

Evaluation of Corrosion Prevention and Control Programs for Reinforced Concrete Bridges in Marine Environments

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ABSTRACT

Corrosion of steel in reinforced concrete bridges is a major concern for the structural integrity, long-term durability, and maintenance of the highway infrastructure. The corrosion mechanisms vary greatly due to the multitude of engineered highway systems with the varying exposure environments, chemistry, and construction materials. Of the many engineering systems in the highway infrastructure, corrosion of reinforcing steel in bridge substructures has been critical. It is therefore highly advantageous to evaluate the performances of implemented corrosion control measures. Five bridges in Florida utilizing various corrosion mitigation strategies were revisited in 2021 to provide a prospective of their corrosion durability after several decades of service. The assessment compared plain to epoxy coated rebar, use of fly ash, and the use of concrete coatings. The presence of flyash in concrete mix designs allow for slower chloride diffusion rates. The presence of concrete surface coatings can allow lower chloride surface concentrations to develop. Bridge service life assessment should not account for chloride ion diffusivity alone as it was shown that elevated initial chloride concentrations can facilitate corrosion conditions. The barrier provided by epoxy-coated rebar can extend the time to initial concrete degradation caused by corrosion, but corrosion can still develop on the coated reinforcing steel.

Keywords: Reinforced concrete, bridges, fly ash, epoxy coated rebar, chloride diffusion

INTRODUCTION

Corrosion of steel in reinforced concrete bridges is a major concern for the structural integrity, long-term durability, and maintenance of the highway infrastructure. Statistics from a national study in 2002 indicated that approximately 15% of the national bridge inventory is structurally deficient because of corrosion and the national annual direct cost exceeded \$8 billion.¹ In the state of Florida, the typical design life expectation for the >6,000 bridges in the state highway infrastructure exceed 75 years. However, approximately half of the bridges are in aggressive marine service where corrosion can be pervasive. The corrosion mechanisms vary greatly due to

the multitude of engineered highway systems with the varying exposure environments, chemistry, and construction materials. Even though much research and recommendations have been made by the state transportation departments and technical organizations such as NACE and ACI²⁻³ to promote corrosion durability of highway bridge infrastructures, history and current maintenance needs remind owners of the need to continue to improve designs to control corrosion and to develop tools to assess future performance and maintenance needs.

Of the many engineering systems in the highway infrastructure, corrosion of reinforcing steel in bridge substructures has been critical. This is in part due to its structural importance and high visibility to the general public, especially for highway bridges that serve large populations in coastal regions that are vulnerable in the aggressive corrosion environments. Of the national annual direct costs for highway bridges, \$2 billion was related to corrosion of steel in bridge concrete substructures. In Florida, recent bridge work plans identified bridge substructure repair as the second highest maintenance need (Figure 1).

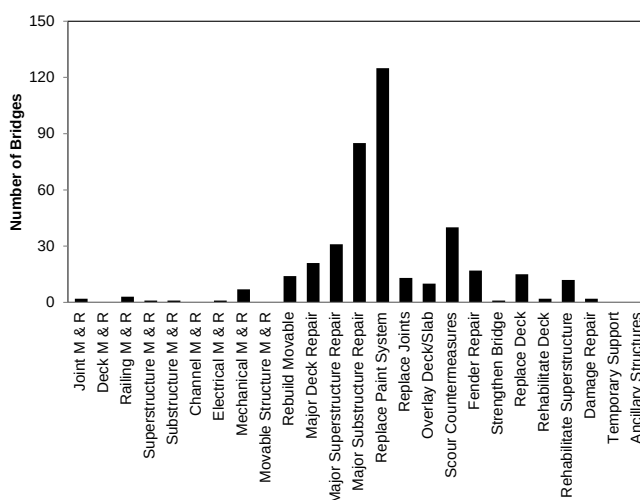


Figure 1: Florida department of transportation bridge work plan for 2015.⁴⁻⁵

Despite the positive changes in material specifications and design practices that have provided safer and more durable structures, the increasing pressures to maximize bridge service (sometimes beyond original design life), intricacies in the corrosion degradation mechanism intensify. Complexities of modern structural systems, the highly aggressive exposure environments, changes in building and material technologies, and sometimes variability in construction quality all provide challenges to maintain good bridge preservation programs. It is therefore highly advantageous to evaluate the performances of implemented corrosion control measures.

REVIEW OF FLORIDA BRIDGE CORROSION DURABILITY

Corrosion of steel in reinforced concrete substructures in marine exposure is largely associated with chloride-induced corrosion, and the corrosion performance of structures is largely dependent on the quality of the concrete material (that is in part related to its mix design), construction and casting methods, design, exposure environments, and application of mitigation technologies to resist chloride-induced corrosion. Concretes with high cement factors (low water-to-cement ratio) and use of pozzolanic materials such as slag and fly ash typically have beneficial diffusion and electrical properties. Certain casting methods such as that for spun-cast cylinder piles were also

shown to produce concrete elements with high concrete quality.⁶⁻⁷ Precast concrete elements generally would have the expectation to have better workmanship than cast-in-place concrete to minimize casting imperfections such as honeycombing and cold joints.

Concretes with low chloride ion diffusivity (D) are able to resist the diffusional transport of chloride ions from the natural water and concrete surface (with a surface concentration C_S) inwards towards the surface of the reinforcing steel (clear cover x), thus delaying the time (t_i) to which a critical chloride ion concentration (C_T) can accumulate to initiate active corrosion. The time t_i can be computed by the function shown Equation 1 following a solution to Fick's 2nd law of diffusion assuming spatial and temporal constant D and C_S as well as a fixed value for C_T .

$$t_i = \frac{x^2}{4D \left(\operatorname{erf}^{-1} \left(1 - \frac{C_T}{C_S} \right) \right)^2} \quad (1)$$

In addition to the ability to resist chloride ion diffusion, high quality concrete exhibit high concrete bulk resistivity. This electrical characteristic not only describes the concrete makeup (ie cement factor, permeability, and moisture content) but also has often been well correlated to low corrosion rates. High concrete resistivity will allow poor ionic coupling of local anodes to the extended cathode regions and mitigate macrocell formation.⁸⁻¹⁰

Concrete structural elements susceptible to crack development would allow for more adverse conditions by providing direct path of deleterious chemical compounds to facilitate corrosion initiation and thus affect the overall corrosion durability of an element.⁹⁻¹⁰

Corrosion control measures often address means to extend the time to corrosion initiation as the corrosion engineering principles here are widely understood and put into practice. The main passive approaches include to delay the time for chloride transport to the reinforcing steel surface (by application of barrier coatings on the rebar, increasing the concrete cover length, utilizing less permeable materials such as incorporating supplementary cementitious materials (SCM), or applying coatings/overlays on the concrete) or to increase the critical chloride threshold levels for corrosion initiation (by using corrosion resistant steel alloys and application of active coatings on the rebar). Other approaches include application of admixed inhibitors to develop surface films or modify electrochemical characteristics of the corrosion system to reduce corrosion rates. Active approaches to delay or prevent corrosion initiation include application of electrochemical techniques such as cathodic protection (CP), cathodic prevention, and other proposed techniques such as chloride extraction and concrete re-alkalinization.

Field research on Florida concrete bridges have been conducted in 2002, 2005, and 2010.^{6,10,11} A summary of concrete characteristics by the bridge construction date is shown in Table 1. The table generally shows the trends in time for construction practices including the use of higher concrete quality, addition of fly ash and increase in concrete clear cover. Florida has widely adopted the strategy to extend the time to corrosion initiation by increasing the concrete cover and utilizing high performance concretes. Use of SCM has shown good effect to decrease the concrete chloride ion diffusivity. Florida concrete bridges with low chloride ion diffusivity (in the order of 10^{-9} cm²/s) exhibited low corrosion activity whereas severe corrosion was observed in the bridges with high chloride ion diffusivity (in the order of 10^{-7} cm²/s).^{10,12} Although chloride ion diffusion in bulk concrete was much reduced in the bridges with high quality concrete, the presence of wide concrete cracks can allow localized preferential chloride transport. Table 1 shows that concrete cracking can be significant even for structures with newer mix designs. The localized cracks can allow for local anodes to form. In some cases, concretes with high electrical

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resistivity may mitigate extensive corrosion such as that observed in the Sunshine Skyway Bridge, where damaged epoxy-coated rebar (ECR) exposing steel and high chloride content at the crack region did not result in severe corrosion. In other bridges, localized corrosion was observed on rebar that intersected a wide pre-existing crack (>1 mm) through concrete with low permeability concrete.^{10, 12-14}

Epoxy coatings on the reinforcing steel (ECR) would ideally provide a barrier layer on the rebar to prevent the chemical interactions of chloride ions to depassivate the steel.¹⁴⁻¹⁵ Although no longer specified by the State due to experiences such as severe corrosion developing in as little as 5 years in some bridges built in the 1980s in the Florida Keys, fusion-bonded epoxy-coated rebar (ECR) has been in continued use (particularly for bridge decks) in northern states in the country. The corrosion was attributed to the presence of coating defects and holidays that after some time in service embedded in the concrete (in part relating to moisture and chloride presence as well as mechanisms involving cathodic disbondment) would allow for localized corrosion to occur and subsequently progress to extended damage to the rebar and then concrete delamination and spalling.^{10,15-16} A dual coated rebar with an epoxy and arc-sprayed zinc coating has been developed to mitigate the localized corrosion at defect sites.¹⁷⁻²⁰ There exists a few ECR bridges in the State bridge inventory that would be of interest for further study including twin bridges in Melbourne built in the early 1980s where both ECR and conventional rebar were used. There, corrosion damage of reinforced concrete has begun to manifest when plain rebar was used.

Concrete coatings and/or sealers are used to provide corrosion protection to reinforced concrete elements by protecting against the intrusion of moisture and chlorides into the concrete substrate, thus increasing the amount of time until initiation of corrosion. Multiple types of concrete coatings and/or sealers have been developed to be applied to new and/or existing bridges, such as boiled linseed oil, epoxies, polyurethanes, silicones, and others. Project 12-19A conducted by the National Cooperative Highway Research Program in 1981 was implemented to develop a basis for comparison of multiple types of concrete coatings/sealers for objective performance evaluation, and the findings of this study are presented in NCHRP Report 244.²¹ Based on test methods designed to evaluate reduction of water absorption into concrete, reduction in chloride content in concrete, and visual performance, the three best performing products were alkylalkoxy silane, one epoxy composition, and methyl methacrylate. In a laboratory test consisting of Southern Climate Exposure, these materials reduced chloride content by 97, 93, and 99 percent, respectively.²¹ Section 413 of FDOT Standard Specifications for Road and Bridge Construction outlines current requirements for the installation of surface sealers of concrete elements, which specifies alkyl-alkoxy silane as the penetrant sealer.²² Class 5 applied finish coatings on concrete such as acrylic coatings can provide barrier to chloride intrusion and are specified in Section 400.

Florida has employed CP systems for corrosion mitigation of many bridges. CP for reinforced concrete comes in many varieties and purposes. The two main varieties of CP systems include impressed current systems where current is supplied from an external power source and galvanic systems where active metals are used to provide beneficial galvanic polarization. Impressed current systems have used various anode materials often designed incorporated with pile jackets. Galvanic CP systems can include bulk anodes, embedded discrete anodes, meshes, and arc-sprayed anodes. The galvanic CP systems can be used either to mitigate incipient anodes that develop in concrete repairs or placed as any array in concrete prior to concrete spalling. Concrete-embedded and surface-anodes can also be designed with incorporation with repair jackets. Interest may lie in assessing the efficacy of CP systems due to interactions with marine fouling organisms. Recent research indicated that fouling organisms can affect polarization and current

distribution on submerged steel piles. Also, fouling organisms attach to concrete structures as well and similar deficiencies in CP may occur. ²³⁻²⁵

Table 1
Trends in Florida Concrete Bridge Material Characteristics ^{6,10,11}

Bridge Name		Year Built	Average D (cm ² /s)	ρ (kΩ-cm)	Cement factor (kg/m ³)	Fly Ash	Widest crack width (mm)	Clear Cover (cm)
Hathaway ¹	-	1960	1x10 ⁻⁹	100-200	390-474	No	0.3	3.1
Pensacola Bay ¹	-	1960	1.9x10 ⁻⁹	70-100	390-474	No	0.3	2.3
Boca Ciega Bay	BCB	1962/86	3.1x10 ⁻⁸	36	362	No	0.4	8.2
Brooks ¹	-	1964	2.5x10 ⁻⁹	-	390-474	No	0.2	2.9
Melbourne Cswy	MBP	1978	9.9x10 ⁻⁹ - 4.4x10 ⁻⁸	2-48	-	-	Delam./ spalls	9.5-14.6
William Marler ²	CHO	1979	1.8x10 ⁻⁸	16-128	388	No	>1	7.6
Niles Channel ²	NIL	1980	2x10 ⁻⁷	-	388	No	>1	7.6
Indian Key ²	INK	1981	~10 ⁻⁷	-	388	No	>1	7.6
Channel 2 ²	CH2	1981	~10 ⁻⁷	0.4-12	388	No	>1	15.3
Snake Creek ²	SNK	1981	9x10 ⁻⁸	4-50	388	No	0.28	15.3
Lillian ²	PER	1981	3.1x10 ⁻⁹	113-275	-	Yes	0.25	10.2
S. Andrews Ave. ^{2,3}	NWR	1981	1.8x10 ⁻⁸	-	-	No	Hairline	11
Seven Mile ²	7MI	1982	2x10 ⁻⁷	5-24	388	No	>1	7.6
Channel 5 ²	CH5	1982	~10 ⁻⁷	-	388	No	>1	7.6
Long Key ²	LOK	1982	2.9x10 ⁻⁷	-	388	No	>1	7.6
Vaca Cut ²	VA1	1982	2.6x10 ⁻⁷	4-50	388	No	0.28	15.3
Vaca Cut ²	VA2	1982	2.6x10 ⁻⁷	4-50	388	No	0.28	15.3
Lehman Cswy ²	IT2	1983	3.9x10 ⁻⁸	4-12	-	No	0.25	9.2
Lehman Cswy ²	IT3	1983	3.9x10 ⁻⁸	4-12	-	No	0.25	9.2
Melbourne Cswy ²	MBE	1985	8.6x10 ⁻⁹ - 8.7x10 ⁻⁸	4-48	-	No	>1	9.9-13.7
New Pass	NPB	1986	1x10 ⁻⁸	115	390	-	0.15	11
Sunshine Skyway ²	SSK	1986	1.1x10 ⁻⁹	150	445	20% Type F	0.64	10.2
Dames Point	DPE	1989	7.5x10 ⁻⁹	52	390	No	0.33	8.9
Sunrise Blvd. ^{2,3}	ITA	1989	2.5x10 ⁻⁷	4-10	-	No	0.18	10.9
Sunrise Blvd. ^{2,3}	ITB	1987	3.8x10 ⁻⁹	9-180	-	Yes	0.18	12.0
Safety Harbor	SHB	1990	7.1x10 ⁻⁹	54	434	20%	0.10	8.3

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						Type F		
New Smyrna	NSB	1990	2.7×10^{-8}	10	390	No	0.3	-
Howard Frankland ²	HFB	1991	7.3×10^{-9}	High MΩ-cm	388	35% Type C	>1	10.2
Courtney Campbell Cswy	CCC	1992	4×10^{-9}	137	445	20% Type F	0.08	9.9
Bay Side	BSB	1993	8.5×10^{-9}	66	434/390	20% Type F	0.15	9.4
McArthur Csy	MAC	1995	6.5×10^{-9}	-	434	20% Type F	-	-
St. George Island ¹	SGI	2003	1.8×10^{-9}	50-200	~500	Yes	0.05	8.1

(¹) Spun-cast cylinder piles. (²) Epoxy-coated rebar. (³) Class 5 Applied finish coating.

REVISTING CORROSION CONTROL MEASURES

Five bridges in Florida (Table 2) utilizing various corrosion mitigation strategies were revisited in 2021 to provide a prospective of their corrosion durability after several decades of service. The assessment compared plain to epoxy coated rebar, use of fly ash, and the use of concrete coatings. Review of bridge inspection reports from 2003 to 2021 was made for the bridge substructure elements subjected to tidal water exposure. A summary of the concrete deterioration by the inspection condition state for structural element surface area is shown in Figure 2. Description of the condition state levels is listed in Table 3.

Table 2
Bridge Comparisons

Bridge Name		Year Built	Concrete Coating	Cl ⁻ Diffusivity (cm ² /s)	Fly Ash	Rebar	Clear Cover (cm)
S. Andrews Ave.	NWR	1981	Yes	1.8×10^{-8}	No	ECR	11
Sunrise Blvd.	ITA	1989	Yes	2.5×10^{-7}	No	ECR	10.9
Sunrise Blvd.	ITB	1987	Yes	3.8×10^{-9}	Yes	ECR	12.0
Melbourne Cswy	MBE	1985	No	8.6×10^{-9} - 8.7×10^{-8}	No	ECR	9.9-13.7
Melbourne Cswy	MBP	1978	No	9.9×10^{-9} - 4.4×10^{-8}	No	Plain	9.5-14.6