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Factors Affecting Adhesion on Concrete of Arc-Sprayed Zinc[☆]

R. Brousseau,^{*} M. Arnott,^{*} S. Dallaire,^{**} and R. Feldman^{*}

ABSTRACT

Arc-sprayed zinc coatings are more frequently used as anode for the cathodic protection of reinforced concrete structures. However, as with any other conductive coating, zinc should be applied with the highest possible adhesion in order to serve as a durable anode. Factors affecting the adhesion of zinc on concrete are discussed here for the first time. Preheating the concrete surface prior to zinc application has been found to be particularly beneficial. The measured adhesion values have also been found to vary significantly with the pull out procedure.

KEY WORDS: cathodic protection, concrete, metallized, reinforcement, zinc

INTRODUCTION

Corrosion of the steel reinforcement in bridges and parking garages is being increasingly mitigated by the rehabilitation technique called cathodic protection. This technique involves negatively polarizing the steel reinforcement with a rectifier and an auxiliary anode

applied on the concrete surface to be protected. Since the early 1970s, several types of cathodic protection systems have been investigated.¹⁻⁸ These systems all differ with respect to the type of material used for the anode. In order for the system to provide an adequate service life, the anode should preferably cover as much concrete surface as possible. This will minimize the current density at the anode, preventing an excessive electrochemical formation of acids at the anode/concrete interface, which can significantly reduce the service life of the anode. Spreading the anode as much as possible on the surface of concrete structure will also provide a better distribution of protective cathodic currents to the steel rebars.

It is very important for an anode, particularly when applied on a vertical plane, that it adheres well to the surface of the concrete structure to be cathodically protected. Poor adhesion has been found to be a problem for conductive coating anodes and for the cementitious overlay encapsulating the titanium mesh anode.^{9,10}

One cathodic protection system that has recently commanded much attention uses thermally sprayed zinc as the anode.¹¹⁻¹³ This type of cathodic protection system was installed for the first time in 1983 on the Richmond-San Rafael Bridge in the San Francisco

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Bay. It is still performing well today. However, some adhesion problems have been recently experienced in the field when the zinc is arc sprayed.

The present research was designed to find ways to overcome this problem. Some of the studied factors have been found to strongly increase the adhesion of arc-sprayed zinc on concrete.

EXPERIMENTAL

Concrete Sample

The dimensions of the arc-sprayed concrete samples were as follows: 36.6 by 36.6 by 5.6 cm (14.4 by 14.4 by 2.2 in.). Only one concrete mix formulation was used for all samples (Table 1). To simulate structures subjected to deicing salts, 2 kg of chloride/m³ of concrete were added (4.4 lb/1.3 yd³). The physical properties of the concrete are presented in Table 2.

After demolding, the samples were placed in a fog room at 23°C (73°F) 100% RH for 28 days after which they were placed in large, sealed plastic tubs.

Sandblasting

The concrete samples were removed from the sealed plastic tubs 48 h prior to sandblasting. Their surface was subsequently sandblasted with 16 mesh silica sand at an air pressure of 758 kPa (110 psi), which produced a smooth finish consisting mainly of sand and cement. Note that unless stated otherwise, all concrete samples used in this project were prepared as described above.

When the much more angular and harder aluminum oxide was used as grit material, a rougher concrete surface with significantly more exposed

aggregate was obtained. After sandblasting, the samples were returned to the sealed plastic tubs.

Arc Spraying

All arc sprayings were performed with a 620 kPa (90 psi) air pressure, at 26 V, 300 A, and at a spray distance of 15.2 cm (6 in.). To make the coatings as uniform as possible in thickness, the gun was mounted at right angle to the specimen on an automated transverse unit. Spraying was performed with either pure zinc metal or a zinc:aluminum alloy (85:15). The wire diameter was 3 mm (1/8 in.).

The metals were sprayed to a 0.4 mm (16 mil) thickness. The spray pattern was determined by making 10 horizontal passes over a steel plate. The deposition thickness was then measured using a micrometer. The deposition profile can be seen in Figure 1. From this information, it was determined that by stepping the gun up 3.8 cm (1.5 in.) on each pass and repeating the whole process six times, a uniform 0.4 mm (16 mil) thickness could be produced over the entire sample.

Initial attempts to apply zinc or the Zn:Al (85:15) alloy to the room temperature concrete were unsuccessful. The spray parameters used were those described at the beginning of this section. A reason for the difficulties may have been that the concrete had been manufactured only three months earlier. Results from a field study¹⁴ have suggested that arc-sprayed zinc will not adhere as well to new concrete as to old concrete. Early in this study, the metallic coatings curled up and away from the edge of the concrete samples. Large residual tensile stresses are believed to have developed within the coatings to levels exceeding the adhesion bond strengths to concrete. Bond strengths were typically in the range of 0 to 690 kPa (0 to 100 psi). They were measured with an elcometer bond strength tester and 25 mm (0.98 in.) diameter dollies. Experiments were subsequently conducted with the aim of achieving higher bond strengths.

The following surface conditionings of concrete samples were investigated:

- Wetness;
- Surface temperature; and
- Sandblasting grits.

The results of this investigation are summarized below. All of these preliminary bond strength measurements, unless stated otherwise, were made using an elcometer and 25 mm (0.98 in.) dollies.

RESULTS AND DISCUSSION

Wetness

The surface of one sample was sandblasted with silica sand and subsequently given a light spray with a

TABLE 1
Concrete Mix Composition

Component	Weight Ratio to Cement Content
Type 10 Portland cement	1
Commercial concrete sand	2
9.5 mm (3/8 in.) limestone	3
NaCl	0.009
Air entraining agent	0.001
Water reducer	0.011
Water-to-cement ratio	0.40

TABLE 2
Physical Properties of the Concrete

Slump	3.0 in.	7.6 cm
Air-entrained content	5.75%	5.75%
Compressive strength, 28 day	7760 psi	53.5 MPa

FIGURE 1. Deposition profile of zinc when arc sprayed using a gun, at 26 V, 300 A, with 620 kPa (90 psi) air pressure, and a spray distance of 15.2 cm (6 in.).

mist of water immediately before thermal spraying. The zinc was arc sprayed when the concrete surface was at room temperature. No bond strength developed between the zinc and the concrete. The applied metal was easily pulled off from the concrete as a single sheet. When concrete samples were arc sprayed similarly, but only after being sandblasted and kept at 100% RH, a bond strength average of 524 kPa (76 psi) was obtained. It appears that a high moisture content can prevent proper adhesion of the zinc on concrete.

Surface Temperature

The surface temperature of the concrete prior to the metallizing was found to have a very significant effect on the bond strength of arc-sprayed coatings, as indicated by the results shown in Table 3. Surface preheating of some concrete samples was done by applying a natural gas flame to it for approximately one minute prior to arc spraying. The concrete surface temperature was raised to approximately 120 to 150°C (248 to 302°F) as determined by a thermographic camera. The thermographic camera was calibrated using surface thermocouples and thermal pencils rubbed against the concrete samples.

Scanning electron micrographs of cross sections of the zinc/concrete interface (Figures 2 and 3) also show a significant difference between a sample kept at room temperature and a sample preheated to 120 to 150°C prior to arc spraying. The preheated samples show a very intimate contact of the zinc with concrete, and when no heat is applied, voids and gaps can be seen between the zinc and concrete.

The increase of zinc adhesion when the concrete is preheated prior to arc spraying can be explained as follows: molten zinc droplets being arc sprayed onto a cold concrete substrate will solidify much more rapidly than on a hot substrate. This means less penetration

TABLE 3
*Effect of Surface Temperature
on Bond Strength*

Surface Bond Strength at 21°C		Hot Surface Bond Strength	
kPa	psi	kPa	psi
527	75	3103	450
172	25	1862	270
552	80	2069	300
483	70	3448	500
138	20	1586	230
621	90	1724	250
758	110	1931	280
690	100	2414	350
690	100	3379	490
620	90	2483	360
Avg. 524	Avg. 76	Avg. 2400	Avg. 348

of the molten zinc into the porous cement matrix before solidifying. In addition, the pores of a wet or relatively saturated body will contain water, and this will also prevent deep penetration of the molten zinc. Since the initial adhesion of zinc on concrete is purely mechanical, it is obvious that the deeper the attachment, the stronger its adhesion will be to concrete.

Sandblasting Technique

Surface texture can also influence the mechanical bond between the zinc and concrete. In order to study this parameter, concrete samples were sandblasted with aluminum oxide. Since aluminum oxide is a much harder and has more angular grit material than silica sand, it should produce a rougher concrete surface. Trials indicated that the aluminum oxide removed more concrete material during the sandblasting procedure, particularly the softer cement mortar, resulting in more exposed coarse aggregate. The exposed aggregate had a very low porosity and a relatively smooth surface. Since the zinc coatings could not adhere well to the aggregate surface, lower bond strengths were obtained with the aluminum oxide sandblast (Table 4). However, this might not be true if softer or more porous aggregates were used. It is worth noting that the concrete surfaces of the samples used in this test were preheated to 150°C (302°F) prior to application of a zinc:aluminum (85:15) coating in both instances.

Effect the Measuring Technique on Bond Strengths

Additional bond strength measurements were made using a Patti tester. This adhesion measuring instrument is based on an automatic, pneumatic system that creates a constantly increasing pulling force on the anode coating. Larger dollies, 50 mm

(a)

(b)

FIGURE 2. Scanning electron micrographs of zinc/concrete interface when the concrete was kept at room temperature prior to arc spraying. The micrographs are magnified by (a) 20X and (b) 200X.

(a)

(b)

FIGURE 3. Scanning electron micrographs of zinc/concrete interface when the concrete was preheated to 120 to 150°C prior to arc spraying. The micrographs are magnified by (a) 20X and (b) 200X.

TABLE 4

Effect of Sandblasting Grit on Bond Strength of ZnAl (85:15) Coatings

Bond Strength on Samples Sandblasted with Silica		Bond Strength on Samples Sandblasted with Alumina	
kPa	psi	kPa	psi
2069	300	1379	200
2758	400	1379	200
1724	250	1310	190
2896	420	827	120
2069	300	1379	200
4138	600	2620	380
2069	300	1034	150
Avg. 2530	Avg. 367	Avg. 1421	Avg. 206

(1.97 in.) diameter, were used since this dolly size provides for averaging any inconsistencies of the concrete surface.

As shown in Table 5, measurements recorded with the Patti and the larger dollies produced higher bond strength data than the elcometer using 25 mm (0.98 in.) diameter dollies, 4.8 cm² (0.75 in.²). This difference in apparent bond strength may be attributed to two important factors. The first occurs in the operation of the equipment, whereby the Patti produces a constant increase in pulling pressure, and the elcometer uses a manually operated screw system that is operator dependent. The second factor is that

TABLE 5

Comparison of Bond Strength Measurements Recorded Preheated Concrete Samples Sandblasted with Silica Sand

Anode Material	Average Bond Strength		Measuring Instrument
	kPa	psi	
Zinc	3474 ± 407	504 ± 59	Patti, 50 mm dollies
Zinc aluminum (85:15)	3436 ± 572	499 ± 83	Patti, 50 mm dollies
Zinc	2400 ± 675	348 ± 98	Elcometer, 25 mm dollies
Zinc aluminum (85:15)	2530 ± 641	367 ± 93	Elcometer, 25 mm dollies

TABLE 6

Zinc Bond Strengths Measured with a Patti Pneumatic Pulling Tester^(A)

Adhesion Test #	Sample 1		Sample 2		Sample 3	
	kPa	psi	kPa	psi	kPa	psi
1	3644	528.5	3413	495.0	3875	562.0
2	3182	461.5	2951	428.0	4151	602.1
3	2905	421.3	2951	428.0	3644	528.5
4	2675	387.9	3690	535.2	3321	481.6
5	3736	541.9	3459	501.7	4013	582.0
6	3598	521.8	3736	541.9	3598	521.8
Average	3290	477.1	3367	488.3	3767	546.3

^(A)Overall average 3,474 kPa (503.9 psi), standard deviation 406 kPa (58.9 psi).

TABLE 7

Zinc:Aluminum (85:15) Bond Strengths Measured with a Patti Pneumatic Pulling Tester^(A)

Adhesion Test #	Sample 1		Sample 2		Sample 3	
	kPa	psi	kPa	psi	kPa	psi
1	3413	495.0	3090	448.1	4013	582.0
2	2351	341.0	4059	588.7	3736	541.9
3	2951	428.0	2767	401.3	3505	508.4
4	3367	488.3	3182	461.5	4198	608.8
5	2582	374.5	4290	622.2	3921	568.7
6	3367	488.3	3090	448.1	3967	575.4
Average	3006	435.9	3413	495.0	3890	564.2

^(A)Overall average 3,436 kPa (498 psi), standard deviation 571 kPa (82.8 psi).

the Patti has a self-aligning system that ensures that the pulling force is normal to the dolly surface. The elcometer does not have an aligning system, and any unevenness in the concrete surface will introduce a peeling factor into the test that can dramatically reduce the measured bond strengths. Tables 6 and 7 show the individual pull test values recorded with the Patti tester for zinc and Zn:Al, respectively.

CONCLUSIONS

❖ The adhesion of arc-sprayed zinc coatings on concrete has been shown to be affected by factors such as the moisture content, temperature, and surface texture of the cementitious substrate. Preheating has been shown to increase significantly the adhesion of the arc-sprayed coatings on concrete.

❖ Other factors such as spray thickness per pass, total applied thickness, voltage, type of concrete, chloride content, carbonation level, etc., should also be investigated in a future research project.

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