EPOXY-COATED REINFORCING STEEL BARS IN NORTHERN AMERICA

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ABSTRACT

Epoxy-coated reinforcing bars are commonly utilized within Northern America to protect structures against corrosion-induced deterioration. Epoxy-coated reinforcing has been used since 1973 and during the last 36 years has been used in over 60,000 bridges in the US along with countless parking garages, marinas and roadways. Since 1991, the Concrete Reinforcing Steel Institute has provided plant certification for plants making this product, and critical manufacturing issues relating to this certification and field handling are discussed within this paper. The paper also outlines history of use, standard specifications, manufacturing and corrosion protection mechanisms and information on the field performance and use examples are provided.

Key Words

Corrosion, epoxy, reinforcing, certification, durability

INTRODUCTION

Epoxy-coated reinforcing steel bars have been used for corrosion protection in over 60,000 bridge structures in the US, covering an area of over 72,000,000 m^2. 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 these products demonstrating that epoxy-coated reinforcing steel provides a low cost, highly effective corrosion protection system for concrete.

HISTORY

For most of the 1900's corrosion of bridge decks in Northern America was not considered a significant concern. Properly designed and constructed bridges rarely experienced corrosion-related distress. This changed dramatically in the 1950s when highway agencies began applying deicing salts to highways and bridges to keep roadways free of snow and ice. This "bare pavement" policy made roadways safer for the traveling public but resulted in a dramatic increase in deterioration due to corrosion on highways and bridges from chloride penetration. Between 1950 and 1979 annual usage of deicing salts in the United States rose from 900,000 tonne per year to 11,000,000 tonne per year (1 to 12 million ton) [1].

According to the Federal Highway Administration (FHWA), the cost of repairing or replacing structures deteriorated by corrosion was estimated to be more than $20 billion, and is said to be increasing at a rate of $500 million per year. In 1979 the General Accounting Office (GAO) noted that 32 states had more than 160,000 federal-aid system bridges that had moderate to very major corrosion problems [2].

In response the National Bureau of Standards (now the National Institute for Standards & Technology) initiated tests on various liquid and powdered coatings. These coatings were examined for their corrosion protective qualities, chemical and physical durability, and chloride permeability. Based on the testing, fusion-bonded epoxy coating applied to reinforcing steel was proposed as a way to improve the corrosion resistance of bridge decks [3].

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 540,000 t (600,000 ton) of epoxy coated rebar is produced yearly in the US and Canada and over 60,000 bridges and numerous buildings, wharfs and other structures contain epoxy-coated steel reinforcing bars. According to a report produced in 2004, it remains the 2nd most common strategy to prevent reinforcement corrosion after increasing the concrete cover [4]. Other corrosion resistant bars, such as galvanized or stainless steel bars occupy less than 3 percent of the total North American reinforcing bar market.

STANDARD SPECIFICATIONS

Within North America, several specifications are generally utilized for the specification for epoxy-coated bars. These are shown in Table 1. The most commonly used specifications are ASTM A775 and AASHTO M254. In addition, recommendations for use are found in the Concrete Reinforcing Steel Institute Manual of Standard Practice [5] and American Concrete Institute documents.

Table 1: Specification for Epoxy-coated bars and Dowels

ASTM A775/A775M-07a	Standard Specification for Epoxy-Coated Steel Reinforcing Bars
ASTM A934/A934M-07	Standard Specification for Epoxy-Coated Prefabricated Steel Reinforcing Bars
ASTM D3963/D3963-01	Standard Specification for Fabrication and Jobsite Handling of Epoxy-Coated Steel Reinforcing Bars
ASTM A884/A884M-07	Standard Specification for Epoxy-Coated Steel Wire and Welded Wire Fabric for Reinforcement
AASHTO M254	Standard Specification for Corrosion-Resistant Coated Dowel Bars

APPLICATIONS

Epoxy-Coated Steel Reinforcing Bars (rebar) may be used in any concrete subjected to corrosive conditions. These may include exposure to deicing salts or marine waters.

Bridges: In 2008, there were over 60,000 bridges out of over 700,000 in the National Bridge Inventory that contained epoxy coated steel rebar. It remains the 2nd most common corrosion protection method used by State Departments of Transportation following increased concrete cover.

Parking Decks: At least $600 million is spent yearly to repair parking decks in the U.S. This damage is primarily caused by deicing salts carried on cars and left in the garage during winter. Epoxy-coated steel reinforcing bars can protect these structures against corrosion and costly damage.

Marine Structures: Corrosion of concrete reinforcement has always been a problem in marine structures. Epoxy-coated steel reinforcing bars have demonstrated over the past 35 years that they can help reduce the damage caused by corrosion.

Pavement: Epoxy-coated steel reinforcing bars may be used in continuously reinforced concrete pavements (CRCP) and epoxy-coated dowel bars are frequently used in jointed pavements. In a recent survey of 33 transportation agencies, it was found that approximately 18 million dowel bars are used in the US each year [6]. Dowel bars are typically 32 to 38 mm (1.25 to 1.5 in.) in diameter, 460 mm (18 in.) long and spaced 305 mm (12 in.) apart. They are generally inserted into the middle of the slab and coated with a bond-breaker that prevents bond of the bars to the concrete slab. This prevents the slabs from moving in a vertical direction relative to each other, but allows them to move with changes in temperature and concrete shrinkage.

Repair: Epoxy-coated steel reinforcing bars have been used to supplement existing steel reinforcing bars during repair. These coated bars do not provide a good cathode, thus reducing the risk of “ring anode” corrosion in surrounding repair areas. Epoxy-coated dowels are frequently used in concrete pavement repairs to reduce damage at the new and old concrete intersection that often occurs if uncoated dowels are used.

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 1a shows corrosion in concrete for uncoated steel. 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. It has been calculated that the amount of corrosion required to crack concrete is approximately 25 micron (0.001 in.) [7].

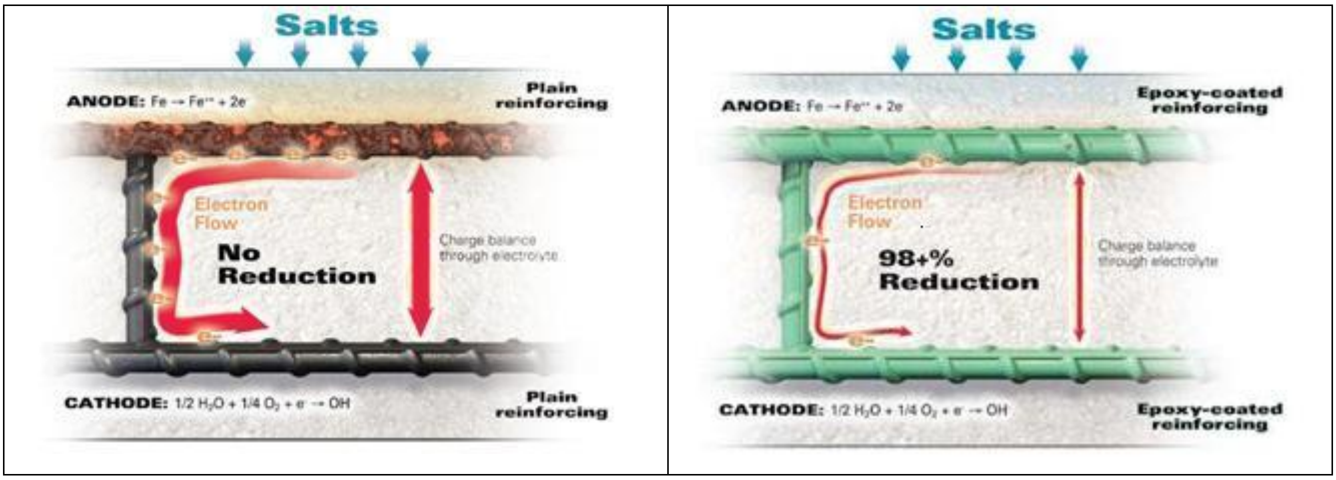

Figure 1a: Corrosion of uncoated bars in concrete slab
Figure 1b: Corrosion of coated bars in concrete slab

Where epoxy-coated steel is used in the top mat of a slab only, anodes can only 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 60-93 percent reduction in corrosion rates when epoxy-coated bars are used in a top mat only [8]. Another problem with using black bars in the bottom of a deck that utilizes epoxy-coated 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 decks start corroding, reducing the service life of the deck.

Where epoxy-coated steel is used in both mats as shown in Figure 1b, anodes may form at breaks or holes in the coating; however, cathode locations are also limited, reducing the ability for electrons to flow. Laboratory tests have demonstrated over 98 percent reduction in corrosion rates even when damage is present [8].

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

MANUFACTURING AND QC PROCESS

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 fabric) after it has been fabricated following ASTM A934. Regardless of the facility's configuration, the four basic steps manufacturing steps are required.

1. **Surface Preparation:** Reinforcing bars are blast-cleaned to a near white metal finish using abrasive grit. This cleans the steel of contaminants, mill scale and rust. It also roughens the surface to give it a textured anchor profile. During this process, salt contamination is also removed.
2. **Heating:** Bars are heated to approximately 230°C (450°F), typically using electrical induction heaters.
3. **Powder Application:** The heated steel is passed through a powder-spray booth where the dry epoxy powder is emitted from a number of spray nozzles. As the powder leaves the spray gun, an electrical charge is imparted to the particles. These electrically charged particles are attracted to the grounded-steel surface providing even coating coverage. When the dry powder hits the hot steel, it melts and flows into the anchor profile (i.e., the microscopic peaks and the valleys on the surface) and conforms to the ribs and deformations of the bar. The heat also initiates a chemical reaction that causes the powder molecules to form complex cross-linked polymers which give the material its beneficial properties.
4. **Cure:** Following powder application, the coating is allowed to cure for a short period (approximately 30 seconds) during which time it hardens to a solid. In some plants, the curing is often followed by an air or water quench that quickly reduces the bar temperature to facilitate handling.

Many different research programs have shown that quality control is critical for the performance of epoxy-coated reinforcing bars [9]. In response, the Concrete Reinforcing Steel Institute (CRSI) initiated a voluntary certification program for the manufacture of epoxy-coated steel reinforcing bars starting in 1991. 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. Almost all manufacturing plants within North America are certified by CRSI.

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 steel is covered in ASTM D3963 Standard Specification for Fabrication and Jobsite Handling of Epoxy-Coated Steel Reinforcing Bars. Jobsite handling is also covered in the Appendix X1 of ASTM A775.

ASTM D3963 requires all visible coating damage to be repaired. If the bar has more than 2 % 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 % 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. It should be noted that 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 concrete 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 plastic headed vibrator to consolidate concrete

FIELD PERFORMANCE

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% 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 [10].

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 [11]. Some 20 years later, only five of the 300 structures containing epoxy-coated reinforcing steel bar in Florida exhibit corrosion deterioration and it is widely believed that this deterioration was due to extremely poor bar manufacturing and site construction practices. Bars were also 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 [12]. This exposure has been shown to reduce the performance of epoxy-coated bars [13].

Many field studies have been conducted on epoxy-coated reinforcing steel bars over the past 35 years that has found good performance. For example, in 2007 a study conducted in Georgia and North Carolina found no concrete distress induced by corrosion of epoxy-coated bars in the substructure of four bridges [14]. In this study 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 standards governing the use of epoxy-coated reinforcing steel.

In 2008, Minnesota DOT reported on the condition of four bridges built between 1973 and 1978 which were found to be generally in good condition with some light cracking, few delaminated areas and only modest corrosion [15].

A 2009 study from NYDOT evaluated Bridge Element Deterioration Rates using data from field inspections of bridge structures with and without epoxy-coated bars. This report 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 [16]."

In 2009, South Dakota celebrated a 33-year career of Mr. Wilson from their Bridge Office [17]. During this time 1,300 bridges were built. 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 rebar corrosion.

During September 2009, studies were conducted by Wiss, Janney, Elstner Associates (WJE), on Bridge 2930 in West Virginia. This bridge was constructed in 1974, making it one of the oldest in the world. In August 1993, a significant number of surface delaminations were observed near the southern section of the deck. This corrosion accounted for 0.225% of the deck area and covered approximately 4 m^2 (40 ft^2). At that time, this distress was linked with the performance of epoxy-coated reinforcing steel. In the recent studies it was found that the bridge consists of two sections, a northern 1300 m^2 (15000 ft^2) section, containing epoxy-coated bars in both mats and a southern 300 m^2 (3000 ft^2) section containing black reinforcing bars. No delaminations were found in the epoxy-coated bar section and substantial damage was observed in the black bar section.

Some literature concluded that loss of coating adhesion leads to catastrophic corrosion failure [18]; however it has been found that adhesion loss and concrete distress are not directly related and widespread corrosion failure has not been observed, despite bars being in concrete with relatively chloride levels. That paper also commented on poor coating cure; however, industry studies determined that these conclusions could not be substantiated [19].

In addition to field studies, many laboratory studies have verified the performance of epoxy-coated reinforcing steel [8, 20].

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 as well as the United States. The 150 m (504-ft) main span across the Mississippi River was completed in just 47 days and opened to traffic 339 days after start of construction. The total cost of the structure was $234 million and it is currently handles 140,000 vehicles per day. High-strength, high-performance reinforced concrete was utilized throughout the bridge along with 4500 t (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 it 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 3800 t (4200 ton) of epoxy-coated reinforcing was used.

Georgia Aquarium, Atlanta Georgia: The Georgia Aquarium was opened in 2005 and is the largest aquariums in the world, housing more than 100,000 animals of 500 different species. Over 76,000 m^2 (100,000 yd^3) of concrete of concrete were used along with epoxy-coated reinforcing steel.

Crystal Bridges Museum of American Art, Bentonville Arkansas: The Crystal Bridges Museum of American Art is being built in 40 hectare (100 acres) of forest in Bentonville, Arkansas. The 9200 m^2 (100,000 ft^2) building contains two structures, which are both dams and bridges, that cross a ravine forming two great ponds. These structures are formed using concrete containing epoxy-coated reinforcing bars.

Trump Tower, Chicago Illinois: The 96-story trump tower was designed by Skidmore Owings and Merrill. This 415 m (1362 ft) building is adjacent to the main branch of the Chicago River, with a view of the entry to Lake Michigan beyond a series of bridges over the river. In order to protect the parking deck from corrosion damage, the first 12 stories of the structure contain epoxy-coated reinforcing steel.

CONCLUSIONS

Epoxy-coated steel reinforcing bars may be used in any concrete subjected to corrosive conditions. These include bridges, parking decks, marine structures, and pavements and the material may also be used during concrete repair. These bars have been used for corrosion protection in over 60,000 bridge structures in the US, covering an area of over 72,000,000 m^2. It remains the 2nd most common strategy to prevent reinforcement corrosion, after increasing the concrete cover.

Countries that have not utilized epoxy-coated reinforcing bars continue to be plagued by corrosion problems. Many field studies on epoxy-coated reinforcing steel bars over the past 35 years have found good performance including recent reports from Minnesota, Georgia, North Carolina, New York, South Dakota and West Virginia.

Some literature concluded that loss of coating adhesion leads to catastrophic corrosion failure; however it has been found that adhesion loss and concrete distress are not directly related and widespread corrosion failure has not been observed, despite bars being in concrete with relatively chloride levels. Despite concerns expressed in the 1980’s, only five of 300 structures in Florida containing epoxy-coated reinforcing steel bar exhibit corrosion deterioration. It is now widely believed that this deterioration was due to extremely poor bar manufacturing and site construction practices.

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