

CATHODIC PROTECTION OF THE YAQUINA BAY BRIDGE

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ABSTRACT

The Yaquina Bay Bridge in Newport, Oregon, was designed by Conde B. McCullough and built in 1936. The 3,223-foot (982 m) structure is a combination of concrete arch approach spans and a steel through arch over the shipping channel. Cathodic protection is used to prevent corrosion damage to the concrete arches. The Oregon Department of Transportation (Oregon DOT) installed a carbon anode coating (DAC-85) on two of the north approach spans in 1985. This anode was operated at a current density of 6.6 mA/m² (0.6 mA/ft²). No failure of the conductive anode was observed in 1990, five years after application, or in 2000, 15 years after application.

Thermal-sprayed zinc anodes 20 mils (0.5 mm) thick were applied to half the south approach spans beginning in 1990. Thermal-sprayed zinc anodes 15 mils (0.4 mm) thick were applied to the remaining spans in 1996. These anodes were operated at a current density of 2.2 mA/m² (0.2 mA/ft²). In 1999, four zones on the approach spans were included in a two-year field trial of humectants to improve zinc anode performance. The humectants LiNO₃ and LiBr were applied to two zones; the two adjacent zones were left untreated as controls. The humectants substantially reduced circuit resistance compared to the controls.

INTRODUCTION

Reinforced concrete structures, such as bridges and buildings, are particularly susceptible to salt-induced corrosion problems in coastal areas and in areas where deicing salts are used. Problems develop when salts permeate the concrete and accumulate at the rebar-concrete interface. Rebar, which is normally passive in the high pH concrete environment, loses passivity and begins to corrode when a threshold level of salt is exceeded.¹ The corrosion product occupies a volume much greater than the steel it replaces. This leads to tensile stresses at the rebar-concrete interface which can crack the concrete,² cause delamination of the cover concrete, and accelerate subsequent corrosion damage. Efforts have been made to minimize rebar corrosion by a number of approaches, including epoxy coating and galvanizing the rebar, special concrete mix designs, sealing the concrete surface, and cathodic protection (CP). Cathodic protection is the most effective approach for high chloride environments.³⁻⁴

The state of Oregon has a rugged and beautiful coastline linked by a series of bridges on US highway 101. The major bridges were designed by Conde B. McCullough and built in the late 1920s and 1930s. A number of these bridges are listed on the National Historic Register. The decision to replace or to preserve older bridges along the Oregon coast involves not only issues

of public funds and public safety, but historic considerations as well. The 1987 replacement of the Alsea Bay Bridge in Waldport, Oregon, cost approximately \$45 million and resulted in public protest of the loss of a landmark McCullough-designed bridge. Cathodic protection is the approach the Oregon Department of Transportation (DOT) is using to prevent further corrosion damage to the remaining historic bridges.

The Yaquina Bay Bridge in Newport, Oregon, was built in 1936, [Figure 1](#). The 3,223-foot (982 m) structure is a combination of steel and concrete arches. The main span is a 600-foot (183 m) steel through arch flanked by two 350-foot (107 m) steel deck arches. There are five reinforced concrete deck arch secondary spans and fifteen concrete deck girder approach spans. The objective here is to present results on the long-term performance of thermal-sprayed zinc and carbon conductive paint anodes used in impressed current cathodic protection (ICCP) systems on the Yaquina Bay Bridge.

ZINC ANODE

Planar thermal-sprayed zinc anodes, 20 mils (0.5 mm) thick, were applied to half of the south approach spans beginning in 1990. The twin-wire arc-spray process was used to apply zinc to the concrete surface. The twin-wire arc-spray process feeds wire from each of two spools through flexible leads to the spray head. Charge is transferred to the wires at the spray tips creating an electric arc which melts the wires. Compressed air is typically used to atomize the molten metal into droplets and propel them to the surface. [Figure 2](#) shows the equipment used to thermal spray the Yaquina Bay Bridge zinc anodes. Prior to thermal spraying, the concrete surface was sandblasted to produce suitable surface for anchoring the zinc anode, then air blasted to remove dust and larger particles. The early research of Brousseau et al.⁵⁻⁷ showed that low or reduced anode initial bond strengths result from high moisture levels in the concrete, low concrete surface temperatures, too much exposed aggregate, and surface contamination. Therefore the concrete surface of the bridge was preheated to a temperature between 250° to 320° F (120° to 160° C) before thermal spraying.

Some of the uncertainties in using thermal-sprayed zinc anodes are the factors that affect long-term performance and service life. To provide an understanding of the long-term performance of thermal-sprayed Zn anodes, accelerated laboratory aging studies were conducted.⁵⁻⁹ These studies were conducted on zinc anodes applied to preheated and unheated concrete slabs. One group of test slabs were wetted on a daily basis and a second group were wetted on an occasional basis when high CP system voltages developed. The accelerated aging studies showed the anode bond strength dropped precipitously in less than 10 years at Oregon DOT bridge ICCP conditions for the occasionally wetted slabs, both preheated and unheated, [Figure 3](#). In contrast, the anode remained bonded to the concrete for up to 27 years of service for the slabs wetted daily. In the laboratory tests, preheating the concrete surface just prior to anode application improved the initial bond strength substantially, as much as 2.1 MPa (300 psi).⁸⁻¹² However, over the long term there was no difference in the anode bond strength with and without preheating of the concrete slabs. Using bond strength as a service life criteria, these results indicated that preheating the concrete prior to anode application was unnecessary, and that anode wetting and the cycle of wetting and drying were critical factors in achieving a long anode service.

Anode thickness is an important consideration in the operation of planar zinc anodes. An anode that is too thin will not have the desired service life. An anode that is too thick will add unnecessary expense and may delaminate due to internal stresses within the coating. The laboratory tests showed that approximately 3 mils (0.08 mm) of zinc were consumed after the equivalent of 27 years service at Oregon DOT ICCP conditions.⁸ As a result Oregon DOT made the following changes in zinc anode application: (1) preheating of the reinforced concrete surface to a temperature between 250° and 320° F (120° and 160° C) was no longer required;

and (2) zinc anode thickness was reduced from 20 mils (0.5 mm) to 12-15 mils (0.3-0.4 mm). Thermal-sprayed zinc anodes 15 mils (0.4 mm) thick were applied to the remaining south approach spans on the Yaquina Bay Bridge in 1996.

The laboratory aging studies showed the importance of moisture at the Zn-concrete interface in improving the performance of CP systems. Humectants are substances that promote the retention of moisture. The humectants lithium bromide (LiBr) and lithium nitrate (LiNO_3) have been applied to thermal-sprayed Zn anodes in GCP systems⁸⁻¹³ and in ICCP systems.¹⁴⁻¹⁶ They work by lowering the activity of water in the solution. Figure 4 shows water activity at 25°C in a binary solution of water and LiBr or LiNO_3 using data from Zaytsev and Aseyev.¹⁷ This system can be viewed as an example of the environment at the zinc anode-concrete interface. Based on cold water solubility limits¹⁸ of 1.45 kg/L of water (16.7 m [molal]) for LiBr and 0.898 kg/L of water (13 m) for LiNO_3 , the calculated relative humidity (RH) above the saturated solutions would be 8% and 45%, respectively. In an environment of 50% RH, the saturated solutions of LiBr and LiNO_3 would absorb water until the concentrations of the solutions were reduced to about 8 m for LiBr and 11 m for LiNO_3 .

CP Zones 10, 11, 13, and 14 on the Yaquina Bay Bridge south approach, with areas of approximately 465 m² (5000 ft²), were chosen for a two-year humectant field trial. The ICCP system was powered off in October 1999 and humectants were applied to two zones (Figure 5): Zone 13 with one coat of 30-40 wt. % LiNO_3 and Zone 11 with two coats of 52-56 wt. % LiBr. Zones 10 and 14 on each side of the treated zones were left untreated as controls. The ICCP system was powered on the day after the humectants were applied. The CP currents were: 0.99 mA/m² (0.09 mA/ft²) for Zone 10, 3.95 mA/m² (0.4 mA/ft²) for Zone 11, 3.21 mA/m² (0.30 mA/ft²) for Zone 13, and 1.34 mA/m² (0.13 mA/ft²) for Zone 14. The anode voltages and currents for the treated and control zones were monitored daily.

The circuit resistance of the two treated and two control zones on the Yaquina Bay are shown in Figure 6. The four zones are located over land but adjacent to the bay, are identically sheltered by the bridge deck, and differ in distance from the bay. Zone 10 (control) is the farthest from water, about 131 m (430 ft), and the driest of the four zones. Zone 14 (control) is closest to water, about 76 m (250 ft), and the least dry. Between these two zones are the LiNO_3 -treated zone 13 at 94 m (310 ft) and the LiBr-treated zone 11 at 113 m (370 ft). In the absence of humectant, the circuit resistance of the treated zones would be expected to lie between that of zones 10 and 14. Instead the humectants have substantially reduced circuit resistance compared to either control. This reduction is associated with increased conductivity of the electrolyte (concrete) and reduced anode concentration polarization at the anode-concrete interface resulting from the additional moisture attracted by the humectants. The LiNO_3 -treated zone had a somewhat lower circuit resistance than the LiBr-treated zone.

Visual inspection of the thermal-sprayed zinc anodes on the south approach spans made in October 1999 prior to the application of the humectants and again in October 2000 showed no signs of delamination nor peeling of the anode.

Microscopy showed that Zn anodes and humectant-treated Zn anodes developed the same reaction zones at the anode-concrete interface.⁸⁻⁶ Zinc oxide and zinc hydroxy chloride anode dissolution products accumulated at the anode-concrete interface. In addition, zinc diffused into the cement paste, replacing some of the calcium in the cement paste near the anode-concrete interface. Calcium was present in the bulk concrete at normal levels and at a reduced level in the cement paste near the zinc anode-concrete interface. With aging, chloride and sulfur diffused from the bulk cement paste and accumulated at the zinc-concrete interface. The Br x-ray map showed that the highest concentration of Br was in the reaction layer immediately adjacent to the anode.¹⁶ Unlike Br, the NO₃ component of the humectant is not detectable by x-rays.

CARBON ANODE

Oregon DOT installed planar carbon anodes ([Figure 7](#)) on two of the north approach spans in 1985 making these the oldest CP carbon anodes still in service in the nation.¹⁹ The area protected was divided into four separate zones, each approximately 1700 ft² (158 m²). The primary anode was platinum-niobium wire and carbon conductive paint was the secondary anode. The carbon anode covered the bottom of the deck between the beams, the beam sides, and the bottom of the beams. The carbon anode was applied as conductive paint with a wet film thickness of 35 to 40 mils (0.9 to 1 mm) that resulted in a dry film thickness of 20+ mils (0.5+ mm). The carbon anode was top coated with an acrylic paint for cosmetic purposes.

From June 1985 until May 1986, the CP systems were operated with improperly functioning rectifiers. New rectifiers were installed in May 1986 and operated in the constant-voltage, current-limited mode. The current density¹⁹ for each zone was approximately 0.60 mA/ft² (6.6 mA/m²). The zones were running at 0.27 to 0.39 mA/ft² (2.8 to 4.1 mA/m²) in 1990²⁰ and in 2000 at 0.25 to 0.30 mA/ft² (2.6 to 3.1 mA/m²).

[Figure 8](#) shows that the carbon circuit resistance in zones 1, 2, and 3 remained relatively stable after the new rectifiers were installed. No data was available for zone 4 in 2000. The circuit resistance for the carbon anode after extended service is at roughly the same level as planar titanium anodes²¹⁻²² and considerably lower than planar zinc anodes.⁸⁻¹³

Measurements of the concrete tensile strength and the zinc coating bond strength were made using a Proceq portable tester. Aluminum dollies with a diameter of 5 cm (1.9 in) were epoxied to the zinc coating with a high viscosity, high strength, and short cure time (5 min) epoxy. [Table 1](#) shows the carbon anode bond strengths after approximately 15 years of service ranged from 27 to 118 psi (0.19 to 0.81 MPa) for all the zones, with an average of 77 \pm 32 psi (0.53 \pm 0.32 MPa). Thus, the carbon anode remains well bonded to the concrete after extended service.

[Table 2](#) compares the bond strength of the carbon conductive paint anode after 15 years of service with those of the thermal-sprayed zinc and titanium anodes at 15 to 20 years of service at Oregon DOT bridge ICCP conditions. The bond strength for the zinc anode ranged from 174 to 232 psi (1.2 to 1.6 MPa)⁸⁻¹³ and for the titanium anode from 38 to 51 psi (0.26 to 0.35 MPa).²¹⁻²² The zinc anode bond strength is higher because of secondary mineralization of zinc dissolution products with the cement paste. The lower results for the carbon and titanium anodes occurs because of acidification of the concrete at the anode-concrete interface and deterioration of the cement paste. Nevertheless, the bond strength of the carbon anode is adequate for anode service and the anode remains well bonded to the concrete.

The pH at the carbon anode-concrete interface was measured using a micro-pH electrode. The exposed surface of anode samples pulled from the concrete in the bond strength measurements was wetted with a drop of high purity water. The pH electrode was touched to the wetted surface in a stirring action to agitate the surface and loosely adhering cementitious material. The pH electrode was calibrated at pH 7 and 10 before the measurements. To check for any drift in electrode performance, the pH of the standards were measured again after the anode measurements; there was none. The pH of the anode-concrete interface in the four CP zones ranged from 3.8 to 8.1 with most of the values below pH 7, [Table 1](#). This represents substantial acidification of the interface and lower values than seen for zinc⁹⁻¹³ or titanium²¹⁻²² anodes.

Since the bond strength and interfacial pH measurements were taken at the same spot on the carbon anodes ([Table 1](#)), they have been compared in [Figure 9](#) to determine if a relationship exists between them. Both measurements would be affected by electrochemical

aging: bond strength by changes in the chemistry of the anode-concrete interface, pH by the consumption of alkaline species in the concrete. Given that there are a couple of outliers in the data, the data indicate that local bond strength and pH are linked, with the bond strength decreasing as the pH decreases. Earlier results have shown how pH varies with electrochemical age for zinc anodes.¹⁰⁻¹² Furthermore, current distribution to a planar anode surface will vary with proximity to the underlying rebar (21). In other words, the average electrochemical age of an anode zone is not necessarily the age of the anode at a specific location. It follows then that local pH and bond strength will vary over the anode surface as a function of the local electrochemical age. It further means that electrochemical age specific properties (pH, bond strength, interfacial chemistry, interfacial permeability to moisture, interfacial electrical resistance) will vary with location on the anode surface.

Depolarization measurements taken from 1985 to 1988¹⁹ exceeded the 100 mv criteria in less than 4 hours. In depolarization measurements made in 1990,²⁰ 95.8% of the readings decayed by more than 100 mv in 42 hours. All decays were greater than 100 mv in 24 hours and 81.3% decayed by more than 200 mv. The 100 mv decay in 4 hours indicated that the rebar is well protected by the carbon anode.

SEM Interfacial chemical analyses were conducted on cross-sections of the carbon anode-concrete interface polished to a 1_μm diamond finish. The cross-sectioned anode samples were coated with palladium prior to imaging in a scanning electron microscope (SEM). X-ray maps were measured using the energy-dispersive x-ray analyzer (EDS) with an atmospheric thin window for low atomic number elements. Figure 10, top right, shows a backscattered electron (BSE) SEM photomicrograph of a carbon-concrete interface from zone 2. The brighter regions represent higher atomic number elements in a BSE image. This BSE image shows four distinct layers, the acrylic paint, the carbon anode, a reaction layer in the cement paste, and the unaltered cement paste. It is evident from the BSE image that the carbon anode makes a good bond to the concrete.

The remaining images in Figure 10 are x-ray maps showing the elemental distributions of carbon (C), calcium (Ca), and silicon (Si), respectively. In the x-ray maps, the brighter regions represent higher concentrations of the element. The C x-ray map shows carbon in the anode and elevated levels of carbon in the cement paste near the anode-concrete interface. The Ca x-ray map shows Ca in the bulk concrete and a well developed Ca depleted zone adjacent to the carbon anode. This is similar to what happens when an inert anode such as titanium is used and is due to acidification of the anode-concrete interface.¹⁷ Ca x-ray maps for samples taken from zones 1 and 4 showed only isolated areas of Ca depletion. This suggests the samples were taken from areas well away from the rebar where the local current density and, hence, electrochemical age was substantially lower than the location sampled in zone 2. The Si x-ray map shows Si in the carbon anode and in the aggregates. The Cl X-ray map (not shown) indicated no chloride present at the anode-concrete interface. These Cl results are unusual since Cl will migrate to the anode surface during cathodic protection.^{8-13, 25} It is possible that the anode is sufficiently permeable to moisture that, over time, Cl at the interface is leached from the concrete and removed by surface moisture (dew, fog, wind driven precipitation). In 1992, Broomfield and Tinnea²⁰ found lower levels of chloride in a core sample from a carbon anode CP zone as compared to a core sample from an area of the bridge without CP.

Figure 11 shows depth profiles presented as element line scans across the carbon anode-concrete interface. The acrylic paint topcoat is shown at the extreme left edge of the figure. The C anode is adjacent to it and is identified by the high C concentration. The unaltered cement paste can be identified by the high calcium concentration at the right side of the figure. The area between the anode-concrete interface and the unaltered cement paste is a roughly 1.3 mm thick reaction zone where Ca is depleted because of acidification of the interface. This zone also contains an unusually high level of C, suggesting that C in some form has migrated into the reaction zone.

CONCLUSIONS

The planar thermal-sprayed zinc anodes on the south end of the Yaquina Bay Bridge are functioning well after 5+ years service. Based on laboratory bond strength measurements, they should remain well bonded to the concrete for more than 25 years. However, CP circuit resistance should increase with electrochemical age. Increasing the moisture content of the interface can reduce the circuit resistance by improving conductivity at the interface and dispersion of zinc dissolution products. Early results from humectant-treated zones on the bridge have shown that circuit resistance can be reduced by the application of either lithium bromide or lithium nitrate solutions to the zinc anode surface where it is absorbed into the anode-concrete interface.

The planar carbon anodes on the north end of the Yaquina Bay Bridge are functioning well after 15 years service. It remains reasonably well bonded to the concrete. The CP circuit resistance is low. It appears to be providing adequate protection to the rebar. The anode is relatively inexpensive to apply, easily repaired in the field, and easy to remove if that became necessary.

Results suggest that electrochemical age specific properties (pH, bond strength, interfacial chemistry, interfacial permeability to moisture, interfacial electrical resistance) *may vary* with location on the anode surface due to variations in local current density as a consequence of proximity to the underlying rebar.

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TABLE AND FIGURES

Table 1 – Carbon Anode Sample Location and Properties

Pull sample number	Anode Zone number	Bond Strength, psi (MPa)	Carbon anode pH
BS1	1	48 (0.33)	4.59
BS2	1	74 (0.51)	5.84
BS3	2	58 (0.40)	3.77
BS4	2	118 (0.81)	5.27
BS5	3	27 (0.19)	6.04
BS6	3	75 (0.52)	6.70
BS7	4	118 (0.81)	7.34
BS8	4	95 (0.65)	8.11

Table 2 – Anode Bond Strength After 15-20 Years

Anode	psi	MPa
Carbon	77 ± 32	0.53 ± 0.32
Zinc	174 - 232	1.2 - 1.6
Titanium	38 - 51	0.26 - 0.35



Figure 1 - Yaquina Bay Bridge built in 1936 and located on the Oregon Coast at Newport.



Figure 2 - Thermal spraying using the twin-wire arc spray process.

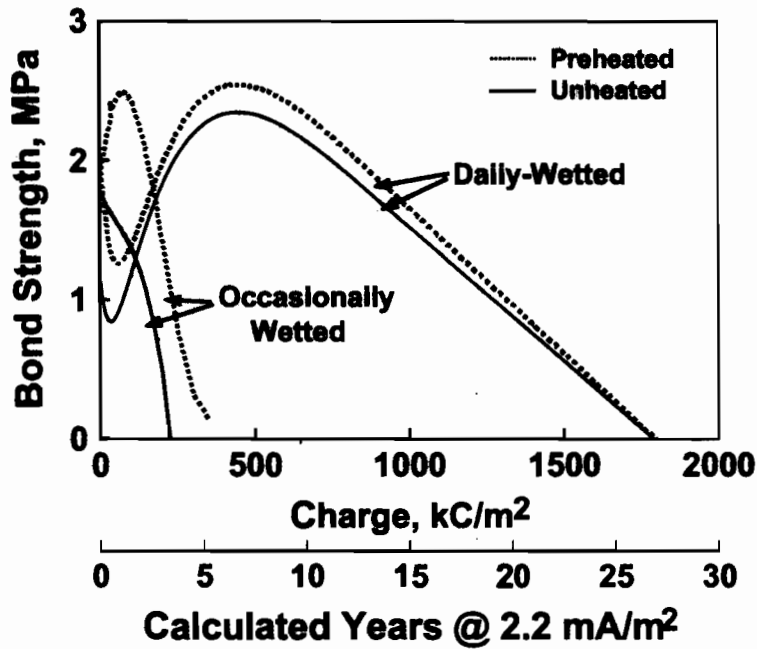


Figure 3 - Bond strength as a function of charge for preheated and unheated zinc-coated concrete slabs under daily-wetted and occasionally-wetted conditions.

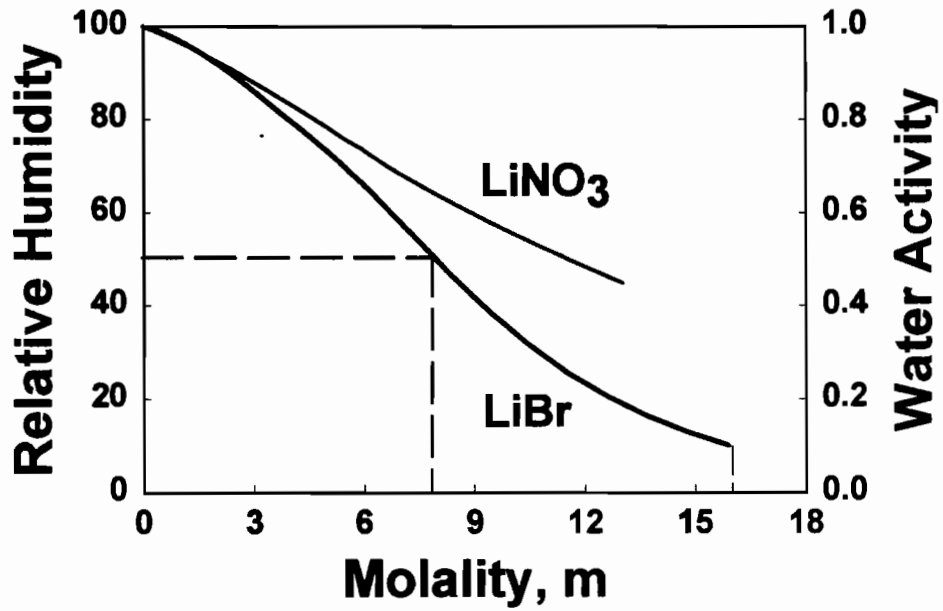


Figure 4 - Water activity as a function of humectant concentration



Figure 5 - Spraying humectant on the Yaquina Bay Bridge.

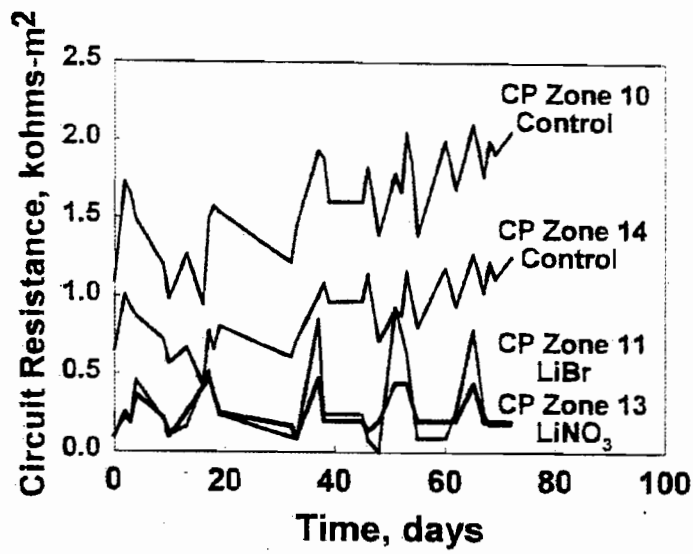


Figure 6 - Circuit resistances of humectant-treated and control CP zones.



Figure 7 - Carbon anode coating on the north end of the Yaquina Bay.

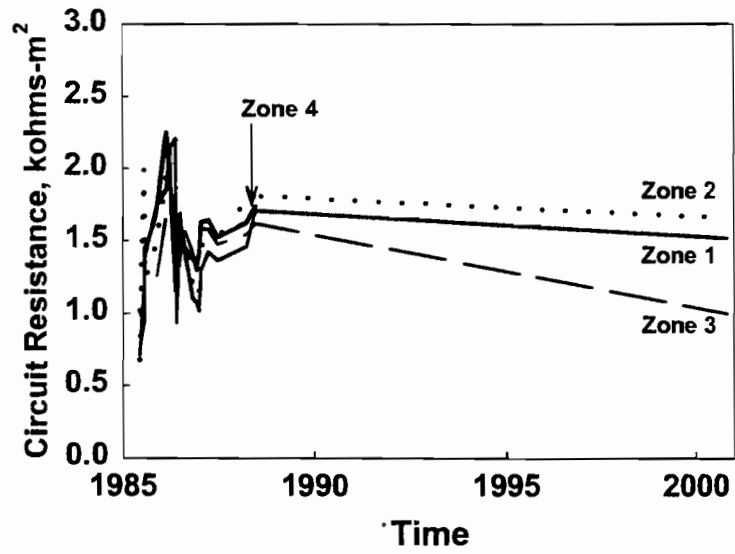


Figure 8 - Carbon anodes circuit resistances in zones 1 through 4

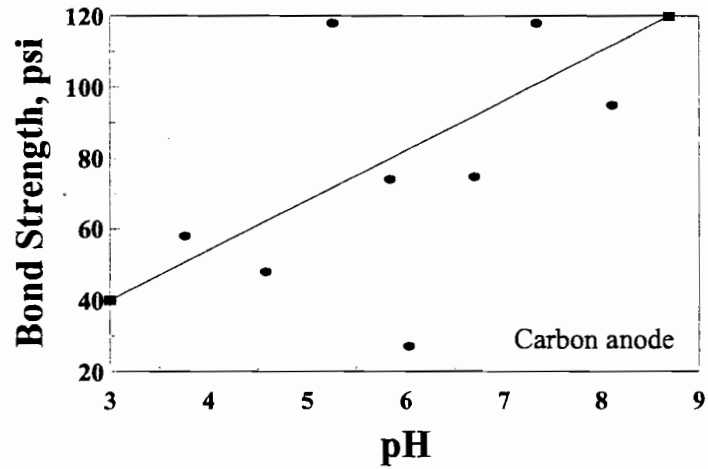


Figure 9 - Bond strength versus pH showing that anode electrochemical age specific

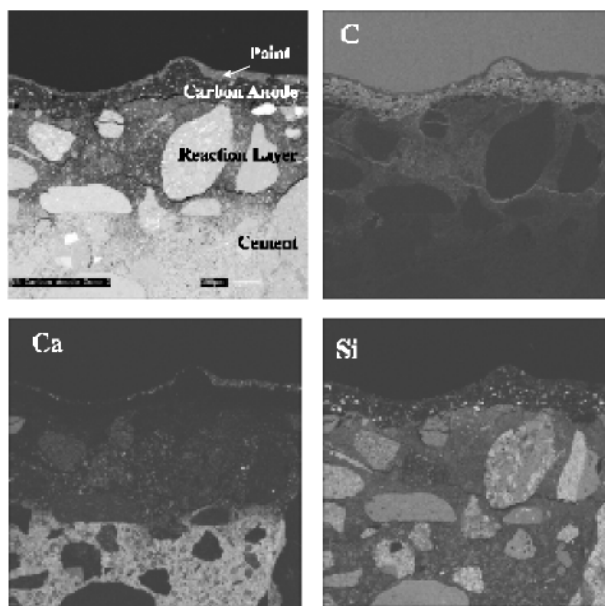


Figure 10 - Photomicrographs of the carbon anode in zone 2. BSE SEM image and x-ray maps for C, Ca, and Si.

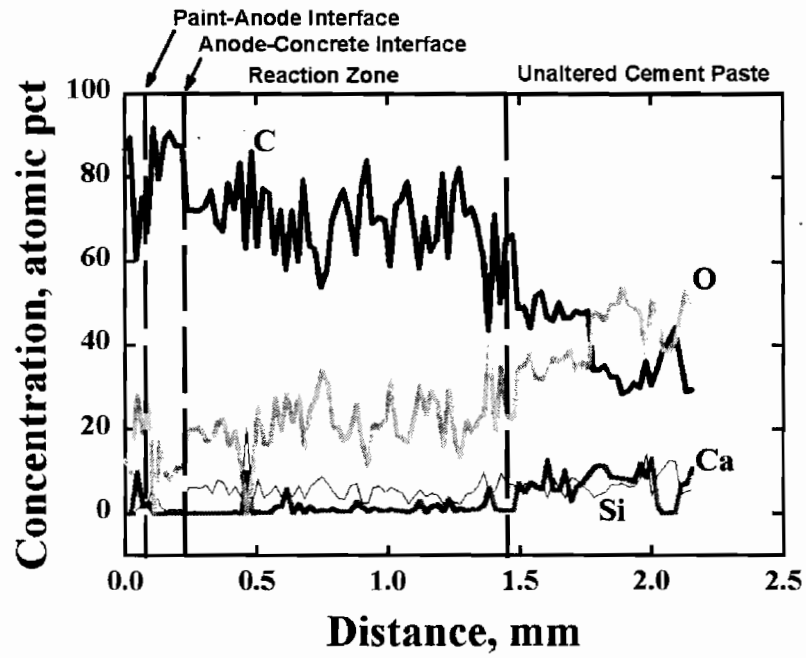


Figure 11 - Depth profile for carbon anode-concrete interface showing C, O, Ca, and Si elemental lines scans