Galvanic Cathodic Protection of Reinforced and Prestressed Concrete Using a Thermally Sprayed Aluminum Coating

By Steven F. Daily

Reinforced concrete structures such as bridges, parking decks, and buildings are particularly subject to corrosion in marine and northern deicing salt environments. Problems develop when the salt penetrates the concrete and reaches the surface of the reinforcing steel. Reinforcing steel, which is normally in a passive state due to the high alkalinity of the concrete, loses passivity and begins to corrode when a threshold level of chloride-ion concentration is exceeded.[1] The corrosion products or rust can occupy several times the volume of the original steel, causing tensile forces to develop in the concrete. These stresses lead to cracking of the concrete cover, delamination, spalling, and further corrosion damage to the structure.

A Federal Highway Administration (FHWA) report on corrosion protection of concrete bridges estimates that the total cost to eliminate the backlog of deficient bridges is between $78 billion and $112 billion.[2] A number of approaches have been used to minimize reinforcing steel corrosion in chloride-contaminated concrete structures, such as overlays, sealers, and migrating corrosion inhibitors. However, in concrete structures where chloride-ion content is significant (that is, > 5 lb/yd^3 [3 kg/m^3]), these types of approaches may be insufficient to slow the corrosion activity to a point where corrosion-induced damage to the concrete is insignificant. Other forms of corrosion mitigation may include electrochemical chloride extraction (ECE) and cathodic protection (CP). ECE is a technique that involves the application of a high current to physically remove chlorides from the concrete. This method, however, typically requires 6 to 8 weeks for treatment and is not suitable for prestressed or post-tensioned concrete. CP is a corrosion-control method that imposes an external voltage on the steel surface, which forces the steel to become cathodic, thereby mitigating corrosion. Both impressed current (active systems) and galvanic (passive systems) are used. CP is still considered one of the only technologies that has proven to stop corrosion of reinforcing steel, regardless of the chloride-ion content in the concrete.

Cathodic Protection Technology

The basic concept of cathodic protection is relatively simple. The corrosion process forms a battery and produces a small amount of electric current. If an equal amount of current is applied so that it flows in the opposite direction from the natural corrosion current, then the corrosion process is halted. CP of steel in concrete is quite simply a means of fighting fire with fire or, in this case, electricity with electricity. The corrosion process generates electric currents. CP supplies a source of current to counteract the corrosion current. Hence corrosion can be eliminated.

Galvanic CP systems are relatively simple compared with impressed current systems. Galvanic systems are based on the principle of dissimilar metal corrosion and the relative position of specific metals in the galvanic series. Commonly used galvanic anodes include zinc, magnesium, and aluminum-based alloys. Unlike impressed current systems, galvanic systems have the advantage of no auxiliary power supply and no requirement for monitoring and maintenance. The current that is produced by a galvanic anode is a function of its environment (that is, moisture and temperature conditions). Galvanic anodes installed in wet and humid environments will typically produce higher levels of current than anodes in drier, less humid conditions. Also, because of their low driving voltage, galvanic anodes are suitable for cathodic protection of prestressed and post-tensioned concrete, without the concern of hydrogen embrittlement.

Aluminum Alloy: Initial Research

In 1994, a research program was funded by the FHWA to develop new sacrificial anode materials for cathodic protection of reinforced and prestressed concrete bridge substructures. As part of the research effort, a new galvanic anode was developed for corrosion control. The study identified an aluminum-zinc-indium (Al-Zn-In) alloy that is capable of providing improved cathodic protection to steel embedded in chloride-contaminated concrete.

The Al-Zn-In anode is applied to concrete

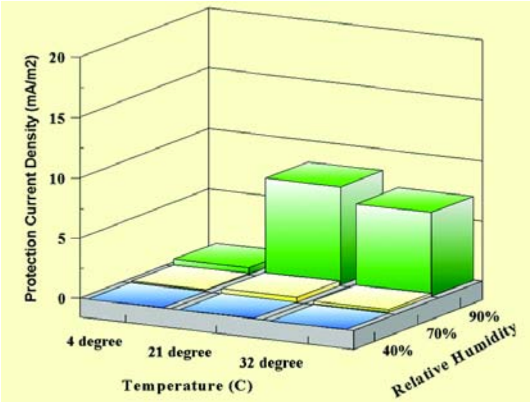

Figure 1(a): Temperature humidity chamber performance of thermally sprayed zinc

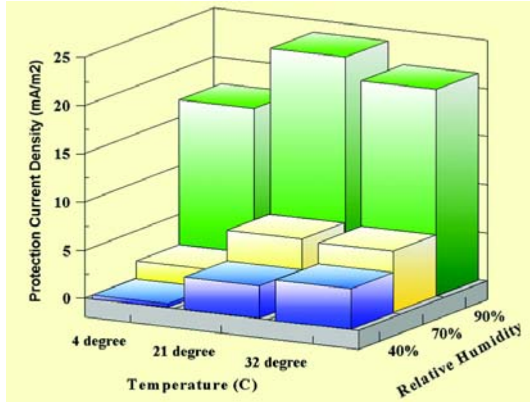

Figure 1(b): Temperature humidity chamber performance of thermally sprayed Al-Zn-In

structures using electric arc spray equipment to form a galvanic coating. The alloy developed during the laboratory-testing portion of the FHWA contract consisted of 80% aluminum, 20% zinc, and 0.2% indium (Al-20Zn-0.2In). The anode was shown in laboratory testing to provide a degree of cathodic protection to steel embedded in concrete that was superior to that provided by pure zinc.[3] Figure 1(a) and (b) show the current produced from zinc and the Al-Zn-In alloy on chloride-contaminated concrete test blocks in a temperature-humidity chamber. In these tests, cathodic protection was supplied at temperatures ranging from 4 to 32 °C (40 to 90 °F) and from 40 to 90% relative humidity. The current generated from the aluminum alloy was much greater than pure zinc, even at lower temperature and humidity levels.

San Luis Pass Bridge

Since the initial FHWA study, the aluminum alloy has been applied successfully to several reinforced concrete structures in both marine and northern deicing salt environments. The largest installation to date is the San Luis Pass Bridge in Galveston County, Texas. It is a 38-year-old bridge that spans a 1.3 mi (2.1 km) distance between Brazoria County and Galveston County, Texas (Fig. 2). On this structure, the aluminum alloy is applied to 117 conventionally reinforced concrete bent caps and 470 prestressed concrete beams. The work is part of a $10 million Galveston County rehabilitation project, which includes a cathodic protection system to protect against corrosion of the prestressing strands and reinforcing steel.

A trial system using the Al-Zn-In galvanic anode was first installed on the San Luis Pass Bridge in 1996. Engineering consultant Turner, Collie & Braden of Houston, Texas, evaluated repair options and prepared design specifications for the structure rehabilitation using the Al-Zn-In anode for long-term corrosion control. The aluminum-zinc-indium (Al-Zn-In) system is applied to over 322,000 ft^2 (30,000 m^2) of concrete beams and bent caps using electric arc spray equipment (Fig. 3).

Figure 2: San Luis Pass Bridge, Galveston, Texas

Figure 3: Arc spray application of aluminum-zinc-indium (Al-Zn-In) anode

Environmental Conditions and Life Expectancy

It is important to realize that thermally sprayed galvanic systems such as Al-Zn-In are self-regulating and that cathodic protection levels and current densities will vary with time based on environmental conditions. Current is greatly influenced by moisture content at the anode/concrete interface and the current delivery will fluctuate with time as the resistance changes. Galvanic anodes installed in wet and humid environments will typically produce higher levels of current than anodes in drier, less humid conditions. This higher level of current can significantly lower the life expectancy of the system. Temperature also affects current output, and, in extremely cold climates (that is, below freezing), current may be negligible. In dry concrete conditions, current may drop off to a point where protection levels are reduced. In these conditions, however, the corrosion rate of steel-in-concrete may be extremely low or insignificant. Based on predicted consumption rates and test data, the aluminum alloy can be expected to provide a reasonable life expectancy of 10 to 15 years before re-application is required.

Installation of Aluminum-Zinc-Indium (Al-Zn-In) Galvanic Anode System

Requirements for Successful Operation

The feasibility and success of the aluminum-zinc-indium (Al-Zn-In) system is greatly influenced by several factors, including:

Surface Preparation—Proper concrete surface preparation with abrasive blasting equipment is critical to ensure adequate bonding between the concrete and thermally sprayed anode. Concrete surfaces are prepared after all repairs have been completed. A clean, dust-free, and dry surface shall be provided with adequate anchor profile for good bonding. Care shall be taken not to expose large aggregate tips during the abrasive blasting operation that otherwise could affect coating adhesion and possibly increase the interfacial anode resistance. Guidelines for surface preparation should follow the manufacturer's installation specifications and ICRI Specification No. 03732, Selecting and Specifying Concrete Surface Preparation for Sealers, Coatings, and Polymer Overlays.

Electrical Continuity of the Reinforcing Steel—Continuity of the embedded reinforcing steel or prestressing strands is required for any cathodic protection system. If the embedded steel is not continuous, it will not receive cathodic protection current. Normally this is not a problem on structures with significant reinforcing steel, such as bridges, wharves, and jetties. Sufficient redundancy is normally provided by the fact that multiple bars cross and lap one another. For prestressed concrete beams, stirrups usually provide continuity between strands; however, care should be taken to ensure that all strands are electrically continuous. To avoid unwanted excavation, continuity should be checked on all exposed steel during the concrete repair stage and at a minimum of five locations per 1000 ft^2 (93 m^2) where reinforcing steel is not exposed. Continuity testing is performed by using the DC resistance or millivolt drop method. Bonding of discontinuous steel is accomplished by welding or simply by using uncoated steel wire ties.

Environmental Conditions—The in-service environment for the galvanic thermal spray coatings requires a certain degree of moisture to enhance the overall conductivity of the system. Moisture may be apparent from rainfall, splashing, or wetting. Candidate structures for galvanic systems should be contaminated with chloride ions, which provide lower concrete resistivity. The structures should be situated in environments where moisture is present and the relative humidity is high.

Experience of Thermal Spray Operator—The thermal spray operator or nozzleman shall demonstrate adequate technical training and field experience to safely and proficiently apply the anode coating on concrete surfaces. Normally, thermal spray operators are prequalified on concrete test panels prior to commencing field operations.

Thermal Spray Application

The Al-Zn-In alloy is now being produced using cored wire technology. The 1/8-in. (3.175-mm) diameter cored wire consists of an outer sheath of ultra high purity aluminum and a hollow core filled with Al-Zn-In powder. The cored wire is supplied on spools and applied onto the concrete surface using electric arc spray. The arc spray technique is considered the most effective method for achieving high productivity, good mechanical bond, and a cohesive uniform coating. The electric arc spray system simultaneously feeds two wires at a uniform speed through the spray gun. Upon application of high amperage (300 amps) across the electrode tips, the wire melts and the molten metal is subsequently forced onto the concrete surface using pneumatic air pressure to form a metallic coating. The coating should be applied in multiple passes and should overlap on each pass in a crosshatch pattern before the first layer of material cools down. Uniform gun movement should be used to ensure a consistent thickness. Sufficient anode material should be applied to achieve a minimum thickness of 12 mils (300 microns).

The concrete is normally repaired with standard repair mortars or shotcrete prior to surface preparation and thermal spray application. Repair materials should be cementitious in nature, having resistivity values less than 50,000 ohm-cm. Epoxy bonding agents for repair materials will provide a dielectric barrier to current flow and should be avoided.

Exposed reinforcing steel and partially exposed reinforcing steel chairs will provide an electrical connection between the anode and steel cathode. To provide for additional redundancy, however, anode connector plates are installed (Fig. 4). These consist of 4 x 4 in. (100 x 100 mm) perforated aluminum sheets. The sheets are placed over a threaded stud that is connected directly to the reinforcing steel. The stud is usually installed first and then the structure is cleaned and metallized. The connector plate is then installed, anchored down with a nut and washer, and then a second layer of coating applied over the plate area. The Al-Zn-In coating is extremely conductive. Usually one connector plate is sufficient for 1000 ft^2 (93 m^2) of concrete surface.

Testing System Performance

On larger commercial projects, the anode is shorted directly to the reinforcing steel. Quality control procedures consist of visual inspection, periodic adhesion tests, and thickness measurements using a reverse eddy current instrument calibrated for the Al-Zn-In alloy. If anode current and potential testing is required, then this is accomplished by installing an instrumented test window. The test window consists of a small isolated area of anode coating that is electrically discontinuous from the reinforcing steel except for a wire connection from the anode to the steel. A typical test window may consist of 50 ft^2 (5 m^2) of isolated anode area. A disconnect switch is installed in the wire and a precision resistor or shunt is installed in series to measure anode current. Prior to the thermal spray application, a silver-silver chloride reference electrode (small monitoring probe) is installed in the concrete beneath the test window. The reference electrode should be located in sound concrete with high half-cell potentials exceeding –350 mV (CSE) per ASTM C 876. Anodic (high half-cell potential) areas will typically represent the most difficult areas to protect on a concrete structure. Alternately, the reference electrodes may be located at the edge of concrete repair where a macrocorrosion cell has developed. Care should be taken not to expose the steel in the reference cell cutout, as the potential should reflect the true corrosion potential of the steel in the native (chloride contaminated) concrete and not the new repair mortar. The cathodic protection criteria used to assess system performance are normally 100 mV of polarization development or decay over a minimum 4 h period. In theory, if this level of polarization is achieved on the reinforcing steel, then corrosion has stopped. By measuring anode current in the test window, calculations can be made regarding anode consumption and life expectancy. The system installed on the bridge will continue to be monitored.

Advantages and Limitations

Thermal spray galvanic anode technology has many recognized advantages over impressed current systems, such as simplicity, ease of application to complex surfaces, and low maintenance requirements. Because galvanic anodes normally operate below the threshold for hydrogen embrittlement, they are considered safe for cathodic protection of prestressed and post-tensioned concrete. The amount of current that is generated by a galvanic anode is greatly influenced by environmental factors such as moisture and temperature, that can have an adverse affect on service-life expectancy. Galvanic systems are considered self-regulating, and anode current and protection levels will vary with time.

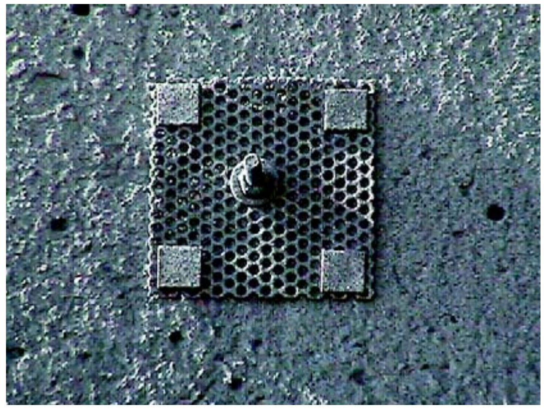

Figure 4: Anode connector plate

The feasibility and success of the galvanic anode system is greatly influenced by several factors, including concrete surface preparation, electrical continuity of the reinforcing steel, and the availability of moisture to improve overall conductivity. Finally, an experienced thermal spray operator is critical to ensure proper coating application and adhesion.

References

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