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Highway IDEA Program

Evaluation of Al-Zn-In Alloy for Galvanic Cathodic Protection of Bridge Decks

Final Report for Highway IDEA Project 100

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Evaluation of Al-Zn-In Alloy for Galvanic Cathodic Protection of Bridge Decks

IDEA Program Final Report

For the Period October 2003 to August 2009

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TABLE OF CONTENTS

EXECUTIVE SUMMARY

An alloy was developed under FHWA Project FHWA-RD-96-171 for use as a galvanic anode for the protection of steel reinforced concrete bridge substructures. The alloy consists of 20 percent zinc, 0.2 percent indium with the balance aluminum (U.S. Patent 6,673,309). Indium is the component that keeps the anode active even in dry environments. The anode was designed to be applied to concrete using thermal spray technology, typically electric arc spray. The recommended thickness of the coating is 12 mils. Based on predicted consumption rates, the alloy is expected to provide 10 to 15 years service life based on a consumption rate of 0.5 mil per year. Since the first trial system was installed in 1995, this alloy has been installed on more than 15 structures with a total surface area of about 300,000 ft^2.

The objective of project NCHRP-100A was to develop a galvanic mesh anode for bridge deck application. The concept was to develop an expanded mesh or perforated sheet that would last at least 25 years, be durable for construction, not interfere with concrete overlay bonding and be of a size that is practical for transportation and field installation.

This work was planned in two stages. Stage 1 was to develop the anode mesh. Stage 2 was to install the anode on two bridge decks of 1,000 to 2,000 square feet surface area to evaluate the anode performance and to produce concrete test blocks for anode evaluation in the laboratory and calculate anode consumption rate. The evaluation period for the bridges and test blocks was to be twelve months.

In the early stages of the project, it was learned that the aluminum alloy developed under the FHWA program was too brittle to be formed into the desired mesh. Various alternative configurations and alloy variations were tried. The final form consisted of thermally sprayed anode material on an aluminum mesh or a sheet that was subsequently expanded to form a mesh. Laboratory trials showed that the alloy was an effective anode in providing cathodic protection to concrete embedded rebar.

A limited bridge trial was conducted that further proved the constructability and effectiveness of the anode. However, problems were encountered that caused the project to be halted pending further research that is beyond the intent of the program. These problems included limited availability of a suitable substrate alloy, gas generation and delamination of the overlay at the anode.

INTRODUCTION

Since early 1970's corrosion has been recognized as one of the major causes to the deterioration of reinforced concrete bridge structures in the United States. The maintenance costs for bridge structures exposed to salt environments have become large expenditures for many bridge owners. Over the last 30 years, cathodic protection (CP) has been proven to be a highly cost-effective technique in controlling concrete deterioration from chloride induced corrosion for existing concrete bridge structures. This message was delivered by the U.S. Federal Highway Administration (FHWA) to local government agencies in mid 1980's that CP is the only method known to stop corrosion regardless of the level of chloride contamination within the concrete structure and it would provide a major economic benefit to the U.S. (Department of Transportation Memorandum, Federal Highway Administration, "Bridge Deck Deterioration: A 1981 Perspective" FHWA Office of Research, Washington, DC, Dec. 1981). The FHWA further encouraged states to protect existing bridges before they reach the stage where replacement is necessary. The FHWA strongly suggested that CP systems should be used more frequently as a cost-effective means to extend the useful life of chloride contaminated bridges (Memorandum, Federal Highway Administration, "FHWA Position on Cathodic Protection Systems Revisited" Office of the Administration, Washington DC, May 24, 1994).

Since the first impressed current CP system was installed on a bridge deck in California in 1973, the technology has advanced significantly. The majority of CP systems for reinforced concrete structures are of the impressed current type. With impressed current CP systems, an external direct current (DC) power supply, or rectifier, is used to force CP current from the anode through the concrete to the reinforcing steel, resulting in no corrosion activity on the steel surface.

The most widely used impressed current CP anode is expanded titanium mesh, which is 4 feet wide by 0.078-inch thick, and the diamond mesh size is approximately 1 in. x 2 in (2.54 cm x 5 cm). The titanium mesh is unrolled on a deck concrete surface and is fastened to the concrete substrate using plastic fasteners. A concrete overlay is used for good contact and as a riding surface.

The disadvantage of the impressed current CP systems is the rectifier, which requires a certain amount of monitoring and maintenance over the life of the system. If the owner cannot maintain the rectifiers, the corrosion of the reinforcing steel eventually redevelops and damages the concrete. Due to the maintenance difficulties of the rectifiers by many bridge owners, uses of impressed current CP systems have not been significant in some states and local agencies.

Based on such a situation, the FHWA initiated major R&D projects for corrosion control of bridge structures in 1993 to develop new sacrificial (galvanic) CP systems. Since the source of the CP current is the galvanic anode, it does not require rectifiers. In addition, conduit and wiring associated with the rectifier are also eliminated. Therefore, the simplicity of the system and the fact that no maintenance or monitoring is required, is attractive to many structure owners. When two different metals (steel and galvanic anode) are electrically connected to each other, a galvanic cell is established. As a result, electrical current flows naturally from the galvanic anode to the steel through the concrete electrolyte. (H.H. Uhlig and R.W. Revie, *Corrosion and Corrosion Control*, 3rd Ed., J. Wiley & Sons, NY, 1985, pp 217-232)

FHWA contracted with Corrpro Companies, Inc. to develop a new galvanic anode system for concrete structures from 1994 to 1999. (M. Funahashi and. W.T. Young, "Development of a New Sacrificial Cathodic Protection System for Steel Embedded in Concrete," FHWA Report No. FHWA-RD-96-171, May 1997 and M. Funahashi and W.T. Young, "Field Evaluation of a New Aluminum Alloy as a Sacrificial Anode for Steel Embedded in Concrete" FHWA Report No. FHWA-RD-98-058, April 1998). The alloy developed consisted of 20 percent zinc, 0.2 percent indium with the balance aluminum. The study indicated that Al-Zn-In is capable of providing sufficient CP current to steel embedded in chloride contaminated concrete. The anode was designed to be applied to the concrete using thermal spray technology. Further refinements since the end of the contract included limitation of impurities and the use of cored wire technology. The 1/8-inch diameter wire consists of aluminum sheet and an aluminum-zinc-indium powder. Indium is the key component, which keeps the anode active even in drier environments. The alloy is applied onto concrete surfaces using electric arc spray. The arc spray system simultaneously feeds two wires at a uniform speed through the spray gun. Upon application of high amperage across the electrode tips, the cored wire melts and the molten aluminum alloyed metal is subsequently forced onto the concrete surface using pneumatic air pressure to form a metallic coating. The recommended thickness of the coating is 12 mils. Based on predicted consumption rates, the alloy can be expected to provide 10 to 15 years based on the consumption of 0.5 mil per year. Since the first trial system was installed in 1995, this alloy has been installed on more than 15 structures with a total surface area of about 300,000 ft^2.

Since the thermally sprayed CP system was developed to be applied to concrete surfaces of bridge super and substructures, the intent of this project was to develop a galvanic CP system for bridge deck structures. The development criteria were as follows.

1. The galvanic anode material is sufficient to last a minimum of 25 years.
2. The anode mesh is durable for construction application.
3. The mesh openings are sufficiently large enough not to hinder the concrete overlay bonding.
4. The sheet size is practical for transportation and field installation.

ANODE DEVELOPMENT

Anode Mesh, Al-20Zn-0.2In Alloy

The concept was to produce an expanded mesh or perforated sheet from the original Al-20Zn-0.1In alloy with the size of the openings and metal volume sufficient to meet the criteria. We contracted with the Drexel University materials Engineering Department to produce the metal in sheet form for further processing into expanded metal or perforated sheet. However, the high zinc content presented problems in producing the sheet material. The as-cast alloy was brittle

and even small amounts of deformation caused cracking. An alloy with a lesser zinc content (5 percent) was successfully rolled.

Similar problems were noted in the FHWA research during procedures to roll the alloy into strip form for testing. While the lack of workability of the as-cast alloy was not a problem for the FHWA research, we concluded that it is a limiting factor for the current research. The fabricator could not overcome this problem. A second trial to produce a mesh using a direct casting method was considered. A casting company evaluated the feasibility (Zinco Division of Continental Metals, Inc., Chicago, IL), however, the cost of the mesh anode production was not economical and the maximum size of one mesh anode was too small for a bridge deck application.

Extruded Anode Strips

Since in the FHWA research we found that the Al-20Zn-0.2In alloy could be formed by extrusion we evaluated fabricating the anode sheets in a grid format. To further examine this possibility, we had an extrusion company (Profile Precision Extrusions, Phoenix, AZ) extrude a billet into strips. This process was successful.

The dimensions of the strip were 1/8-in thick (0.315 cm) by ½-inch (1.27 cm) wide by 10 feet (305 cm) long. The strips were reasonably ductile and workable. The chemistry of sample strips was tested and found to be within acceptable limits. The concept was to fabricate the strips into a 'panel' with the strips oriented vertically to the deck surface and spaced at either 6 or 9 inches (15.2 or 22.9 cm), similar to a grid. The spacing of the strips would be determined by the anodes' ability to protect the reinforcing and to provide protection for 25 years. Figure 1 illustrates the concept.

A practical method of connecting the anode strips together was developed using a swaging method whereby they were attached with steel tubes in a grid pattern. The method was successful in producing an anode grid with suitable electrical continuity between strips and rigidity of the unit. This method also allowed an easy method of attaching one grid panel to the next. A method of coating the anode-to-steel connection points using a preformed mold that also acted as a spacer to raise the grid from the bridge deck was also developed.
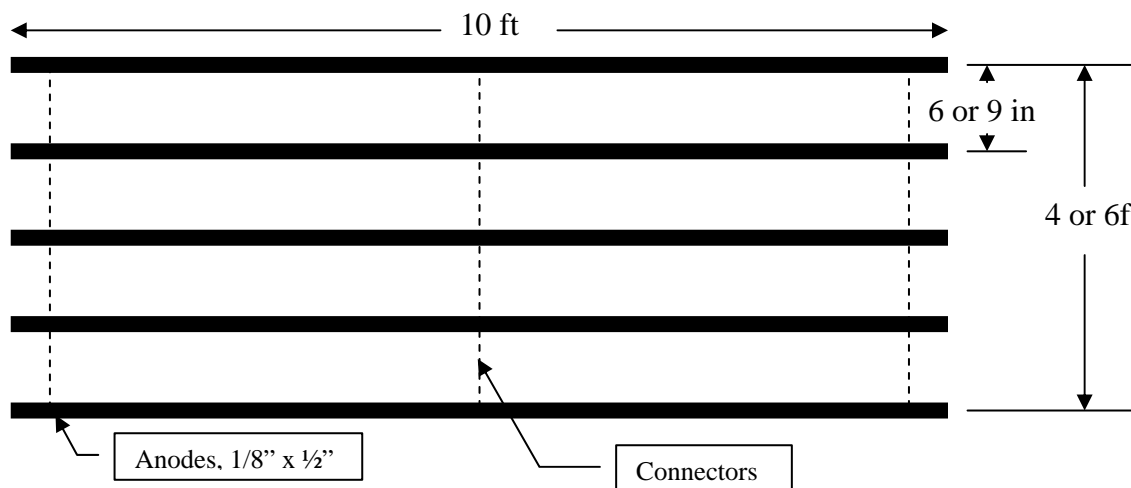
FIGURE 1. Anode panel schematic.

In order to test the anode strips, we fabricated two test slabs using premixed concrete. Each test block was 2 ft x 2 ft x 6 in (61 cm x 61 cm x 5 cm) and contained No. 5 reinforcing bars arranged in a grid [6-in (15.2 cm) rebar spacing] and an embedded silver-silver chloride reference electrode mounted adjacent to the reinforcing. The concrete was mixed with sodium chloride to stimulate corrosion on the reinforcing bars. After a 30-day cure period, the aluminum alloy anodes were placed on the top of the slab and encased in 1-in (2.54 cm) of ready mix concrete. For the purposes of this test, the anodes were connected with galvanized steel wire secured to the strip using rivets and the connection coated. Slab A contained three anode strips at a spacing of 9-in (22.9 cm). and Slab B contained four anode strips at a spacing of

6-in (152 cm). The two test slabs were placed in operation on January 12, 2004. Table 1 shows the initial operating parameters.

TABLE 1. Initial slab operating data.

	Slab A	Slab B
Distance between anode strips	9 in (22.9 cm)	6 in (15.2 cm)
Chloride content, lb/yd^3	7.5	7.5
E_{CORR} before activating anodes, mV SSC	358	527
$E_{REBAR-ANODE}$ at 1 week, mV SSC	647	944
I_A at 1 week, mA	4	2.25
Current per unit length of anode, mA/in	0.061	0.028
Depolarization at 1 week, mV after 4 hours	195	111

The current output of the anodes and on-potential were monitored hourly using a remote monitoring system. Figures 2 and 3 show the current and on-potential up to the point when the test was ended in August 2004. The slabs were ponded periodically. Cracks were discovered over two of the anodes in Slab A after about 2 months. We removed a core sample from Slab A over one of the cracks and found that it extended to the anode. Corrosion had caused the anode thickness to swell by 39 percent. The anode was found to have deteriorated in a lamellar manner with long thin splinters. The bottom of the anode (nearest the cathode) was more affected than the top. Since then additional cracks developed over the anodes in both Slab A and Slab B. We continued to monitor the potential and current once a day using a data logger. However, since Slabs A and B were cracked their continued usefulness both as indicators of anode life and anode usefulness were questionable, and we stopped moistening the slabs. Since the slabs were inside, this caused the slabs to dry out, the current to gradually decrease and the rebar potentials to return to near initial values. Data from the remote monitoring system was downloaded and the testing on these slabs was terminated in August.
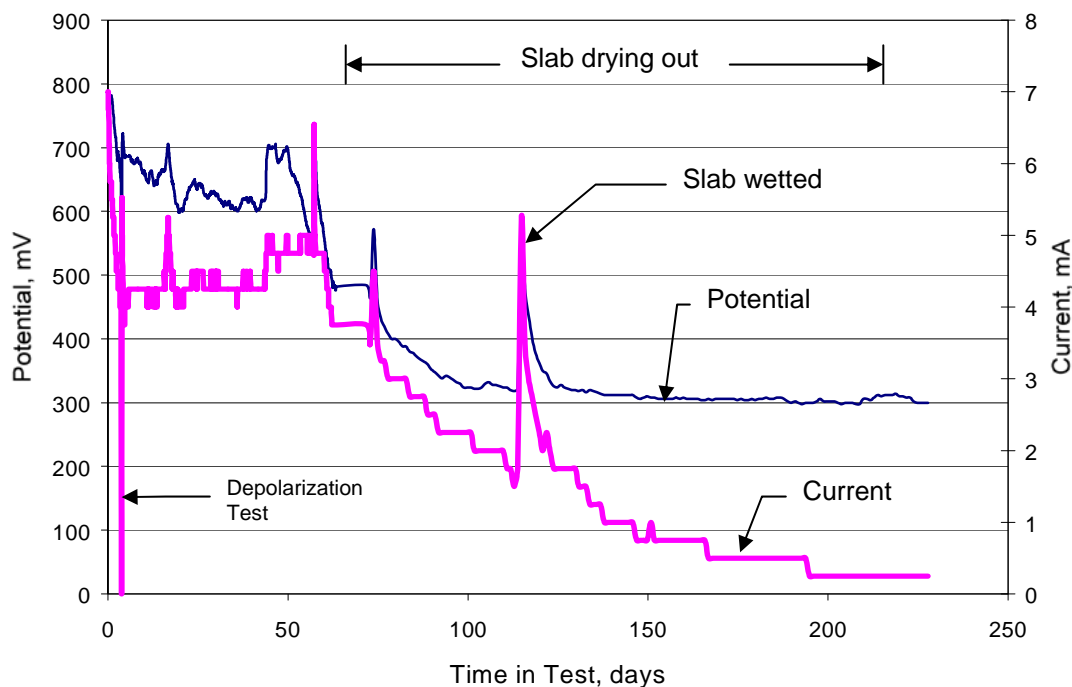

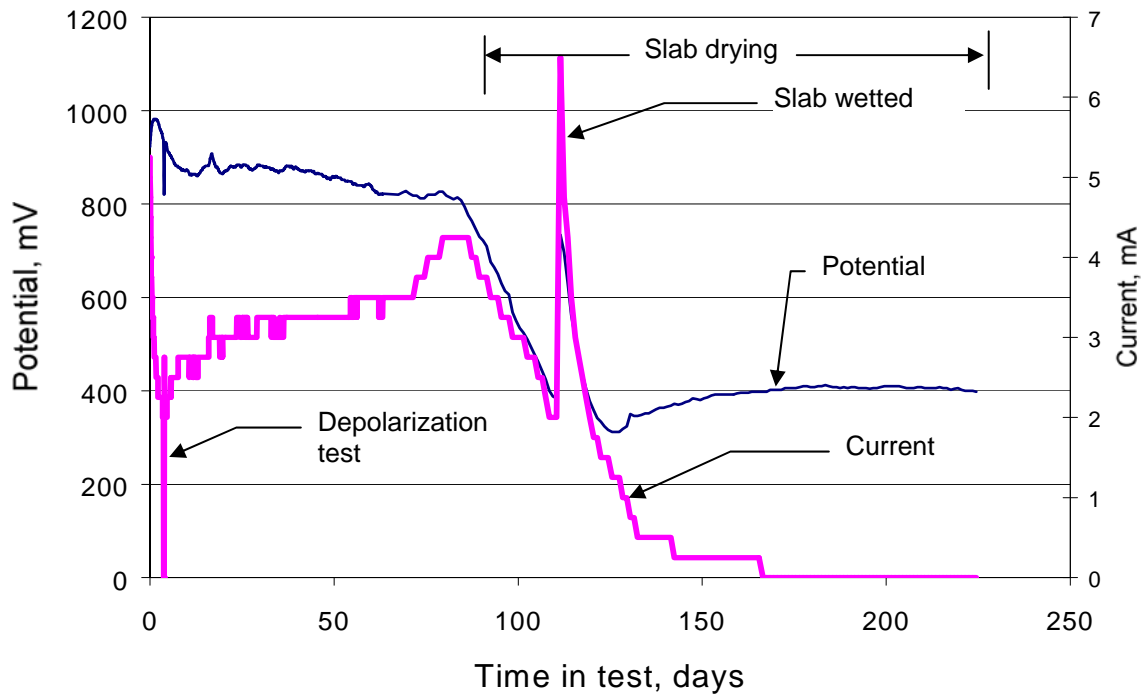FIGURE 2. Current output and potential of Slab A.

4

FIGURE 3. Current output and potential of Slab B.

Because the cracks appeared to be caused by stresses induced by the corrosion products, we reconfigured the anode so that it would absorb the corrosion product stresses rather than transmitting them to the concrete. We had the anode extruded into a strip 0.5 in (1.3 cm) wide by 0.28 in (0.71 cm) wide with a U-shape cross-section, in order to yield to corrosion product stresses. We also fabricated two parallel anode strips each 1/8 in (3.18 mm) thick by 1/2 in (12.7 mm) wide with a foam core to absorb the stresses. Two samples of each type of anode were installed in a 2 ft x 2 ft x 6 in (61 cm x 61 cm x 5 cm) concrete slab made with ready mix concrete with rebars [No. 5 rebars at 3 in (7.6 cm) spacing] and containing 15 lb/cu yd of chloride. The U-shaped anode cracked the overlay after 10 days and one of foam cored anodes cracked the overlay after 2 weeks and the parallel strips cracked the overlay after 4 months.

We theorized that the strip anode is too wide and the corrosion product exerts too much stress on the relatively weak concrete overlay used in our tests. Because of this, the strip anode concept was abandoned and two alternative anode configurations were tested. These are: (1) a return to the original concept of a perforated sheet using a more ductile alloy and (2) the anode alloy thermally sprayed onto an aluminum mesh.

Since the original aluminum alloy is too brittle to form into a sheet, we reviewed the test data in the original FHWA study and decided to use an alloy with less zinc and indium in order to improve formability yet retain desirable anode characteristics. An alloy consisting of aluminum, 5 percent zinc and 0.05 percent indium was selected. The alloy was cast at Corrpro's Edmonton foundry and rolling trials were conducted by EMV Technologies, LLC, Bethlehem, PA. The rolling trials were successful and small sheets, 1/8-in (0.318 cm) thick, were produced. Trials were also conducted by a metals fabricator on a standard alloy with a similar composition (AA 7075) to determine if the alloy could be perforated using conventional methods. This trial was also successful.

Test blocks [7 in x 12 in (17.8 cm x 30.5 cm)] were cast using ready mix concrete with and without chloride. Anode strips 1/8 in (3.18 mm) thick x 1/2 in (12.7 mm) wide x 8 ¾ inch (22.22 cm) long having both 5 percent zinc and 20 percent zinc composition were embedded in the concrete and connected to steel cathodes. The concrete was kept moist with tap water. Cracks developed after 4 months in all of the test blocks except the 5 percent zinc strip in the salt free concrete. The 5 percent zinc anode in chloride free concrete discharged 1.65 mA/ft^2 after 7 months.

Anode Mesh Using Thermal Spray

An anode configuration using the original Al-20Zn-0.1In alloy thermally sprayed onto an aluminum expanded metal mesh was tested. Limited laboratory testing indicated that pure aluminum performed well as an anode in concrete. The alloy layer on the surface was expected to initially polarize the steel rebar and the anode would remain active after the alloy layer was depleted. The active layer would also form porosity around the anode to absorb corrosion product and control stresses exerted by the corrosion products. Aluminum sheets 0.125 in (0.318 cm) thick by 4 ft (1.22 m) by 8 ft (2.44 m) were coated with 15-20 mils (381-508 μm) of the Al-20Zn-0.1In alloy using the thermal arc spray technique at Corrpro's Edmonton facility. Two mesh sizes were used [1/2 in (1.27 cm) and 3/4 in (1.9 cm)]. Aluminum alloy 3003 expanded metal was used for the initial trial. This alloy was expected to have a limited life knowing that a purer form would be needed for longer term trials.

Two concrete slabs, 2 ft (0.609 m) wide by 2 ft (0.609 m) long by 6 in (15.24 cm) thick, were constructed using ready mix concrete. An electrically continuous grid made of No. 4 steel rebars on 6 in (15.2 cm) centers served as the cathode. No salt was added to the concrete. A 2 ft (0.609 m) by 2 ft (0.609 m) sample of each mesh size was embedded in the slabs with 1-inch concrete cover. The anode wire connection was in the center of each sheet. Gas bubbles were noted emanating from the concrete over the anodes after pouring the concrete, but these did not seem to cause any permanent pores in the concrete. The anodes were externally connected to the steel reinforcing bar grid through a shunt three days after installing the anode. The slabs, which were stored in an unheated warehouse, were ponded periodically with salt water and maintained for about 600 days.   Figure 4 shows the current levels, which fluctuated due to moisture levels and temperature. Anode potentials of the two mesh anodes were measured at intervals by disconnecting the anode and rebars and measuring instant-off and depolarized potentials. Table 2 presents the results, which show that the anode stayed active throughout the test duration. The cracks in the large mesh block are unexplained but could have been caused by stresses where the anode connection wire came out of the concrete. No delamination of the concrete was found in the area of the cracks.

TABLE 2. Potentials of anode and rebar in test slab.

Mesh Slab	Day	Anode Potential, mV CSE		Comments
		Instant-off	**Depolarized**	
Large	0	-1078	--	Cathode potential -107 V, Initial current 45 mA
Large	94	-370	-652	Slab dry
Large	95	-672	--	
Large	182	-1030	-1100	
Large	349	--	-1141	
Large	529	-1037	-1060	No concrete distress
Large	544			Fine cracks radiating from center at wire.
Large	598			Cracks up to 6 in. long radiating from center connection. Test terminated.
Small	0	-942	--	Cathode potential -285 V, Initial current 50 mA
Small	94	-452	-909	
		-707		
Small	182	-560	-1000	
Small	349	--	-1031	
Small	529	-820	--1005	No concrete distress
Small	544			No concrete distress
Small	598			No concrete distress. Test terminated.

The mesh anodes for the bridge trial (to be discussed) were produced by thermally spraying (electric arc) the anode material onto aluminum alloy 3003 expanded metal sheets. While the laboratory tests and field trial of the thermally sprayed mesh anode showed that this was a good anode, the cost of production was high. That is because there is too much waste in spraying the anode alloy onto a mesh substrate. Therefore, we sought to produce the anode by expanding a sheet having the anode alloy already applied. We successfully produced an expanded metal mesh with the Al-Zn-In

alloy coating by applying the alloy to a solid sheet of AA3003 and then expanding the sheet. An anchor profile was first applied to the sheet by sweep blasting then the Al-Zn-In was applied to a thickness of 4-5 mils per side using the electric arc-thermal spray process. The sprayed sheet successfully passed a mandrel bend test to check for adhesion of the coating to the sheet. Five 0.067 in thick x 4 ft x 6 ft sheets of expanded mesh were produced. Each sheet had a diamond mesh pattern 1-1/4 in x 2-1/2 in. The alloy remained adhered to the sheet during the expansion process. Three of the sheets were roller flattened and three were left as-expanded. Figure 5 shows a close-up of the mesh.
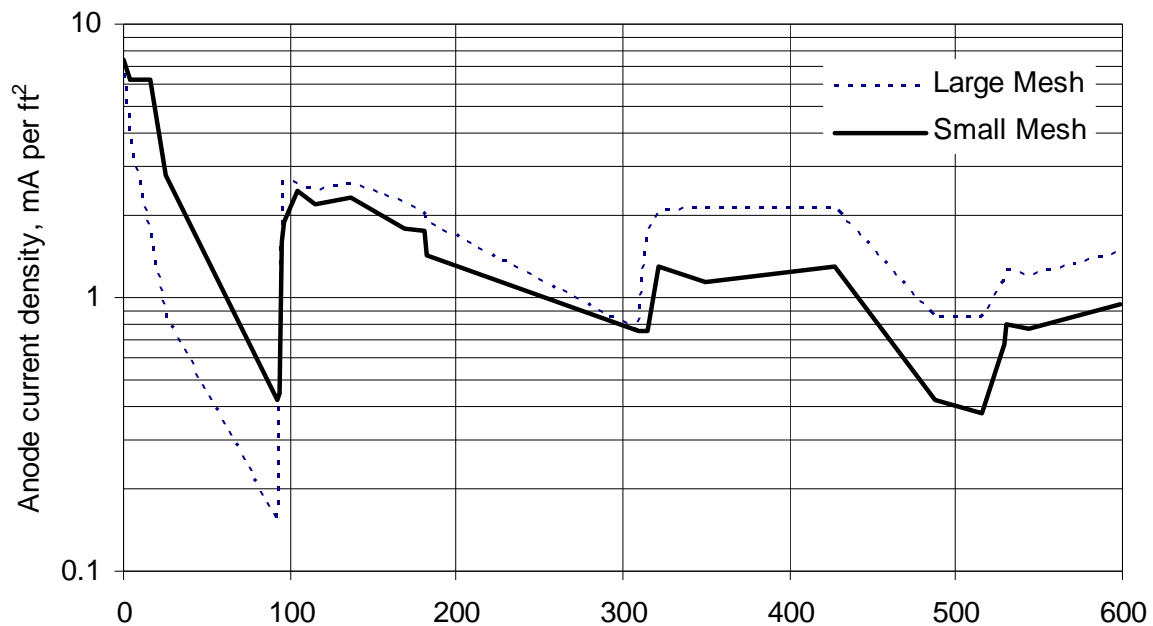

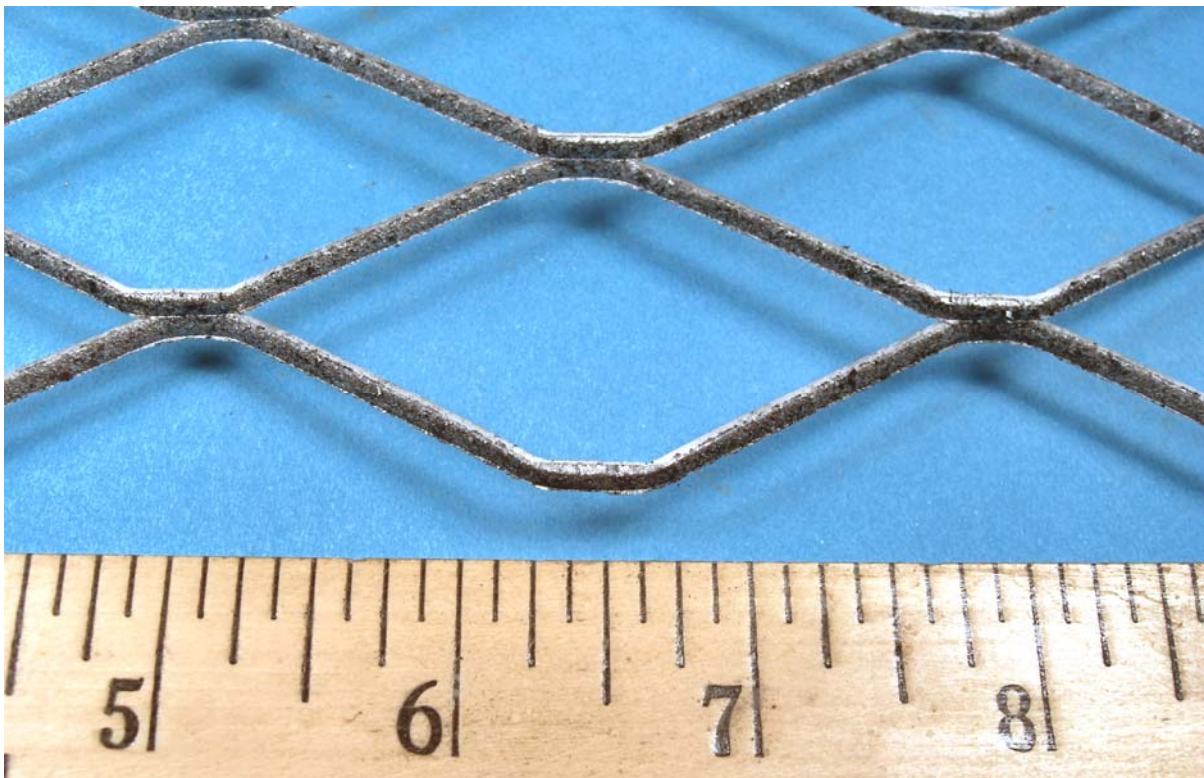**FIGURE 4. Current from thermally sprayed aluminum mesh anodes.**

FIGURE 5. Close-up of the expanded mesh with aluminum alloy anode coating.

Aluminum alloy 3003 (UNS 93003) was used since these trials had the purpose of proving whether the expanded metal mesh could be produced; however, this alloy might not be a good base metal for long term tests or usage on a bridge. In practice, a purer (99.5% aluminum) sheet (alloy 1350, UNS A91350) was planned for the full scale bridge trials. However, this alloy is relatively difficult to obtain and ultimately resulted in unreasonable delays in meeting the goals of this project.

BRIDGE INSTALLATION

We installed a galvanic anode mesh on the shoulder of a bridge deck in Missouri on Interstate 44 over the Little Bourbese River at mile marker 214, between Bourbon and Cuba, MO (Missouri bridge No. A12112EB). The mesh used for the bridge trial was fabricated by thermally spraying aluminum – 80 percent zinc – 0.2 percent indium anode alloy onto expanded aluminum sheets. Alloy 3003 mesh sheets, 0.060 in (0.152 cm) thick by 4 ft (1.22 m) by 8 ft (2.44 m) having 1 in (2.54 cm) x 2.75 in (6.99 cm) diamond pattern openings were used. Table 3 presents a description of the anode system and initial operating information. Figures 6 through 8 show the anode at various stages of the installation in the shoulder of the bridge. Figure 9 shows the junction box for testing the system. Prior to the mesh installation, silver-silver chloride reference electrodes were placed at anodic sites at the edge of the repair patches.

TABLE 3. Anode system description

		E_{CORR} native, mV SSC*
Al-Zn-In thickness, inch per side..........	0.010	
Anode area installed, sq ft	553	
Reference electrode 1	Located at top bar at old patch	302
Reference electrode 2	Located at bottom bar, old patch	157
Reference electrode 3	Located at top bar, new patch...............	199
Reference electrode 4	Located at bottom bar, new patch.........	135
Initial anode potential, volts	1.2	
Resistance, anode to steel, ohms...........	0.3	
Initial anode current, mA......................	1,248 after 15 minutes or 2.25 mA/SFc	
1 week anode current, mA	756 or 1.27 mA/SFc	

* All reference electrodes are silver-silver chloride

The mesh was installed on July 22, 2005 and the anode was connected on September 20, 2005. The panels were light, relatively stiff, and easy to lay out, although excessive bending of the strands caused the coating to flake off. The panels were laid along the outside curb with the 8 foot length extending out from the curb. This reduced the number of connections that needed to be made. The anode sheets were connected using aluminum fasteners. The connection was coated with Scotchcoat and sandwiched between two pieces of Scotch mastic pads. The anode was kept electrically isolated from the bridge structure to allow current, potential and depolarization measurements, but this might not be necessary in actual practice. Plastic Christmas tree fasteners were used to secure the mesh to the deck. For redundancy, two anode lead wire connections were made to the anode mesh using aluminum fasteners coated as described above. The anode mesh held up very well to the construction activity. Concrete trucks were able to drive over the anode. During the pour the anode to steel open circuit potential was 1.2 volts. The depth of cover was about 2 ½ inches.

One area of concern was that the anode was very active from the alkalinity of the wet concrete and produced gas bubbles from self corrosion. The gas pushed bleed water to the surface and smoothed out the raked finish. The bubbles occurred about 20 minutes after the concrete covered the anode and continued for 2 hours until the concrete was covered by burlap for curing. These bubbles ceased after a while and did not appear to extend down to the anode; however, this would be unacceptable for a finished concrete surface. Missouri DOT used boiled linseed oil to seal the deck. At some time before the last data set in October 2008, Missouri DOT used an asphalt emulsion sealer on the deck.

The system was temporarily energized for five minutes 30 minutes after the pour was complete. Table 4 presents the initial operating characteristics. The anode was permanently activated after the concrete cured for about 60 days and the junction box was installed.

TABLE 4. Initial anode operating data, 30 minutes after concrete poured.

Voltage: 1.2 volts to a silver-silver chloride reference electrode
Current: 0.6 amps (1.08mA/sfc) on 553 sf.
RC 1   Polarized 315 mV more negative than the static of -199 mV (top mat)
RC 2   Polarized 250 mV more negative than the static of -194 mV (bottom mat)
RC 3   Polarized 285 mV more negative than the static of -257 mV (top mat)
RC 4   Polarized 170 mV more negative than the static of -170 mV (bottom mat)

**FIGURE 6. Anode mesh prior to being set against curb and overlay application.
Note white wire which went to the junction box.**

**FIGURE 7. Installed anode mesh prior to overlay application. Black squares are coated connections between
anode sheets. The white wire goes to the junction box,**
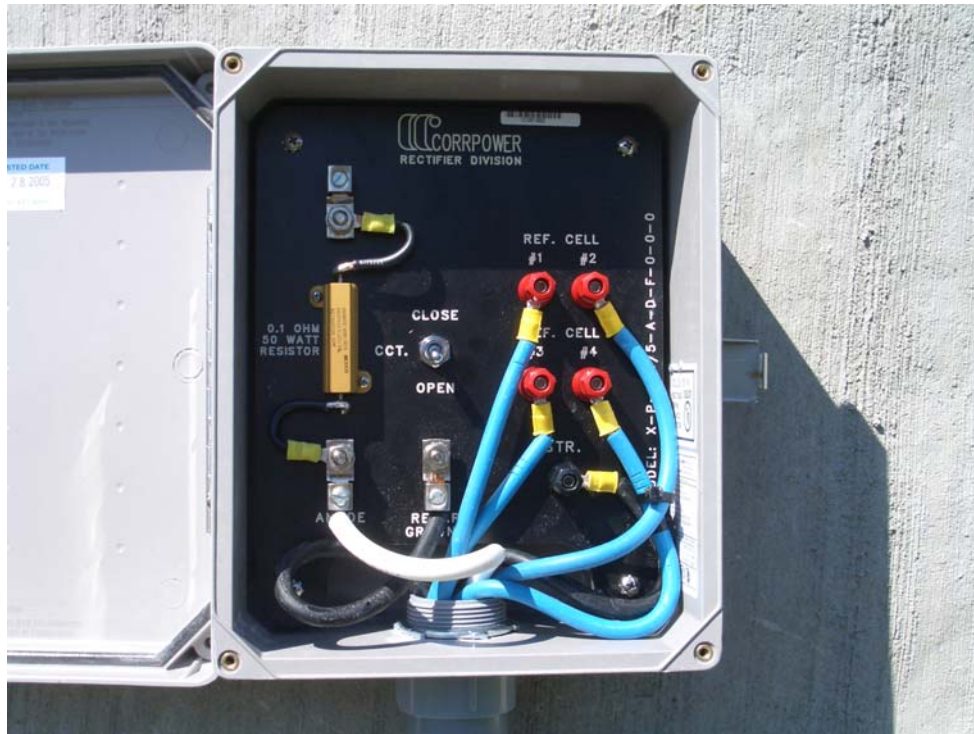
FIGURE 8. Overlay placement on anode.

FIGURE 9. Anode junction box showing 4 reference electrode terminals, shunt, structure wire and disconnect switch for instant-off potential readings.

Current, depolarization data and observations were taken periodically since the anode installation either by Corrpro or Missouri DOT personnel. The first depolarization test was taken September 27, 2005 and the latest test

occurred on October 3, 2008. Figure 10 summarizes this data. Figure 10 plots the number of days in test vs. depolarization after at least 2 hours in millivolts (mV) at each test electrode on the left axis and current density expressed as milliamperes per square feet (mA/SFc) of concrete surface area on the right axis. The temperature at the time of the test, anode-to-structure instant-off potential and whether the deck was wet or dry at the time of measurement is indicated.
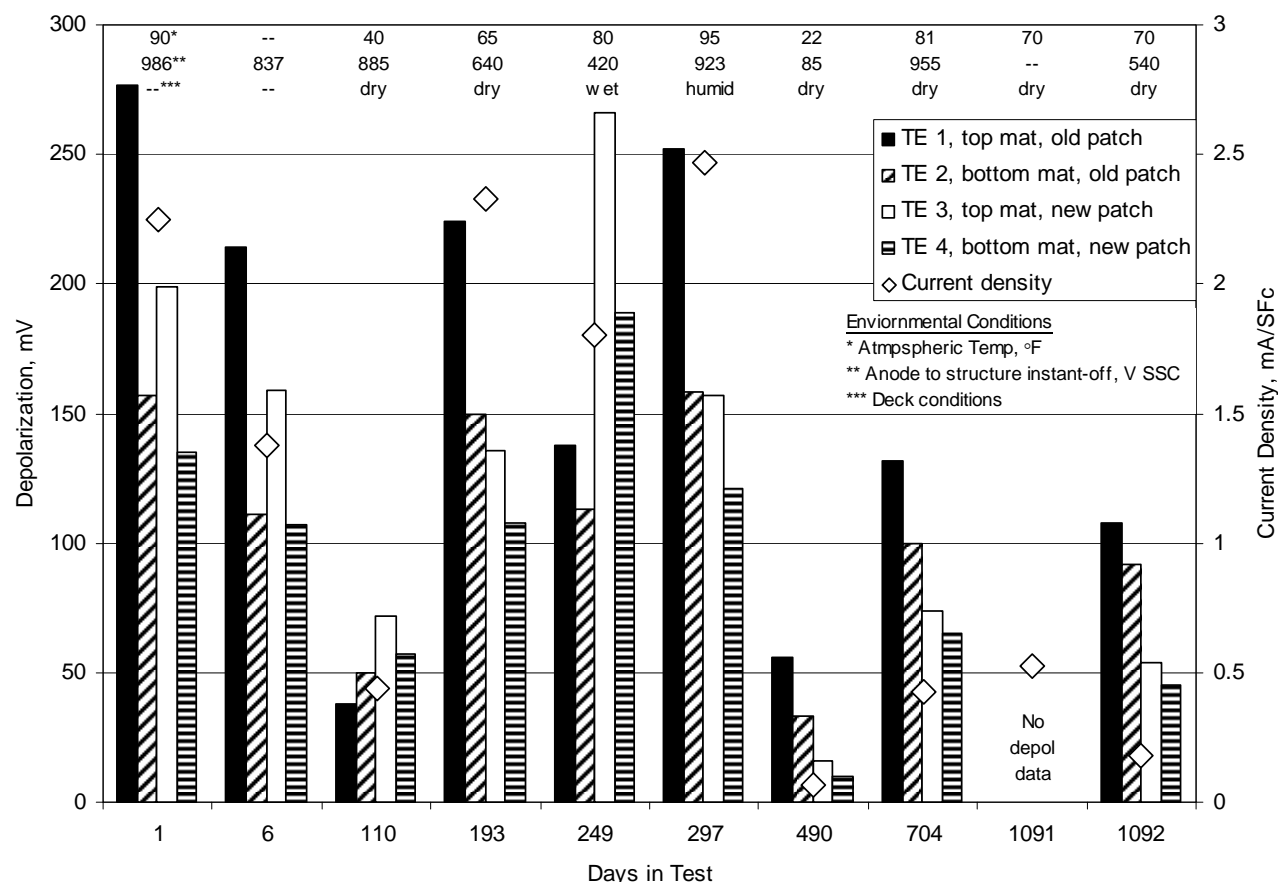

FIGURE 10. Depolarization (bar graphs), current density (line graph) and environmental conditions during bridge deck mesh anode tests on Cuba, Missouri bridge.

The data show that the anode produced sufficient current to protect the rebar based on a criterion of 100 mV depolarization per NACE International SP0290, *Impressed Current Cathodic Protection of Reinforcing Steel in Atmospherically Exposed Concrete Structures*. Depolarization was below the 100 mV criterion at several of the measurements, but returned to protected levels in subsequent measurements. The variation is likely caused by variations in temperature and moisture of the concrete. This is normal with a galvanic anode and has been noted in a previous study (*Field Evaluation of a New Aluminum Alloy as a Sacrificial Anode for Steel Embedded in Concrete*, M. Funahashi and W. Young, FHWA-RD-98-058, FHWA, Washington, DC, 1998). The referenced study involved piles subject to splash above seawater. The variation in current and depolarization is probably emphasized even more on a bridge deck that dries out quickly. Current has also fluctuated widely, with the last three measurements being about 0.5 mA/SFc or lower. Further testing over time would be needed to determine if these values are normal fluctuation due to environmental conditions or another reason.

During the September 5, 2007 survey, we found that part of the overlay had delaminated. Measurement showed that 123 ft^2 (11.4 m^2) or 22 percent of the surface at the anode was delaminated. We sounded the remainder of the overlay beyond the mesh and there were no delaminations. Several 4-in diameter cores were taken by the Missouri DOT in the delaminated areas. The cores broke at the anode mesh plane. The overlay was bonded to the substrate below the anode. During the October 3, 2008 testing, we found that the delaminated area on the west end of the shoulder had increased to 240 ft^2, or 43.4 percent of anode area. The delaminations were not explored to determine the cause and they might be caused by a weakening of the interface in the plane of the anode sheet. At that point it was decided that, while

the anode was relatively easy to install and provided adequate cathodic protection to the embedded steel reinforcing, there are issues that require additional study and solutions before the anode can be used in a full scale bridge trial, which are beyond the scope of this study. These issues are:

- Availability of a suitable aluminum alloy to serve as the base material for the mesh.
- Gas evolution from the anode during installation of the overlay
- Apparent delamination of the overlay

CONCLUSIONS

1. The original Al-20Zn-0,2In alloy is too brittle to be formed into a mesh or expanded metal using conventional methods. Further research might find an appropriate method to do this, but for the objectives of this study, a different anode configuration is more appropriate.

2. Alternate anode configurations of the Al-20Zn-0.2In alloy were investigated, e.g., an extruded strip configured as a grid, are not appropriate for bridge deck use because (1) the corrosion products exert too much force on the overlay and might crack the concrete and (2) the configuration is not practical from a constructability standpoint.

3. An aluminum alloy with a 5 percent zinc and 0.05 percent indium content has been tested and is capable of being fabricated into a perforated sheet that is practical from a constructability standpoint and provides adequate characteristics to provide cathodic protection to the rebar.

4. An alternate configuration where the Al-20Zn-0.2In alloy was thermally sprayed onto aluminum expanded metal mesh was successfully demonstrated to provide cathodic protection to embedded steel rebar in both laboratory testing and a limited field trial for over two years. The production of the anode in this manner, however, is not cost effective.

5. It was successfully demonstrated that the mesh anode could be produced by thermally spraying the anode alloy onto an aluminum sheet and then expanding the sheet to produce the diamond pattern sufficient to allow concrete and aggregate to pass through.

6. The mesh anode can be easily installed on a bridge deck without significant disruption to construction activities.

7. Despite the anode being readily installed and effective, there are issues that require additional study and solutions before the anode can be used in a full scale bridge trial, which are beyond original intent of this study. These issues are:

- Availability of a suitable aluminum alloy to serve as the base material for the mesh. It is thought that a relatively pure aluminum alloy is needed for the base sheet for the anode to remain active in concrete. This alloy is not readily available.
- Gas evolution from the anode during installation of the overlay. While some gas generation is thought to be desireable to absorb corrosion products from the aluminum to prevent disbondment, excessive gas generation can form pores in the concrete that might lead to cracking and delamination. A less active form of the anode alloy might solve this problem.
- Apparent delamination of the overlay. This might be caused by a weakening of the concrete overlay-to deck interface by the plane of the mesh and might be corrected by a different geometry of the mesh. Further study is needed.