Metalizing for Corrosion Prevention on Concrete and Steel Bridges

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ABSTRACT

Life-cycle cost, durability, and low environmental impact make metalized coatings an attractive option for protection reinforced concrete bridges and steel bridges from corrosion damage, particularly in high-chloride environments such as coast or marine locations or where deicing salts are used. On reinforced concrete bridges, Zn and catalyzed-Ti metalized coatings are successfully functioning as anodes in cathodic protection systems on coastal bridges to prevent reinforcing bar corrosion and the resulting damage to the concrete. Solvent-based acrylic carbon paint and Zn-hydrogel are also functioning well as cathodic protection anodes. On steel bridges, metalized coatings are successfully serving as barriers to corrodants and providing galvanic protection in areas of Zn or 85Zn15Al coatings provide the longest life-to-first-maintenance. Sealed coatings provide the lowest life-cycle cost. Industry specifications covering all aspects of the metalizing process on steel are available.

CORROSION DAMAGE TO U.S. BRIDGE INFRASTRUCTURE

A 1993 report to the U.S. government stated that 44% of the more than 500,000 bridges in the United States were either structurally deficient or should be posted for weight restrictions (*Burke 1994*). The cost to rehabilitate or replace all structurally deficient bridges in the U.S. is estimated at $50US billion (*Novak 1990*). Costs for bridge maintenance, rehabilitation, and replacement due to corrosion damage are a necessary but nonproductive use of public resources. Safety concerns, disruptions in service, and economic impacts of catastrophic bridge failures are further liabilities for bridge owners and users. Chloride-induced corrosion damage affects both reinforced concrete bridges and steel bridges, whether they are located in coastal environments or in colder climates where they are exposed to repeated applications of deicing salts.

Concrete Structures

Reinforced concrete (RC) bridges are a significant fraction of the Nation's bridge inventory. The cost of damage to RC bridges and parking garages in the United States due to deicing salts alone is estimated to be in the range $o.3-1.0US billion per year (*Transportation Research Board 1991*). Problems develop when salt diffuses into the concrete, raising the salt concentration at the reinforcing bar-concrete interface above a threshold level for corrosion initiation, about 0.74 kg Cl/m^3 (1.25 lb/ft^3) for black iron bar (*McDonald et al. 1998*). The passive film normally present on the reinforcing bar breaks down above this concentration, reducing the pH and initiating corrosion. The iron oxide reaction products formed by corrosion are substantially higher in volume than the iron consumed by corrosion, leading to tensile forces that crack the concrete, cause delamination of the cover concrete, and ultimately mechanical deterioration of the bridge.

Steel Structures

Steel structures corrode by reacting with moisture and oxygen to form rust. Aggressive high-chloride environments found in coastal or marine environments and in areas where deicing salts are used accelerate the deterioration of steel unless the steel is isolated from the corrodants or the corrosion rate is reduced by electrochemical means. The design of steel bridges further accelerates corrosion damage by the presence of joints, fasteners, fraction-grip bolts, cavities and crevices that collect corrodants, such as soil, water, and atmospheric pollutants, and by the presence of dissimilar metals, stray currents, and concentration cells that can lead to intense localized corrosion. Paints are the most widely used material for protecting steel structures from corrosion damage. They create a barrier between the steel and corrodants that can last without maintenance in mild environments up to 20 years, and typically 15 years. In more corrosive environments, these times are substantially shorter and the consequences of corrosion damage to a structure may be more severe, both economically and for public safety. Structures are expected to last longer to diminish the strain on over-committed public resources and private capital. Bridges originally designed for 50 years service are now considered serviceable for 100 years, and longer for very significant structures. The shift to low VOC (volatile organic component) paints puts further stress on the costs of maintaining steel structures for extended service.

Metalizing

Metalizing with the active metals zinc, aluminum, and their alloys can produce a long-lasting protective coating on concrete and steel structures. It is a simple process when done correctly. Metalizing or "thermal spraying is a group of processes in which finely divided metallic or nonmetallic surfacing materials are deposited in a molten or semi-molten condition on a prepared substrate to form a spray deposit" (*AWS 1985*). The group of processes includes flame spray, arc spray, spray weld, and thermo-spray. Metalizing is a proven technology used around the world for many years. Remarkably, until the late 1990s bridge metalizing in the United States was rare. The metalizing industry has gone through two decades of building awareness of metalizing's benefits by providing the information to specify and apply the coating. The long history of metalizing, improved spray rates, and the owners' shift in emphasis from initial cost only to life-cycle-cost (LCC) have opened the door to metalizing bridges. Bridge owners, with the support of the Federal Highway Administration, have responded with increasing demand for metalized bridge coatings. The availability of qualified applicators must now increase to satisfy the growing demand and to that end the industry is addressing operator training and operator/contractor qualifications. The shift from initial cost to life-cycle-cost, i.e., how much does it cost not to metalize, can save the structure owner a significant amount of money over a 50-year period. Fundamental to these savings are long life-to-first-maintenance.

CONCRETE BRIDGE THERMAL-SPRAYED ANODES FOR CATHODIC PROTECTION

Condition Evaluation

A severe environment characterized by the continual delivery of chloride ion and moisture to the concrete and insufficient cover concrete over reinforcing bar, particularly shear stirrups, characterizes the chloride-induced corrosion damage of many of Oregon's coastal RC concrete bridges (*Cramer et al. 2000*). In coastal environments, chloride penetration of the underside of the deck is a typical source of corrosion damage. Where deicing salts are used, chloride penetration of the deck topside and especially joints leads to corrosion damage. Most maintenance and repair efforts to contain this damage are ineffective without confronting the cause of the damage, chloride in the concrete at sufficient concentration to initiate corrosion. Visual, delamination, and potential surveys are useful tools for identifying damaged areas and evaluate structure condition. To a limited degree, petrographic examination of the concrete is also useful.

One of the most powerful techniques for evaluation the corrosion state of a bridge, both past, present and, to some degree, future is powder sample of the chloride contaminated concrete to determine the chloride profile and analyze it in terms of diffusion and electro-migration processes (*Cramer et al. 2000; Covino et al. 2002*). This is done taking concrete powder samples at narrow depth intervals, i.e., 1 cm (0.5 inch), from the surface into

the concrete 10-15 cm (4-6 inches). Special attention must be paid to avoiding cross contamination between samples. Samples are analyzed for total chloride and calcium, using the calcium value to correct for varying amounts of aggregate in the samples. Effective diffusion coefficients obtained from this analysis can be used to examine when threshold levels of chloride are reached at cover depths of shear stirrups and the various mats of reinforcing bar. The effective surface chloride concentration gives a measure of the severity of the environment for chloride-induced corrosion damage. Values of the diffusion coefficient and surface chloride concentration can and do vary over the structure depending on orientation, sheltering, and local meteorological patterns. In the several instances where sufficient inspection records existed, there was a reasonable correlation between these data and the first appearance of corrosion damage on RC bridges (*Cramer et al. 2000; Covino et al. 2000*).

Cathodic Protection

Bridge owners must eventually replace, repair, or rehabilitate corrosion damaged RC bridges. Cathodic protection (CP) is one of the most effective techniques for controlling corrosion damage and preventing further deterioration of RC bridges (*Mudd et al. 1988*). More than 500 bridges in North America are currently protected by CP systems (*Jackson 1997*). Current distribution to the reinforcing bar is a critical factor in the design and effectiveness of these systems. The California Department of Transportation (CALTRANS) pioneered the use of conductive coating anodes for optimum current distribution in bridge CP systems by installing thermal-sprayed Zn anodes on Pier 4 of the Richmond-San Rafael Bridge (California, USA) in 1983 (*Carello et al. 1989*).

Conductive Coating Anodes

Conductive coating anodes provide a uniform distribution of current to reinforcing bar in brides and are particularly suitable for structures with complex surface detail. They can be applied to existing bridges without sacrificing surface detail and without altering the external appearance of the structure (*McGill et al. 1999; Cramer et al. 1999, 2002; Covino et al. 2002*). Like other bridge anode systems they are usually susceptible to acidification of the anode-concrete interface and therefore exhibit effects of electrochemical aging as the interfacial chemistry is altered with service. Since 1988, the Oregon DOT has installed impressed current, conductive-coating anode CP systems on eight bridges, Table 1. Total installed anode area is 81,000 m^2 (870,000 ft^2).

Rehabilitation, Surface Preparation, Continuity and Shorts

Rehabilitation of Oregon's coastal bridge includes removal of unsound concrete, replacement of reinforcing bar with more than 50% section loss, sandblasting exposed reinforcing bar and concrete to remove rust and loose concrete, applying patch concrete to restore the bridge to roughly original structural specifications and, in the case of historic bridges, to their original surface detail and appearance (*ODOT 2001*). Surface preparation includes light sandblasting of the concrete to remove the laitance layer and loose concrete, and produce a medium sandpaper surface texture without overly exposing the aggregate (which tends to reduce the bond strength of the conductive coating anode). All structural steel in a CP zone is electrically tied together to provide electrical continuity. "Tramp" steel pieces, i.e., nails, wires, benches, in the concrete that could short the reinforcing bar to the conductive coating anode on the concrete surface are removed prior to or during application of the anode. If the reinforcing bar and anode become shorted during impressed current cathodic protection (ICCP) service, efforts are made to locate and remove the short, or the CP zone is converted to a sacrificial anode (SACP) zone.

Table 1. Oregon DOT Conductive Coating Anode CP Projects.

Bridge	Year Installed	Area m^2 (ft^2)	Anode material	Thickness, mm (mils)
Cape Creek Bridge	1991	9,530 (102,500)	TS Zn	0.51 (20)
Yaquina Bay Bridge - arches	1994	18,170 (195,500)	TS Zn	0.57 (22.6)
Depoe Bay Bridge	1995	5,940 (63,960)	TS Zn	0.55 (21.7)
Yaquina Bay Bridge - south approach	1997	6,041 (65,000)	TS Zn	0.51 (20)
Cape Perpetua Viaduct	1997	57 (607)	TS Zn	0.50 (19.7)
Big Creek Bridge	1998	1,865 (20,026)	TS Zn	0.38 (15)
Rocky Creek (Ben Jones) Bridge	2001	3,700 (40,000)	TS Zn	0.38 (15)
Cummins Creek	2001	1,865 (20,000)	TS Zn	0.38 (15)
Rogue River (Patterson) Bridge	2003	33,000 (350,000)	TS Zn	0.38 (15)
Yaquina Bay Bridge – north approach	1986	645 (6910)	C paint	0.50 (20) dft[1]
Depoe Bay Bridge	1995	280 (3015)	TS Ti	0.10 (4)
Cape Perpetua Viaduct	1997	57 (610)	TS AlZnIn	0.40 (15.8)
Cape Perpetua Viaduct	1997	57 (610)	Zn hydrogel	0.25 (10)
TOTAL installed area		**81,206 (873,780)**		

[1]dft = dry film thickness

In ICCP systems on the Oregon coast, conductive coating anodes are typically operated under current control at a current density of 2.2 mA/m^2 (0.2 mA/ft^2) based on anode area (*Cramer et al. 1990; Covino et al. 2002*). Protection of the reinforcing bar is determined by periodic depolarization measurements followed by current density adjustments as necessary. In-service performance of the anodes may differ from that in accelerated laboratory studies, which probably define worst-case performance, owing to the higher rate of the electrochemical reactions in accelerated studies compared to the rate of transport processes.

Thermal-sprayed Anodes
In Oregon, thermal-sprayed anodes are applied to coastal RC bridges using the twin-wire arc spray process which allows high production rates (*Covino et al. 2002*). Typical thermal-spray parameters are given in Table 2 for a zinc and aluminum wire in 3.2 and 4.8 mm (1/8 and 3/16 inch) wire diameters (*Rogers 2000*). The 4.8 mm (3/16 inch) diameter wire is typically used. The atomizing gas is compressed air at 0.62-0.79 MPa (90-110 psi); spray orientation is normal to the sprayed surface at a distance of 15-23 cm (6-9 inches). Multiple passes in an X-Y pattern are used to build up coating thickness. Preheating of the concrete is not necessary prior to spraying and does not benefit the long-term adhesion of the anode (*Covino et al. 2002*). However, the concrete must be clean and dry and the workspace should have a relative humidity of 60% or less (*ODOT 2001*). Acceptance criteria for thermal-sprayed Zn anodes on coastal RC bridges were a coating thickness of 0.37 mm (14.7 mils), and anode bond strength of 0.34 MPa (50 psi).

Zinc anode: Thermal-sprayed planar zinc anodes for ICCP have been installed on eight Oregon coastal bridges, Table 1 (*Covino et al. 2000*). Field and laboratory anodes were applied to lightly sand blasted concrete

Wire Type	Wire Size inch	DC amps	DC volts	Spray Rate Lb/hr	Spray Rate Kg/hr	Deposition Efficiency %	Deposition Rate Lb/hr	Deposition Rate Kg/hr	Wire Density Lb/in3	Wire Density g/cm3	Deposition Volume Rate In3/hr	Deposition Volume Rate Cm3/hr
Zinc	1/8		27									
Zinc	1/8		27									
Zinc	1/8		27									
Zinc	1/8		27									
Zinc	1/8		27									
Zinc	3/16		27									
Zinc	3/16		27									
Zinc	3/16		27									
Zinc	3/16		27									
Zinc	3/16		27									
Aluminum	1/8		32									
Aluminum	1/8		32									
Aluminum	1/8		32									
Aluminum	1/8		32									
Aluminum	3/16		32									
Aluminum	3/16		32									
Aluminum	3/16		32									
Aluminum	3/16		32									
85Zn/15Al	1/8		28									
85Zn/15Al	1/8		28									
85Zn/15Al	1/8		28									
85Zn/15Al	1/8		28									
85Zn/15Al	1/8		30									
85Zn/15Al	3/16		30									
85Zn/15Al	3/16		30									
85Zn/15Al	3/16		30									
85Zn/15Al	3/16		30									
85Zn/15Al	3/16		30									