

Cathodic Protection of Reinforced Concrete by Using Metallized Coatings and Conductive Paints

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ABSTRACT

Corrosion-caused distress to reinforced-concrete structures is a serious and continuing problem. A practical mitigation measure is cathodic protection of the embedded reinforcing steel. In this paper the results of an ongoing laboratory and field study that tests proprietary conductive paints and flame-spray metallizing as conductive coatings/anodes on concrete are described, and their physical characteristics, behavior, and economics as part of cathodic protection systems are also discussed. Results to date indicate that several of the paints and most of the metals tested provide adequate conductivity and bond to the concrete, but differ significantly in ease of application, toxicity, aesthetics, and economics. Of the materials tested, zinc metallizing appears to provide the most viable combination of physical characteristics and economics for cathodic protection of concrete reinforcement.

Concrete normally provides excellent protection from corrosion to embedded reinforcing steel by forming a thin, stable oxide layer on the surface of the metal. This layer acts as a barrier to further corrosion, a phenomenon known as passivation. Chloride ions can destroy this passivating oxide film and allow corrosion to proceed at a rapid rate, given an adequate supply of oxygen and moisture.

One successful method of stopping or significantly reducing the corrosion process is the introduction of direct current (dc) to the corrosion cell, but flowing in the opposite direction to the natural process. This current, delivered by an external source, blocks the normal flow of charges and thus converts the corroding area (the anode) into a non-corroding area (a cathode). This method is called cathodic protection (CP).

The first reported application of CP to above-ground reinforced concrete was by the state of California in 1959 (1), and the first application of CP to a concrete bridge deck was reported by the state of California in 1974 (2). Since then a number of agencies have revised and improved the pioneering system (3-5) and, currently, CP is considered a reliable means of controlling corrosion in the top mat of bridge deck reinforcing steel (6-10).

The pioneering system distributed CP current evenly throughout the surface of the concrete by means of a layer of coke breeze (small particles of coke, a byproduct of the petroleum industry, consisting of approximately 97 percent carbon; it is a good conductor).

More recently, considerable interest has been shown in substituting coke with conductive paints, conductive mortars, conductive (platinum-coated) wires set into cut grooves, and other materials with a combination of conductive and adhesive properties

(11-13). The aim of these studies was to develop a conductive layer with the satisfactory current distribution capabilities of the coke system but improving on one or more of its disadvantages [better adhesion, use on vertical surfaces such as bridge substructures, avoiding trapped water, eliminating asphalt concrete (AC) overlays, reducing costs, and so forth].

In this paper the interim results of a study concentrating on tests and evaluation of two general types of conductive material--proprietary conductive paints and sprayed molten metals applied by the flame-spraying process--are presented. Conductive paints are applied in a conventional manner. The flame-spraying process involves melting a continuously fed metal wire by an oxygen-acetylene flame and spraying the molten metal by compressed air onto the concrete surface (14). Adhesion is achieved primarily by mechanical bond to the prepared (sand-blasted) concrete surface. (It should be noted that flame spraying is one of three methods of metallizing, the other two being arc spraying, in which the wire is melted by an electric arc, and plasma spraying, in which the metal, in the form of powder, is melted in a nitrogen-oxygen or argon-hydrogen gas flame.)

Testing concentrated on the properties that have a direct influence on their suitability for CP applications: conductivity, consumption of anodes, adhesion to concrete, resistance to weathering, environmental impact, aesthetics, and economics.

The basic workplan was to select as many commercially available conductive materials (paints and metals) as practicable and perform initial laboratory testing to determine their physical characteristics and suitability. Following this initial determination, the most promising of these materials were selected and they were applied to a reinforced-concrete slab mounted in an outdoor exposure. When sufficient testing and evaluation has been performed on the slab, the most promising of the surviving candidate materials were selected and applied to a real-world structure.

Currently, the laboratory and concrete slab testing have been completed, and two candidate materials, flame-sprayed zinc and flame-sprayed Sprahabitt A, alloy have been applied to a real structure (pier 4 of the Richmond-San Rafael Bridge in San Francisco Bay) and are delivering CP current to the reinforcing steel. In this paper the findings to date are documented.

SELECTION OF MATERIALS

Review of the literature and inquiries to industry resulted in the selection of seven paints and six metals or alloys in wire form. The paints were manufactured and sold specifically for their conductivity. Several had been investigated in a previous study (11). The metals and alloys were selected on the basis of reasonable cost and availability in wire form; their expected performance as conductors of CP current was unknown, because their use in this manner had not been considered or tested before this

project. The paints and metals tested are given in the following lists.

The paints tested were as follows:

1. Cho-Shield 4130--a carbon-filled latex paint (by Chomerics, Woburn, Massachusetts);
2. E-Kote 3062--an iron-filled acrylic paint (by Acme Chemicals and Insulation Company, New Haven, Connecticut);
3. E-Kote 3063--a nickel-filled acrylic paint (by Acme Chemicals and Insulation Company);
4. Electrodag 112--a graphite-filled acrylic paint (by Acheson Colloids Co., Port Huron, Michigan);
5. Konductokure--a carbon-filled concrete curing compound (by Master Builders, Cleveland, Ohio);
6. Con-Deck W-0731--a carbon-black filled latex paint (by Wescorp/DAL Industries, Inc., Mountain View, California); and
7. Con-Deck W-0735--a carbon-black filled latex paint (by Wescorp).

The metals tested were as follows:

1. Aluminum SF--a 43 alloy that contains 94 percent aluminum and 6 percent silicon (by METCO Inc., Westbury, Long Island, New York);
2. Aluminum--a 1100 commercially pure 99+ percent aluminum (by METCO);
3. 405 Bond--a clad wire, 80 percent nickel encased in a 20 percent aluminum outer sheath (by METCO);
4. Metcoloy #2--a 420 stainless steel; contains 13 percent chromium and 0.5 percent nickel (by METCO);
5. Sprababbitt A--a tin base (lead-free) babbitt that contains 89 percent tin, 7.25 percent antimony, 3.5 percent copper, and 0.25 percent lead (by METCO); and
6. Zinc--commercially pure, 99+ percent zinc (by METCO).

LABORATORY TESTING

Conductivity

A series of tests was devised and performed in order to test the ability of each material to conduct CP current and to obtain an estimate of its rate of consumption. All wires were 0.125 in. nominal diameter.

Wire Consumption

All metals in wire form were tested in the circuit shown in Figure 1. A measured and weighed length of each wire was immersed in a container of salt water (3.5 percent NaCl solution by weight). The wire was partly coated with wax so that a length of 2.5 in. would be in contact with the water. An external power supply created a potential in the range of 1 to 2 V between the wire and the aluminum foil lining of the container. This caused the wire to discharge current into the water and thus consume itself. Testing was ended when a significant portion had been consumed, but before the wire broke at its thinnest point. Subsequent weighing and computations provided values for consumption rates (Table 1).

CP Current Delivery to Reinforced Concrete

All paints and metals were tested in the circuit

LEGEND

- 3.5% (BY WEIGHT) SALT SOLUTION
- WIRE
- WAX COATED AREAS
- VOLTMETER
- RESISTOR

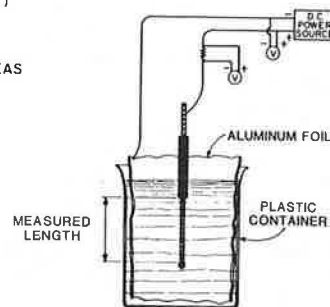


FIGURE 1 Schematic--wire consumption test.

TABLE 1 Consumption Rates of Metals in Wire Form

Metal	Consumption Rate	
	Ampere-Hours per Pound	Pounds per Ampere-Year
Aluminum SF	1,057.3	8.3
Aluminum 1100	1,115.9	7.8
405 Bond	1,184.3	7.4
Metcoloy #2	440.8	19.9
Sprababbitt A	327.0	26.8
Zinc	366.7	23.9

shown in Figure 2. Each material was painted or sprayed in the form of stripes on the surface of all reinforced-concrete test specimens. Applied quantities were estimated, but because of the small areas involved, the precision of these values was low. The main usefulness of this test was to imitate real-life conditions (with the exception of current density) and establish whether or not some coatings (especially the metals) would lose bond or quickly develop a poorly conductive oxide layer between themselves and the concrete.

LEGEND

- APPLIED COATING
- CONCRETE BLOCK WITH EMBEDDED STEEL REBAR
- TAP WATER
- VOLTMETER
- RESISTOR

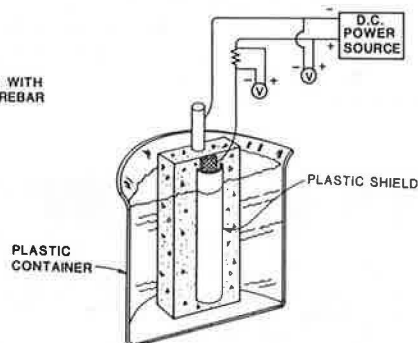


FIGURE 2 Schematic--CP current delivery to reinforced-concrete specimen.

The concrete specimens measured 2.25 x 4.5 x 15.0 in. and each contained a 0.5-in.-diameter embedded reinforcing bar. Because most real-structure CP applications would be retrofitted on already salt-contaminated structures, the reinforced-concrete specimens were selected from a stockpile that had been previously exposed to months of immersion in saturated salt water.

Coating was performed after a light sandblasting to remove any laitance and provide surface roughness, or tooth, for mechanical bonding.

The reinforced-concrete specimens were immersed in a container of tap water. As water was absorbed into the concrete, it reactivated the salt within and thus provided resistance values that were closer to real-life structures during wet periods.

To ensure that CP current would be discharged directly from the conductive coatings to the concrete, the exposed surface of the coatings had to remain dry. This was accomplished by a plastic shield epoxied around the conductive material and sealed at the bottom. Being "in the dry," the coatings could not discharge current into the water, but acted in a manner that simulated real-life conditions.

An external power supply created a constant potential of 12 V between the conductive material and the embedded steel. This caused the coating to discharge current into the concrete and thus consume itself. In most cases the current delivered to the steel was considerably in excess of that needed to provide full cathodic protection; the aim of the test was to consume the coating at a rapid rate.

Testing was ended after approximately 500 hr. For some specimens, the circuit resistance became so high that testing was ended sooner; for others, it appeared that they could have continued to discharge current for a longer time period.

It was found that, in most cases, circuit resistance increased with time as current was being delivered, which indicates a consumption of conductive material and a gradual buildup of an oxide layer, but the effect was not severe. No disbonding was noted on the coatings that had satisfactory original bond.

Adhesion to Concrete

A critical property of conductive coatings is their ability to adhere well to concrete surfaces, both clean and salt contaminated, and to maintain their adhesion over many years while delivering CP current.

Pullout bond tests were conducted by using a 0.75-in.-diameter aluminum dolly epoxied to the coating surface. The epoxy is allowed to cure, and the dolly is then pulled with a calibrated device until bond failure occurs (Figure 3). The tensile stress at failure, in pounds per square inch, is directly read from the device (an Elcometer Adhesion Tester Model 106).



FIGURE 3 Adhesion tester and dollies on coated concrete.

Bond of Newly Applied Coats

Soundings of the entire surface and pullout tests were conducted at six different locations on each coating after it was placed on a reinforced-concrete specimen and allowed to cure. All materials bonded well, with test values ranging from 125 to 525 lb/in.². On average, the initial bond for both paints and metals was 300 lb/in.². Most disbonding occurred at the concrete and coat interface, although some paints failed within their layer, and some metals pulled concrete with them.

Bond Versus Coating Thickness

Although not all materials were tested, it was found that some materials, while offering satisfactory bond when applied in thin coats, would readily disbond when thicker coats were attempted. Aluminum curled and peeled-off readily, whereas Sprababbitt A and zinc remained well-bonded after being applied to a maximum thickness (to date) of 24 and 35 mils, respectively.

Weatherability

All paints and metals were applied to lightly sandblasted cement mortar plates (3 x 12 x 0.375 in.). A set of plates was then exposed outdoors, and a duplicate set was subjected to testing in an accelerated weathering chamber. The principal aim of these tests was to visually detect any obvious deterioration or change in appearance due strictly to weathering.

Outdoor Exposure

Specimens were mounted on wooden racks facing south and mounted vertically. The location was the roof of a building in Sacramento, California, which has a semirural, noncorrosive atmosphere, with air temperature extremes from 28° to 106°F and total rainfall of 37 in. during the test period. To date (January 1984), the specimens have been exposed for 1.3 years. The last inspection, at 0.9 year, indicated that all specimens were adhering well and had no major structural defects such as cracking.

Weathering Chamber

Specimens were mounted in an accelerated weathering chamber conforming to ASTM G53-77. This chamber subjected the specimens to cyclic conditions consisting of alternate 4 hr of ultraviolet light at 140°F, and 4 hr of moisture condensation at 104°F. Inspection of the specimens was conducted at 1,000 hr and at 2,000 hr, at which time the test was ended. These inspections indicated that all specimens were adhering well and had no major structural defects.

The paints remained in satisfactory condition, with a slight chalking noted in some, and the metals exhibited a slight darkening in color. The only exceptions were the 405 Bond and Metcoloy #2, which developed rust-colored stains. Results from the outdoor exposure were compatible with the weathering chamber.

Environmental

Inquiries to the various paint and metal wire suppliers provided information on the environmental as-

pects of their products (Table 2). In addition, environmental and health hazards from sandblasting should also be considered.

With the exception of the E-Kote paints and Metcoloy #2, all materials tested were apparently either nonhazardous or required that the operator wear a respirator. In practice, a mask delivering bleed air from an air compressor is used.

TABLE 2 Environmental Aspects of Materials Tested

Material	Environmental Aspects
Cho-Shield 4130	Water-based solvent; no hazards listed
E-Kote 3062	Solvent-based cellosolve acetate and methyl cellosolve, 25 percent; note that the state of California issued a hazard alert (May 1982) on glycol ethers (cellosolve solvents); they list harm to reproductive systems of test animals
E-Kote 3063	Same solvents and warning as E-Kote 3062
Konduktokure	Can be several formulations under ASTM C 309 type I for concrete curing compounds; no hazards assumed
Con-Deck W-0731	Water-based solvent; no hazards listed
Con-Deck W-0735	Water-based solvent; no hazards listed
Aluminum SF	No solvents; excessive fume concentration requires respiratory protection
Aluminum 1100	No solvents; excessive fume concentration requires respiratory protection
405 Bond	No solvents; excessive fume concentration requires respiratory protection
Metcoloy #2	No solvents; alloy contains 13 percent chromium and requires complete respiratory protection in the fume area; fumes are extremely hazardous
Sprababbitt A	No solvents; alloy contains 0.25 percent lead and requires respiratory protection
Zinc	No solvents; fumes are toxic; respiratory protection should be provided wherever the fume concentration is sufficiently high to warrant it

Aesthetics

Many reinforced-concrete structures are exposed to public view. This necessitates consideration of the aesthetic qualities of each conductive coating.

All conductive paints tested were either black in color or very dark grays, approaching black. All metals tested were light silvery gray in color, although each material had its own characteristic shade.

After discharging considerable CP current, oxides leached to the surface of the coatings. Each had its own visual characteristics, with most paints showing some gray, except for E-Kote 3063, which showed some bright green. Each metal provided its own character-

istic oxide--the aluminum being black or white, Metcoloy #2 being rusty, and the rest being a whitish color.

Economics

Pertinent data and cost estimates (in 1983 dollars) of the materials in raw form and applied in-place are given in Table 3. Because paints can be applied at a considerably faster rate than metals, this is reflected in lower labor costs. In addition to the costs presented in Table 3, a light sandblast (at \$0.50/ft²) would be necessary to provide adequate bond on all coatings, and is especially critical for the metallic coatings.

The final economic analysis must include data on the efficiency of each material: How many ampere-years will a given weight (or thickness) of coating deliver under real-life conditions, and what is the maximum useful quantity that can be applied? The continuing study is addressing these questions, but it is not completed as of this date. Initial indications suggest that the efficiency of flame-sprayed zinc is at the 50 percent range, which, if confirmed, is a highly acceptable figure from the economics standpoint.

Evaluation of Test Results

Following the laboratory phase of testing, a selection was made of the more suitable materials for further larger-scale testing. The evaluation and selection was conducted, essentially, by noting the undesirable characteristics of the materials, as follows:

1. Environmental hazards: E-Kote 3062, E-Kote 3063, and Metcoloy #2;
2. Poor conductivity: Con-Deck W-0731;
3. Poor bond: Aluminum SF and Aluminum 1100;
4. Poor resistance to weathering: none;
5. Poor aesthetics (assuming black is acceptable): Metcoloy #2 and 405 Bond; and
6. High cost: Cho-Shield 4130, Konduktokure, Con-Deck W-0735, 405 Bond, and Sprababbitt A.

This initial evaluation pointed to zinc as the superior candidate for further testing. It appears to be an inexpensive material with excellent conductivity and bond to concrete. It was decided to study the performance of some of the most promising materials on a larger-scale test under outdoor exposure

TABLE 3 Estimated Economics of Materials Tested

Material	Material Cost		Weight		Spray Rate (lb/hr)	Percent Solids	Percent Loss ^b	Cost of Coating (\$/lb)	
	Dollars per Gallon	Dollars per Pound	Pounds per Gallon	Pounds per Foot ^a				Material Only	Material In-Place
Cho-Shield 4130	22.00		6.7		27	37	25	15	21
E-Kote 3062	25.20		19		76	75	25	2	3
E-Kote 3063	70.80		16		64	63	25	9	11
Electrodag 112	41.40		9.7		39	34	25	15	19
Konduktokure	14.75		11.5		46	65	25	3	5
Con-Deck W-0731	32.00		10		40	55	25	8	10
Con-Deck W-0735	27.50		9		36	29	25	10	14
Aluminum SF		2.34		0.0142	12	100	25	3	12
Aluminum 1100		2.30		0.0141	12	100	25	3	12
405 Bond		24.53		0.0274	5	100	25	33	54
Metcoloy #2		2.66		0.0417	13	100	25	4	12
Sprababbitt A		9.86		0.0396	50	100	45	18	21
Zinc		1.18		0.0376	32	100	50	2	8

^aWeight for 1/8 in. diameter wire.

^bMeasured for Sprababbitt A and zinc; estimated for the rest.

on a simulated real structure. The materials selected were E-Kote 3063 (its environmental hazard was unknown at that time), Metcoloy #2, with a thin overcoat layer of Aluminum 1100; Sprababbitt A; and zinc.

SIMULATED FIELD TESTING

Four selected materials were applied in an outdoor exposure to a 12-year-old reinforced-concrete slab. This slab (6 ft x 7 ft x 5.625 in.) was cast on March 19, 1971, in connection with a previous project and was heavily contaminated with salt.

For this test the slab was sandblasted and mounted vertically, thus simulating a wall. Vertical stripes (4 x 60 in.) of conductive materials were applied to the smooth (formed) face of the slab. Smaller stripes (4 x 20 in.) were also applied as reserves (Figure 4).

Before the coating application, electrical con-



FIGURE 4 Reinforced-concrete slab with coated stripes.

nection devices (Figure 5) were fastened flush with the concrete surface by using epoxy. These connectors consisted of a 2 x 2 x 0.03-in. copper plate, which received a coating along with the concrete, and a binding post to which the conductor carrying the CP current was connected. The epoxy (a dielectric) prevents the current from being discharged directly from the copper plate to the concrete. Instead, the current flows to the conductive coating and is distributed over the entire coated surface.

In order to bring the extremely dry condition of the slab to a more normal stage, a mist sprinkler system was installed and operated for 2 sec every 10 min, keeping the surface slightly damp. The coatings were subjected to two basic tests: bond to concrete and delivery of CP current and subsequent consumption.

Adhesion to Concrete

Three 0.75-in.-diameter aluminum dollies were epoxied to each material at different locations on the

LEGEND

- APPLIED COATING
- CONCRETE
- EPOXY (BOND & DIELECTRIC SHIELD)

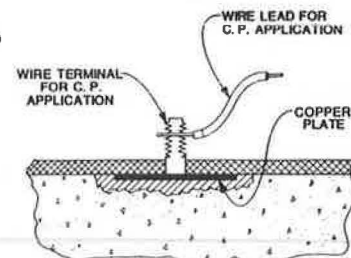


FIGURE 5 Schematic—electrical connectors.

TABLE 4 Bond Tests on Reinforced-Concrete Slab

Material	Disbonded Area (%)	Bond Strength ^a (lb/in. ²)
E-Kote 3063	— ^b	175
Metcoloy #2/aluminum	10	100
Sprababbitt A	— ^b	150
Zinc	— ^b	200

^a Average of three tests.

^b None.

stripe. In addition, the stripes were sounded for disbonded areas. The results of the adhesion tests are given in Table 4.

Coating Consumption

All four materials were tested in the circuit shown in Figure 6. The external dc power supplies were adjusted to deliver a constant current of 0.050 amperes (30 milliamperes per square foot of coating) up to the point where the circuit resistance required a maximum of 30 V. Current and voltage were continuously monitored with automatic data-recording devices. It should be noted that the current density being applied was considerably higher than the expected value in an operational system. This was done to obtain useful data in a period of months, rather than years. Figure 7 presents the test record to

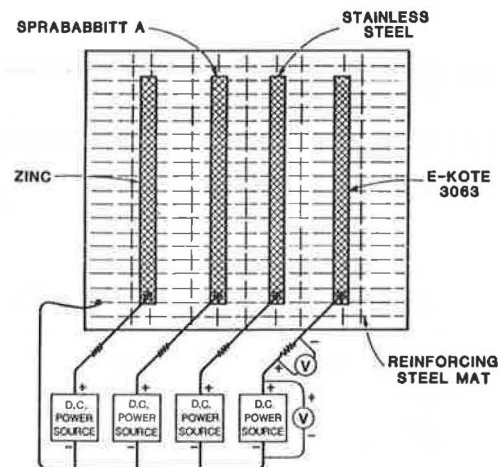


FIGURE 6 Schematic—CP current delivery to reinforced-concrete slab.

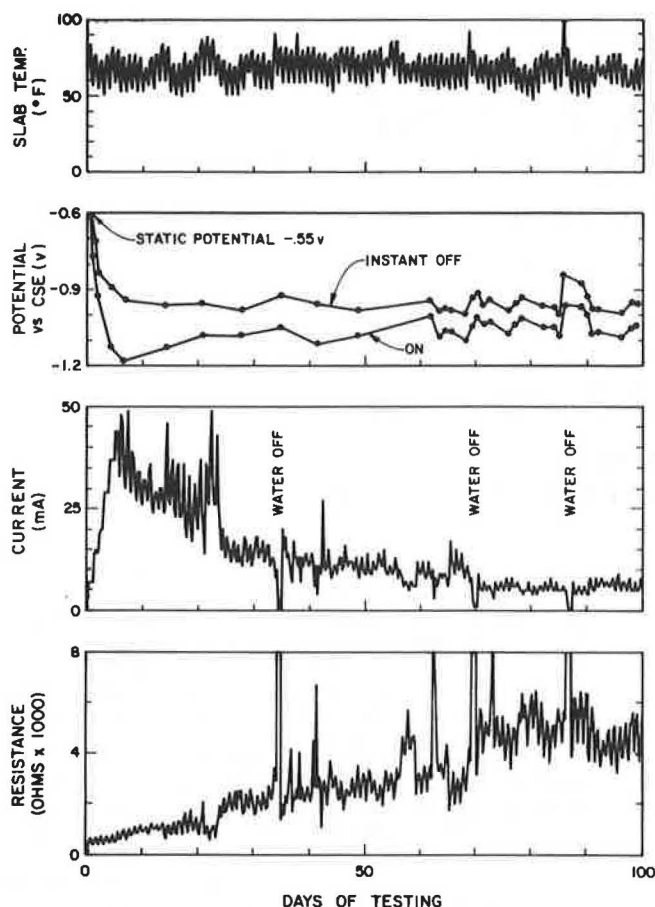


FIGURE 7 Record of zinc strip data for reinforced-concrete slab.

date for the zinc stripe, along with the polarized potentials taken of the reinforcing steel (on and instant-off potentials) versus copper-copper sulfate.

FIELD APPLICATION ON A REAL STRUCTURE

A reinforced-concrete pier of a major structure was selected for application and testing of flame-sprayed zinc. In addition, flame-sprayed Sprababbitt A was also selected because of its bond, conductivity, and aesthetics (although its current cost would not make it economical).

The structure is pier 4 of the Richmond-San Rafael Bridge, located in the northern half of San Francisco Bay. Each pier consists of two reinforced-concrete columns (3.5 x 3.5-ft cross section) of varying height. Pier 4 columns are 20 ft high and their base is cast monolithically onto 6-ft-diameter solid reinforced-concrete shafts. The column bases are about 10 ft above high tide and are subject to a combination of salt air, fog, rain, and wave action. The resulting corrosion distress has been severe enough to necessitate replacement of entire columns in nearby piers.

One column was coated with zinc and the other with Sprababbitt A. Before coating, the concrete was sandblasted and copper and stainless-steel electrical connections (Figure 5) were epoxied onto the concrete surface. To study the distribution of current, the metals were applied in four horizontal bands on each column, with 6-in. bare gaps between them, as shown in Figure 8. The bare gaps were used as locations for taking electrical potential measurements.

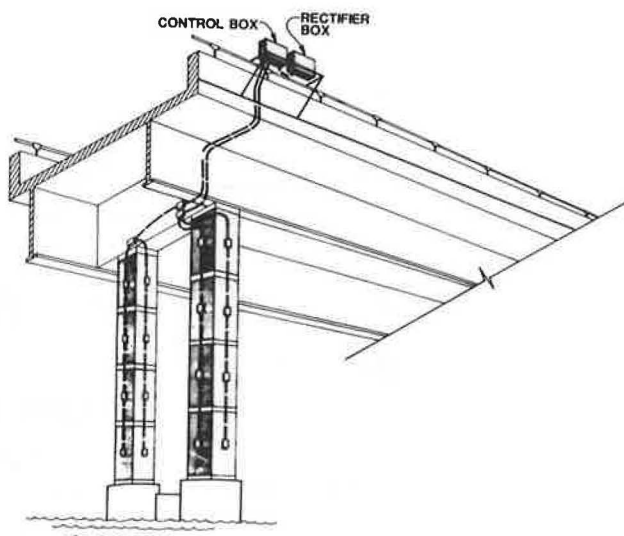


FIGURE 8 Pier 4, Richmond-San Rafael Bridge.

Adhesion to Concrete

Four 0.75-in.-diameter aluminum dollies were epoxied to each band, one to each face of the column. In addition, the coated areas were sounded for disbonded areas. The results of the adhesion tests are given in the following table (note that the bond-strength measurements are from an average of 14 tests):

Material	Disbonded	Bond
	Area (%)	Strength (lb/in. ²)
Sprababbitt A	None	225
Zinc	None	330

Coating Consumption

Each column was connected to its own CP power supply, which consisted of a commercial ac to dc rectifier capable of delivering 50 V and 5 amperes. Connections to each coated band were made as in the circuit used previously on the concrete slab. CP current was applied by adjusting these constant-voltage-type rectifiers initially to 3 V nominal output, and allowing the current to vary, depending on the concrete resistance.

Because of the changing environment (temperature, wind, tides, fog, rain, and so forth), the current densities varied, as expected, averaging to date 0.98 and 0.84 milliamperes per square foot of steel for Sprababbitt A and zinc, respectively, with peaks approaching, and at times exceeding, 2 milliamperes per square foot during wet weather (Figure 9).

CONCLUSIONS

It is too early to evaluate the results on the pier. At this time, both coatings are performing well. It is estimated that, at the present average current densities, the coatings will theoretically last 17 years for Sprababbitt A (estimated coating = 0.29 lb/ft²) and 21 years for zinc (estimated coating = 0.30 lb/ft²). Allowing an efficiency factor (estimated at this time to be 50 percent) the Sprababbitt A should provide CP for about 9 years and the zinc for about 10 years.

Currently, cathodic protection of reinforced concrete by using flame-sprayed zinc appears to be a viable and economic method of controlling corrosion.

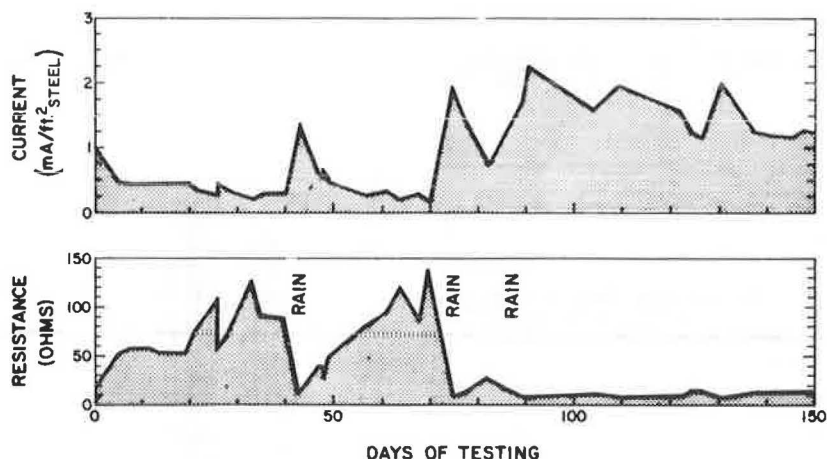


FIGURE 9 Record of zinc-coated column—pier 4, Richmond-San Rafael Bridge.

The technique offers a significant breakthrough in the technology, leading the state of California to apply for a pertinent U.S. patent. Of the materials tested, zinc appears to be superior in several areas, including bond to concrete, environmental hazards, and cost.

Based on the findings to date, the estimated total cost of applying CP to a 10,000 ft² bridge deck by using zinc and including an asphaltic-concrete overlay or wearing course would be \$4.20 to \$5.20 per square foot for a 10-year design life. This contrasts with \$30 or more per square foot for a deck replacement.

Further study is recommended to develop nonhazardous formulations for the more promising conductive paints and to test other metals and alloys, such as aluminum-zinc or mild steel. Arc spraying and plasma spraying should also be investigated for suitability in field applications.

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Neither the state of California nor the U.S. government endorse products or manufacturers. Trade or manufacturers' names appear herein only because they are considered essential to the object of this

document and as convenient identification labels. (It is not practical to refer to paints by their formulations throughout the text.)

It should be noted that the products mentioned in this study have not been used in the manner intended by their manufacturers, but in a novel man-

ner. Success or failure in this project should not reflect on their performance when used in normal service.

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Cathodic Protection of Bridge Substructures: Burlington Bay Skyway Test Site, Design and Construction Phases

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ABSTRACT

The design and construction phases of a research program to develop an effective cathodic protection system for use on bridge substructures are described. Construction of four experimental systems on columns of the Burlington Bay Skyway Bridge was completed in 1982. One sacrificial anode system and three impressed-current systems were installed, each covering approximately 38 m² of column surface. The sacrificial anode system used zinc ribbon anodes with a shotcrete overcoat. A conductive polymer concrete was used as the primary anode in all the impressed-current systems. In System 1 the anodes were used with a shotcrete overcoat. System 2 consisted of the primary anodes with an exposed secondary anode of conductive paint. System 3 employed a secondary anode network of multifilament carbon strand, also with a shotcrete overcoat. A range of instrumentation was designed and installed to determine the effectiveness and efficiency of the four systems.

Considerable efforts have been expended in recent years to develop methods for the rehabilitation of highway bridges that have deteriorated as a result of the corrosion of embedded reinforcement. Most of this work has concentrated on bridge decks (1,2), but similar deterioration is present in substructure elements where it is more difficult and expensive to repair.

Of all the methods available for the repair of structures, only cathodic protection positively arrests the corrosion process. A system of cathodic protection has been used for the rehabilitation of bridge decks in Ontario since 1974 (3,4). Although the principles of this treatment are applicable, the

materials and methods of construction used for bridge decks cannot be used on substructures.

OBJECTIVES OF RESEARCH PROGRAM

The overall objective of the research program initiated by the Ontario Ministry of Transportation and Communications in 1981 was to develop a method for the permanent repair of bridge substructures.

Cathodic protection was selected as the most promising method of achieving this goal. A number of projects were begun in support of the program objective. These included laboratory and exposure-plot studies of the various components of cathodic protection systems. The major project in the program involved the design, installation, and evaluation of four experimental systems. Each system consisted of a small-scale section applied to a real structure such that data could be collected to be used in the design of a full-scale demonstration of cathodic protection on a bridge substructure. The specific objectives of this project were to

1. Determine the effectiveness and efficiency of each system in stopping corrosion,
2. Make a technical and economic comparison of the systems, and
3. Identify potential long-term deficiencies.

The design and construction phases of this project are described in this paper.

GENERAL REQUIREMENTS OF A CATHODIC PROTECTION SYSTEM

Cathodic protection is a process that prevents the anodic corrosion reaction by creating an electric field at the surface of the metal so that current flows into the metal (5). This sets up a potential gradient at the metal surface that prevents the release of metal ions as the product of corrosion.

The source of the electric field that opposes the