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Laboratory Study of Sacrificial Anodes for Reinforced Concrete

R. Brousseau and B. Baldock*

ABSTRACT

The output of sacrificial current by two metallized coatings was monitored under well-defined conditions. Experiments were conducted at two relative humidities (RH). The performance of a zinc-aluminum alloy (78:22) was equal or slightly superior to that of pure zinc-coated anodes. However, there was a steady decline in current density output with time, which was attributed to oxidation products forming at the sacrificial anode/concrete interface.

KEY WORDS: aluminum, anodes, coatings, current density, relative humidity, reinforced concrete, zinc

INTRODUCTION

Steel reinforcement corrosion is a costly problem that has led to premature deterioration of a large number of concrete bridges and parking structures. Cathodic protection (CP) is being used increasingly to reduce corrosion of steel reinforcement. Galvanic CP has stimulated considerable interest in the civil engineering community because of its simplicity. The protective current flow in a galvanic system is induced by the electromotive force (EMF) that arises between the steel and the sacrificial anode metal. No special wiring, rectifiers, electrical short clearing between the anode and steel, rectifiers, and maintenance or corrosion monitoring are required.

Thermally sprayed zinc is being used increasingly as an anode for CP of steel-reinforced concrete

structures. Zinc coatings have been implemented successfully as an impressed current anode in California, Oregon,¹ and Ontario. The Florida Department of Transportation is starting to use metallized zinc as a sacrificial anode on its marine structures.²⁻⁴ Recently, a more reactive metallized coating made of an aluminum-zinc-indium alloy has been developed.⁵⁻⁶ Although this new alloy shows superior electrochemical performance, its stiffness and brittle mechanical properties make poor-quality wires that can be difficult to metallize.

The scope of the present work was to examine how metallized zinc coatings perform as sacrificial anodes in well-defined environments (e.g., at 50°C and 50% or 90% relative humidity (RH)). The performance of a zinc-aluminum alloy (78:22) was investigated for comparison to that of pure zinc.

EXPERIMENTAL

Effectiveness of the galvanic protection was tested on reinforced concrete samples made with type 10 normal Portland cement, admixed with 1% sodium chloride (NaCl) by mass of cement and made with a water to cement ratio of 0.5. Additional samples were made with a 0.43% water-to-cement ratio for some of the bond-strength tests of the metallized coatings. Most samples were fabricated with a single level of two steel reinforcing bars (Figure 1). The different configurations represented concrete covers of 20 mm, 50 mm, and 125 mm (0.79 in., 1.97 in., and 4.92 in.) between the steel reinforcement and the arc-sprayed coatings. All samples were manufactured in triplicates for a total of 36 samples.

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FIGURE 1. Schematic of the metallized samples used to monitor the galvanic current flow.

A graphite pseudo-reference electrode was poured in all samples. This reference electrode was used to measure electrochemical potential shifts that occurred during the 4-h depolarization surveys following interruption of the galvanic current flow.

The top surface of each concrete sample was grit-blasted with no. 40 silica sand and air dried for a few days after being cured for 28 days at 100% RH. The grit-blasting was sufficient to roughen the surface without exposing the aggregate in the concrete. Any dust or loose particles on the surface were removed by blowing with compressed air after grit-blasting. The surface of the concrete was pre-

heated to 50°C immediately prior to arc spraying to ensure an adequate bond was obtained between the metallized anode and the concrete substrate. Preheating the surface of the concrete was performed since it was found to maximize the adhesion of arc-sprayed zinc on concrete in previous studies.⁷ The temperature of 50°C was chosen because it would increase bond strength while remaining field practical. The samples then were arc-sprayed with zinc, or with a zinc-aluminum alloy (78:22) using an automated application system. All arc sprayings were performed with 620 kPa air pressure, 26 V, 300 A, and at a spray distance of 15 cm (5.90 in.). All thermal spraying was performed with wires 3 mm (0.118 in.) in diameter. Thickness of the applied coatings was 0.4 mm (0.016 in.). Initial bond-strength measurements were performed on a few samples using a pneumatic adhesion tester.

Once metallized, the reinforced concrete samples were placed in one of two environments: a 50% or 90% $\pm$ 5% RH at a temperature of 50°C $\pm$ 2°C. The samples were connected to a data acquisition system so that automated current and depolarization measurements could be performed. Current measurements were obtained by measuring the voltage drop across a 2- Ω precision shunt resistor that was installed in series between the coating and the steel rebars. Surface area of the metallized anode on each sample was 236 cm² (36.59 in.²).

RESULTS

Initial bond-strength data of the metallized coatings are presented in Tables 1 and 2. Measurements were performed on concrete samples with two preheating temperatures and two water-to-cement ratios. Initial adhesion of the zinc-aluminum alloy

TABLE 1
Bond Strengths of Arc-Sprayed Zinc on Concrete

Concrete Water-to-Cement Ratio	0.43		0.50	
Preheating surface temperature	50°C	120°C	50°C	120°C
Bond-strength averages (kPa)	1,313	2,636	1,515	2,359
Standard deviations (kPa)	212	274	400	465
Number of pull tests	31	28	32	29

TABLE 2
Bond Strengths of Arc-Sprayed Zinc-Aluminum (78:22) on Concrete

Concrete Water-to-Cement Ratio	0.43		0.50	
Preheating surface temperature	50°C	120°C	50°C	120°C
Bond-strength averages (kPa)	1,530	3,084	1,120	2,640
Standard deviations (kPa)	320	327	286	494
Number of pull tests	15	12	15	13

(78:22) was generally equal, if not slightly superior, to that of pure arc-sprayed zinc. No final bond-strength measurements were taken since the samples remain under investigation. However, no apparent deterioration was observed.

The current density values of the triplicate samples was averaged and analyzed. Unfortunately, the magnitude of the observed current densities did not correlate with the three different concrete covers used to manufacture the samples. The significant scatter in the data ($\pm 50\%$) coupled with a limited number of samples (triplicates) made it impossible to observe the expected reduction in galvanic current density with thicker concrete covers. Therefore, the current density values of all samples sprayed with the same metal coatings were averaged. Results for the 50% and 90% samples are presented in Figures 2 and 3, respectively. Initially, there was an exponential decline in the galvanic current density at both RH, which appeared to stabilize toward the end of the experimental program. The samples stored at 90% RH generally had current densities two to three times higher than those at 50% RH. The current delivered by the zinc-aluminum alloy was similar to that delivered by the pure zinc at both RH.

Depolarization shifts were measured on the samples to determine if the criteria developed by NACE International would be met.¹¹ This criteria stipulates that adequate CP is achieved if the potential of the steel, after current interruption, shifts by a minimum of 100 mV within 4 h of current interruption. Longer depolarization periods can be used for this criteria.

The potential values of the steel reinforcement and the metallized anode were recorded versus a graphite pseudo-reference electrode that was embedded permanently in each concrete sample. The averaged depolarization shifts that were recorded several times during the experimental program are presented in Figures 4 and 5 for the two RH.

As noted, the potential shift of the steel reinforcement should have exceeded 100 mV after the current was interrupted for 4 h. The 100-mV criteria was achieved after 134 weeks for the zinc-aluminum (78:22) alloy samples at 90% RH. For pure zinc, the criteria was met only for the initial 80 weeks, although both the zinc and the zinc-aluminum (78:22) alloy provided similar galvanic current densities. All metallized samples maintained at a 50% RH produced shifts in the 40-mV to 50-mV range after 134 weeks of monitoring.

Depolarization tests usually were measured over a 4-h period. However, occasionally longer depolarization periods were measured. Table 3 lists the

FIGURE 2. Galvanic current density time profile for metallized samples stored in a 50% RH chamber.

FIGURE 3. Galvanic current density time profile for metallized samples stored in a 90% RH chamber.

average depolarization recorded after 4 h, 24 h, and 72 h of interruption of the galvanic current generated by the two metallized coatings. This data indicated 4 h was insufficient to measure all the cathodic polarization provided to the rebars by the metallized coating anodes. In practice, the surface area of the reinforcing steel and of the metallized concrete surface has a ratio of $\approx 1:1$, except in beams and columns. In this experiment, the surface area ratio of steel to anode was 1.4:1.

EMF between the metallized coatings and rebars was measured on all samples before the wiring to the data acquisition system was completed. Average EMF values were highest for the zinc-aluminum alloy (78:22), as listed in Table 4. After the metallized anodes and steel reinforcing bars were wired together electrically, the open-circuit potential values were recorded between the anode and steel after 4 h of depolarization. Although this was not a true EMF, it suggested that the zinc-aluminum (78:22) alloy could produce a higher driving voltage.

In an earlier study, it was found that wetting the surface of the metallized coatings would enhance the galvanic current output.² Sagues and Powers briefly applied a damp paper towel to the metallized coating

¹¹ NACE Standard RP0290-90, "Standard Recommended Practice for Cathodic Protection of Reinforcing Steel in Atmospherically Exposed Concrete Structures." NACE Book of Standards, vol. 1 (Houston, TX: NACE, 1990).

FIGURE 4. Average depolarization shifts measured on samples stored in 50% RH.

FIGURE 5. Average depolarization shifts measured on samples stored in 90% RH.

and observed a strong current increase.² After the paper towels were removed, it took ≈ 48 h for the galvanic current generated by metallized zinc to decrease back to base levels. To verify the merits of surface wetting in activating metallized zinc coatings, the blocks usually maintained in a 50% RH were immersed periodically for 7 days in deionized water. As predicted, wetting the samples increased the current output of the sacrificial coatings, with the

increase being highest for the zinc-aluminum alloy (78:22), as shown in Figure 6.

DISCUSSION

Significant drying of the concrete samples occurred at 50% RH. Since the EMF remained relatively constant, a decrease in flow of galvanic current was not surprising as concrete drying increased. The system, however, was not passivated. Tests have shown that if the metallized samples were wetted with water, current flow would be increased. This, and the observation that higher galvanic currents were recorded in the samples maintained at 90% RH implied that metallized coating anodes would be most active where concrete resistivity was lower or where there was weathering such as rain, snow, and seawater splashing. Fortunately, this also occurs in most areas susceptible to greater reinforcing steel corrosion. Galvanic CP with metallized coatings, therefore, can be described as self regulating.

Concrete drying alone could not explain all of the decrease in the flow of galvanic current. This was obvious from the current-vs-time curves recorded at 90% RH, where continuous concrete drying was unlikely to explain the slow but consistent decrease of galvanic current. Another possible cause for such a decrease was the formation of zinc oxidation products at the anode/concrete interface. These products hindered further electrolytic current flow through the pores of the concrete normally filled with solution.

Contrary to what was expected, the experimental data did not show that a lower cover thickness of the concrete resulted in a higher galvanic current. Alloying zinc with 22% Al increased the EMF that drove the flow of galvanic current from the anode to the rebars. However, the increase of galvanic current with this alloy was limited, and a more electronegative coating should be developed for drier concrete or for structures with higher steel density. Another alternative would be to develop a solution that could be sprayed on the metallized zinc to enhance its performance as a sacrificial anode for reinforced concrete.

TABLE 3
Extended Depolarization Data Obtained
After 41 Weeks and 80 Weeks on the Samples Maintained at 50% RH

Sample	4-h Depolarization (mV)		24-h Depolarization (mV)		72-h Depolarization (mV)	
	41 Weeks	80 Weeks	41 Weeks	80 Weeks	41 Weeks	80 Weeks
Zinc 20 mm	60.3	41	86.3	68	93.3	78
Zn:Al 20 mm	50.0	43	75.3	72	84.0	77
Zinc 50 mm	54.0	30	72.7	46	79.3	
Zn:Al 50 mm	54.7	46	77.0	73	83.7	71
Zinc 125 mm	44.3	27	62.7	44	69.3	78
Zn:Al 125 mm	53.0	50	69.7	72	73.3	73

TABLE 4
Open-Circuit Potential Difference

Metals Coupled	RH Condition	Open-Circuit Potential Difference (mV) ^(A)		
		Initial	32 Weeks	79 Weeks
Zn-Fe	50%	353	213	168
Zn:Al (78:22) -Fe	50%	451	477	387
Zn-Fe	90%	352	303	209
Zn:Al-Fe (78:22)	90%	397	384	370

^(A) Measurements taken at 32 weeks and 79 weeks were taken after only 4 h of depolarization.

CONCLUSIONS

- ❖ Sufficient galvanic CP to prevent corrosion of the reinforcing steel should be provided by the metallized anodes for at least a 2-y period in humid environments or where there is occasional surface wetting of the metallized coatings.
- ❖ Potential depolarization shifts are higher if longer depolarization periods are used. Compared to a metallized coating anode made of pure zinc, the zinc-aluminum alloy (78:22) had similar bond strengths, a higher EMF, and similar galvanic current output and cathodic polarization levels to the reinforcing steel.

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FIGURE 6. Current density change during repetitive wetting of the samples stored at 50% RH.

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