DO EPOXY-COATED BARS PROVIDE COST-EFFECTIVE CORROSION PROTECTION?

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ABSTRACT

This paper discusses issues relating to the performance of epoxy-coated bars and provides updated information on alternative products. The ongoing development of specifications for these products will be presented. Finally, the difficulty of cost analyses for long-life corrosion protection systems will be outlined. The data will demonstrate that epoxy-coated bars are cost-effective and provide long-lived corrosion protection for concrete.

INTRODUCTION

In 1974, a report was presented by the National Bureau of Science on forty-seven coating types that were tested to protect reinforcing steel against chloride induced corrosion (1). Since then, over 720,000,000 sq ft of deck have utilized fusion-bonded epoxy-coated bars in over 65,000 bridge decks. Numerous other structures have been protected in North America through the use of epoxy-coated bars. In the 1980s, concern was raised regarding the effectiveness of these products based upon poor performance observed in the Florida Keys. Since then, considerable research has been conducted and over 200 research papers have been presented on the performance of epoxy-coated reinforcing bars, making them the most researched corrosion protection system for reinforcing steel.

RECENT FIELD STUDIES DEMONSTRATING EXCELLENT PERFORMANCE

During the past 37 years epoxy-coated reinforcing has demonstrated excellent performance and widespread failure predicted by some researchers in the 1990s due to corrosion of epoxy-coated bars has not been observed. Some of the more recent field studies are presented below.

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 (2). In that 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 specifications governing the manufacture of epoxy-coated reinforcing steel.

Minnesota

In 2008, studies were conducted on four bridges built in the 1970s in Minnesota containing epoxy-coated bars (3). The bridge decks were found to be in generally good condition, with few delaminated areas and only modest corrosion. While the researchers found no sign of increased corrosion activity in coated bars in the bridge with a lower mat of uncoated bars, rust stains on the bottom of the deck suggested corrosion activity in these bars. Minnesota Department of Transportation continues to use epoxy-coated bars in both mats for decks.

New York State

In 2009, a report was published by NYSDOT that utilized bridge inspection data from over 17,000 highway bridges across the state (4). A comparison was made considering cast-in-place structural decks made using either black or epoxy-coated bars. The analysis concluded that "*…structural decks with epoxy-coated rebars perform significantly better than those with uncoated rebars, especially in the later years. This is because of higher corrosion in decks with uncoated rebars."*

West Virginia

In 2010, the performance of bridge decks in West Virginia was evaluated (5). This study found that the 33 – 35 year old decks containing epoxy-coated bars were generally in good to excellent condition, whereas companion black bar decks were overlaid or otherwise rehabilitated after 18 to 21 years to address deterioration of the deck surface. No delaminations were observed in decks containing both upper and lower mats of epoxy-coated reinforcing steel, despite high chloride contents in the concrete.

The report further found that the limited active corrosion in the epoxy-coated bars correlated to three factors: high chloride concentration, low coating thickness and extended exposure to chloride concentrations above the black bar chloride threshold.

UNDERSTANDING REASONS FOR POOR PERFORMANCE

Probably the most critical reports on the use of epoxy-coated bars have been based upon deterioration observed in bridges in the Florida Keys. Corrosion distress was observed at the water-line in the $45 million Seven-mile Bridge in the mid-1980s, within 6 years of construction. Overall, only 9 of the 300 structures containing epoxy-coated reinforcing steel bar in Florida exhibit any corrosion deterioration (6). Reportedly coated bars were left beside the ocean for up to a year prior to embedment in highly salt contaminated concrete with only 1 in. of cover (7). Further, the concrete used was highly permeable and subjected to high salt loading from the marine waters. Hearsay evidence indicates that the bars were corroding and "bleeding red rust" prior to placement into the concrete in several of these structures. Thus, while costly to Florida, the performance observed in these select structures is not believed to be indicative of the performance of epoxy-coated bars in general.

In 1994 Sagues et al. reported on side-by-side bridges (700181 and 700174) constructed in 1985 on US-42; one containing epoxy-coated bars and the other with black bars (8). At that time, the bridge constructed using black bars exhibited visual corrosion, while the one using epoxy-coated bars did not. In 2010, visual examination of these two structures revealed that corrosion induced damage was significant on the black bar bridge, whereas the bridge containing epoxy-coated bars did not exhibit corrosion-induced deterioration. A similar pair of bridges (700077 and 700143) on SR-404 was built in 1971 using black bars. In 2006, these structures required approximately $1.2 million to repair corrosion-related deterioration.

These limited examples demonstrate that, even though the performance of epoxy-coated bars in some locations in Florida were less than expected, performance of these structures with black reinforcing bars would have been even worse. Further, the importance of manufacturing and field quality control are now well recognized.

SPECIFICATIONS FOR EPOXY-COATED BARS

Since the 1990s, significant work has been conducted improving the manufacturing specifications for epoxy-coated bars. In the 1980s, one researcher reported that backside contamination, which is a measure of bar cleanliness prior to coating, was commonly greater than 40 percent (9). Such conditions would certainly lead to poor coating adhesion. The CRSI Voluntary Plant Certification Program, which was introduced in 1991, requires that backside contamination be less than 15 percent (10).

In a field study conducted in Virginia, bars that were manufactured in the 1980s exhibited holiday counts that greatly exceeded the specification limit at that time (11). Such poor manufacturing practices will certainly lead to poor durability.

The most commonly used standard for epoxy-coated reinforcing is ASTM A775 *Standard Specification for Epoxy-Coated Steel Reinforcing Bars*. Table 1 presents the chronology of ASTM A775, showing changes that have been made to this standard in a response to field and laboratory research. The most important changes include the introduction of anchor profile, which would improve the bond of the coating to the steel, the requirement for all damage to be repaired, and the increase in coating thickness.

ASTM D3963 *Standard Specification for Fabrication and Jobsite Handling of Epoxy-Coated Steel Reinforcing Bars* should be used to specify handling and fabrication of epoxy-coated bars. Further, bars should be purchased from plants that are certified under the CRSI Voluntary Plant Certification Program.

Table 1: Chronology of changes to ASTM A775

Year	Change	Prior version
1981	First version approved	-
1989	Permissible damage reduced to 1%	2%
1989	Introduction of anchor profile of 1.5-4 mil	-
1990	Repair of all damage	Repair of damage >0.1 in.^{2}
1993	Coating thickness 7 – 12 mil	90 percent between 5 and 12 mil
1994	Increase bend test to 180°	120°
1995	Reduce allowable holidays to less than 1 per foot	2 per foot
1995	No coating deficiency allowed	0.5 percent
1995	Coat within 3-hours	8 hours
1997	Coating adhesion CD test	-
1997	Cover bars stored outside if longer than 2 months	-
2004	Coating thickness increased for larger diameter bars. 7-16 mil (Nos. 6-18)	7 – 12 for all bar sizes
2004	Clarified individual thickness measurements No single measurement <80% of minimum or >120% of maximum	-
2006	Clarification on thickness measurements added	-
2007	Added patching material requirements	-

DESIGN LIFE PREDICTION

Simplified models have been used by many to understand corrosion deterioration and to predict service lives of concrete structures. The most common is based upon work by Tuuti (12), shown in Figure 1 that includes:

1. Time for corrosion initiation (T_i)
2. Time for crack propagation (T_c)
3. Time to repair where surface cracks evolve into spalls (T_s)

The model by Tuuti is subject to considerable input variability as shown schematically in Figure 2.

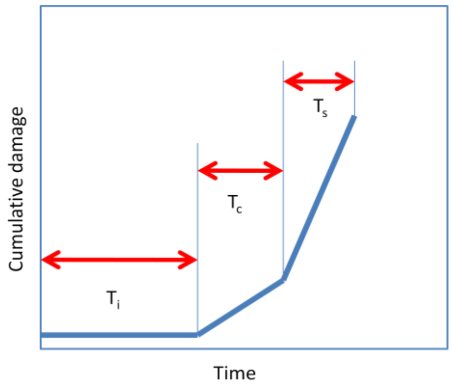

Figure 1: Simplified model of cumulative concrete damage (after Tuuti)

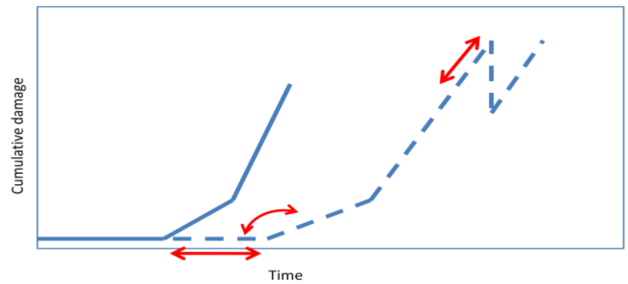

Figure 2: Schematic model showing the wide range of predicted design lives dependent on model assumptions

The predicted life of a concrete structure requires detailed knowledge of the following:

- Surface applied chloride
- Concrete permeability
- Effect of cracks on permeability
- Amount of cracking
- Corrosion threshold for a particular reinforcing
- Rate of corrosion
- Oxide expansion
- Acceptable deterioration prior to repair
- Repair options
- Repair durability
- Estimated design life

Many models use Fick's Second Law of Diffusion to calculate the ingress of chloride into sound concrete, using estimated clear cover, concrete diffusion coefficients and the amount of applied chloride.

The amount of chloride on a deck is highly variable as shown in Table 2 (13). Future salt use is difficult to predict and may be affected by the amount of atmospheric moisture (14).

Table 2: Salt applications in various states.

State	Salt Applications					
	tons/lane mile			times /year		
	Maximum	Minimum	Average	Maximum	Minimum	Average
Illinois	15	2.4	6.5	93	12	50
New Jersey	6.5	2.75	4.5	44	30	37
Pennsylvania	6.25	0.75	3.5	50	10	30
Utah	9	0.1	2.5	60	2	25
Wisconsin	30	8	12	205	50	85

The permeability of bulk concrete is determined by the pore structure, chemistry of the cement and additives along with the water-cement ratio and types and quantities of aggregates. Review of literature finds significant variations in the estimated values of permeability for similar concretes. For example;

Lawler and Krauss (15) presented life-cycle results using 0.15 in^2/yr, for concrete with a w/c of 0.42, whereas the computer program Life-365 uses a value of 0.43 in^2/yr (16).

Prediction of chloride ingress using bulk concrete properties is complicated by the presence of cracks and most models do not consider the effect of cracks at all. Lawler and Krauss(15) provide a methodology for consideration of cracks, whereby they increase the permeability of the bulk concrete by a factor of 5 and make an assumption as to the amount of deck area covered by cracks.

Once a model is defined to establish chloride ingress, then additional assumptions must be made regarding the amount of chloride to initiate corrosion. Brown et al. (17) report that commonly cited threshold concentration values are approximately 1.2 lb/yd^3 of chloride ion by weight of concrete or 0.2% chloride by weight of cement; however, Azad (18) reports that the threshold level varies from 1.0 to 2.1 lb/yd^3 chloride ion by weight of concrete. He further reported that there is no consensus on the permissible limits of chloride concentration but a concentration level of 0.35-1.0% by weight of cement may trigger corrosion.

The effect of variability, such as that described above for diffusion and surface chloride, as well as cover on the calculated time to corrosion initiation using a Fick's model is shown in the example in Table 3. Here, moderate changes in input variables may increase the time to corrosion initiation from 11 to 42 years. Such changes will have significant impact on any further cost calculations.

Table 3: Example demonstrating effect of changes in variables on predicted time to corrosion initiation using Fick's diffusion

Parameter	Assumption 1	Assumption 2
Cover (in.)	2.8	3.2
Permeability (in.in/year)	0.15	0.075
Surface chloride (lb/cu yd)	10	7.5
Assumed threshold (lb/cu yd)	1.2	1.5
Calculated time to corrosion initiation (years)	**11**	**42**

The propagation period involves the period after initiation and includes the period to cracking and repair. For black reinforcing bars, many of the current models assume a standard 5-year propagation period that appears to be based upon limited research (19). Kranc and Sagues (20) have included variables such as temperature, oxygen availability, cathode areas and concrete resistivity in detailed models for concrete piers; however, such models are significantly complicated when subjected to varying environmental conditions, such as bridge decks.

Assumptions regarding the propagation period have been made for other materials. For epoxy-coated bars a standard propagation period of 20 years has been proposed; however, the rate of corrosion of epoxy-coated bars is significantly influenced by the availability of cathodic areas (5). As few structures containing epoxy-coated bars have required repair, this value is regarded as conservative and results in conservative estimates of design life.

Many transportation agencies rely on the individual districts to determine the timing of repairs. Fitch et al. reported that deck rehabilitation decisions are made on the following (21):

- Amount of deterioration
- Available funding and labor
- Condition of the superstructure
- Volume of traffic

- Rate of physical deterioration

Fitch et al. examined data from 18 structures that had been rehabilitated in the previous year and found decks had damage (spalling, delamination and patching) ranging between 1.0 and 29.8 percent of the deck surface (21).

Assumptions must be made to the effectiveness of repairs, however; representative data on the performance of repairs is scant. Many of the models assume a 10 year period for patch repairs and 20 years for an overlay. A report by Michigan DOT indicates that a deep overlay that goes below the bar has a life of 25 years, whereas a shallow overlay has a life of 15 years (22).

The above discussions highlight that the prediction of service life requires significantly more information than generally available. While some have attempted to include statistical variability, the resulting lives are subject to significant input interpretation and consequential error.

ALTERNATIVE REINFORCING

Other types of reinforcing have been proposed for use in concrete. These include: solid stainless steel (ASTM A955), clad stainless steel, zinc and epoxy dual-coated (ASTM A1055), galvanized (ASTM A767), and low carbon chrome (ASTM A1035). All of these products provide improved performance over black reinforcing bars; however, only stainless steel bars have demonstrated improved corrosion performance over epoxy-coated bars.

It should also be noted that care should be taken in choosing the type of stainless steel for reinforcing bars as some have failed to perform adequately (23). Galvanized and low carbon chrome bars have failed to perform greater than epoxy-coated bars in laboratory tests and have not been recommended as a replacement for epoxy-coated bars (24).

The cost of black reinforcing bars is around $0.25/lb and epoxy-coating generally adds $0.10 – 0.20/lb. According to the Galvanized Reinforcing Resource Center[1], galvanized bars cost around $0.05/lb more than epoxy-coated bars. Bars meeting ASTM A1035 are approximately $0.80/lb. Stainless steel bars may cost $3 - $5/lb dependent on the grade. Stainless-clad bars are not currently manufactured in North America, but have been reported to cost around $2.50/lb.

Initial costs remain an important factor for selection of construction materials. McDonald et al. found that use of stainless steel reinforcing may increase the total cost of a bridge by 6 to 15 percent (25) while the cost of epoxy-coated bars increase the deck by a more modest 0.5 – 3 percent.

LIFE CYCLE COST ANALYSES

The FHWA "*promotes Life-Cycle Cost Analysis (LCCA) as an engineering economic analysis tool that allows transportation officials to quantify the differential costs of alternative investment options for a given project.*" However; NCHRP Report 483 states (26):

> *"Application of life-cycle costing to bridges is not a straightforward procedure. The professional performing the analysis must have a working knowledge of economic principles; be acquainted with bridge repair techniques, costs, and effectiveness; have access to a good costing database; know the most likely alternatives to be pursued; and have a good knowledge of how a bridge behaves over the long term. Poor decisions can result if the user applies the wrong assumptions."*

Kepler et al. discussed the cost of repair and found that a significant portion of the total cost of the repair comes from incidental costs, rather than the actual repair or material costs (27). These incidental costs

[1] http://www.galvanizedrebar.com/cost_economics.htm

include: mobilization, traffic control, and repairs and improvements to other parts of the bridge, such as drains, barrier rails, and approaches. For 27 bridges in Kansas, Kepler et al found that repairs averaged $12/sf, with a minimum of $3/sf and a maximum of $26/sf.

The Office of Management and Budget (OMB) provides discount rates for use in purchasing decisions. In 2010, the real discount rate presented is 2.8 percent for a 30 year program; however, rates over the past 30 years have ranged from 2.8 per cent in 2009 to 7.9 percent in 1982. Low discount rates favor materials with high durability requiring little or no maintenance. Using the values of 2.8 and 7.9 percent discussed above, the present value of a $100 repair in 20 years will be $57 or $22, respectively. If the same $100 repair does not occur until after 60 years, the present values will be $19 or $1, respectively.

As shown above, cost calculations that are frequently presented are subject to significant interpretation and consequent errors.

MODEL CALIBRATION

A commonly used program for determination of corrosion performance of concrete structures is LIFE-365 (16). This program includes a Tuuti calculation model as well as a life-cycle cost program. While frequently used, this program and many similar programs have not undergone rigorous calibration against the performance of real structures. Two examples using LIFE-365 are presented.

A calculation was made using the program for a bridge deck in Chicago with a thickness of 9 in. a cover of 2.5 in., and a 0.44 w/c concrete. The program calculates that the chloride threshold will be reached after only 4.5 years and that spalling of black bars will occur after 10.5 years. For epoxy-coated bars the program assumes that the corrosion threshold for epoxy-coated bars is the same as that for black bars. The program then calculates a service life is 24.5 years. There have been no instances where epoxy-coated bars have failed within this service period in Illinois and that the decks with epoxy-coated bars in Illinois are performing well after almost 35 years of use.

A second calculation to determine the design life of a circular column with 3 in. of cover in a marine tidal environment located in Miami. The program calculates that for a 0.42 w/c ratio concrete spalling of black bars would occur after only 8 years, whereas Type 316 stainless will spall after only 15 years, clearly in error. No researcher has been able to make Type 316 corrode within concrete in any test.

ALTERNATE PROTECTION SYSTEMS

Designers are presented with a wide choice of corrosion protection systems. Along with different bar types, designers may include concrete additives such as silica fume and fly ash that reduce permeability, corrosion inhibitors, or use coatings or sealers to reduce chloride ingress.

In 2004, Russell presented a synthesis of highway practice relating to concrete bridge decks (28). He found that strategies to reduce corrosion included use of increased concrete cover, low-slump dense concrete overlays, latex-modified concrete overlays, interlayer membranes, asphaltic concrete systems, and epoxy-coated reinforcement. In the survey the three strategies currently being used by most respondents to prevent corrosion of reinforcement in bridge decks were increased clear cover to the reinforcement, epoxy-coated reinforcement, and low-permeability concrete.

Russell found that concretes with low water-cementitious materials ratios and supplementary cementitious materials resulted in concretes that led to an increase in the amount of cracking, which provides the chlorides with an easier path to the reinforcement. He further reported that results with membranes appear to be mixed and that the life of the membrane system is limited more by the life of the protective cover over the membrane than by the life of the membrane itself.

DEALING WITH UNCERTAINTY

Bertrand Russell stated "*Everything is vague to a degree you do not realize till you have tried to make it precise* (29)." In this statement, he could have been talking about life-cycle cost analysis. As shown above, life-cycle analyses are full of nuances that may substantially modify conclusions. Any product can be made cost effective, dependent on the assumptions. For example, black reinforcing bars become cost effective if the discount rate is high. A paper by Lawler and Krauss (15) showed in their analysis that the choice of the most cost-effective corrosion-protection system based upon cost alone was highly dependent on the variables selected.

So, what factors should a designer consider in selecting a corrosion protection system?

The first is to consider the experience that has already been gained from the 700,000 bridges already in existence in North America. In the last 37 years, epoxy-coated bars led to substantial maintenance cost savings.

The second is to deal with the reality of initial cost. It is difficult to justify using money on unproven technologies or those that will increase the cost of the structure by 10 percent. Structures with epoxy-coated bars have already provided their initial 40 year design life and they appear to be ready to provide many future years of service.

The third consideration is that agencies should consider structural use. There may be occasions when exotic and expensive bars are justified; however, these should be limited to those situations where repair is difficult and traffic disruption causes significant issues.

Finally, agencies need to ensure that products are installed correctly and that concretes used are appropriate.

SUMMARY AND CONCLUSIONS

This paper outlines the use and performance of epoxy-coated bars during the past 37 years. While instances of minor corrosion have been detected, the bars have provided suitable corrosion protection compared with black reinforcing bars and other systems. Where corrosion has been observed, it has generally been related to cracked concrete, low coating thickness and high chloride levels.

The paper discusses the performance of bridges in the Florida Keys and concludes that the performance of these structures is not indicative of the performance of epoxy-coated bars in general, but a result of poor manufacturing, handling and installation.

The importance of manufacturing and field quality control are presented along with changes in these specifications over time. The product produced in 2010 is significantly better than the product produced in the 1970s and these changes should provide improved durability.

A review of life-cycle modeling is presented. This review demonstrates the large number of variables that can substantially affect conclusions. Further, the paper discusses issues such as repair cost and life as well as discount rates. Examples demonstrating variability and risks of poor modeling are presented.

A brief review of other reinforcing bars is presented, indicating that while all of these products provide improved performance over black reinforcing bars; only stainless steel bars have demonstrated improved corrosion performance over epoxy-coated bars. Choice of stainless steel reinforcing may increase the total cost of a bridge, eliminating them from economic consideration. The risks of cracking in high performance concretes and the potential increase in chloride penetration are discussed.

The paper concludes that designers and specifiers should consider the experience gained from 65000 structures containing epoxy-coated bars over the past 37 years. Structures with epoxy-coated bars have already demonstrated a 40-year design life and they appear to be ready to provide many additional years of low maintenance service. For these reasons, epoxy-coated bars provide cost-effective corrosion protection.

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