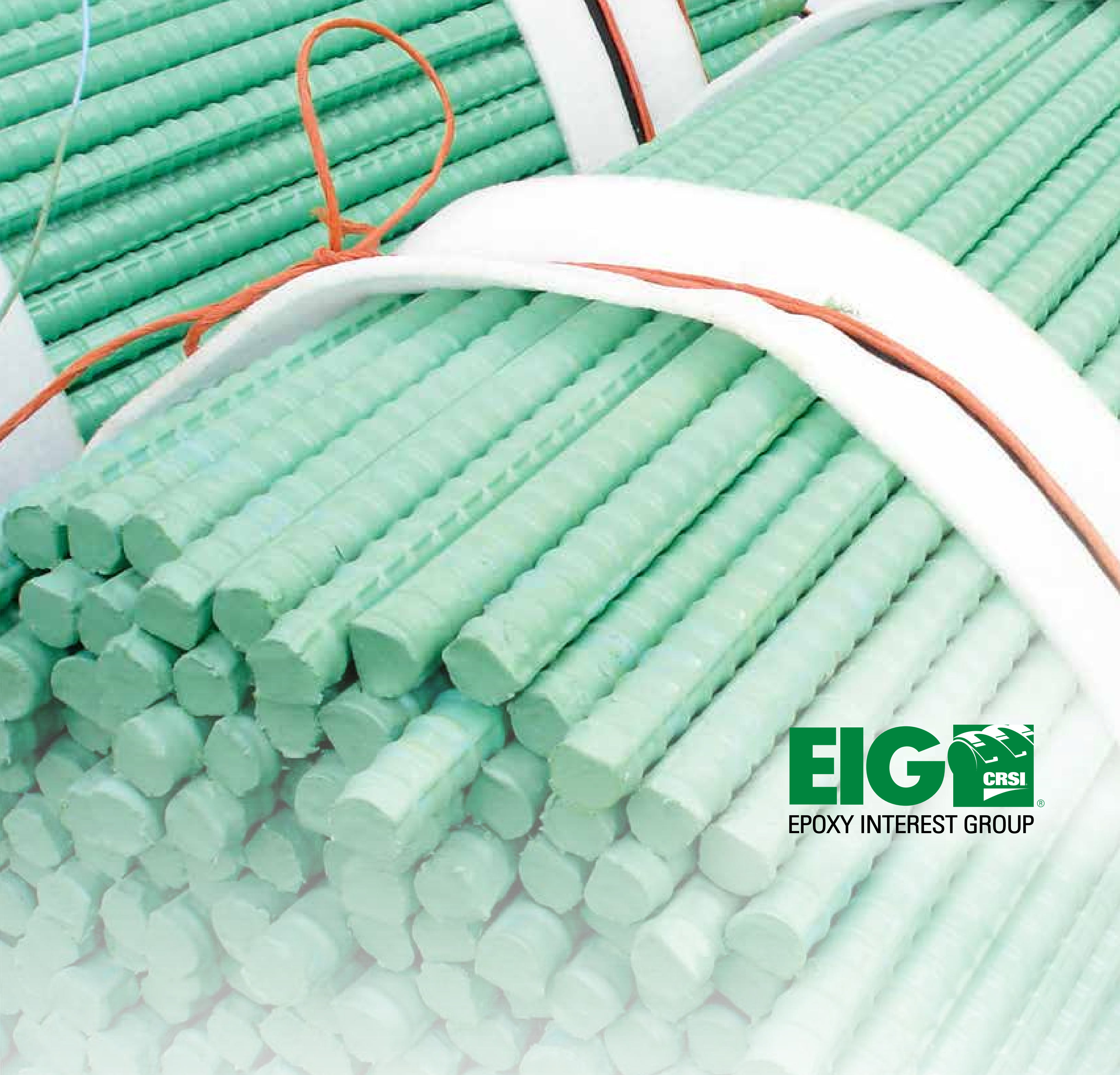

EIG CRSI
EPOXY INTEREST GROUP

COMPARING THE PERFORMANCE OF EPOXY-COATED AND GALVANIZED REINFORCING STEEL

A Literature Review

Epoxy-coated reinforcing steel was first used in 1973 on the Schuylkill Bridge near Philadelphia, PA, as a method to reduce corrosion damage to bridge structures. It remains the principal method for protection of concrete structures in North America against corrosion damage and is commonly specified in the Middle East and Asia. This document illustrates why epoxy-coated reinforcing steel has been chosen in preference to galvanized reinforcing steel.

INTRODUCTION

During the past 40 years, substantial research has been conducted comparing the performance of epoxy-coated and galvanized reinforcing steels. This document outlines several research studies demonstrating why epoxy-coated reinforcing steel has become the material of choice in protecting concrete structures against corrosion.

Based upon the 2011 National Bridge Inventory, there are more than 74,097 bridge decks using epoxy-coated reinforcing steel covering an area of 885 million sq ft, while only 1,072 decks covering an area of 9.9 million sq ft use galvanized steel. Thus, epoxy-coated reinforcing steel has been used in over 67 times more bridge decks covering over 90 times more area than galvanized reinforcing steel. Between 2010 and 2011 the National Bridge Inventory reported an increase of 3,231 bridge decks containing epoxy-coated reinforcing steel and only 19 using galvanized reinforcing steel.

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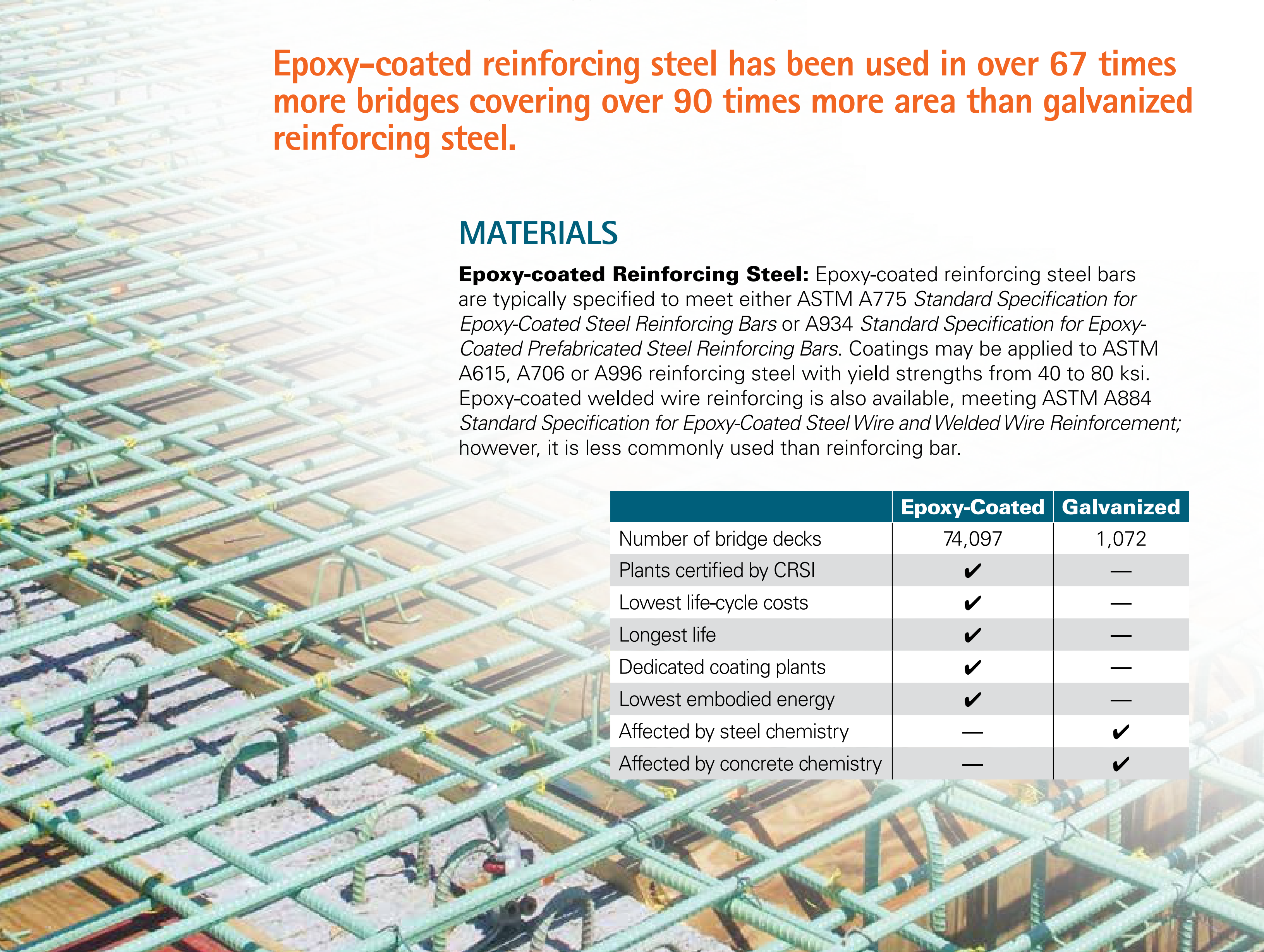


MATERIALS

Epoxy-coated Reinforcing Steel: Epoxy-coated reinforcing steel bars are typically specified to meet either ASTM A775 *Standard Specification for Epoxy-Coated Steel Reinforcing Bars* or A934 *Standard Specification for Epoxy-Coated Prefabricated Steel Reinforcing Bars*. Coatings may be applied to ASTM A615, A706 or A996 reinforcing steel with yield strengths from 40 to 80 ksi. Epoxy-coated welded wire reinforcing is also available, meeting ASTM A884 *Standard Specification for Epoxy-Coated Steel Wire and Welded Wire Reinforcement;* however, it is less commonly used than reinforcing bar.

	Epoxy-Coated	Galvanized
Number of bridge decks	74,097	1,072
Plants certified by CRSI	✔	—
Lowest life-cycle costs	✔	—
Longest life	✔	—
Dedicated coating plants	✔	—
Lowest embodied energy	✔	—
Affected by steel chemistry	—	✔
Affected by concrete chemistry	—	✔

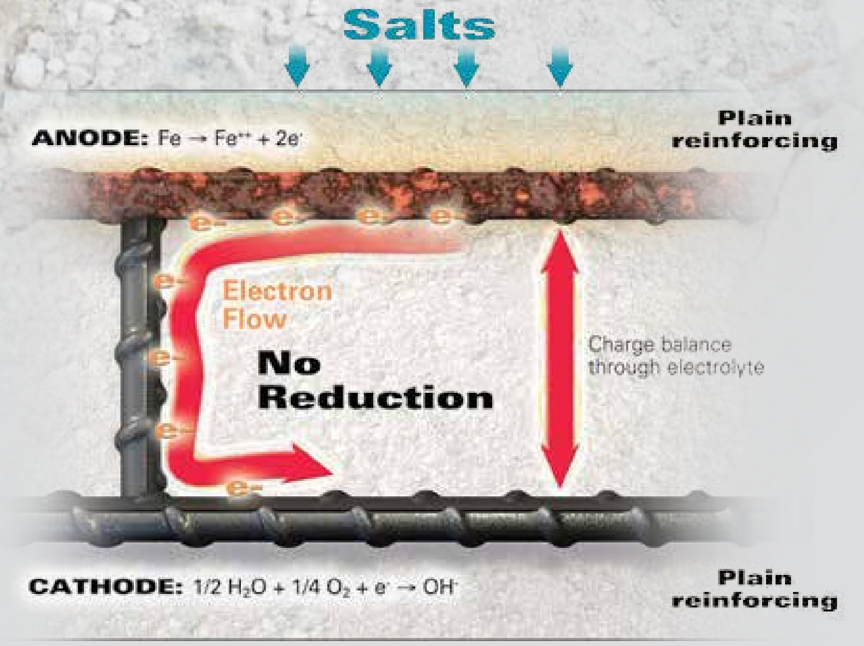
Corrosion of Steel in Concrete

When steel is placed into concrete it develops a passive oxide film due to the high pH of the concrete. This passive film prevents further corrosion. Bars extracted from very old concrete may exhibit no evidence of corrosion.

The protective film on reinforcing bars may be disrupted by carbonation of the cement paste, which reduces the pH surrounding the bar, or through the ingress of chloride ions into the concrete, from either deicing salts or sea water. The rate of carbonation and penetration of chloride ions is governed by the permeability of the concrete, which may be reduced using concrete with lower water-cement ratios or additions of materials such as fly ash, silica fume or slag cement. The presence of cracks may also enable either carbonation or chloride ingress to be accelerated. Carbonation is generally not considered a major issue in North America due to the use of low water-cement ratio concretes.

The amount of chloride ion to initiate corrosion of uncoated steel in concrete is generally considered to be 1.2 to 2.0 lb/yd³ by weight of concrete. Once this level is reached, the passive film on the steel is disrupted and corrosion initiates. As the volume of corrosion products that result from the corrosion are greater than the initial metal, cracking and damage to the concrete occurs, leading to expensive concrete repairs.

Various methods to reduce concrete damage have been used, including: reducing the concrete permeability by using lower water-cement ratios and pozzolans, surface sealers and membranes; using corrosion inhibitors in the concrete mixture; and changing the type of reinforcing steel.



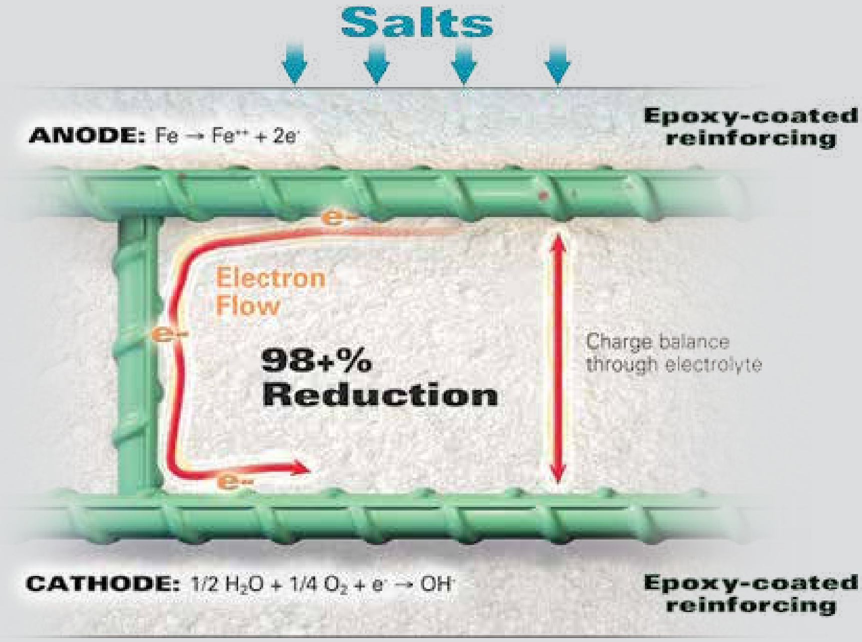


Photo courtesy of Flatiron

Epoxy-coated reinforcing steel is generally provided from dedicated plants that manufacture epoxy-coated reinforcing steel using requirements of the Concrete Reinforcing Steel Institute (CRSI) Certification Program for Epoxy-coated Manufacturing Bar Plants. This program, celebrating its 20th anniversary in 2012, outlines the basic requirements for a quality control program to ensure that a plant and its employees are trained, equipped and capable of producing fusion bonded epoxy-coated reinforcing steel in conformance with the latest industry standards and recommendations. Many State Departments of Transportation require that bars are manufactured under this CRSI certification program.

Galvanized Reinforcing Steel:

Galvanized reinforcing steel is generally processed alongside other products and most galvanizers do not specialize in the coating of reinforcing steel. There are no independent certification programs for galvanized reinforcing steels.

Galvanized bars are created by dipping reinforcing steel into a bath of molten zinc at about 840°F. This results in layers of iron, zinc-iron alloys and pure zinc. The silicon content of the steel influences the formation of these layers and may result in thick layers of zinc-iron alloys, which are brittle and susceptible to flaking during bending. The performance of the bars may be strongly affected by the thickness of the outermost pure zinc layer. As reinforcing bar chemistry varies due to the type of scrap steel used in its manufacture, the performance of galvanized bars may be expected to vary considerably.

Performance of Galvanized Coatings in Concrete

According to the American Galvanizing Association, galvanizing provides a zinc coating that completely covers the steel surface, sealing it from the corrosive action of the environment. The zinc also provides a sacrificial (cathodic) action that protects the steel even where damage or minor discontinuity occurs in the coating.

During curing of the concrete, the zinc surface of galvanized reinforcement reacts with the alkaline cement paste to form stable, insoluble zinc salts accompanied by hydrogen evolution. Chromates are required to passivate the zinc surface, minimizing the evolution of hydrogen during the reaction between zinc and the concrete.

A 10-year testing program of uncoated and galvanized bars in concrete slabs found that the galvanized bars were subject to the same type of macroscopic corrosion as black steel bars (Clear 1981). In concrete with a water-cement ratio of 0.40, both the long-term exposure data and the rate-of-corrosion data indicated that the use of galvanized bars did not provide extra benefit over using black steel. However, in concrete with 0.50 w/c, when galvanized bars were used in both mats, the corrosion rate and the corresponding metal loss were about 30 percent and 22 percent, respectively, in comparison to black steel. This suggests that tests conducted at high water-cement ratios may result in estimated design lives longer than that obtained in field placements.

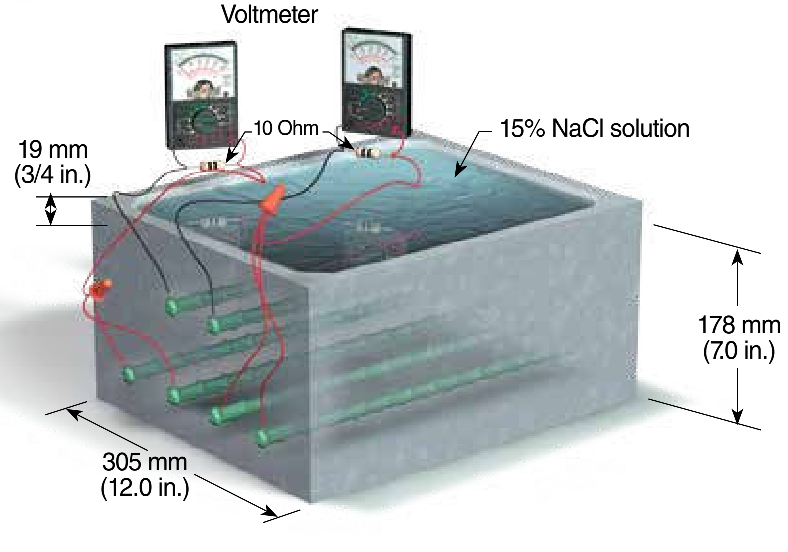
In 1983 Shimida and Nishi reported 5-year results on galvanized and uncoated bars and found that concrete splitting was not significantly delayed (Shimida and Nishi 1983).

In another study, concrete specimens that were partially immersed in saturated sodium chloride solutions showed corrosion began at roughly the same time for specimens made with galvanized bars and with black steel, suggesting that there was no benefit from galvanizing the steel bars (Virmani and Clemena 1998).

Macias and Andrade studied the behavior of the zincate salt formed on the surface of the galvanized bars when they are placed into concrete (Macias and Andrade 1987). They found that below a pH of 13.3, the zincate salt forms a stable passive layer; however, above a pH of 13.3, the zincate forms large crystals that do not protect the reinforcing steel. Such high pH levels are promoted by cements that contain increased alkali contents, more typical of that being produced today.

In 1989, Treadaway and Davies examined galvanized reinforcement and found that slabs cast with galvanized reinforcement exhibited significantly more cracking than slabs cast with conventional steel (Treadaway and Davies 1989).

Saraswathy and Song evaluated four types of galvanized reinforcement and found only one performed better than conventional steel (Saraswathy and Song 2005).



Southern Exposure (SE) Specimen

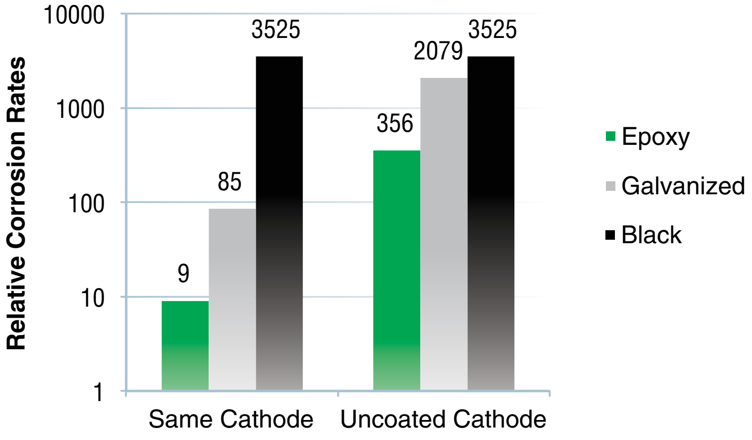
Haran et al. showed that while the corrosion rate of the zinc layer of galvanized reinforcement in the presence of chlorides was greater than that of conventional steel, the corrosion of the underlying reinforcement was delayed (Haran, Popov et al. 2000).

In 1992, Rasheeduzzafar et al. reported on tests conducted on uncoated, galvanized and epoxy-coated reinforcing steels, evaluated as part of a 7-year exposure site program (Rasheeduzzafar, Bader et al. 1992). Bars were cast in prismatic specimens of 0.45 water-cement ratio good-quality concrete containing three levels of chloride: 4, 8, and 32 lb/yd^3. The specimens were exposed to the environment of Eastern Saudi Arabia on a site at King Fahd University of Petroleum and Minerals, Dhahran. The results showed that uncoated bars suffered severe rust-related damage for all three chloride levels. Significant loss of section and rib degradation was observed for the bars in the 8- and 32-lb/yd^3 chloride-bearing concrete. It was found that for galvanized reinforcing steel there was a delay in the onset of cracking, a reduction in metal loss, and amelioration in the incidence and severity of concrete failure condition. However, in both 8- and 32-lb chloride concretes, there was severe corrosion accompanied by concrete cracking. For the species containing epoxy-coated reinforcing steel, no corrosion or cracking were observed in the specimens loaded with either 4 or 8 lb/yd^3 of chloride.

In 1998, McDonald et al. reported on extensive studies for the FHWA on organic, ceramic and metallic coatings and solid metallic reinforcing bars (McDonald, Pfeifer et al. 1998). These studies reported on 96-week southern exposure tests conducted using uncoated, galvanized and epoxy-coated reinforcing steel. When the same material was used for the anode and cathode bars, the measured macrocell voltage for damaged epoxy-coated reinforcing steel bars was 9 times less than that of the damaged galvanized reinforcing steel bars during the 96 weeks of testing. The value for damaged epoxy-coated reinforcing steel was also only 0.2 percent that of the uncoated bars tested in the series.

When an uncoated bar was used for the cathode in these same tests, the measured macrocell voltage for damaged epoxy-coated bars was 5.8 times less than that of the damaged galvanized reinforcing bars in uncracked concrete during the 96 weeks of testing.

Measured macrocell voltage for epoxy bars was 9 times less than that of the galvanized bars in uncracked concrete during the 96 weeks of testing



Relative Corrosion of Black, Galvanized and Epoxy Bars

(McDonald et al. 1998)

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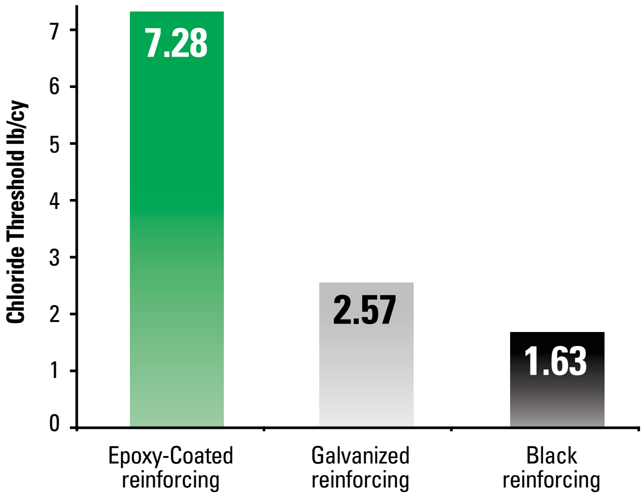
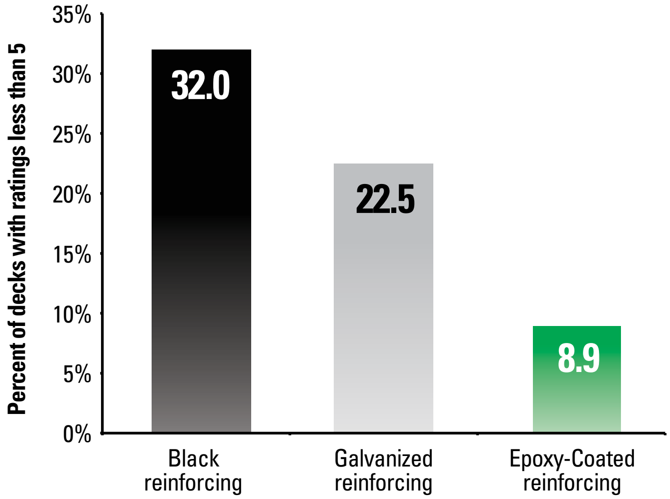
Decks with galvanized reinforcing steel were 2.5 times more likely to require repair compared to those containing epoxy-coated reinforcing steel



Chloride Threshold

(O'Reilly et al. 2011, Darwin al. 2009)



Decks with Less than 5% Rating

Darwin et al. studied the critical chloride corrosion threshold of galvanized reinforcement and found that galvanized steel had an average critical chloride corrosion threshold of 2.57 lb/yd^3 of chloride ion by weight of concrete compared to 1.63 lb/yd^3 for conventional reinforcement (Darwin, Browning et al. 2009). In similar studies, Darwin et al. found that the critical corrosion threshold for epoxy-coated reinforcing steel bars were significantly greater at 7.28 lb/yd^3 of chloride ion by weight of concrete (O'Reilly, Darwin et al. 2011).

In 2005, Pianca et al. reported of studies conducted on three bridges containing galvanized reinforcing bars in Ontario and found corrosion of the galvanized steel commenced soon after the assumed threshold for the uncoated bars was reached (Pianca and Schell 2005).

Evaluation of NBI Data

Review of the 2012 National Bridge Inventory using data for bridges constructed from 1973 to 1983 in Pennsylvania found 954 decks constructed using uncoated bars, 281 constructed using epoxy-coated reinforcing and 89 using galvanized reinforcing, not counting decks reconstructed during this period.

Many agencies use a rating of 5 or lower to project bridge repairs. For decks constructed during this period using uncoated bars, almost 32 percent of decks exhibited a rating lower than 5. Similarly, for decks with galvanized or epoxy-coated reinforcing steel the percentage of decks rating less than this value is 22.5 and 8.9 percent, respectively. Thus, 30- to 40-year-old decks with epoxy-coated reinforcing steel are 2.5 times less likely to require repair than those with galvanized reinforcing steel.

SUMMARY

This paper has shown that epoxy-coated reinforcing steel performs significantly better in both field and laboratory studies than galvanized reinforcing steel. This improved performance has led to epoxy-coated reinforcing steel to be used more frequently in both marine and inland environments to protect structures against corrosion-induced damage.

A Better Product Using 40 Years of Improved Manufacturing and Coating Technologies.

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