"Long-Term Corrosion Behavior of Epoxy Coated Rebar in Florida Bridges", K. Lau, A. A. Sagüés, R. G. Powers, Paper No. 07306, 10 pp., Corrosion/2007, NACE International, Houston, 2007.

LONG-TERM CORROSION BEHAVIOR OF EPOXY COATED REBAR IN FLORIDA BRIDGES

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ABSTRACT

Epoxy-coated rebar (ECR) was used by the Florida Department of Transportation (FDOT) up to the early 1990's, but severe corrosion was observed after only a few years of service in several major FDOT ECR bridges built with highly permeable concrete. Corrosion projections based on concrete permeability indicated that corrosion damage was likely to be present by now for other FDOT bridges built with highly permeable concrete. Early corrosion initiation was not projected for other ECR bridges built with low permeable concrete, but there was concern that thin structural cracks and associated chloride ingress may have locally promoted deterioration. In an investigation in progress, field observations and laboratory examination of extracted ECR samples did show active corrosion in two Florida ECR bridges built with highly permeable concrete, confirming projections. Little to no corrosion was observed on ECR from another bridge with low permeability concrete, and no correlation between the presence or position of thin cracks and corrosion deterioration was observed. Further tests are in progress.

Keywords: corrosion, epoxy, coating, rebar, disbondment, durability

INTRODUCTION

Epoxy coated steel reinforcement (ECR) was used for corrosion control in Florida DOT (FDOT) marine reinforced concrete bridges from the late 1970's up to the early 1990's. The use of ECR for new FDOT structures was discontinued upon mounting evidence of severe corrosion in some of the existing bridges. Earlier investigations assessed the corrosion condition of 20 FDOT ECR bridges after ~5-12 years of service[1]. A model of the corrosion mechanism of ECR in marine concrete was developed[2]. The corrosion was viewed as resulting from the presence of coating production imperfections (within allowable limits at the time of construction) then aggravated by fabrication, handling, and a severe construction yard environment which promoted coating-metal disbondment[3-5]. Disbondment was found to become more extended after only a few years of service in the marine structures. Penetration of chloride ions to the rebar level resulted in severe undercoating corrosion, aggravated by extended macrocell formation with cathodes elsewhere in the rebar assembly[6-7].

Durability prognosis evaluations were formulated based on the research findings and application of an initiation-propagation deterioration model[1,4,8]. Based on measured concrete permeability properties, the model projected development of corrosion after about one more decade of service in some additional FDOT ECR structures (Category A structures), and a lesser likelihood of early corrosion in other bridges with lower concrete permeability (Category B). Several Florida ECR bridges are now at the age of expected corrosion propagation. The present investigation examines the corrosion condition of those structures one decade later to validate and modify projections, including introducing allowance for the possible effect of thin structural cracks on early corrosion in low permeability concrete[9]. Those cracks are usually <0.3 mm wide and typically one or more meters of waterline perimeter apart, but significant preferential chloride penetration through those cracks has been noted at low elevations where the concrete is wet. To date, condition has been assessed in two category A bridges (Vaca Cut and Snake Creek) and partially in one Category B bridge (Sunshine Skyway Bridge). Initial results of this research in progress are presented here.

EXPERIMENTAL PROCEDURE

Field Methodology

All accessible marine drilled shafts in the two Category A bridges were examined. In the larger Category B bridge, representative locations from several substructural component types (columns, footers, struts, and caps) were selected for examination, focusing on thin preexisting cracks on concrete sections at low elevations exposed to sea splash as well as on drier higher elevation trestle caps. Elevations are reported as distance above the high tide level (AHT)

Concrete core samples (~10 cm diameter) were extracted to expose and collect ECR samples as well as for assessment of chloride penetration. Concrete clear cover was noted and checks for concrete delamination were made by hammer sounding. When cracks were observed, pairs of cores were collected along the same elevation typically ~15 cm apart on center with one core centered on crack. For Category A bridges, drilled shafts that were previously part of an earlier investigation (1991) were reexamined and cores were extracted at similar elevations as earlier. The in-situ condition of the exposed ECR coating was noted. Spot knife tests for coating disbondment were conducted.

Electrical continuity between coring-exposed ECR segments was tested when possible to determine possible sources of corrosion macrocell phenomena. Half-cell potentials were measured with a copper/copper-sulfate reference electrode (CSE) along the elevation of the drilled shaft. Concrete surface resistance was measured with a Wenner array probe with an inter-probe spacing of 3 cm chosen as a compromise between sampling size and possible interference from embedded rebar.

Nominal polarization resistance, Rp, was measured at selected elevations of the Category A bridges where steel corrosion was observed. A 310 cm^2 titanium mesh auxiliary electrode and a CSE reference electrode were applied to the external concrete surface with a wet sponge, placed above the rebar near the coring point where the working electrode connection to the rebar was made. A scan rate of 0.15 mV/s at ±25 mV OCP was used in the measurements. An area-corrected Rp value was not evaluated due to inherent uncertainty in polarized bar length and complications from evaluating undercoating corrosion[10]. Instead, results are reported for comparative purposes as nominal corrosion current, I_{nom}, evaluated by formal application of the Stern-Geary relationship I_{nom} = B/Rp, with B ~ 26 mV[11].

Laboratory Methodology

Autopsy of the coating was conducted for evidence of coating breaks, disbondment, backside contamination[12], and corrosion under the epoxy coating. The coating thickness was measured with a magnetic coating thickness gage.

Chloride ion penetration profiles of field-extracted concrete cores were made for Category A bridge samples as of date. The samples were analyzed for total (acid-soluble) chloride concentration; results are given in mg of Cl^- ion per gram of dry concrete. Diffusion coefficients, D, and surface chloride concentrations, C_s, are estimated by least-error-fitting of the chloride content data to a solution to Fick's second law that assumes C_s=constant. Volumetric porosity was measured following ASTM procedures.

RESULTS

Category A: Vaca Cut and Snake Creek.

The substructure of these short bridges has only reinforced concrete drilled shafts in contact with the seawater. Concrete deterioration was generally inconspicuous with the exception of vertical cracks (0.08-0.3 mm wide) on two shafts in Vaca Cut and one in Snake Creek, out of a total 26 shafts in water at the two bridges. The drilled shaft containing the largest crack in Vaca Cut (0.3 mm width, 70 cm AHT, ~13 cm deep had also internal cracks (diagonal and transverse), leading from reinforcement depth, that had not yet propagated to the concrete surface. The crack at Snake Creek was 0.08 mm thick, ~30 cm high from 4 cm below high tide line to 26 cm AHT, and ~18 cm deep. The reexamined drilled shafts did not have any discernable deterioration. Concrete delamination could not be detected by hammer sounding on the any of the concrete sections (sound or cracked) from either bridge likely due to the large concrete cover (~13-15 cm).

In Vaca Cut, two shafts were cored in five locations fully exposing ECR in three cores. Two of those cores were an on-crack and off-crack pair at the largest vertical crack, 46 cm AHT. The ECR both on- and off- the main crack showed extensive corrosion (Figure 1). Lesser but still significant corrosion distress was observed on samples from a core at 165 cm AHT. There, the distress was limited to small coating breaks of rusty appearance and to thin rust spots and discoloration on as much as 10% of the steel substrate observed after removal of the coating. ECR was fully exposed at four core locations in Snake Creek, including a low-elevation on- and off-crack pair that showed significant corrosion but not as severe as in Vaca Cut. Complete coating disbondment was observed on all ECR samples from both bridges.

Where it could be examined, backside contamination was ~<1%. The average epoxy coating thickness was ~0.2 mm (Figure 2), generally consistent with product specifications.

Vertical and horizontal ECR exposed by coring in the same column were mostly found to be electrically continuous. Half-cell potential mapping of the ECR generally showed potential values (more negative than -300mV CSE), traditionally indicative of corrosion activity for plain rebar in atmospherically exposed concrete (Figure 3). Although potential may not be a reliable indicator of active corrosion of ECR in marine concrete, it is noted that all the rebar which had showed visual signs of corrosion were similarly negative. Concrete resistivity reached <5 kΩ-cm, indicative of highly permeable concrete (Figure 4). A general trend of lower resistivity at low elevations was consistent with expectations of near water saturation there.

The nominal corrosion current in sound concrete was 5 – 65 μA in Vaca Cut and 63 μA in Snake Creek. The nominal corrosion current by a crack in Vaca Cut was 110 – 180 μA.

The chloride penetration profiles are shown in Figure 5. The D values for Vaca Cut were very high (1e-7 to 2.76e-7 cm^2/s) and less but still indicative of high permeability for Snake Creek (4.73e-8 cm^2/s). The average C_s value was similar to those measured in other Florida marine bridges (~7 mg/g, ~17 kg/m^3).[9] The chloride content of the cracked concrete samples were higher than in the sound concrete within the area of the drilled shaft susceptible to sea splash (<46 cm AHT) which gives indication of preferential chloride penetration through the cracks. The volumetric porosity of the concrete from both bridges were high (~20%), consistent with the high permeability observed.

Category B: Sunshine Skyway Bridge.

The low approach span substructure consists of 512 reinforced concrete columns with footers and struts exposed to direct sea splash, and 256 cap beams at ~7 m AHT. The high approaches have elliptical post-tensioned columns. The average clear cover of the outer mat steel ranged from 9-11 cm in the various substructural components.

At low elevations, hairline cracks (<0.03 mm) were commonly observed on the concrete footers (<60 cm AHT) and columns (<200 cm AHT). Larger vertical cracks (~0.3 mm) with efflorescence were found on the elliptical post-tensioned columns. No concrete delamination was observed or detected by hammer sounding on any cracked or sound sections. A total of 12 cores were extracted from these low elevation locations. In the field, no evidence of corrosion was observed on the surface of the ECR exposed by coring, except for vestigial rust at small coating breaks such as high points on ribs where the coating had been damaged during or before construction. That rust did not appear to reflect ongoing corrosion. Spot knife tests of outer mat ECR exposed at the bottom of the core but not extracted, as well as from extracted bar segments indicated disbondment, in agreement with the laboratory findings described below. Whenever vertical as well as horizontal bars were exposed by coring, mutual electrical continuity was observed. Half cell potentials (Figure 3) ranged from values indicative of passive behavior to <- 600 mV. The more negative values were observed at some (but not all) of the lowest elevations. As mentioned above, the significance of these values is limited. The surface resistivity of the concrete at elevations where the concrete was very wet (e.g. <=0.3 m AHT) (Figure 4) ranged from (~15-150 kΩ-cm), consistent with the low permeability concrete used in this bridge. Carbonation penetration into the surface of the concrete at elevations exposed to sea splash was typically negligible in sound concrete, and in cracked concrete including on either side of the crack deeper into the core.

The trestle cap beams, which are at higher elevations, often had wider structural cracks (up to 0.6 mm), some with heavy efflorescence. No concrete delamination was observed or detected. Moisture was more prevalent at some of the cap beams which were exposed to runoff water at deck expansion joints. Isolated concrete spalls (apparently not corrosion related) in the same vicinity of the cracks were occasionally found in cap beams.[13] A total of 10 cores were extracted from the cap beams. As in the lower elevations, minor to no corrosion was observed on the ECR exposed by coring except for vestigial rust at small coating breaks. Spot knife tests on outer mat ECR were not conducted in the field. There was no indication of electrical continuity between the vertical bars exposed by coring. Potentials measured at exposed ECR locations ranged from -70 mV CSE > E >-490 mV CSE. . The concrete surface resistivity was 70-300 kΩ-cm with no clear difference between sound and cracked locations. Carbonation in sound and cracked concrete was typically small, ~1-2 mm but in one sound concrete case reached ~5 mm.

The average epoxy coating thickness from outer mat ECR at all locations was ~0.2 mm (Figure 2), as expected from material specifications. To date, coating autopsy was completed for four ECR samples from cracked low elevation concrete and ten ECR samples extracted from the cap beams; six from cracked concrete and four from companion sound concrete cores. Figure 6 is representative of the metal and coating underside appearance of samples with disbonded coating as described below.

In the low elevation samples the coating could be easily separated from the substrate on the entire specimen surface, indicating complete coating disbondment. Backside coating contamination was typically observed on 1-2% of the peeled coating. Consistent with field observations, vestigial rusting was observed on the steel substrate exposed by coating breaks. The steel surface exposed after removing the coating was mostly bright metal with some discolored zones around the coating breaks. No preferential corrosion or coating disbondment was observed at the ECR zone intersected by a crack, compared to the rest of the rebar segment. In the cap beam coring, complete coating disbondment was observed on seven of the ten ECR samples, while failure of the coating upon knife peeling was mostly cohesive on the remaining three samples. Backside coating contamination in the disbonded samples and presence of rust and discoloration were comparable to those noted in the low elevation samples. No correlation was found between the presence or position of the crack and the extent or location of rusting or coating disbondment in the ECR segments.

DISCUSSION

Severe ECR corrosion and coating disbondment was observed at low elevations at the Vaca Cut Bridge and to a lesser extent in Snake Creek. The corrosion was sometimes associated with cracks. These cracks were not noticed in the investigation a decade earlier, and in one instance there was associated deeper cracking closer to the rebar. The findings suggest that the cracking was the result of expansive corrosion products, but the evidence is limited and at least some preexisting cracking cannot be completely ruled out at present. Corrosion was minor at higher elevations, consistent with lower chloride contents at the rebar depth there. At low elevations in those bridges chloride penetration was high, consistent with the high chloride diffusivities and permeability observed from the present cores and in earlier investigations. It is noted that at the crack locations chloride ingress was particularly severe and if the cracking was due to corrosion products the added chloride ingress would have occurred during the last decade. In general, previous model predictions of corrosion development at ECR in these bridges by the time of this study are essentially confirmed by the present findings. Further sampling of highly permeable sound and cracked concrete exposed to sea splash is in progress.

In contrast with the category A bridges, corrosion at ECR in the Sunshine Skyway Bridge was limited to minor rusting at coating breaks and discoloration, usually nearby, underneath disbonded coating. The cracks under consideration were observed early on and did not result from corrosion. Although enhanced chloride penetration through cracks has been well documented[9], the present results revealed no physical evidence of enhanced deterioration on ECR in cracked concrete at either the low elevations near the waterline or at the higher elevation cap beams. It is cautioned however that these results are preliminary. Sampling to obtain a greater population of ECR segments in cracked concrete exposed to sea splash, where conditions are most severe, is in progress and results will be presented subsequently. The findings to date are consistent with earlier model predictions that did not anticipate early corrosion development in this structure, based on the high concrete quality and the thick concrete cover used.

This investigation is in progress, including investigation of several other marine structures built with ECR. Results will be presented in subsequent updates.

CONCLUSIONS

Expectations of early development of corrosion of ECR in bridges with concrete of high chloride diffusivity were confirmed. In those structures there was severe corrosion of ECR at crack locations but also in apparently sound concrete at similar elevations.

In a structure with high quality concrete and deep concrete cover the ECR had extensive disbondment, minor rust at coating breaks and discoloration underneath disbonded coating. However, no instances of severe corrosion were observed and there was no correlation between presence or position of thin concrete cracks and any form of rebar deterioration.

These results are preliminary and will be further substantiated by tests in additional locations.

ACKNOWLEDGEMENT

This investigation was supported by the State of Florida Department of Transportation and the U.S. Department of Transportation. The opinions, findings and conclusions expressed in this publication are those of the authors and not necessarily those of the supporting agencies.

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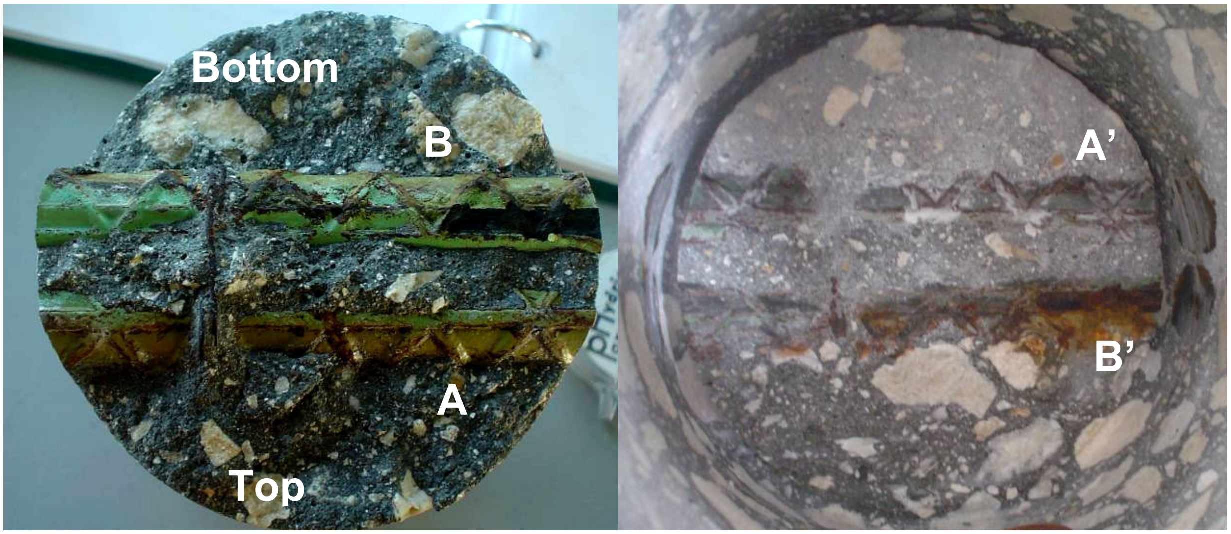

Figure 1. Severe ECR corrosion observed at the Vaca Cut bridge. Drilled Shaft (VA2A) ~45 cm AHT on crack (0.33 mm).The location of ECR A and B corresponds to the position at the bottom of the core hole A’ and B’, respectively.

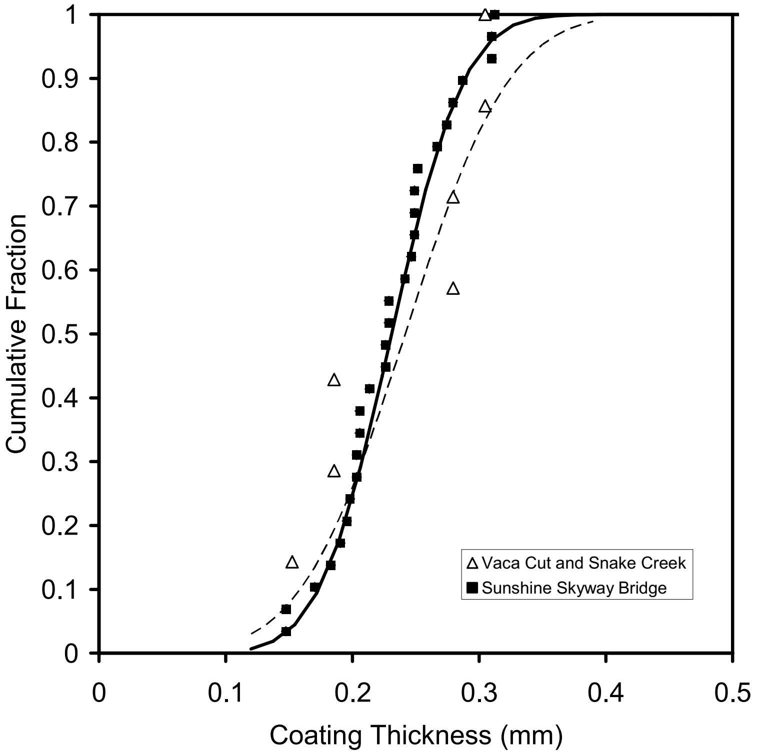

Figure 2. Cumulative Fraction of Coating Thickness

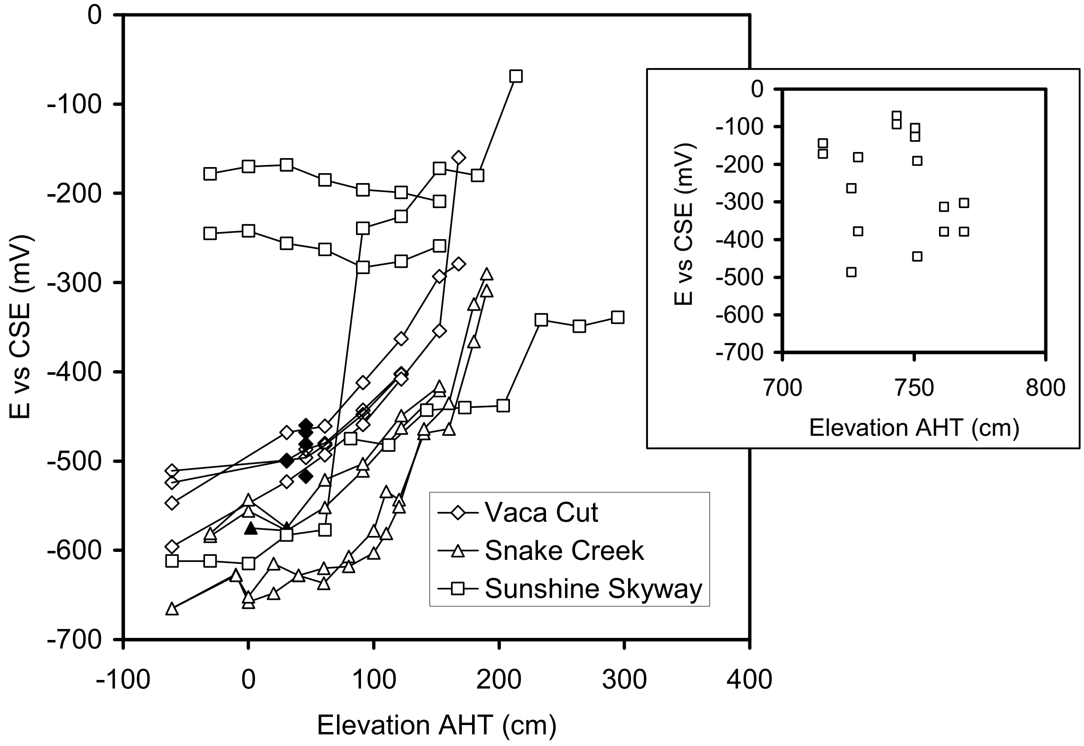

Figure 3. Half-cell potentials as function of elevation.

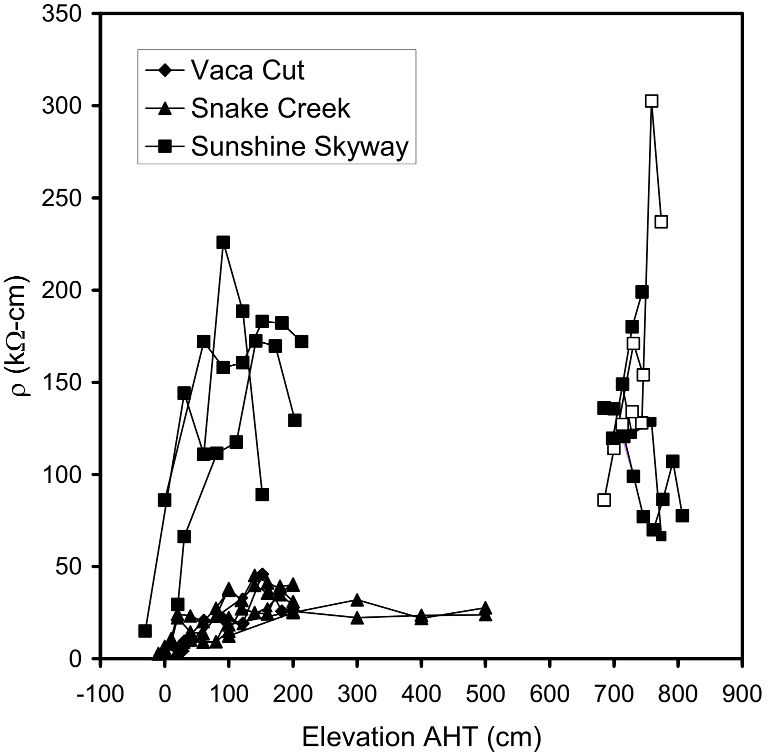

Figure 4. Concrete resistivity as function of elevation.

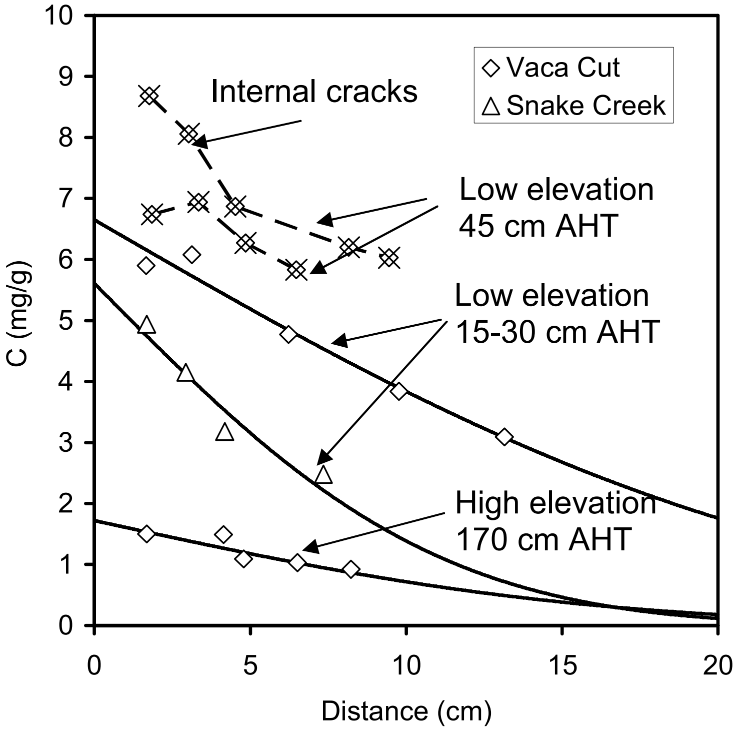

Figure 5. Chloride concentration as function of depth. X: cracked concrete. Solid line: fitted trends to obtain diffusional parameters.

Figure 6. Typical steel and undercoating condition in disbonded ECR extracted from Sunshine Skyway Bridge, showing minor rust at coating breaks, and nearby discoloration of the metal surface. Trestle cap beam, 7.5 m AHT (SSK140E2).