Cost-Effective Methods for Improving the Corrosion Resistance of Concrete

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ABSTRACT

During the past 40 years, substantial changes have occurred in concrete and reinforcing bar technologies used to reduce corrosion-induced damage in concrete structures. This paper will describe protection mechanisms and an overview of products that may be used to reduce corrosion damage. Systems reviewed include pozzolans, corrosion-inhibitors, galvanized, epoxy-coated and stainless steel reinforcing. The cost-effectiveness of various systems will also be discussed.

Keywords: Corrosion, Concrete, Durability, Cost, Epoxy-coated, Reinforcing Steel

INTRODUCTION

The deterioration of concrete structures due to corrosion has resulted in significant economic impact to public and private investments. For example: an analysis by the Federal Highway Administration (FHWA) in 2001 concluded that the annual cost of corrosion in the public port authority sector of the ports and waterways can be estimated at $182.3 billion[1], and the average annual direct cost of corrosion for highway bridges (including steel) was estimated to be $8.29 billion[2]. Over 24,000 parking garages are located throughout the United States; however, at least $600 million is spent yearly to repair parking decks, typically a result of corrosion from deicing salts carried into the garage by cars. Parking garages without appropriate corrosion protection may show deterioration within 10 to 15 years and costs for repairs may exceed $10/sf[3]. In addition, contractors generally need to remove a minimum of 100 spaces from service in order to affect a repair, which affects revenue in pay-to-park structures. Thus, it is important to understand available options for reducing damage due to corrosion in concrete structures and to analyze the economic consequences of these decisions.

CAUSES OF CORROSION

For corrosion to occur, four factors are required – (i) anode, (ii) cathode, (iii) an electrical pathway and (iv) an ionic path as shown in Fig. 1 for uncoated steel. At the site of corrosion an anode forms, where electrons are released and the metal is converted into a metal ion. These electrons travel through an electrical path to the cathode. At the cathode, electrons react with ions in the concrete, such as water and oxygen. Finally, an ionic pathway is required between the anode and cathode to maintain charge balance within the corrosion cell. Interruption of any of these factors slow corrosion.

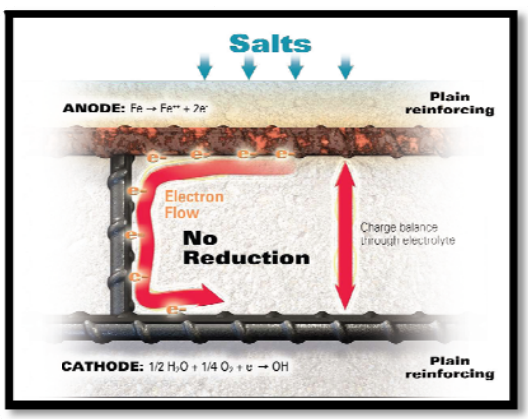

Fig. 1 Corrosion Cell: Anode, Cathode, Ionic and Electrical Path.

Anode formation for uncoated steel in concrete may be initiated by the breakdown of the protective oxide films that forms on the surface of the steel due to the high pH of the concrete. This protective film loses effectiveness in the presence of sufficient chloride or if the concrete experiences a reduction in pH. The most common cause of corrosion in concrete structures in North America is the ingress of chloride ions from deicing salts or marine waters. A reduction of pH may occur when carbon-dioxide in the environment reacts with the calcium hydroxide in the cement paste through a process termed "carbonation." Methods used to mitigate damage from chloride ions have largely mitigated carbonation-induced deterioration.

It generally takes a certain quantity of chloride to induce corrosion and this level is typically termed the *"corrosion threshold."* Once the critical corrosion threshold has been reached, the corrosion propagates until expansive forces from the oxides crack or delaminate the concrete covering the bars. The time for this process to occur is termed the propagation period and is highly dependent on the cathodic area, as well as the moisture, air and water contents of the concrete.

The exact mechanism of corrosion of steel due to the accumulation of chloride ions is not well understood, but it is believed that chloride ions enhance the iron dissolution through the formation of a soluble iron chloro-complex with green rust as the main solubility-limiting phase [4].

INGRESS OF CHLORIDE

The ingress of chloride into sound concrete is frequently assumed to follow Fick's 2nd Law of diffusion, which depends largely on the diffusion coefficient for the particular concrete. It is generally expressed as shown in Equation 1.

$$C(x,t) = C_s - C_s.erf\left[\frac{x}{2\sqrt{D_{eff}.t}}\right] \qquad \text{(Equation 1)}$$

Where

C_s = surface concentration of chloride
D_{eff} = effective diffusion coefficient
x = concrete cover
t = time
C(x,t) = concentration at depth (x) and time (t)

The time (t) for chloride ions to penetrate sound concrete is dependent on the concrete permeability (D), the amount of chloride at the surface of the concrete (Cs) and the distance that the reinforcing bar is away from the concrete surface or cover (x). To increase the time until the critical chloride threshold is reached, the effective diffusion coefficient (D_{eff}) may be decreased or the cover (x) increased. In practice, increasing the cover for horizontal surface above 75 mm (3 in.) or for vertical surfaces above 100 mm (4 in.) is impractical and may lead to substantial additional cracking.

While Equation 1 is mathematically elegant, concrete is frequently non-homogenous and diffusion coefficients and chloride exposures in various areas of the structure may be substantially different. Further, cracks may propagate through to the reinforcing steel, nullifying any benefits from low diffusion coefficients.

In 2006, Lindquist et al. presented data on the effect of cracks on chloride ingress for bridge decks[5]. Chloride contents at different deck ages are presented in Fig. 2 at a depth of 3 in. for bridge decks with average annual daily traffic greater than 7,500. The chloride contents increase with deck age, even at cracked locations.

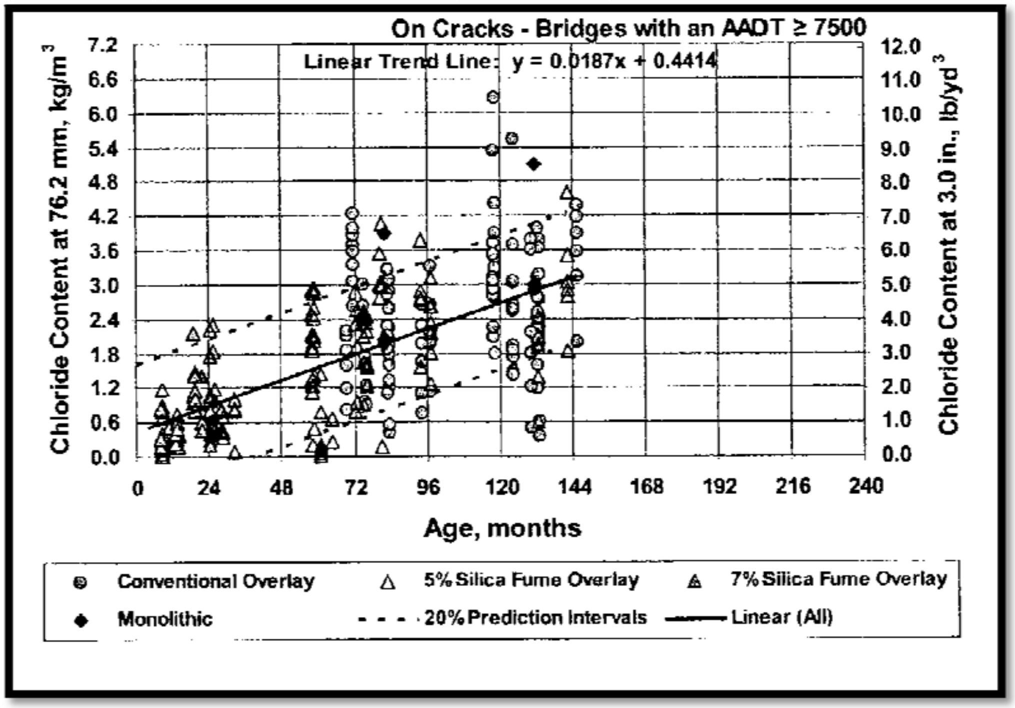

Fig. 2 Chloride content taken on cracks interpolated at depth of 3 in. vs. placement age for bridge decks with AADT > 7500 [5].

CORROSION PROTECTION

There are many methods of providing corrosion protection to concrete and the performance of various types of concrete, reinforcing bars and corrosion-inhibitors has been subject to significant research over the past 40 years.

CONCRETE PERMEABILITY

One approach to increasing the time until corrosion initiates is to reduce the concrete permeability. Reducing the permeability of the concrete also reduces ionic flow, slowing the corrosion current and extending the propagation period. Principal methods used to reduce the permeability of the concrete are through reduction of the concrete water-cementitious ratio, or through the addition of pozzolans, such as silica fume, fly ash and slag cement (ASTM C1240, C618, and C989). It is possible to reduce the concrete permeability by an order of magnitude substantially delaying the onset of corrosion.

Methods used to reduce concrete permeability may also result in the concrete having a higher elastic modulus and reduced creep, increasing the risk of cracking and thus providing a ready pathway to allow chloride to penetrate directly to the reinforcing. Individual mixtures may be evaluated for cracking resistance using ASTM C1581. Additional consideration of thermal and early age cracking should also be made.

INHIBITORS

Corrosion inhibitors may be specified using ASTM C1582. The most commonly used corrosion inhibitor is calcium nitrite; however, three other classes of admixture are identified by a report recently published by ACI Committee 212 titled "Report on Chemical Admixtures for Concrete[6] as amine carboxylate, amine-ester and alkenyl carboxylate. The amount of protection provided by these admixtures is largely dependent on the admixture dosage. The performance of corrosion inhibitors is largely governed by the dosage used in the concrete. O'Reilly et al. recently concluded: "*Corrosion inhibitors… reduce corrosion rates in uncracked concrete; however, corrosion inhibitors are significantly less effective in cracked concrete*."[7] They further found that the performance of these materials was less than epoxy-coated or stainless reinforcing.

GALVANIZED REINFORCING STEEL

Galvanized reinforcing bars may be specified according to ASTM A767 and have been frequently used to improve the performance of reinforced concrete against carbonation-induced corrosion. Andradé and Alonso found that the corrosion resistance of the galvanized bars depended highly on the chemistry of the cement and the zinc layers, and that differences in coating microstructure may result in significant differences in performance[8]. Care is also required if galvanized bars are connected to uncoated bars as the zinc coating will galvanically corrode, protecting the uncoated steel, and the protective layer may be depleted prior to the arrival of the chloride ions[9]. Darwin et al.[10] determined that the critical corrosion threshold for galvanized bars was 2.57 lb/yd^3, while uncoated steel in the same program demonstrated a value of 1.63 lb/yd^3. O'Reilly et al. concluded that twice as much corrosion was required for galvanized bars to crack concrete as for uncoated steel[7].

EPOXY-COATED REINFORCING STEEL

Epoxy-coated reinforcing bars are generally specified according to either ASTM A775 or A934 and the use of this product has increased over the past 40 years. In Japan, epoxy-coated reinforcing bars are required for bridge structures within 1 km (0.6 mile) of the coastline and the material is being more commonly used for marine structures, such as wharfs and piers in the Middle East, Korea, China and India.

Fusion-bonded epoxy on the steel surface substantially reduces the amount of area that is exposed to the ingress of chloride. The coating effectively reduces the anode and cathode areas and makes electrical pathways between bars more difficult (Fig. 3). As corrosion reactions are frequently governed by the cathode, this factor substantially reduces the corrosion rate once corrosion is initiated. In tests conducted for the Federal Highway Administration (FHWA), corrosion rates of less than 2 percent of the uncoated bars were observed, even when bars with substantial damage were used[11]. Several researchers have also found that epoxy-coated bars performed well in cracked concrete[12, 13]. Long-term tests conducted in Canada have found effective performance of epoxy-coated reinforcing bars exposed in a marine environment compared with other materials[14].

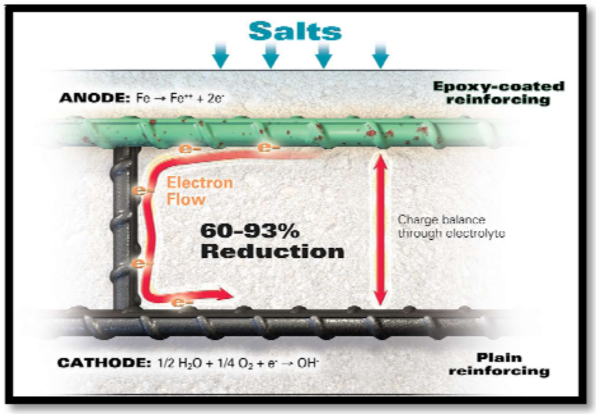

Fig. 3 Corrosion of Epoxy-coated reinforcing steel.

Some highly cited instances of poor behavior of epoxy-coated bars have been documented [15], but generally these relate to poor bar manufacture, handling and concrete conditions. The most commonly cited example was that of concrete bridges in Florida, where early age deterioration was observed. The paper by Powers reports very high chloride concentrations and areas with only 1 in. of cover. Recent verbal discussions with industry representatives revealed that the product was also manufactured with chloride ions between the coating and the steel, leading to osmotic water absorption through the coating. The product was also left beside the jobsite on barges for many months, being exposed to both substantial UV, sea water. Abrasion of these bars also occurred.

Since 1991, substantial improvements have been made in the manufacture of epoxy-coated reinforcing bars in North America through a voluntary plant coating certification program offered by the Concrete Reinforcing Steel Institute (CRSI). Specifications for handling epoxy-coated bars are contained in ASTM D3963 and ACI 301 *Specifications for Structural Concrete.* In 2010, a paper was published on the performance of the nearly 300 bridge structures in Florida containing epoxy-coated bars[16]. Of these, only 4 percent showed distress after 30 years of service and the majority was predicted to provide 100 year design lives.

In West Virginia, excellent performance of epoxy-coated reinforcing steel bars in bridge decks was observed[17]. These 34- to 36-year-old decks did not exhibit corrosion-induced distress, even at cracked locations, whereas companion structures containing uncoated reinforcing bars had been repaired after approximately 17 years of service. Figures 4 and 5 show the performance of a single deck that contained both epoxy and black bars in different sections of the deck. The amount of hatched area, signifying delaminated concrete, in Figure 4 is significant in the structure containing uncoated reinforcing steel, whereas there was no observed delamination in the areas with epoxy-coated reinforcing steel.

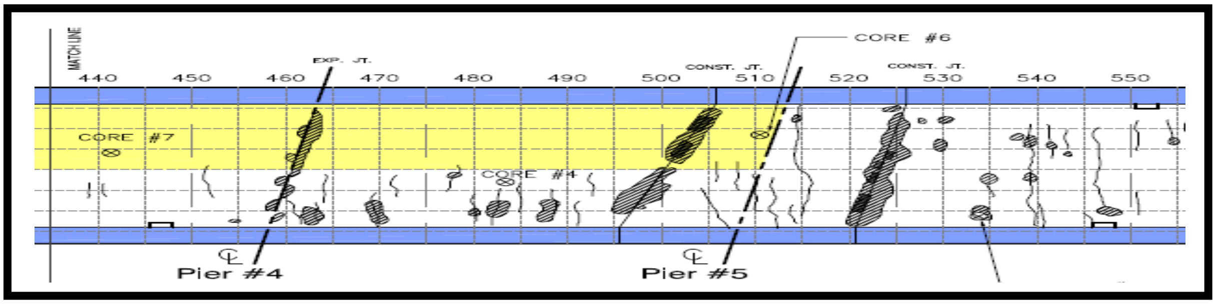

Figure 4: Field observations of deck containing black bars. Note significant areas of delamination identified by hatched areas.

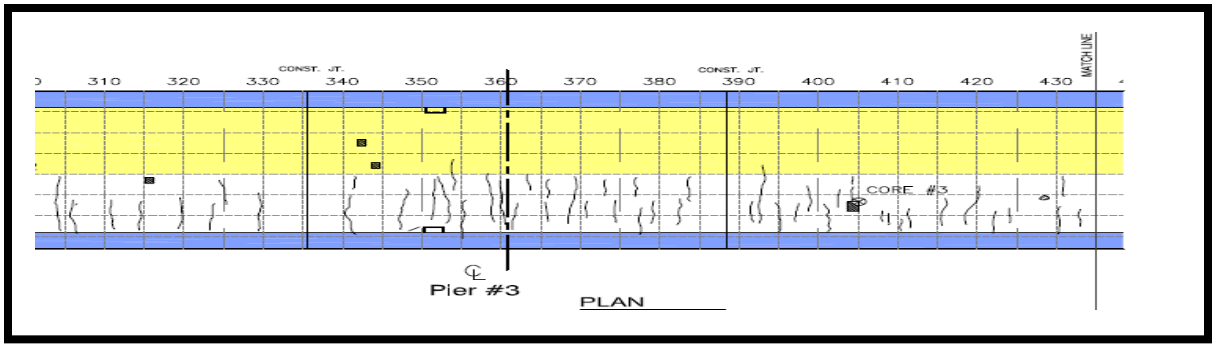

Figure 5: Field observations of deck containing epoxy-coated reinforcing steel. Note no areas of delamination compared with Figure 4.

STAINLESS-STEEL REINFORCING

Stainless steel reinforcing bars may be specified according to ASTM A955; however, the performance largely depends on the chemistry of the particular stainless steel[18]. Progreso Pier, in Mexico is frequently cited as an example of excellent performance of stainless steel reinforcing. This structure, built in 1940, is considered to be the oldest concrete structure containing stainless steel reinforcing[19]. While generally good performance was observed, the report states that at several locations there was: "serious laminated corrosion on the visible reinforcement and the reinforcement area was reduced to approximately 60 – 70 percent." A typical area of corroded reinforcing steel is shown in Fig. 6.

A report from the Naval Facilities Engineering Command raised a significant issue regarding the need for oxygen to maintain passivity of stainless in a marine environment [20]:

> "Stainless steel requires oxygen to maintain passivity, stainless steel is known to corrode rapidly when it is totally and continuously submerged in contact with seawater. Oxygen content is always of concern when using SS, since it influences the stability of the passive film governing corrosion resistance. With direct submersion, pits commonly initiate under crevices that limit access of oxygen. These crevices may be formed in a number of ways including metal-to-metal contact, biofouling, etc. The situation is exacerbated by

> any situation that generates differences in O_2 content along the surface. When used as reinforcement, it is these differences and the influence of chloride content and pH, as well as the water O_2 content that will dictate corrosion activity…"

During evaluation of cracking of the concrete curb at the Magnetic Silencing Facility, Point Loma, losses of stainless steel cross-section exceeded 50 percent [21]. This report concluded that "the reinforcement is inadequate for its environment despite being of stainless steel composition, which has generally been considered superior in marine concrete."

Figure 6: Corrosion of bridge in Progresso containing stainless steel reinforcing.

CORROSION INITIATION AND PROPAGATION

In order to determine the life of a structure, initiation and propagation periods need to be determined. Initiation periods will be dependent on the amount of chloride required to sustain corrosion, while the propagation period will depend on the corrosion rates.

The value of corrosion threshold depends on the steel and cement chemistry and typical values range from 1.2 to 2 lb/yd^3 for uncoated steel reinforcing. Recent work by O'Reilly et al.[7] presented research on the effectiveness of various corrosion-protection systems including corrosion inhibitors [i) calcium nitrite, ii) esters and amines and iii) disodium tetrapropenyl succinate] and various reinforcing bar types. Based upon that work, critical threshold coefficients were presented, as shown in Table 1 for various systems evaluated.

TABLE 1: Critical Chloride Corrosion Thresholds for Corrosion Protection Systems [7, 10]

System	Corrosion Threshold (lb/yd^3)
Black reinforcing	1.58
Epoxy-coated reinforcing	7.28
Stainless 2205 reinforcing	26.4
Corrosion inhibitors	0.83 – 3.05
Corrosion inhibitors and epoxy-coated reinforcing	1.69 – 9.85
Galvanized	2.57

The work by O'Reilly et al. demonstrates that the epoxy-coated reinforcing steel has a significantly greater corrosion threshold than that of black reinforcing. This increase in threshold, based upon a large number of test samples was attributed as follows: "The values for ECR are significantly greater than that of conventional reinforcement. To initiate corrosion on a coated bar, the chloride threshold must be reached at a damage site, as opposed to uncoated bars, which initiate corrosion once the chloride threshold is reached anywhere on the bar surface. This results in an increase in average chloride content at the depth of the reinforcement for coated bars at corrosion initiation."

The propagation rates are highly dependent on the type of concrete and reinforcing material chosen. For deck concrete, O'Reilly et al. calculated propagation rates, based upon measured corrosion in test slabs.

TIME TO REPAIR

Using data obtained from Lindquist et al.[5] for chloride in cracked concrete, O'Reilly et al. calculated the time for bars to reach the corrosion threshold for various systems as shown in Table 2[7].

For cracked concrete, the authors indicated that black bars would require repair after 14 years and up to 33 years if a corrosion inhibitor is used. For epoxy-coated bars in the cracked concrete, the authors indicated a single repair after 50 years, increasing to 63 years if a corrosion inhibitor is used. No repairs are used for the stainless steel bars during the 75 year analysis period.

COST EFFECTIVENESS

Unless unlimited resources are available, rational economic analyses are required to effectively use limited resources. 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[22]."

TABLE 2: Time to Initiation, Time to Cracking and Time to First Repair[7]

	Time to Initiation		
System	Time to Initiation	Time from Initiation to Cracking	Expected Time to First Repair*
	(years)	(years)	(years)
Black reinforcing	2.2	6.8	14
Epoxy-coated reinforcing	20.3	24.8	50
Stainless 2205 reinforcing	67.6	224	297
Corrosion inhibitor	1.0 – 4.1	6.8 – 26.6	16 – 33
Corrosion inhibitor and epoxy-coated reinforcing	2.5 – 24.0	24.8 – 45.6	50 – 63
*Note that the authors assumed a time to first repair 5 years after cracking.			

NET PRESENT VALUE

In economic analysis it is common to use net present value (NPV) to determine the effectiveness of any chosen strategy. Calculation of the net present value depends strongly on the discount rate and the timing of maintenance operations as shown below.

$$NPV = \sum \frac{R_t}{(1+i)^t}$$

Where
R_t = Net cash flow at time t
i = discount rate
t = time of cash flow

The net cash flow is determined from incomes and expenditures that may occur during the structures life. Typically, design lives of 75 or 100 years are assumed. It should be noted that when discount rates are low, highly durable options are favored and conversely, when discount rates are high, less durable options are favored.

Values of discount rates are frequently published by the U.S. Office of Management and Budget (OMB) for government projects[23]. Current estimates are that a discount rate 2.3 percent should be used for projects with lives greater than 30 years. General values of 3 to 5 percent are also commonly recommended; however, there appears to be no consensus as to the appropriate value, particularly when considering projects that are designed for 75 to 100 years. In a 1994 report from Transport Canada, a discount rate range between 7.5 percent and 12.5 percent was suggested for sensitivity analysis[24].

INITIAL AND LIFE-CYCLE COSTS

The costs of concrete, reinforcing materials and repair are frequently difficult to obtain. Further, costs of materials may vary significantly based upon regional availability, resulting in significantly different life-cycle results.

Based upon discussions with concrete producers, the additional cost of concrete containing pozzolans compared with normal cement concrete is generally low and for this reason these materials should be strongly considered for all projects.

In 2011, O'Reilly et al. produced a report that contained cost data for many materials and these values provide a baseline for analysis[7]. Reported costs of black, epoxy and 2205 stainless steel reinforcing was \$0.35, \$0.45 and \$2.35 per lb, respectively. Placement costs were estimated at \$0.52 per lb and that the average amount of steel in a deck was approximately 275 lb/yd^3, based upon an average of 12 bridges. They reported that the in-place cost of normal concrete was \$562 yd^3 and that repair costs were \$283/yd^2. In the analysis it was assumed that repairs of this type would last 25 years.

Values reported by O'Reilly et al are shown in Fig. 7. Costs for concrete containing inhibitors are shown as average values for the three types of materials tested. Initial costs for decks containing black bars using these values would be \$189/yd^2. Modest increase in costs for epoxy-coated bars or corrosion inhibitors is shown in Table 3. Use of type 2205 stainless bars result in a cost premium of \$130/yd^2 or an increase of almost 70 percent. Such large increases would clearly present fiscal challenges to many agencies.

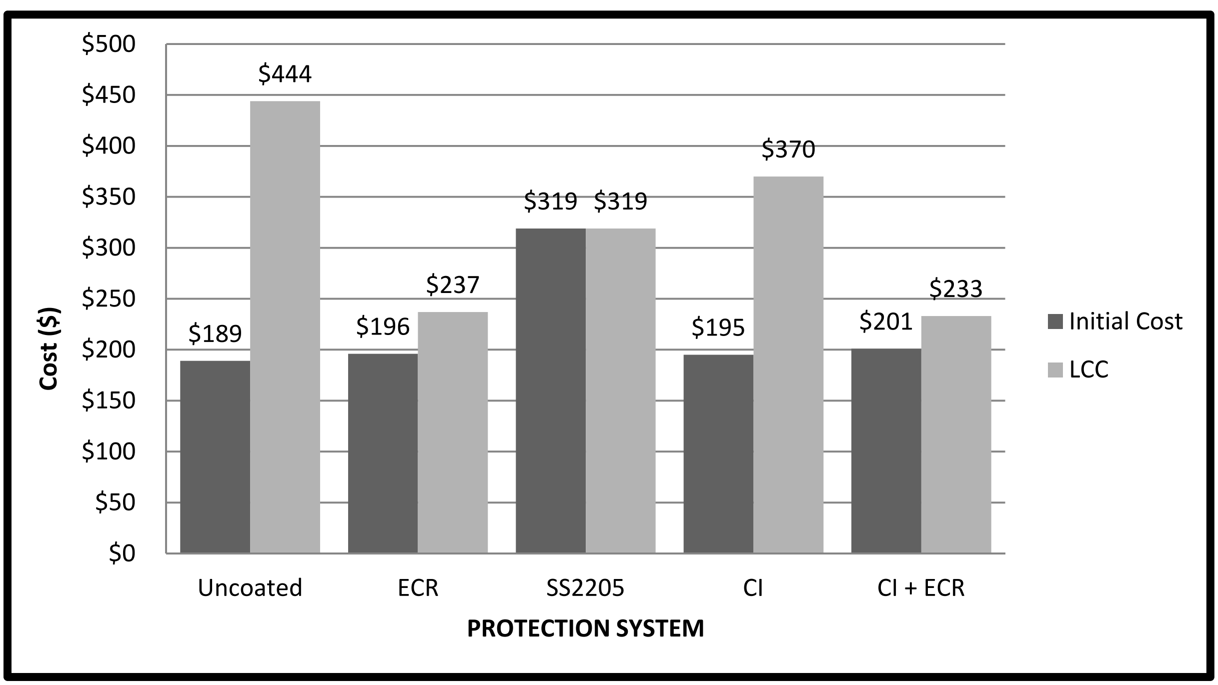

Fig. 7: Initial and life-cycle costs for various design alternatives.

O'Reilly et al. calculated that the life-cycle costs using a discount rate of 4 percent were $444, $237 and $319 per sq yd, for black, epoxy and stainless bars, respectively. Life-cycle costs for concrete containing corrosion inhibitors and uncoated bars range from $308 to $432. If a combination of corrosion inhibitors and epoxy-coated bars are used, then the life-cycle cost reduces to $224 - $242.

While both epoxy and stainless steel options result in life-cycle costs that are significantly less than that of the black bars, epoxy-coated bars presented substantially lower costs than the stainless steel. These savings were of the order of $80 to $100 per sq yd. Such savings would further increase if the life of epoxy-coated reinforcing is increased.

OTHER METHODS

Other reinforcing bar coatings and materials, such as nickel or copper claddings have been suggested[12]; however, these products have yet to become commercially available. Proprietary products, such as ASTM A1035, have found use in some agencies; however, recent tests have shown that bars meeting this specification corrode readily in salt spray[25]. They also have poor performance in tests that are used to evaluate stainless steel reinforcing [26] and for this reason are not recommended. This performance is further dependent on whether the bars are provided in an as-received or pickled condition.

Glass and Basalt fiber bars have been suggested for structures; however, these are largely considered experimental. These bars may also present structural challenges due to their lack of yield compared with steel and may not have suitable fire performance.

Cathodic protection provides an external current that reverses reactions at the anode and may be provided to protect the concrete against corrosion damage[27]; however, this method of protection is typically used during repair rather than as a method to suppress initial corrosion.

OTHER FACTORS

When selecting methods to protect structures against corrosion, factors such sustainability and availability should be evaluated.

SUSTAINABILITY

The sustainability of materials used in construction is receiving significantly more attention, particularly in government funded projects. In general, use of pozzolans is considered a good strategy to reduce carbon footprint and promote the use of post-industrial waste. Epoxy-coated and galvanized bars are generally manufactured using over 95 percent of recycled steel; compared with only 75 percent for specialty steels, such as stainless steel. Further, processing energy for stainless steel may be significantly greater than for epoxy-coated or galvanized bars due to the higher melting temperature of this material.

AVAILABILITY

Pozzolans are more readily available in North America east of the Mississippi River; primarily due to the location of coal deposits and corrosion inhibitors are widely found and available from several companies.

While galvanizing operations are found throughout the country, very few have experience with reinforcing bars. Many are unable to coat bar lengths greater than 40 ft and most do not have facilities for the required chromate treatment.

Epoxy-coated reinforcing bars are widely available in North America from over 35 suppliers in North America. Since 1991, most of these plants have been certified by CRSI as part of a program that evaluates a plant's capacity to produce and handle high-quality product. These bars may be generally fabricated and on jobsites within a week of ordering.

Stainless steel reinforcing is only produced by limited manufacturers and substantial lead times may be required. Further, fabrication of these products requires additional care to ensure that the stainless reinforcing is not contaminated by foreign materials and that the bars are appropriately pickled after fabrication.

CONCLUSIONS

This paper presents information on the specification, use and performance of various methods to protect concrete against corrosion-induced damage, generally caused by the ingress of chloride. Concrete is frequently non-homogenous and chloride exposures in various areas of the structure may be substantially different. Further, cracks may propagate through to the reinforcing steel, nullifying any benefits from low concrete diffusion. Thus, protection methods that utilize the concrete alone may not provide the expected long-term benefits. The additional cost of concrete containing pozzolans compared with normal cement concrete is generally low and for this reason these materials should be strongly considered for all projects.

The performance of corrosion inhibitors is largely dependent on the admixture dosage and may be used in combination with other protection systems.

The performance of galvanized reinforcing steel is dependant on the chemistry of the cement and the zinc layers, and differences in coating microstructure may result in significant differences in performance.

The performance of epoxy-coated reinforcing steel has generally been excellent and the few instances of poor performance of concrete containing these bars were related to poor manufacturing, handling or concrete conditions. Use of this product worldwide is still increasing. Epoxy-coated reinforcing steel reduces available anode and cathode areas on the bars and makes electrical pathways between bars more difficult, resulting in substantially reduced corrosion rates. More recently it has been determined that epoxy-coated reinforcing steel has a significantly greater corrosion threshold than that of black reinforcing.

The performance of stainless steel reinforcing bars largely depends on the chemistry of the particular stainless steel. While frequently excellent performance is cited, several examples of poor performance of stainless steel in concrete are presented.

Minimal increases in initial costs occur when epoxy-coated bars or corrosion inhibitors are used, while the use of stainless bars results in a substantial cost premium. Recent life-cycle cost analyses show that use of epoxy-coated bars is significantly lower than other protection systems and that these costs may be substantially lower than that of stainless steel.

Finally, when selecting methods to protect structures against corrosion, factors such sustainability and availability should be evaluated.

REFERENCED ASTM STANDARDS

A775 Standard Specification for Epoxy Coated Steel Reinforcing Bars
A767 Standard Specification for Zinc Coated (Galvanized) Steel Bars for Concrete Reinforcement
A934 Standard Specification for Epoxy Coated Prefabricated Steel Reinforcing Bars
A955 Standard Specification for Deformed and Plain Stainless Steel Bars for Concrete Reinforcement
A1035 Standard Specification for Deformed and Plain, Low Carbon, Chromium, Steel Bars for Concrete Reinforcement
C618 Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete
C989 Standard Specification for Slag Cement for Use in Concrete and Mortars
C1240 Standard Specification for Silica Fume Used in Cementitious Mixtures
C1581 Standard Test Method for Determining Age at Cracking and Induced Tensile Stress Characteristics of Mortar and Concrete under Restrained Shrinkage
C1582 Standard Specification for Admixtures to Inhibit Chloride Induced Corrosion of Reinforcing Steel in Concrete
D3963 Standard Specification for Fabrication and Jobsite Handling of Epoxy Coated Steel Reinforcing Bars

REFERENCES

1. Koch GH, Brongers MPH, Thompson NG, Virmani YP, Payer JH: "Corrosion Cost and Preventive Strategies in the United States." vol. FHWA-RD-01-156. Washington D.C.; 2001.
2. Yunovich M, Thompson N, Virmani Y: Corrosion of Highway Bridges: "Economic Impact and Life-Cycle Cost Analysis." *Concrete Bridge Conference; Charlotte, N. C.*. National Concrete Bridge Council; 2004
3. Shiu K, Stanish K: "Extending the Service Life of Parking Structures." *Concrete International-Detroit*- 2008, 30-43.

4. Sagoe-Crentsil K, Glasser F: "Constitution of Green Rust and its Significance to the Corrosion of Steel in Portland Cement." *Corrosion* 1993, 49.
5. Lindquist W, Darwin D, Browning J, Miller G: "Effect of cracking on chloride content in concrete bridge decks." *ACI Materials Journal* 2006, 103-467.
6. *Report on Chemical Admixtures for Concrete*,212 AC edition, Farmington Hills, Mich.: American Concrete Institute; 2010.
7. O'Reilly M, Darwin D, Browning J, Carl E. Locke J: "Evaluation of Multiple Corrosion Protection Systems for Reinforced Concrete Bridge Decks." Lawrence, Kan.: The University of Kansas Research Inc. ; 2011.
8. Andrade C, Alonso C: "Electrochemical Aspects of Galvanized Reinforcement Corrosion." San Diego: Elsevier Inc.; 2004.
9. Safiuddin M: "Performance of galvanized steel reinforcing bars against corrosion in concrete." *BRAC University, BU Journal* 2005, 2.
10. Darwin D, Browning J, O'Reilly M, Xing L, Ji J: "Critical Chloride Corrosion Threshold of Galvanized Reinforcing Bars." *ACI Materials Journal* 2009, 106.
11. Lee S, Krauss P: "Long-Term Performance of Epoxy-Coated Reinforcing Steel in Heavy Salt-Contaminated Concrete." vol. FHWA-HRT-04-090. McLean, Vir.: Federal Highway Adminstration; 2004.
12. McDonald DB, Pfeifer DW, Sherman MR: "Corrosion Evaluation of Epoxy-coated, Metallic-Clad and Solid Metallic Reinforcing Bars in Concrete." vol. FHWA-RD-98-176. pp. 137 p. McLean, Vir.: Federal Highway Administration; 1998: 137 p.
13. Draper J, Darwin D, Browning J, Carl E. Locke J: "Evaluation of Multiple Corrosion Protection Systems for Reinforced Concrete Bridge Deck." (FHWA ed., vol. DTFH61-03-C-00131. Lawrence, Kan.: University of Kansas; 2009.
14. Kondratova I, Bremner TW, Erdogdu S: "Long Term Testing of Concrete Slabs containg epoxy-coated steel in a marine environment." In *Durability and Protection of Constructions from Corrosion, Construction, Reconstruction*. International Congress MOSCOW; 1999, pp. 548-554:
15. Powers RG: "Corrosion Evaluation of Substructure - Long Key Bridge." Interim Report. vol. Corrosion Rept 87-9A. pp. 34. Gainesville, Fla.: Florida Department of Transportation; 1987:34.
16. Sagues AA, Lau K, Powers RG, Kessler RJ: "Corrosion of Epoxy-Coated Rebar in Marine Bridges---Part 1: A 30-Year Perspective." *Corrosion* 2010, 66.
17. Lawler J, Krauss PD: "Condition Survey of Older West Virginia Bridge Decks Constructed with Epoxy-Coated Reinforcing Bars." Northbrook: Epoxy Interest Group of CRSI; 2010.
18. Bower J, Friedersdorf L, Heuhart B, Marder A, Juda A: "Application of Stainless Steel and Stainless-Clad Reinforcing Bars in Highway Construction." vol. HWA-PA-2000-011. University Park, Pa.: Pennsylvania Department of Transportation; 2000.
19. RAMBOL: "Pier in Progreso Mexico, Inspection Report; Evaluation of Stainless Steel Reinforcement." RAMBOL; 1999.
20. Burke D, Drake J: "Durable Lightweight Concrete for the Modular Hybrid Pier." vol. TR-2205-SH. Port Hueneme, Calif.: Naval Facilities Engineering Service Center; 2002.
21. Polly D, Burke D, Hoy D: "Corrosion of Stainless Steel Reinforcement in the Concrete Deperming Pier at Point Loma." vol. TR-2305-SHR Port Hueneme, Calif. 93043-4370: Naval Facilities Engineering Service Center; 2008.

22. Life-Cycle Cost Analysis [http://www.fhwa.dot.gov/infrastructure/asstmgmt/lcca.cfm]
23. Discount Rates for Cost-Effectiveness, Lease Purchase, And Related Analyses [http://www.whitehouse.gov/omb/circulars_a094_a94_appx-c/]
24. Lovin JAA: “Guide to Benefit-Cost Analysis In Transport, Canada.” vol. TP11875E: Economic Evaluation and Cost Recover, Transport, Canada; 1994.
25. Cui F, Krauss PD”: Corrosion Resistance of Alternative Reinforcing Bars: An Accelerated Test.” Northbrook, IL: Wiss, Janney, Elstner Associates/Concrete Reinforcing Steel Institute; 2006.
26. Surgeon WJ, O’Reilly M, Darwin D, Browning J,: “Rapid Macrocell Tests of ASTM A775, A615 and A1035 Reinforcing Bars.” In *Structural Engineering and Engineering Materials*, vol. SL Report 10-4. Lawrence, Kan.: University of Kansas Center for Research Inc.; 2010.
27. Sohanghpurwala AA: “Cathodic Protection for Life Extension of Existing Reinforced Concrete Bridge Elements.” vol. Synthesis 398. Washington, D.C.: NCHRP; 2009.