coatings rated as either negligible or very low, there were differences in their performance. The chloride permeability of polyurethane, chlorinated rubber, epoxy, or acrylic coatings was approximately 10 percent of that measured in untreated concrete. Polymer emulsion coatings exhibited slightly worse performance, with chloride permeability being approximately 20 percent of that found in untreated concrete. A key point to keep in mind is that a coating's permeability is directly related to the porosity of the film it forms on a concrete surface. At lower porosities, a lower charge passes through the film. Coatings such as polyurethane and epoxies are particularly resistant to chloride ions because they are solvent-based and leave a tough film after curing. The water absorbed by the acrylic, chlorinated rubber, polyurethane, and epoxy coatings ranged from 0.23 percent to 1.85 percent. In comparison, the weight gain for polymer emulsions ranged from 3.3 to 3.4 percent (cf. untreated concrete, which experienced a 5 percent increase in weight). Based on their findings, Almusallam et al. observed that when selecting a sealant, transportation agencies must be attentive to the service conditions it will be exposed to. In settings where chloride is abundant, polyurethane, chlorinated rubber, or epoxies are the most appropriate choices, whereas locations typified by high rainfall and humidity are better served with epoxies, chlorinated rubber, or acrylics.

Al-Zahrani et al. (2002) tested four surface treatments to determine which exhibited the best performance with respect to water permeability, chloride permeability, pull-off strength, and accelerated reinforcement corrosion. Included among the four treatments were: 1) a cement-based polymer-modified coating, 2) a cement-based coating, 3) a polyurethane-based coating system, and 4) an epoxy-based coating system. Specimens underwent tests, including repeated exposure to wetting/drying cycles and heating/cooling

cycles, ASTM C 1202 to assess chloride permeability, ASTM D 4541 to evaluate pull-off strength, and immersion in a 5 percent NaCl solution. The cement-based coating had poorer durability than the polymer- and epoxy-based coatings. Further, the polymer-modified, polyurethane-, and epoxy-based coatings were the most effective at preventing water absorption. After specimens underwent repeated heating/cooling cycles, the polymer-modified and epoxy-based coatings showed a diminished ability to prevent water absorption. The polymer-modified and polyurethane-based coatings provided the best resistance against corrosion by limiting the ingress of chloride ions. Al-Zahrani et al. characterized the polyurethane-based coating system as the best all-around performer. A secondary argument they put forward was that water absorption capacity is a simple metric to predict how well a coating system will protect against corrosion. Conversely, Calder and McKenzie (2009), after testing the long-term field performance of bridge decks treated with a silane-siloxane sealant, concluded that sealants offered modest gains in protection compared to deck surfaces treated with silicate-based products or left untreated. They also found that surface roughness, both at the time of sealant application and during testing, can significantly influence water absorption tests. On this basis, they recommended using the amount of chloride ingress as primary metric to assess the effectiveness of a surface treatment.

Several researchers have examined sealants' ability to prevent water absorption, chloride ingress, and corrosion in aggressive (e.g., marine) environments. For example, Moradillo et al. (2012) studied the performance of concrete structures in the Persian Gulf. They observed degradation of coatings over time, and found that epoxy, polyurethane and aliphatic acrylic coatings offered the best protection against corrosion. Dai et al. (2010), after Tittarelli and Moriconi (2008) found that silane-based treatments did not prevent corrosion in cracked concrete, undertook a study that sought to determine how cracking impacts sealant performance. The experiment used cracked and uncracked concrete specimens with a water-to-cement ratio of 0.68 and tested six treatments: four silane-based products (including one silane-siloxane liquid) and two sodium silicate-based products. One of the silane treatments came in gel form, another was a cream, and the others were liquids. Specimens were cyclically exposed to salt water spray over the course of a year. Each day, specimens were sprayed with salt water — in an outdoor environment — for 8 hours and underwent 16 hours of drying time. Overall, the silane-based products significantly reduced water absorption, while the sodium silicate-based treatments were much less effective. Water resistance and performance correlated with penetration depth. The more deeply a sealant penetrated, the better its performance tended to be. Silane-based treatments that penetrated at least 5 mm beneath the surface prevented corrosion, whereas the sodium silicate-based treatment and a silane-siloxane product did not reduce corrosion in uncracked concrete. In cracked specimens, silane prevented corrosion in areas where it penetrated to a depth of at least 5 mm. When the silane-based and silane-siloxane treatments penetrated up to 5 mm in cracked specimens they reduced the rate of corrosion but did not inhibit it entirely. The silanes in gel and cream form exhibited the best overall performance. The sodium silicate-based pore blockers failed to suppress water absorption and chloride ingress, making them poor choices for protecting reinforced concrete. Dai et al. observed, as well, that within each specimen there was considerable unevenness in the depth of chloride penetration, a fact which they attributed to the spatial variability in concrete microstructures (cf. Pincheira and Dorshorst [2005]).

Although nearly half of state DOTs use it to seal bridge deck cracks, there is little published research on high-molecular-weight methacrylate, a type of gravity-fil sealer (HMWM). HMWM is an adhesive made of methacrylate monomers. It has been used to seal deck cracks since at least the early-1980s. Because of their low viscosity and surface tension, HMWMs effectively penetrate cracks (Rahim et al., 2010, Liang et al., 2014). However, as Hasenkamp et al. (2012) observed, HMWMs, because of their low viscosity, readily flow away from inclined and vertical surfaces. As such, their applications should be restricted to horizontal surfaces. Rahim et al. (2010) provided a comprehensive review of its use. Few studies have looked at its

ability to improve resistance against water and chloride, but most have examined its properties and ability to successfully fill cracks. For example, a study of Virginia bridge decks on which HMWM monomers had been applied filled, on average, approximately 95 percent of cracks' widths; cores extracted from a bridge deck in San Antonio revealed that HMWM, where used, filled approximately 60 to 80 percent of cracks. A study of eight bridge decks in Kansas indicated that HMWM, among other sealants, did not effectively block the ingress of chlorides. However, Rahim et al. (2006) recommend applying HMWM at 3–6 month intervals following bridge construction to lower the risk of chloride penetration, and Liang et al. (2014; see below) commented favorably on the performance of HMWM. In settings where deicing chemicals are not used or where there is no ambient chloride, applying HMWM to narrow cracks may improve structural bond strength and flexural strength.

Liang et al. (2014) studied the performance of four surface treatments on a Colorado bridge: 1) HMWM, 2) super low viscosity, low modulus epoxy 3) low viscosity, high modulus epoxy, and 4) silane. Skid resistance, temperature variation, moisture fluctuations, and chloride concentrations profiles were measured. Immediately following application, all the sealers had lower skid resistance compared to a bare, untreated bridge deck. After one year, the bridge section treated with silane exhibited skid resistance comparable to that of the bare deck. Although the sealers created a pronounced increase in temperature gradients, this increase was small, not large enough to damage the concrete. All the sealers were effective in preventing the movement of moisture into and out of the bridge deck. In terms of chloride resistance, the HMWM and both epoxies, at least initially, blocked the ingress of chloride ions. The silane was less effective. After a year of observations, it became apparent that the epoxies' performance had degraded and did not resist chlorides as successfully. HMWM, however, maintained its durability and continued to perform well. Three-and-a-half years after the treatments were applied, all the sealers offered some level of protection. However, HMWM exhibited the best overall performance.

Pritzl et al. (2015) conducted a follow-up investigation of nine Wisconsin bridges that had received various treatments to inhibit corrosion, including supplementary cementitious materials and penetrating sealers. Some of the bridges were treated only with admixtures, others with sealers only. At least two bridges had the sealer periodically reapplied to ensure ongoing protection. The long-term study examined bridge performance after 12-16 years of exposure. The sealer applied to bridges was a low-viscosity oligomeric organosiloxane material (i.e., a tri-siloxane sealer). Compared to untreated decks, bridges on which the tri-siloxane sealer was applied and reapplied held the ingress of chlorides in check by reducing the effective surface concentrations of chloride. The decks in question were not sealed immediately following their construction. Rather, they were left untreated for several years and then sealed. The chloride profiles of two additional bridges where sealer was applied immediately after construction but not reapplied in subsequent years were similar to untreated bridges. Pritzl et al. suggested that applying sealers once construction has concluded and reapplying them later works to maintain their protective capacity and reduce the infiltration of chloride. A single application following bridge construction is not sufficient to minimize the effects of chloride over the long-term.

Currently, the Alabama Department of Transportation applies epoxy sealers to bridge surfaces to protect them against carbonation and corrosion. To determine whether the state is using sealants effectively, Giannini et al. (2015) investigated the performance of five surface treatments, which were applied to three concrete mix designs. The three mix designs were as follows: 100 percent Portland cement with a water-to-cement ratio of 0.5 (MD1), 100 percent Portland cement with a water-to-cement ratio of 0.4 (MD2), and a mix containing 80 percent Portland cement and 20 percent Class F fly ash (MD3), with a water-to-cement ratio of 0.4. The waterproofing performance of specimens was assessed before and after sandblasting, which was used to simulate traffic wear. To understand sealants' performance in the face of chloride intrusion,

specimens were immersed in a 15 percent solution of NaCl. Figure 6 summarizes the chemical properties and makeup of each sealer.

Initial waterproofing tests (i.e., before sandblasting) indicated that Sealers D and E performed best on average across the three concrete formulations, whereas Sealer A fared the worst. Because grinding and sandblasting compromised their protective abilities, the post-abrasion performance of all sealants declined, although Sealers C and D experienced the most significant drop-offs in waterproofing capacity. Following immersion in the NaCl solution Sealers C and D both had acceptable performance for MDs 1 and 2, but did not perform satisfactorily for MD 3. Sealer E hit the performance threshold for MD 2, but did not offer adequate protection on MDs 1 and 2. Sealers A and D failed for all the concrete mixtures. Overall, Giannini et al. found that Sealers C, D, and E outperformed Sealers A and B, with Sealer E exhibiting the best overall performance. It consistently prevented the ingress of chloride and water. They found Sealer C to be vulnerable to cracking, while Sealer A had the worst overall performance. They cautioned, however, that Sealer A’s poor performance may have been attributable to not following the manufacturer’s application instructions. Nonetheless, they noted that its thinness would likely make it vulnerable to disturbance when exposed to vehicle traffic.

**Table 3.1 The five sealer products evaluated in this study**

Product	Composition	Viscosity (cP)	% Solids	Mixing Ratio	Recommended Application Rate ft <sup>2</sup> /gal (m <sup>2</sup> /L)	Recommended Method of Application
Sealer A	One-Component Sodium Silicate	N/A	~0	N/A	150 – 200 (3.7 – 4.9)	Spray or Flood
Sealer B	Two-Component Epoxy	10 – 30	60	1:1	100 – 300 (3.2 – 7.4)	Flood
Sealer C	Two-Component Epoxy	40	75	1:1	150 – 200 (3.7 – 4.9)	Flood
Sealer D	Two-Component Epoxy	85	100	1:2	150 – 200 (3.7 – 4.9)	Flood
Sealer E	Two-Component Epoxy	105	100	1:2	150 – 175 (3.7 – 4.3)	Flood

**Figure 6** Sealants tested by Giannini et al. (2015)

In a broad review of penetrating sealants, Attanayake et al. (2006) prescribed steps for selecting an appropriate concrete sealant. In addition to explaining how penetrating sealers work, they recounted the procedures necessary to clean a deck surface prior to the application of a sealant. Before applying penetrating sealers decks should be power washed and allowed to dry for at least two days. In wetter or more humid conditions, additional drying time may be necessary. If the environment will not permit drying within a short time period, agencies may want to consider the use of dustless abrasive shot blasting. While having a clean and dry surface is critical for successfully applying sealants, the concrete substrate should retain some moisture as this promotes the chemical reactions necessary for sealants to establish protection.

Figure 7 depicts Attanayake et al.’s flow chart of the recommended decision-making process transportation agencies should consider using when choosing a sealer. Along with this stepwise process, they described several factors to consider when selecting a sealer. At the outset, it is important to inspect the original deck to ascertain whether it is new construction or the result of remedial work, the condition of the deck, previous surface treatments, and the level of surface contamination. From an environmental perspective, agencies

should be attentive to the prevailing atmospheric conditions as well as to the presence of moisture and pollutants. Third, it is critical to investigate sealers' durability. This entails identifying their penetration depth, resistance to ultraviolet radiation and alkalis, characteristic reactivity with hydrated cement paste, and durability in the face of weathering. Next, the level of protection afforded by individual sealers should be examined, including how well they absorb water and chlorides, their water vapor transmission, and resistance to scaling produced by deicing materials. With respect to service performance, it is critical to understand the level of skid resistance a sealer provides. The conditions under which sealants can be applied warrant study as well. Important variables to consider here include steps required to prepare the concrete surface, method of application, a sealant's tolerance of substrate moisture and temperature dependency, and the ease of accessing the site and potential lane closures. Lifecycle costs are also an important consideration, including the unit cost, the number of applications needed to protect concrete, and the cost of labor and maintenance.

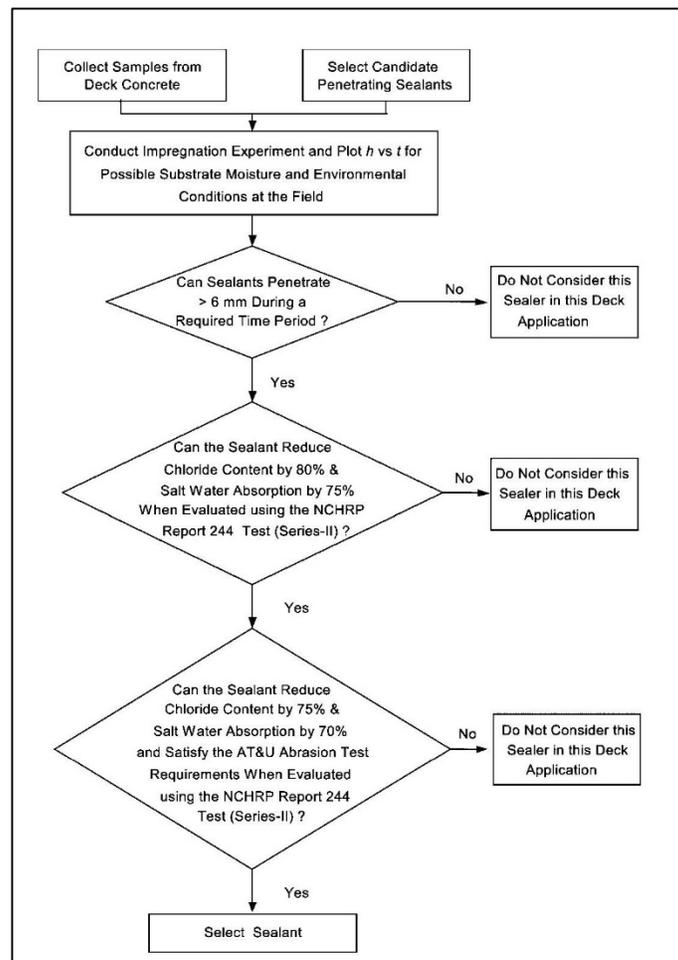


Figure 7 Decision-Making Procedure for Selecting Penetrating Sealants (Attanayake et al., 2006)

### Key Takeaways

- Surface treatments generally offer added protection to concrete bridge decks, which can delay the onset of corrosion and deterioration. The presence of cracking can undermine the performance of some treatments.
- Silanes and siloxanes are the most common form of surface treatment, and most studies have demonstrated they perform better than other materials such as silicates and epoxies.

- The performance of a sealant is contingent on many factors, such as the product used, the environment a bridge is located in, concrete formulation, concrete structure and condition, and traffic levels.
- Numerous studies have demonstrated a strong positive correlation between sealant performance and depth of penetration.
- Some sealants may increase carbonation. However, this may not automatically translate into increase corrosion if there are low moisture levels.
- Most sealants will need to be reapplied at 5–20 year intervals. Some researchers argue they may extend the service lives of bridges up to 50 years with proper maintenance.
- Laboratory studies tend to result in more optimistic assessments of surface treatments than field studies because they cannot replicate real-world conditions.
- Sealants in gel or cream form appear to be more effective than liquid sealers because they adhere to and penetrate the deck surface more deeply.

## 2.6 Multiple Corrosion-Inhibition Systems

As the previous sections revealed, researchers have often investigated the performance of anti-corrosion treatments (e.g., different varieties of steel protection, concrete admixtures, and sealants) individually. Several of the papers cited previously mentioned the utility of combining multiple treatments to delay the onset of corrosion. This section extends these discussions by reporting on studies that have explicitly investigated the performance of multiple corrosion-inhibition systems. Following Darwin et al. (2014), a multiple corrosion-inhibition system is one that incorporates two or more two treatments (e.g., ECR plus a concrete admixture such as fly ash or silica fume). Because relatively few studies have investigated the long-term performance of multiple systems, either in the field or laboratory, this section is comparatively brief.

Berke and Hicks (1998) used a laboratory study to investigate the combined effect of ECR and calcium nitrite on corrosion rates in high-quality concrete. Experimental treatments had water-to-cement ratios of 0.40 and 0.45. A 30 percent calcium nitrate solution was mixed into some specimens, with dosage rates ranging from 2.7 to 5.4 gallons/yd<sup>3</sup> (13.5 to 27 l/m<sup>3</sup>). Specimens with uncoated black steel were used as a control, while some of the bars with epoxy coatings were deliberately damaged to simulate what occurs during installation. Specimens were cast in two forms: lollipops and mini-beams. Concrete lollipops were submerged to a depth of ~3 inches (75 mm) in a 3 percent NaCl solution, while mini-beams were cyclically ponded with a 3 percent NaCl solution. The experiment's duration was seven years. In the lollipops, the beneficial effects of calcium nitrite were evident. After five years, lollipops with just calcium nitrite outperformed those with damaged epoxy coatings and performed comparably to undamaged ECR. The chloride content of lollipops ranged from 20.6 to 25.3 lb./yd<sup>3</sup> (12.2 to 15 kg/m<sup>3</sup>). No specimens with calcium nitrite corroded. After seven years, the chloride contents were between 26.9 and 38.7 lb./yd<sup>3</sup> (16 and 23 kg/m<sup>3</sup>). Significant disbondment was observed, and the researchers attributed the rapid increase in corrosion activity to corrosion spreading beneath the epoxy coatings. Mini-beam specimens containing calcium nitrite also performed well, with no signs of corrosion visible despite the chloride values exceeding the threshold at which corrosion typically initiates. Berke and Hicks remarked that using ECR and calcium nitrite in tandem may produce significant benefits. In all cases, ECR outperformed black steel housed in a concrete mixture that did not include calcium nitrite. Even for flawed ECR, the addition of calcium nitrite will enhance its performance and delays corrosion. Calcium nitrite's primary benefit lies in its ability to increase the chloride threshold at which corrosion begins. However, Berke and Hicks cautioned that the performance of calcium nitrite is contingent upon the amount and quality of concrete cover.

In a series of articles and reports, Cusson et al. (2008; Cusson and Qian, 2007; Qian et al. 2008) reported on the findings of a long-term study of nine corrosion-inhibiting systems that were applied to a bridge in Montreal, Quebec, Canada. As they noted, long-term field investigations are often more valuable sources of information than long-term laboratory studies because they are exposed to ambient meteorological rhythms, the effects of deicing salts, and traffic. One caveat to keep in mind is that the studies did not look at bridge deck performance. Their focus was on reinforced barrier walls. The main reinforcement was located at a depth of ~ 3 inches (75 mm), although ladder bars were present at depths of ~ 0.50, 1.00, 1.50 and 2.00 inches (13 mm, 25 mm, 38 mm, and 50 mm). Table 4 lists the properties of each corrosion-inhibiting system used. Each system was applied to barrier wall approximately 37 yd. (34 m) in length. The walls were cast in fall 1996 and measurements commenced in June 1997. After being cast, researchers found transverse cracking on the barrier walls, which they attributed to uncontrolled thermal effects and autogenous shrinkage, which often occurs when concrete formulations with a high cement content and low water-to-cement ratio are used. Cusson et al. (2008) discussed performance after five years, while Cusson and Qian (2007) reported on performance after 10 years.

**Table 4** Corrosion-Inhibiting Systems (Cusson et al. [2007, 2008] Studies)

Corrosion-Inhibiting System	Description
<b>Control</b>	<ul style="list-style-type: none"> <li>Carbon-steel reinforcement</li> </ul>
<b>Epoxy</b>	<ul style="list-style-type: none"> <li>Epoxy-coated reinforcement</li> </ul>
<b>A</b>	<ul style="list-style-type: none"> <li>Rebar coating (water-based liquid blend, Portland cement, fine silica sand)</li> </ul>
<b>B</b>	<ul style="list-style-type: none"> <li>Organic concrete admixture (alkanolamines)</li> <li>Rebar coating applied only on anchor bars from slab (water-based epoxy, Portland cement)</li> </ul>
<b>C</b>	<ul style="list-style-type: none"> <li>Organic/inorganic concrete admixture (amine derivatives, sodium nitrite)</li> </ul>
<b>D</b>	<ul style="list-style-type: none"> <li>Rebar coating (water-based epoxy, cementitious components)</li> </ul>
<b>E</b>	<ul style="list-style-type: none"> <li>Organic concrete admixture (amines and esters)</li> </ul>
<b>F</b>	<ul style="list-style-type: none"> <li>Organic concrete admixture (alkanolamines and amines, and their salts with organic/inorganic acids)</li> </ul>
<b>G</b>	<ul style="list-style-type: none"> <li>Organic concrete admixture (alkanolamines, ethanolamine, and phosphate)</li> <li>Rebar coating applied only on anchor bars from slab (water-based epoxy, Portland cement)</li> </ul>
<b>H</b>	<ul style="list-style-type: none"> <li>Inorganic concrete admixture (calcium nitrite)</li> </ul>

After five years, half-cell potential across all treatments had undergone the sharpest changes along the top bar (i.e., nearest to the surface), with Treatments D and H producing the lowest corrosion rates on the first and second bars. Treatments A and G were associated with the least-negative half-cell potential values. Treatments A and B were linked to the smallest overall decrease in half-cell potential. Half-cell potentials for the epoxy treatment were more positive than all other treatments after one year, but trended negative thereafter, likely due to the deterioration of epoxy and the beginning of localized corrosion. The most aggressive corrosion rates were detected at locations where there were cracks in the concrete. At depths of ~1 to 2 inches (25 to 50 mm), the chloride content of all barrier walls exceeded the corrosion initiation threshold of 0.1 percent by weight of concrete, while at depths of ~2 to 3 inches (50-75 mm), chloride content did not break the threshold. Chloride ions penetrated most slowly in areas with Treatments E and H. Treatment G performed well in this respect for the first year, but in the following years it showed no

reduction in chloride ingress compared to systems without sealants. Despite the variations in performance, there were no significant differences between the control treatment and walls treated with corrosion-inhibiting systems. Cusson et al. attributed this to the relatively short duration of the study, as corrosion usually does not begin in uncracked concrete within the first five years of environmental exposure. Based on their observations, they concluded that Treatment H had the best performance overall. Treatments B, E, and G were at the greatest corrosion risk, with the highest corrosion rates on ladder bars with 13 mm of cover.

Cusson and Qian (2007) discussed performance of the same barrier walls after 10 years of service. Irrespective of treatment, all barrier walls had chloride levels below or near the threshold value at depths of ~ 2 to 3 inches (50 to 75 mm). Localized pitting corrosion was observed in areas where the concrete had cracked. Likewise, corrosion was active on the bars near the surface (i.e., at depths of ~ 0.50 in (13 mm)) and there was evidence of damage on wall surfaces. Treatments H and F exhibited the least negative half-cell potentials at the ~1 inch (25 mm) level (greater than or equal to -550 mV), meaning they were at the lowest risk of corrosion. Nondestructive testing at the ~1 inch (25 mm) level indicated that Treatment H continued to have the best overall performance, followed by Treatments B, E, and F. Cusson and Qian argued that even a 10-year field observation study was too short to adjudicate a clear winner. Additional years of observation and evaluation are needed to understand the long-term performance of various treatments, which reaffirms the challenge of making definitive judgments about the efficacy of systems based on compressed field or laboratory studies. They argued that the use of corrosion-inhibiting systems should not be used as the primary means to fortify reinforced concrete against corrosion. The systems should be viewed as a second line of defense, and cannot operate as a substitute for good, high-quality concrete, with low water and chloride permeability, and sufficient cover.

Darwin et al. (2011, 2014) assessed the performance of several corrosion-inhibition systems, including fusion-bonded ECR combined with inorganic and organic corrosion inhibitors, reinforcing steel coated with zinc prior to applying epoxy, and chemical pretreatments and epoxy formulations intended to strengthen the adhesion of epoxy to the underlying steel. In total, they examined 11 systems that combined ECR and other corrosion protection systems as well as three systems that consisted of untreated black steel and a corrosion inhibitor. Seven bar types were evaluated, one uncoated and six with fusion-bonded epoxy coating. Different concrete formulations with varying water-to-cement ratios were also used. After specimens were cast, they were exposed to cyclical ponding with a 15 percent NaCl solution. Wet and dry cycles were alternated for 96 weeks. Specimens tested in the field were monitored over a period of 250 weeks. Corrosion occurred on laboratory specimens where the ECR was damaged, however, adding calcium nitrite enhanced resistance against chloride ingress. Calcium nitrite increased the conductivity of the concrete it lowered the diffusion coefficient. The overall effect of calcium nitrite was to reduce the concrete permeability. Less corrosion occurred on both coated and uncoated steel when paired with a low water-to-cement ratio. The benefits of corrosion inhibitors and calcium nitrite were most pronounced in uncracked concrete. Although they enhanced the corrosion resistance of cracked concrete, their effects were less apparent. Bars with multiple zinc-epoxy coatings exhibited better performance, however, this was obtained mostly through the sacrificial loss of zinc. Darwin et al. (2011) concluded that fusion-bonded epoxy coatings bolstered corrosion resistance, extend the service lives of bridges, and offer a cost-effective option to improve concrete durability. Furthermore, use of a corrosion inhibitor with either conventional black steel or ECR will prolong service life, delay the onset of corrosion, and potentially extend the time to repair.

Aldykiewicz et al. (2005) reported on long-term laboratory and field experiments that sought to determine whether different combinations of concrete formulations and admixtures could postpone the onset of

corrosion in severe environments. For the laboratory portion of their work, they looked at several concrete mixtures with water-to-cement ratios between 0.30 and 0.50. These were blended with different combinations of pozzolanic materials (Class F fly ash and silica fume) and calcium nitrite, all in varying amounts. After curing, specimens were ponded in a 3 percent NaCl solution continuously. In the specimens used for field testing, the water-to-cement ratio of different concrete mixtures varied from 0.38 to 0.50, as did the amount of concrete cover. Similarly, the amount of fly ash and calcium nitrite varied among treatments (silica fume was not investigated in a field setting). Some of the reinforcement bars were coated with epoxy. The field trials entailed placing specimens in a pool containing filtered ocean water, the height of which was varied diurnally to simulate tidal exposure. Field specimens were exposed to these conditions for 18 years. For specimens tested in the lab, those with higher water-to-cement ratios (0.48), adding calcium nitrite lowered the diffusion coefficient by a factor of two but increased pore solution conductivity. Adding silica fume significantly reduced concrete permeability. Lower water-to-cement ratios (0.38) did not measurably affect chloride ingress, but adding silica fume yielded a less porous concrete and therefore impeded the ingress of chloride and delayed the onset of corrosion. As such, there was a positive correlation between the delay in the onset of corrosion and the amount of silica fume added. Incorporating fly ash into a mixture tended to diminish the conductivity of concrete. Overall, concrete mixtures that included silica fume and fly ash exhibited the lowest total corrosion. Blending calcium nitrite and silica fume also significantly increased the time to corrosion. For the lab specimens, reductions in diffusion coefficients although sharp at first tended to level off within five years. Among specimens exposed to field conditions, those with a lesser amount of cover (38 mm) experienced significantly longer times to corrosion when calcium nitrite was included. This trend was particularly noticeable in concrete formulations with low water-to-cement ratios (i.e., 0.38). Among specimens manufactured with 70 mm of cover, only those which integrated calcium nitrite displayed enhanced performance. Mixes that only blended fly ash with ECR did not effectively mitigate corrosion. Based on the evidence of laboratory and field studies, Aldykiewicz et al. concluded that concrete formulations with lower water-to-cement ratios extend the time to corrosion. Also, supplementing concrete with calcium nitrite delays the onset of corrosion. The effectiveness of calcium nitrite increases when high-quality concrete is used to provide ample cover. Based on the field testing, Aldykiewicz et al. recommended against using epoxy as the only corrosion inhibitor in environments with high chloride exposure.

### **Key Takeaways**

- Using multiple protection strategies can enhance the resistance of reinforcing steel, but the magnitude of their benefits remains unclear and will likely require further laboratory and field testing.
- Adding calcium nitrite appears to significantly improve corrosion resistance. Multiple studies cited here highlighted its benefits.
- Using multiple treatments can increase service life, however, to maximize their performance they should be used in conjunction with a high-quality or high-performance concrete with low permeability, which restricts the ingress of chloride and water and provides sufficient cover.
- Concrete formulations with low water-to-cement ratios generally inhibit corrosion activity.

## 2.7 Material Pricing

Table 5 summarizes the current average price of key treatments in the previous chapters. While this information can be instructive for readers wanting a quick comparison among treatments, any decision about what treatment or system to use should be guided by a detailed cost-benefit analysis that quantifies the long-term benefits of each.

**Table 5** Average Price of Corrosion-Inhibition Treatments

Treatment	Cost
<b>Reinforcements</b> (material cost)	
Black Reinforcing Steel	\$0.32-\$0.52/lb.
ECR	\$0.46-\$0.80/lb.
Stainless Steel	\$1.82-\$3.44/lb.
Stainless Steel Cladded Reinforcing Steel	\$2.50/lb.
Galvanized Reinforcing Steel	\$0.50-\$0.73/lb.
MMFX® ChromX Reinforcing Steel	\$0.65-\$0.94/lb.
Continuous Galvanized Reinforcing Steel	Pricing not set – expected to be similar to ECR
Fiber Reinforced Polymers	\$1.00-\$1.44/lb.
<b>Admixtures</b> (additional cost per cubic yard of concrete)	
Silica Fume	\$12.00-\$15.00/yd <sup>3</sup>
Fly Ash	\$3.00/yd <sup>3</sup>
Calcium Nitrite	\$15.00-\$20.00/yd <sup>3</sup>
Ground Granulated Blast Furnace Slag	\$6.00/yd <sup>3</sup>
<b>Surface Treatments</b> (material cost)	
Silane	\$0.09/ft <sup>2</sup>
Siloxane	\$0.16/ft <sup>2</sup>
Linseed Oil	\$0.02/ft <sup>2</sup>
Silicates	\$0.14/ft <sup>2</sup>

### Chapter 3 State DOT Survey

KTC prepared a survey for state DOTs that touched on critical topics ranging from the type of reinforcing steel commonly used for bridge construction and maintenance and steps used to reduce the permeability of concrete, to how the application of protective sealants, membranes, and overlays can help reduce corrosion. AASHTO assisted KTC by distributing this survey to all 50 state DOTs. Eventually there were nine responses. The information collected is representative of DOT practices throughout the U.S. On several questions respondents had the option of selecting more than one answer. Accordingly, the total number of responses for each question is typically greater than nine. The remainder of this chapter briefly discusses the survey's findings. Appendix A reproduces the survey in its entirety and contains summary graphs, which readers can use to quickly apprehend the range and frequency of answers for each question.

The first group of questions asked DOTs to identify what types of reinforcing steel they choose for routine bridge construction. The most popular choice is epoxy coated reinforcing steel (ECR), followed by stainless reinforcing steel and black reinforcing steel. Galvanized reinforcing steel, carbon fiber reinforced polymer, and proprietary materials are less common. Overwhelmingly, Grade 60 steel is most frequently used for the epoxy coated bars and black reinforcing steel. Four agencies that have adopted stainless reinforcing steel use austenitic-ferritic (Duplex) while three others use austenitic steel. Multiple grades of austenitic and austenitic-ferritic reinforcing steel are in use at these agencies. A list of the various grades in use is provided in Q1.4 and Q1.5 of Appendix A.

Next, the agencies were asked to comment on what types of concrete they use for bridge construction and what preventative measures they have adopted to inhibit corrosion. Five of the nine agencies use high performance (low permeability) concrete. When asked about the required concrete cover over the upper deck of the mat, seven agencies specified 2.5 inches (63.5 mm) — the other two agencies required minimum thicknesses of 2 and 3 inches (~50 and 75 mm), respectively. None of the responding DOTs supplement concrete with inhibiting admixtures to inhibit corrosion. Two of the nine agencies use surface-applied inhibitors to protect reinforcing steel against corrosion. Just one agency applies densifiers to reduce concrete permeability — and only on new construction. Five agencies report using cathodic protection. Four of these agencies implement it during maintenance operations while the other does so for new construction.

Seven agencies currently use sealants. The most popular of these are silanes/siloxanes, epoxies, and methacrylates. One agency applies Pavon® Indeck, a methacrylate crack sealer. All the DOTs that responded to our question about the timing of application (seven) said they apply sealants during both construction and maintenance activities. There is, however, considerable variability with respect to how often agencies reapply sealants. Three agencies lack a fixed schedule, while the other four reapply them at intervals ranging from three to ten years. Eight agencies apply crack sealants to bridge decks, with methacrylate and epoxies being the most frequently used (two agencies reported using polyurethanes). Five of the agencies currently use healer-sealers to fill and seal cracks.

The final thematic set of questions related to membranes, overlays, and laminates. Eight DOTs currently employ overlays, three use membranes, and one uses other kinds of these materials. Five agencies use membranes during maintenance activities. Six DOTs install overlays during maintenance, and three agencies use them for new construction and maintenance. Just one agency installs laminates during maintenance and new construction, while three agencies report using other materials (e.g., slurries, chip seals) only during maintenance. When asked about the type of membranes they use, two agencies said they have adopted sheeting membranes and two use liquid applied membranes. There is considerable diversity in the types of overlays used. Low slump concrete, latex concrete, and microsilica concrete are equally popular (three responses each), followed by epoxy polymer, asphaltic, and chip seals.

The survey's final two questions asked about methods used to prevent or minimize corrosion as well as the combinations of materials used to do so. Five of the nine agencies routinely leverage *multiple methods* to prevent or minimize the corrosion of bridge decks. The final question asked the agencies to specify what combinations of materials they use to prevent and mitigate corrosion. While five DOTs provided information on combinations of materials, only two — Minnesota and South Dakota — make a link between project type and the materials used. Minnesota's DOT uses epoxy coated reinforcing (ECR) steel and high performance concrete in areas with low average daily traffic (ADTs). In areas with higher ADT and larger populations, it opts for ECR, high performance concrete, and overlays. For bridge projects that cost over \$25 million, the agency combines stainless reinforcing steel with high performance concrete. South Dakota's DOT specified three materials-projects combinations. ADT and the amount of deicing chemicals applied on a route influence what combination of materials the agency selects. On routes with low ADT and little use of deicing chemicals, the agency uses ECR, high performance concrete, and deck sealants. For bridges constructed on routes with more traffic and a higher rate of deicing chemical application, it uses stainless steel, high performance concrete, and deck sealants. For routes with the highest ADT and deicing chemical usage, the agency employs Z-bar or dual coated reinforcing steel, high performance concrete, and deck sealants. Neither agency elaborated on threshold criteria used to decide on what materials are chosen (i.e., they did not specify what constituted low/medium/high ADT or low/high thresholds for deicing chemicals).

### **Key Takeaways**

- ECR and stainless steel are the materials DOTs most commonly use to achieve corrosion resistance on concrete bridge decks.
- DOTs were split on the use of high performance concrete and cathodic protection. None of the DOTs incorporate inhibiting admixtures to reduce corrosion. And just two use surface applied inhibitors. Only one DOT uses densifiers to lower concrete permeability.
- Applying sealants to bridge decks is commonly done during both new construction and maintenance activities (seven of nine agencies report doing so). All but one responding DOT uses crack sealants on decks. Five agencies use heater-sealers to repair cracks.
- Most responding DOTs apply some combination of membranes, overlays, and laminates. The combination of materials and the timing of their installation varies among agencies.
- Five of the nine responding DOTs routinely use multiple corrosion prevention and/or minimization methods for bridge decks.

## Chapter 4 KYTC Bridges with Corrosion-Resistant Rebar and Treatments

KYTC currently has several experimental bridges with decks that contain corrosion resisting reinforcing steel. These are listed in Table 6.

**Table 6** KYTC Experimental Bridge Decks

Bridge Location, Identifier, Date Constructed	Treatment
<ul style="list-style-type: none"> <li>• Elkin State Road Bridge over Two-Mile Creek in Clark County (BN-025C0062N)</li> <li>• Built 2001</li> </ul>	<ul style="list-style-type: none"> <li>• CFRP Bars</li> </ul>
<ul style="list-style-type: none"> <li>• Galloway Road Bridge over North Elkhorn Creek in Scott County (BN-105C00111N)</li> <li>• Built 2003</li> </ul>	<ul style="list-style-type: none"> <li>• Stainless Steel Clad and MMFX® ChromX</li> </ul>
<ul style="list-style-type: none"> <li>• KY 3302 over Sugar Tree Branch in Fleming County (BN-035B00100N)</li> <li>• Built 2011</li> </ul>	<ul style="list-style-type: none"> <li>• Stainless Steel</li> </ul>
<ul style="list-style-type: none"> <li>• KY 2262 Approach Spans over Ohio River in Daviess County (BN-030B00118N)</li> <li>• Built 2012</li> </ul>	<ul style="list-style-type: none"> <li>• Stainless Steel (Top Mat)</li> </ul>
<ul style="list-style-type: none"> <li>• KY 6 over Lynn Camp Creek in Knox County (BN-061B11075N)</li> <li>• Built 2014</li> </ul>	<ul style="list-style-type: none"> <li>• Galvanized Rebar</li> </ul>

KYTC has also used concrete sealers on a number of bridges throughout the state. Several bridges on I-471 over 6<sup>th</sup> Street (northbound and southbound) in Newport (Campbell County) had portions of their decks treated experimentally with different silanes (BN-019B00056L and BN-019B00056R) in 2012. Four bridges on I-24 (westbound over a railroad, eastbound over a railroad, eastbound over Lone Oak Road and eastbound over Poole Road) in McCracken County had several transverse deck cracks routed and sealed experimentally by KTC personnel in 2013 (BN073B00103L, BN073B00104R, BN073B00112R and BN073B00114R) with a methyl methacrylate crack sealer one year after the decks had been washed and sealed using a silane.

## Chapter 5 Conclusions and Recommendations

KYTC uses a standard corrosion protection system for new bridge decks that consists of:

- Class AA concrete
- Epoxy-coated reinforcements in the top and bottom mats
- At least 2.5” of concrete cover over the top mat

KYTC’s *Structures Manual* also recommends the use of additional protective treatments for critical structures. Critical structures are those “whose size, design, location, or importance to the transportation network would create unusual owner and/or user costs if its use were restricted for deck repairs” (see KYTC *Structural Design Manual*, section SD-501-3). These structures are most often found where there are high traffic volumes or major stream crossings. Precast segmental concrete bridges and cast-in-place box girder bridges are also designated as critical structures. The manual lists several options for enhancing the protection of these structures: corrosion-inhibiting admixtures, exotic overlay materials, high performance concrete, and shrinkage compensating cement.

The *Standard Specifications Manual* (601.03.03C 2) instructs the use of AA concrete (used for bridge decks) having a W.C. of 0.42 and using 620 lb. of cement per cubic yard of concrete. The specification allows the substitution of fly ash, ground granulated blast furnace slag, or microsilica at the option of the contractor for up to 40 percent of the weight of cement. Other DOTs are using binary or ternary mix designs with those types of substitutions specified to achieve high performance concrete.

The List of Approved Materials provides detailed contact and product information for materials that have been approved for use on KYTC projects. Neither the *Structures Manual* nor *Standard Specifications Manual* mention the use of concrete sealants; the List of Approved Materials does not reference these either.

KYTC specifications for bridge deck construction are adequate to achieve service lives of 20-plus years prior to requiring repairs — typically by installation of latex overlays. However, like most transportation agencies, the Cabinet is facing serious budgetary constraints, making it even more critical to maximize the service lives of new and rehabilitated bridges. For new bridges, this probably means aiming for a service life of 75-100 years. While this may not be attainable under all circumstances, the corrosion-inhibiting products currently available on the market, when used in combination, are sufficient for achieving this goal in all but the most severe environments. The findings of this report can assist KYTC as it decides whether to implement new strategies to delay the onset of corrosion and therefore extend bridge service life. This paper underscored that the large number of protective strategies (from rebar coatings to concrete admixtures) and laboratory and field testing procedures make it exceedingly hard to adjudicate one material or system as the best. Most studies have examined the performance of materials over relatively short time periods, and laboratory testing cannot replicate the real-world conditions that bridge decks face. Their findings are nonetheless instructive, and may be used as a starting point to identify promising methods to implement on Kentucky’s bridges.

With respect to steel reinforcement, ECR has long been the preferred method of slowing the onset of corrosion. Beginning in the 1970s, transportation agencies rapidly turned to ECR as a cost-effective option for protecting steel from harsh environments — particularly in areas where deicing chemicals are used frequently. Although many of the studies analyzed supported the use of ECR by demonstrating it successfully protects underlying reinforcement, some researchers have questioned its durability, citing the propensity of the epoxy to disbond after prolonged exposure to moisture. Over time, epoxies inevitably break down, and moist and humid environments can accelerate this process. Researchers are generally

confident in the durability of solid stainless steel and believe it can help a bridge achieve a service life of up to 100 years. However, solid stainless steel is prohibitively expensive, and should be reserved for critical projects (e.g., interstate bridges). Other means of protecting steel reinforcement, such as galvanization, may enhance corrosion resistance, but they are not immune from problems. Small holidays in the coatings and imperfectly sealed end caps serve as conduits that facilitate the entry of chlorides and moisture, which promote corrosion. The Virginia DOT is supplanting ECR with chrome reinforcing steel for normal applications because of its performance and low price, which is comparable to black steel. FRP rebars certainly eliminate corrosion, however, there has only been limited testing on these materials and it is unclear if they perform well under a variety of environmental conditions. They should be investigated further to determine if their long-term performance will warrant their future use in KYTC bridge decks.

A second method of mitigating corrosion is to add supplementary cementitious materials (or admixtures) to concrete. Admixtures reduce the permeability of concrete, improve concrete density, and increase the electrical resistivity of concrete — all of which delay the onset of corrosion. The most frequently used admixtures include fly ash, silica fume, ground granulated blast furnace slag, and calcium nitrite. Most of the studies analyzed confirmed there are benefits to using admixtures, as they limit the penetration of chlorides. One potential downside of using an admixture is the slight loss of compressive strength. None of the studies identified suggested the loss of compressive strength would be problematic for bridge performance, however, ongoing and future studies examining the utility of admixtures should be attentive to the issue of compressive strength and determine whether there are tradeoffs involved in their use. As one study (Nidiffer et al., 2014) pointed out, transportation agencies interested in using admixtures should explore ternary concrete formulations that contain at least two admixtures in addition to cement as these may more effectively limit corrosion than binary formulations.

Lastly, surface treatments (i.e., sealants) are organic and inorganic materials that are applied to deck surfaces to prevent the ingress of moisture and chloride. The most commonly used surface treatments are silanes and siloxanes. These have generally proven more effective than silicates and epoxies. There is evidence that indicates surface treatments reduce corrosion and the infiltration of contaminants. A positive correlation exists between the depth of sealant penetration and overall performance. Although some sealers may increase carbonation, this will not necessarily translate into more significant corrosion if excessive moisture is not present. Most sealers need to be reapplied every 5 to 20 years. Transportation agencies should carefully weigh the costs and benefits of repeated applications to decide whether alternative methods of protection will be more cost-effective.

Cracking of bridge decks remains a critical problem. Concrete cracking can allow aggressive materials to access the reinforcing materials directly and short-circuit the benefits of dense, high performance concrete or thick cover. KTC research has indicated a potential benefit of conventional sealants for tight cracks <0.010 inches. However, larger cracks need to be repaired with spot applications of crack sealers or flood applications of healer sealers. Corrosion-resisting reinforcing bars are the critical second line of defense where deck cracking is present. The Virginia DOT (2009) *Guide Manual for Causes and Repair of Crack in Bridge Decks* notes that repairs may work for dormant cracks but repairs to moving cracks may prove short-lived because new cracks may form parallel to the repair. The manual notes that cracks exceeding 0.2 mm (0.007 in) should be filled. It prescribes repair methods including gravity filled polymers (healer sealers), routing and filling with epoxy, and epoxy injection after placement with a polymer mesh.

If there is a consensus among researchers, it is this — treatments are supplemental. By itself, no treatment will adequately slow down the corrosion process. The key to extending the service life of any bridge is the use of a sufficient cover of high quality concrete over reinforcement. Without this, the effectiveness of the treatments discussed in this report will be limited at best.

KYTC and other transportation agencies may want to consider the more extensive use of multiple corrosion-resisting methods to protect against bridge corrosion. For the construction of new reinforced concrete structures, KTC recommends a multiple approach to corrosion resistance. This approach combines high performance concrete, which establishes an effective barrier that limits the rates of chloride penetration and carbonation, with reinforcing bar materials that are more resistant to corrosion (e.g. MMFX® ChromX, or in more critical/severe applications, stainless steel) (Hansson et al., 2010). For existing structural concrete other than decks, sealants and coatings can be used to provide corrosion resistance along with the addition of waterproofing treatments for protecting bridge decks (not addressed in this report).

KYTC practices that prevent corrosion in deck reinforcement and in other reinforced concrete applications can be improved to provide greater service lives. Although KTC now has field performance data for bridges constructed with ECR and concrete overlays dating to the 1970s and 1980s, the use of other methods is more recent, and accelerated laboratory testing can only reveal so much. Arguably, there will not be a comprehensive understanding of how these protective strategies perform until they have been in real-world use for another 20-30 years (perhaps even more in some cases). In the meantime, based on the findings we recommend that KYTC take the following actions:

- Develop specifications for high-performance concrete for use on bridge decks.
- Continue to monitor the performance of current bridge decks that have been constructed with experimental reinforcing steel as well as conventional decks treated with protective sealants.
- Evaluate corrosion activity of painted structural concrete.
- Conduct further evaluations of sealant types and determine which work best with specific concretes.
- Perform a cost-benefit analysis to evaluate the anticipated benefits of using various protection methods/treatments.
- Identify and implement experimental maintenance activities related to sealing bridge decks/cracks.
- Experiment with multiple corrosion-protection systems on newly constructed bridges and apply one or more of those routinely for new bridges and deck replacement projects.

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## Appendix A – DOT Survey Summary

**Q1 - Which of the following reinforcing bar types does your agency use on a routine (non-experimental) basis for new construction?**

Black Reinforcing Steel	27.27%	3
Epoxy Coated Reinforcing Steel	100.00%	11
Chrome Reinforcing Steel - ASTM A1035 MMFX2/ChromX	0.00%	0
Stainless Reinforcing Steel	45.45%	5
Galvanized Reinforcing Steel	9.09%	1
FRP / Carbon	18.18%	2
Proprietary (e.g. Z-bar)	18.18%	2
Other	0.00%	0

**Q1.1 - What grade(s) of black reinforcing steel does your agency use?**

ASTM A 615 grade 60
60
60 grade and 80 grade

**Q1.2 - What grade(s) of Epoxy Coated Bars does your agency use?**

60
Grade 60
Grade 60
60
grade 60 bars coated in accordance with ASTM A 775
AASHTO M31
60
Grade 60
60
60
Grade 60 and 80

**Q1.3 - What type of stainless reinforcing steel does your agency use?**

Austenitic-Ferritic (Duplex)	100%	4
Austenitic	75%	3

**Q1.4 - What grade(s) of austenitic stainless reinforcing steel does your agency use?**

S24000, S24100, S20910, S30400, S31603, S31803, S31653
Unknown
316 LN

**Q1.5 - What grade(s) of austenitic-ferritic (duplex) stainless reinforcing steel does your agency use?**

S32205, S32304
Unknown
60
2205

**Q1.5 - What grade(s) of galvanized reinforcing steel does your agency use?**

Grade 60
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**Q1.6 - What is the tensile strength of FRP/Carbon reinforcement your agency uses?**

95 ksi
100 KSI

**Q2 - Does your Agency use high performance (low permeability) concrete?**

Yes	50.00%	5
No	50.00%	5

**Q2.1 - What is the specified concrete cover (inches) over the upper mat of the deck?**

2 inches	10	1
2.5"	70	7
3" minimum*	20	2

\*One respondent typically uses 3" cover for #6 bars

**Q2.2 - Does your agency use inhibiting admixtures to reduce corrosion of reinforcing steel?**

Yes	0.00%	0
No	100.00%	10

**Q2.3 - Does your agency use surface applied inhibitors to reduce corrosion of reinforcing steel?**

Yes	20.00%	2
No	80.00%	8

**Q2.4 - Does your agency use densifiers to reduce concrete permeability?**

Yes	11.11%	1
No	88.89%	8

**Q2.5 - When are densifiers applied?**

New construction	100.00%	1
Maintenance	0.00%	0
Both	0.00%	0

**Q2.6 - Does your agency use cathodic protection?**

Yes	55.56%	5
No	44.44%	4

**Q2.7 - When does your agency use cathodic protection?**

New construction	20.00%	1
Maintenance	80.00%	4
Both	0.00%	0

**Q3 - Does your agency apply sealants to bridge decks?**

Yes	77.78%	7
No	22.22%	2

**Q3.1 - What type of deck sealant(s) does your agency use?**

Silanes/Siloxanes	85.71%	6
Epoxies	71.43%	5
Methacrylates	42.86%	3
Linseed oil	0.00%	0
Other (specify)*	14.29%	1
*Pavon InDeck		

**Q3.3 - Are deck sealants applied during new construct or maintenance?**

New construction	0.00%	0
Maintenance	0.00%	0
Both	100.00%	7

**Q3.3 - At what frequency are deck sealants re-applied?**

5 years
Do not have a schedule to re-apply
no set frequency
Variable
60-120 months
36 (for InDeck) to 84 (for Silane) (recommended)
5-10 years

**Q3.4 - Does your agency apply crack sealants to bridge decks?**

Yes	88.89%	8
No	11.11%	1

**Q3.5 - What type of crack sealant(s) does your agency use?**

Methacrylate	75.00%	6
Epoxies	75.00%	6
Polyurethanes	25.00%	2
Other (specify)	0.00%	0

**Q3.6 - Does your agency use healer-sealers on bridge decks?**

Yes	56%	5
No	44%	4

**Q4 - Does your agency use membranes, overlays, and/or laminates?**

	YES		NO		Total
Membranes	42.86%	3	57.14%	4	7
Overlays	100.00%	8	0.00%	0	8
Laminates	0.00%	0	100.00%	5	5
Other (slurries, Chip seals, etc.)	100.00%	1	0.00%	0	1

**Q4.1 – When does your agency used membranes, overlays, and/or laminates?**

	New Construction		Maintenance		Both		Total
Membranes	0.00%	0	100.00%	5	0.00%	0	5
Overlays	0.00%	0	66.67%	6	33.33%	3	9
Laminates	0.00%	0	0.00%	0	100.00%	1	1
Other (slurries, Chip seals, etc.)	0.00%	0	100.00%	3	0.00%	0	3

**Q4.2 - What type of membrane does your agency apply? (Select all that apply)**

	%	Count
Sheeting	66.67%	2
Liquid applied	66.67%	2
Other (specify)	0.00%	0

**Q4.3 - What type of overlays does your agency apply? (Select all that apply)**

	%	Count
Low Slump Concrete	37.50%	3
Latex Concrete	37.50%	3
Microsilica Concrete	37.50%	3
Impermeable Asphalt (e.g. Rosphalt)	0.00%	0

Other (specify) - (Epoxy Polymer, Asphaltic, Chip Seals)	25.00%	2
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**Q5 - Does your agency routinely employ multiple corrosion prevention/minimization methods in bridge decks?**

Yes	56%	5
No	44%	4

**Q6 - Using the numerical equivalent of the materials listed below indicate various combinations that your agency employs on bridge decks (new construction) and on what type of route. Example: Epoxy coated reinforcing steel, stainless reinforcing steel, and high performance concrete would be (2, 4 & 9 used on high ADT routes with heavy de-icing chemical usage.**

1 Black Reinforcing Steel	8 Other Proprietary Reinforcement	15 Healer-Sealers
2 Epoxy Coated Reinforcing Steel	9 High Performance Concrete	16 Membranes
3 Chrome Reinforcing Steel	10 Inhibiting Admixtures	17 Overlays
4 Stainless Reinforcing Steel	11 Surface Applied Inhibitors	18 Laminates
5 Stainless Clad Reinforcing Steel	12 Densifiers	19 Cathodic protection
6 Galvanized Reinforcing Steel	13 Deck Sealants	20 Other
7 FRP/Carbon Reinforcing Bars	14 Crack Sealants	

**Minnesota DOT:**

Combination 1 – ECR steel and high performance concrete is used in minimum ADT areas.

Combination 2 – ECR steel, high performance concrete, and overlays are used on routes in more populous areas with higher ADT.

Combination 3 – Stainless reinforcement and high performance concrete is used on bridges with costs above \$25 million.

**Utah DOT:**

Combination 1 – ECR and deck sealant

Combination 2 – ECR and overlays

Combination 3 – ECR and healer/sealers

Combination 4 – Stainless reinforcement and overlays

Combination 5 – Stainless reinforcement and healer/sealers

**South Dakota DOT:**

Combination 1 – ECR, high performance concrete, and deck sealants on routes with lower ADT and lower deicing chemical usage.

Combination 2 – Stainless reinforcement, high performance concrete, and deck sealants are used on routes with higher ADT and deicing chemical usage.

Combination 3 – Z-bar or dual coated reinforcing (metalized and epoxy coated)t, high performance concrete, and deck sealants used routes with higher ADT and deicing chemical usage.

**Missouri DOT:**

Combination 1 – ECR and deck sealants during construction.

Combination 2 – Deck sealants, crack sealants, and overlays throughout the life of the bridge.



Oregon DOT:

Combination 1 – Black reinforcing steel, high performance concrete, deck sealant, crack sealants, and healer-sealers.

Combination 2 – ECR, high performance concrete, deck sealant, crack sealants, and membranes.

Combination 3 – Stainless reinforcing steel, high performance concrete, and deck sealant.

Combination 4 – FRP/Carbon reinforcing bars, high performance concrete, and deck sealant.

Additional Comments:

Epoxy chip seals are being applied after 5-10 years on new bridges in higher ADT and higher de-icing chemical usage areas that we have used epoxy coated steel on. On new bridges in higher ADT and higher de-icing chemical usage areas we are using stainless steel with Z-bar as an alternate. Epoxy chip seals and low slump overlays are also being used on a routine basis for maintenance of existing structures.

**Thanks to the following participating agencies for their efforts in completing this survey.**

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Wyoming Department of Transportation

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Minnesota Department of Transportation

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Texas Department of Transportation

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Utah Department of Transportation

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South Dakota Department of Transportation

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Missouri Department of Transportation

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Oregon Department of Transportation