PERFORMANCE OF BRIDGE DECKS CONTAINING EPOXY-COATED REINFORCING BARS

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ABSTRACT

Epoxy-coated reinforcing bars have been used in the U.S. for over 35 years and according to the National Bridge Inventory are now in over 65,000 bridge structures, covering over 775,000,000 sq ft of deck. This paper presents research that outlines field and plant quality control for these products, showing that such issues have been addressed by the industry and in Standard Specifications. The paper addresses concern that was expressed in the 1980's regarding the long-term durability of epoxy-coated bars in marine structures and shows that these issues appear to be related to poor manufacturing and handling of the bars prior to placement into concrete and the use of poor quality concrete. Examples of good performance are presented, even in samples exposed to high chloride levels. It was concluded that epoxy-coated bars have been widely and successfully used to reduce deterioration of concrete structures for over 35 years.

Key Words: Corrosion, Epoxy-coated, Bridge, Reinforcing bars

INTRODUCTION

Epoxy-coated reinforcing steel bars have been used for corrosion protection in over 65,000 bridge structures in the U.S. alone, covering an area of over 775,000,000 sq ft. This paper provides an outline of the history, applications, standard specifications, corrosion protection mechanisms, manufacturing process, certification and quality, field handling techniques, field performance and current examples for this product demonstrating that epoxy-coated reinforcing steel provides a low cost, highly effective corrosion protection system for concrete.

HISTORY

Corrosion of concrete bridge structures in North America was not considered a significant concern until the 1960's as properly designed and constructed bridges before then rarely experienced corrosion-related distress.

During the winter of 1941–1942, New Hampshire became the first state to adopt a general policy of using salt; however, only 5,000 tons of salt was spread on the nation's highways that winter [1]. In the 1950's, many highway agencies began applying deicing salts to highways and bridges to keep roadways free of snow and ice. A later study conducted by Marquette University [2] found that for two lane roads, the rate for all traffic accidents before salt spreading was about eight times higher than that after and for multi-lane divided freeways, the rate for all traffic accidents before salt spreading was about 4.5 times higher than that after and that the severity of traffic accidents was reduced.

Following this increased use of deicing salts, corrosion of bridges and particularly bridge decks was observed. In response the National Bureau of Standards (now the National Institute for Standards and Technology) initiated tests on various liquid and powdered coatings [3]. Altogether, 47 different coating materials were evaluated to some extent, consisting of: 21 liquid and 15 powder epoxies; 5 polyvinyl chlorides; 3 polyurethanes; 1 polypropylene; 1 phenolic nitrile, and one zinc rich coating. These coatings were examined for their corrosion protective qualities, chemical and physical durability, and chloride permeability. Based on these tests, fusion-bonded epoxy coating applied to reinforcing steel was proposed as a way to improve the corrosion resistance of bridge decks.

Epoxy-coated reinforcing steel was first used in a bridge over the Schuylkill River in Pennsylvania in 1973. Four spans of this bridge were constructed with epoxy coated steel reinforcing bars.

Currently, 600,000 tons of epoxy-coated reinforcing bars are produced yearly in the U.S. and Canada and according to a 2004 Transportation Research Report, it remains the 2nd most common strategy to prevent reinforcement corrosion after increasing the concrete cover [4]. Other corrosion resistant reinforcing bars, such as galvanized or stainless steel occupy less than 3 percent of the total North America reinforcing bar market.

SPECIFICATIONS

The following standard specifications are available for epoxy-coated steel reinforcement:

- ASTM A775/A775M Standard Specification for Epoxy-Coated Steel Reinforcing Bars
- ASTM A934/A934M Standard Specification for Epoxy-Coated Prefabricated Steel Reinforcing Bars
- ASTM D3963/D3963 Standard Specification for Fabrication and Jobsite Handling of Epoxy-Coated Steel Reinforcing Bars
- ASTM A884/A884M Standard Specification for Epoxy-Coated Steel Wire and Welded Wire Fabric for Reinforcement
- AASHTO M284 Standard Specification for Epoxy-Coated Reinforcing Bars
- AASHTO M317 Standard Specification for Epoxy-Coated Reinforcing Bars: Handling Requirements for Fabrication and Job Site

It should be noted that AASHTO M284 references ASTM A775 in entirety and ASTM A775 is the most commonly-used specification for epoxy-coated reinforcing bars.

In most North American coating plants, reinforcing bar is coated in straight lengths and then fabricated (i.e., cut to length and bent to shape) following ASTM A775. A few facilities have the capabilities to coat reinforcing steel (both bars and welded wire reinforcement) after it has been fabricated and most of these specifications following ASTM A934.

In 1997, Gustafson documented changes in ASTM A775 from the 1980's until 1997[5]. It is widely accepted that these changes have resulted in higher quality epoxy-coated bars and improved the durability of the concrete containing these bars. Changes include:

- Reducing the number of allowable holidays
- Repair of all damaged areas prior to placement of concrete
- Inclusion of criteria to enhance adhesion of the coating to the bar such as:
    - Cathodic disbondment
    - Steel roughness
    - Coating delay
- Increasing the required coating thickness
- Increasing the angle of bend for bend tests
- Requiring protective measures if coated bars are stored outdoors for more than two months

Changes in ASTM A775 from the 1980's to 2007 are shown in Table 1.

Table 1: Changes in ASTM A775 from 1980's to 2006

Criteria	1980's	2007
Bar anchor profile	-	1.5-4 mil
Coating delay after blasting	< 8 hours	<3 hours
Coating thickness	90 percent within 5-12 mil	7-12 mil (Nos. 3-5) 7-16 mil (Nos. 6-18)
Coating continuity	< 2 holidays per foot	< 1 holiday per foot
Coating flexibility	120 degree bend	180 degree bend
Cathodic disbondment test	-	Yes
Permissible damage	No patching for damage <0.1 in^2 Maximum damage level 2 percent	All damages must be patched Maximum damage level 1 percent
External storage protection	-	Yes, if > 2 months

Research has shown that quality control is critical for the performance of epoxy-coated reinforcing bars [6]. In 1991, the Concrete Reinforcing Steel Institute (CRSI) initiated a voluntary plant certification program for the manufacture of epoxy-coated steel reinforcing bars. Developed to provide an independent certification, the program 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 steel reinforcing bars in conformance with the latest industry standards and recommendations[7, 8]. Almost all manufacturing plants within North America are certified by CRSI.

In addition to the changes that have occurred with manufacturing specifications, changes have occurred in the use of epoxy-coated bars, with fewer agencies specifying epoxy-coated bars in the top mat alone. As discussed later in this report, these changes significantly affect the corrosion of epoxy-coated bars.

FIELD HANDLING

Just like any material used on a jobsite, appropriate handling of epoxy-coated reinforcing steel is required. These steps are aimed at reducing damage to the bars that would reduce the effectiveness of the coating to perform and provide long-term protection. Fabrication and handling of epoxy-coated reinforcing bars is covered in ASTM D3963. Jobsite handling is also covered in Appendix X1 of ASTM A775.

ASTM D3963 has the following requirements:

- All visible coating damage is to be repaired.
- If the bar has more than 2 percent of its area damaged in any given 300 mm (1 ft) section, the bar may be rejected. Care should also be taken during patching as if the total bar surface area covered by patching material exceeds 5 percent in any given 300 mm (1 ft) section of coated reinforcement the bar may be rejected.
    - Both of these limits do not include sheared or cut ends.
    - These requirements were introduced in the early 1990's, based upon evaluation of field materials that indicated that the critical factor governing performance of epoxy-coated reinforcing steel was damage to the coating.

Handling requirements are described below:

- **Unloading:** Bars should be lifted using a spreader bar or strong back with multiple pick-up points to minimize sag. Nylon or padded slings should also be used. Bare chains or cables must not be used. Unload bars as close as possible to the point of placement to minimize rehandling.
- **Storage:** Store bundles of bars on suitable material, such as timber cribbing. If the bars are to be exposed outdoors for more than 30 days, cover with a suitable opaque material that minimizes condensation. Coated and uncoated bars should be stored separately.
- **Bar Supports:** Use bar supports coated with non-conductive material or plastic bar supports
- **Placement:** Lift and set bars into place, don't drag.
- **Tie Wire:** Use coated tie wire.
- **Field cutting:** Use power shears or chop saw to cut bars. Do not flame cut bars.
- **Traffic:** Minimize traffic over bars.
- **Patching:** All damage (cut ends, cracks and abrasions) should be patched using a 2-part epoxy repair material, approved by the coating manufacturer. Follow manufacturer's directions.
- **Concrete Placement:** Avoid traffic and concrete hoses on placed bars. Consider runway if necessary.
- **Vibration:** Use non-metallic or plastic-headed vibrator to consolidate concrete

While some agencies have commented that implementation of field quality control practices is difficult, it is the author's belief that those agencies that conduct appropriate field inspection prior to concrete placement will benefit from better performing structures.

FIELD PERFORMANCE

Failure of Uncoated (Black) Bars: Countries that have not utilized epoxy-coated reinforcing bars continue to be plagued by corrosion problems. For example, a 2002 report from Norway stated that more than 50 percent of all the larger concrete bridges along the Norwegian coastline either had a varying extent of steel corrosion or had been repaired due to steel corrosion and that most of these bridges were built during the last 25 years [9]. Other countries, such as Britain, have implemented widespread use of cathodic protection, which requires continuous maintenance. To date, no bridge decks within the U.S. that contain epoxy-coated bars have been replaced.

Florida Keys: In the late 1980's concern was raised regarding long-term durability of epoxy-coated reinforcing steel in marine structures, based upon observations of deterioration in the Florida Keys[10] and Florida DOT later decided not to use epoxy-coated bars in their bridge structures. Some 20 years later, only nine of the 300 structures containing epoxy-coated reinforcing steel bar in Florida exhibit corrosion deterioration [11]. Bars for these structures were reportedly left beside the ocean for up to a year prior to embedment in highly salt contaminated concrete with only 25 mm (1 in.) of cover [7]. Further, the concrete used was highly permeable and subjected to high salt loading from the marine waters. This exposure has been shown to reduce the performance of epoxy-coated bars [12].

Virginia Studies: In 1977, McKeel reported on the construction of two bridges on I-77 over Route 620 (Lambsburg Road) in Carroll County, VA [13]. These bridges were built in 1976 and were the first in Virginia to use epoxy-coated bars. Each 3-span bridge had a length of approximately 180 ft. Concrete cover was approximately 2.5 in. Two control bridges were constructed using uncoated bars and these were located north of the experimental bridges on I-77 over Route 775 (Chance Creek Rd, Rt 148).

The current NBI deck rating for both the bridges containing epoxy-coated and uncoated bars are 5; however, inspection of photos of the bridges show that the bridges over Chance Creek using uncoated bars had significantly more repair than the bridges using ECR.

In the McKeel report, it was recommended by the contractor that epoxy-coated supports and ties be eliminated from future specifications. Use of metal chairs and bare tie wire was later adopted by VDOT in August 1976, despite the recommendations for coated bars and chairs from the FHWA, industry and ASTM.

In 1996, three 17-year-old bridge decks in Virginia with epoxy-coated bars were selected for evaluation[14]. Bridge 8003, located at Prices Fork Road and Route 412, Blacksburg, showed very high chloride content at the time of evaluation with a range of chloride values for the 12 cores ranging from 1.12 to 6.56 lb/yd^3. Calculations estimated that the time for corrosion initiation in 12 percent of the bars was 7 years. Thus, even at the time of the survey, high chloride values had been present for over 10 years and that only a very small delamination in the deck was determined, located around cores SA-C1 and SA-C2.

It was reported that the average service life of bridge decks in Virginia was 36 years, with a standard deviation of 13 years and it was believed that the time for black bars to cause spalling after corrosion initiation was 5 years. Using this data, almost 5 percent of the decks should have exhibited significant distress after only 15 years. Despite this prediction, in 2008, Bridge 8003 had an NBI deck rating of 6. The recent data shows that the corrosion propagation period for bridge 8003 using epoxy-coated bars is at least 23 years in a deck with high chloride contents and significant coating damage.

The report further documents that that the holiday count for the bars in bridge 8003 was very high and that 24 of the 36 specimens had continuous holidays, while the remaining 12 had 3 or more holidays per foot. These greatly exceeded the specification limit at that time of 2 per foot of bar. The authors of that report concluded that the large number of holidays was most likely related to the saturation of the epoxy coating, coating debondment, and/or corrosion of the steel under the coating rather than the as-construction condition; however, this view cannot be supported. From discussions with coating manufacturers and bar applicators, continuous holidays are almost invariably a result of poor manufacturing procedures.

In 1998, Pyc reported on the corrosion protection performance of epoxy-coated reinforcing steel bars in 18 concrete bridge decks in Virginia [15]. Documented in this report, deck 2068 (Rt 64 over Cowpasture in Allergany Co.), which was built in 1978, was found to have a chloride level of 5.01 kg/m^3 at ½ in. from the concrete surface. It was computed that the chloride at the bar depth would have been 1.1 kg/m^3, or approximately 1.6 times greater than the corrosion threshold. It was noted that the adhesion of the coating to bars in this bridge were good. In 2008, the structure has a current NBI deck rating of 7, indicating excellent performance of the epoxy-coated reinforcing bars. Thus, the data indicates that the performance of the 170 m long bridge structure is excellent, despite having high chloride contents at the bar level.

In a study reported in 2004 by Keller[16], bridge decks were evaluated that contained uncoated and epoxy-coated bars. The bridge decks epoxy-coated bar were constructed between 1984 and 1991 using a w/c of 0.45. Of the 14 decks evaluated, only one had a delamination and that same deck had a small spall. This deck in Orange Co. had been exposed to significant chloride. In 2008, this same deck was rated by the NBI as a 6, indicating good performance.

Marine Study in Georgia and North Carolina: In 2007, a field evaluation of four bridges in Georgia and North Carolina found no concrete distress induced by corrosion of epoxy-coated bars in the substructure of four bridges[8]. The bridge at Atlantic Beach is shown in Figure 1. It was reported that coating adhesion was a poor indicator of bar performance, even though most bars examined from these bridges had greater coating damage and lower coating thickness than admissible by current specifications governing the use of epoxy-coated reinforcing steel.

Studies for MnDOT: In 2008, Minnesota DOT reported on the condition of four bridges built between 1973 and 1978 in Minneapolis. They found the bridge decks to be generally in good condition with some light cracking, few delaminated areas and only modest corrosion adjacent to expansion joints[17]. NBI ratings for the four bridges are shown in Table 1 along with average chloride contents[18].

Closer evaluation of the chloride in bridge 27062 found that only one bar was subjected to this high value. This core (DSC1) had a chloride value of 5.4 lb/yd^3 at the level of the bar. Despite this high chloride value, delamination of the concrete was not present (See Figure 2).

Figure 1: Bridge at Atlantic Beach, N.C.

Table 1: Data from four bridges in Minnesota

Year built	Bridge Number	Overlay	2008 NBI Deck Rating	Average chloride (lb/yd^3)		Delamination (percent)
				cracked	crack free	
1978	27062	No	6	14.0	1.7	1.0
1973	19015	No	7	1.0	0.3	Nil
1977	27812	Yes	7	2.0	0.4	Nil
1978	27815	Yes	7	10.2	0.4	Nil

Figure 2: Core DCS1 from bridge 27062

Studies for NYSDOT: In 2009, an analysis was conducted of the New York State Department of Transportation bridge inspection database using Markov chains and Weibull-based approaches [19]. The evaluation used historical NYSDOT bridge inspection data going back to 1981 and covered 17,000 structures. A computer program was developed to generate deterioration curves and equations for bridge elements.

The analysis found that decks with uncoated bars change from a deck rating of 7 to 4 in 49 years, while with epoxy-coated rebars, this happens in 62 years. From the study it was concluded that; "structural decks with epoxy-coated rebars perform significantly better than those with uncoated rebars, especially in the later years."

Report of Performance from SDDOT: In 2009, South Dakota celebrated a 33-year career of Mr. Wilson from their Bridge Office [20]. During his career, South Dakota had built 1,300 bridges. He implemented the use of epoxy coated reinforcing steel in bridge decks and to date, not one of those bridge decks has needed repairs or overlay due to bar corrosion.

2009 EIG Sponsored Studies: In September 2009, field studies were conducted by Wiss, Janney, Elstner Associates (WJE), on several bridges in West Virginia. Bridge 2930 was constructed in 1974. In 1993, a significant number of surface delaminations were observed near the southern section of the deck. This corrosion affected only 0.225 percent of the deck area and covered approximately 40 ft^2. At that time, this distress was linked with the performance of epoxy-coated reinforcing steel. However, recent studies of this deck found that the bridge consists of two sections, a northern 15000 ft^2 section, containing epoxy-coated bars in both mats and a southern 3000 ft^2 section containing uncoated reinforcing bars only. No delaminations were found in the epoxy-coated bar section and substantial damage was observed in the uncoated bar section.

Figure 3: Bridge 2930 in West Virginia

Evaluation of coating cure: In 2008, a report was published that concluded epoxy-coatings used on bars cracked in concrete and exhibited poor cure [21]. Detailed review of this report by the author of this paper found that that many of the conclusions cannot be supported and inappropriate techniques were used to evaluate the epoxy coating on the extracted bars.

The Report outlines work conducted using bars obtained from 27 bridges, built between 1984 and 1991. Bridges were 12 to 19 years old when inspected.

Surface cracking of the epoxy coatings was assessed using scanning electron microscopy (SEM) at a magnification of 2000 times. While surface crazing was observed, the researchers failed to demonstrate or refer to work by others that the surface crazing in any way corresponds to loss coating performance. Presumably, should such crazing penetrate to the steel surface, the electrical resistance of the coating would be lost and holidays would be detected; however, this was not shown to be the case.

Careful review of the differential scanning calorimetry (DSC) data and descriptions used found that the DSC technique used by the researchers did not follow standard industry protocol that includes a thermal relaxation step. All but one bar showed a significant glass transition temperature (Tg) shift, indicating a material change. A few were in the range that would be considered instrument variance (up to 4°C Tg shift) but for the most part they were 8-15°C shift. If this was a result of under-cure, the coated bars would exhibit extremely poor flexibility and subsequently fail the ASTM coating bend flexibility tests. This factor would have been found when bars were fabricated.

Close examination of the DSC work shows that the curves demonstrate an endothermic reaction (heat is absorbed by the system). During cure, epoxy coatings give off heat and thus residual cure of coatings show up as an exothermic reaction on DSC. Thus, the DSC method and conclusions reached used by the researchers regarding coating cure are fundamentally flawed.

CORROSION PROTECTION MECHANISMS

Steel placed into concrete develops a passive oxide film due to the high pH of the concrete. This passive film prevents further corrosion. The film may be disrupted by carbonation of the cement paste, which reduces the pH, or through the ingress of chloride ions into the concrete, from either deicing salts or sea water.

Figure 4 shows schematically the corrosion of uncoated steel in concrete. When the passive film on the steel is disrupted, either by a reduction in pH or by the ingress of chloride ions, corrosion initiates at the anode. Iron ions form, releasing electrons. The electrons flow through the steel bars to the cathode. At the cathode, water and oxygen combine with the electrons to form hydroxide. In order to balance the charges, the iron ions and hydroxide flow through the electrolyte or liquid in the concrete. The iron ions released at the anode react with oxygen to form corrosion products or rust, which occupy a greater volume than the original steel, which eventually cracks the concrete. It has been calculated that the amount of corrosion required to crack concrete is approximately 25 micron (0.001 in.)[22].

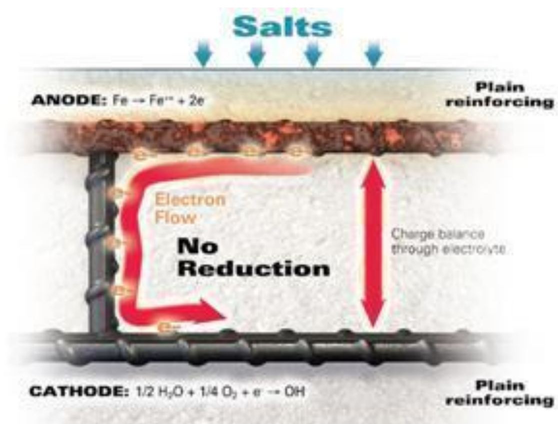

Figure 4: Corrosion of uncoated bars in concrete slab

Where epoxy-coated steel is used in only the top mat of a slab as shown in Figure 5, anodes form at breaks or holes in the coating, thus reducing the total corrosion; however, cathode locations are freely located. Thus, while the total corrosion is reduced, laboratory tests have demonstrated 60 to 93 percent reduction in corrosion rates when epoxy-coated bars are used in a top mat only [8].

A problem with using uncoated bars in the bottom of a deck that utilizes epoxy-coated top bars is that most decks will crack and provide a pathway for chloride ions to the bottom layer of reinforcing steel. Eventually, the bottom mat of the deck start corroding, reducing the service life of the deck. An example of this type of distress is shown in Figure 6.

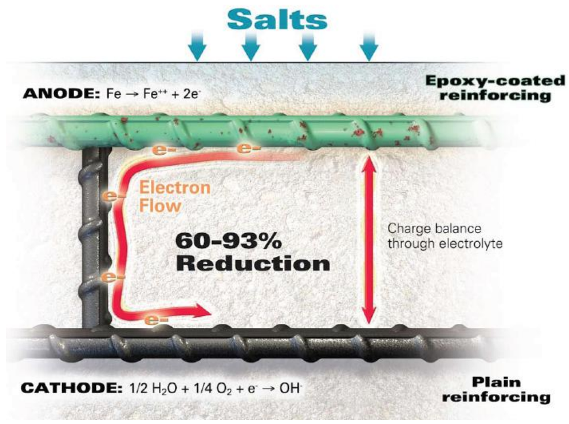

Figure 5: Corrosion of coated bars in upper mat of concrete slab

Figure 6: Deterioration of bridge deck using uncoated bars as bottom mat and epoxy-coated bars as the top mat

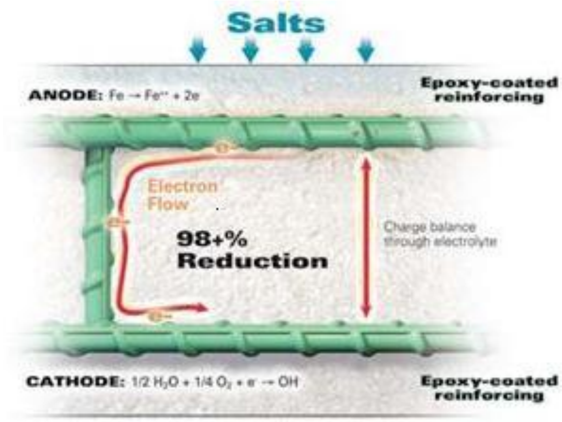

Figure 7: Corrosion of epoxy-coated bars in both mats of a concrete slab

Where epoxy-coated steel is used in both mats as shown in Figure 7, anodes may form at breaks or holes in the coating; however, cathode locations are also limited, reducing the ability of electrons to flow. Laboratory tests have demonstrated over 98 percent reduction in corrosion rates even when damage is present [23] when both mats are epoxy-coated bars.

Some researchers have suggested that the rate of corrosion of epoxy-coated bars is greater than that of non-epoxy-coated bars [21]; however, there is no laboratory or field evidence for this suggestion. In addition, it has been found that even coatings with poor adhesion to the underlying steel provide substantial increases in service life compared with black bars.

EXAMPLES OF USE

The New I-35 Bridge, Minneapolis Minnesota: Following the tragic collapse of the I-35W Bridge in Minneapolis in 2007, very high standards were set in place for bridge construction through Minnesota. The 150 m (504-ft) main span across the Mississippi River was completed in just 47 days and opened to traffic 339 days after the start of construction. The total cost of the structure was $234 million and it currently handles 140,000 vehicles per day. Design criteria included a 100-year design life. High-strength, high-performance reinforced concrete was utilized throughout the bridge along with 5000 ton of epoxy-coated reinforcing steel, manufactured according to ASTM A775 and supplied by CRSI certified plants.

The Woodrow Wilson Bridge between Virginia and Maryland: The 1800 m (6075 ft) long Woodrow Wilson Bridge is one of the most congested bridges in the nation and currently handles 200,000 vehicles per day. The bridge is one of only nine bridges on the U.S. Interstate Highway System that contains a movable span. Epoxy-coated reinforcing steel is used in the 250 mm (10 in.) thick fixed span decks. All reinforcing steel in the pile caps and pedestals is epoxy-coated. Epoxy-coated reinforcing steel is also used throughout the bascule pier. The total cost for the structure was $680 million and the two spans were opened in June 2006 and May 2008. A total of 4200 ton of epoxy-coated reinforcing was used.

CONCLUSIONS

Epoxy-coated reinforcing bars have been used in concrete structures since 1973 and their use was a result of considerable research by the National Bureau of Standards. Currently, 600,000 ton of epoxy-coated rebar is produced yearly in the US and Canada and it remains the 2nd most common strategy to prevent reinforcement corrosion, after increasing the concrete cover.

In most cases, reinforcing bar is coated in straight lengths and then fabricated following ASTM A775. Considerable improvements have been made to manufacturing and handling specifications since the 1980's and these improvements have greatly impacted concrete durability.

Research showed that quality control is important for the performance of epoxy-coated reinforcing bars and in 1991 the Concrete Reinforcing Steel Institute (CRSI) initiated a voluntary certification program for the manufacture of epoxy-coated steel reinforcing bars. Almost all manufacturing plants within North America are certified by CRSI.

Just like any material used on a jobsite, appropriate handling of epoxy-coated reinforcing steel is required. These steps are aimed at reducing damage to the bars that would reduce the effectiveness of the coating to perform and provide long-term protection. Incorporation of appropriate field inspection prior to concrete placement by purchasing agencies is routinely followed.

While in the late 1980's concern was raised regarding long-term durability of epoxy-coated reinforcing steel in marine structures; however, only nine of the 300 structures in Florida containing epoxy-coated reinforcing steel bar exhibit corrosion deterioration. Bars for these deteriorated structures were reportedly left beside the ocean for up to a year prior to embedment in highly salt contaminated concrete with only 25 mm (1 in.) of cover.

Several examples of good performance are presented, even in concrete with high chloride contents. Detailed statistical studies conducted in 2009 for NYSDOT concluded from the pool of 17,000 structures that; "structural decks with epoxy-coated rebars perform significantly better than those with uncoated rebars, especially in the later years."

Reports of widespread poor coating cure cannot be supported and there is no field or laboratory evidence that the rate of corrosion of epoxy-coated bars is greater than that of uncoated bars. In addition, it has been found that even coatings with poor bond provide substantial increases in service life compared with black bars.

Epoxy-coated bars have been widely and successfully used to reduce deterioration of concrete structures for over 35 years. To date, no bridge decks in the US containing epoxy-coated bars have been replaced. These materials provide a cost-effective, high performing corrosion protection system.

ACKNOWLEDGMENTS

Presentation of this paper would not be possible without the support of the Epoxy Interest Group of CRSI.

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