# NONMETALLIC PROTECTIVE COATINGS FOR CONCRETE REINFORCING STEEL

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The study reported here was conducted to determine the feasibility of using organic coatings to protect reinforcing steel embedded in concrete from corrosion accelerated by chloride ions. Coatings were evaluated on the basis of their chemical and physical durabilities, their protective qualities, their bond to steel, and the bond of the coated bars to concrete. These tests, including pullout and creep tests, indicate that 4 epoxies applied by electrostatic spray techniques are suitable for coating reinforcing steel.

•THE PREMATURE deterioration of concrete bridge decks has become a major problem during the past decade  $(\underline{1})$ . Chloride ions from de-icing materials, usually calcium or sodium chlorides, accelerate corrosion of the steel reinforcing bars. As the products of corrosion increase the volume of the bars, the concrete cracks and spalls and expensive repairs are necessary.

Several possible methods of combating this problem are being studied: cathodic protection of the steel, neutralization of the chlorides, waterproof and salt-proof membranes, internal sealing of the concrete by adding low melting point polymer to the plastic concretes, and use of polymer-impregnated or of polymer concrete. Another possible method for protecting the reinforcing is to coat the steel with some protective material. Zinc (2, 3), cadmium (4), nickel (5), and organic coatings (6, 7) have been used or suggested for such protective coatings.

This study was conducted to ascertain the feasibility of using organic materials for protective coatings. Specific objectives of the study were to (a) select the most promising materials based on physicochemical testing and the economics involved in coating, fabricating, and handling the reinforcement; (b) determine the most practical method of testing such coatings; and (c) prepare sample specifications that might be used to obtain such coated bars.

Forty-seven commercially available materials were furnished by various manufacturers (Table 1). Not all were subjected to the same amount of testing. If a material was determined to be unacceptable by some method, further testing was discontinued. For example, those materials that were extremely brittle, those with a loss greater than 3 grams in the immersion test, those with gel times longer than 8 hours, those with poor film integrity and excessive entrapped air in the cured state, those with excessive softening at 60 C, those with more than 500 percent elongation, those that gave off H<sub>2</sub> gas in Ca(OH)<sub>2</sub>, those with excessive film thickness (high creep), and those that softened and decomposed at 37.8 C were eliminated from further consideration. In some cases, not enough material was furnished for the complete testing program.

# TESTING PROCEDURES AND RESULTS

## Tests of Cured Epoxy Disks in Aqueous Solutions

Tests were made of the resistance of the coating materials to various aqueous solutions. Cast disk-shaped, cured epoxy specimens were immersed in water, in an aque-

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# Table 1. Description of coating materials.

Number	Туре	Color	Uncured State	Comments
1	Enoxy	Red	Liquid	
2	Epoxy	Amber transparent	Liquid	
3	Epoxy	Light green	Liquid	
4	Epoxy	Orange	Liquid	Undercoat
5	Epoxy	Brown	Liquid	Polygulfide
6	Epoxy	Grou	Liquid	Toncost
7	Epoxy	Iron orido	Liquid	ropeoar
8	Epoxy	Black	Liquid	
0	Epoxy	Bad	Liquid	Drimor
10	Epoxy	White	Liquid	Filmer
11	Epoxy	Openate	Liquid	
11	Ероху	Valley buff	Liquid	Vatanaina
12	Epoxy			Ketamine
1.0	Epoxy	Eight green	Liquid	Ketamme
15	Epoxy	Light huff	Liquid	
10	Epoxy	Light bull	Liquid	
10	Броху	Cherry	Liquid	
10	Epoxy	Black	Liquid	Carlina
10	Ероху	Black	Liquid	Coaltar
19	Epoxy	Brownish-red	Liquid	
20	Epoxy	Green	Powder	
21	Ероху	Light green	Powder	
22	Epoxy	Light green	Powder	
23	Polyvinyl chloride	Dark olive green	Powder	
24	Polyvinyl chloride	Dark purple	Powder	
25	Epoxy	Blue	Powder	
26	Polyvinyl chloride	Transparent	Primer	
27	Epoxy	Black	Powder	
28	Epoxy	Black	Powder	
29	Epoxy	Yellow	Powder	
30	Polyvinyl chloride	Pale green	Powder	
31	Epoxy	Light green	Powder	
32	Epoxy	White	Powder	
33	Urethane	Dull orange	Liquid	Unsolicited
34	Phenolic nitrile	Red	Liquid	
35	Urethane	Black	Liquid	100 percent solids
36	Urethane	Black	Liquid	100 percent solids
37	Epoxy	Black	Liquid	Adhesive
38	Epoxy	Gray	Powder	
39	Epoxy	Brown	Powder	
40	Epoxy	Red	Powder	
41	Epoxy	Red	Powder	
42	Epoxy	Red		
43	Epoxy	Red	Powder	
44	Zinc-zinc silicate	Gray	Liquid	
45	Coal tar epoxy	Black	Liquid	Coal tar
46	Epoxy	Red	Liquid	Polysulfide
47	Polypropylene	Clear	Powder	

Figure 1. Permeability cell (A-compartment containing distilled water, B-epoxy film sandwiched between 2 glass plates, each having centered 1-in. diameter holes, and C-compartment containing 3M NaCl).



ous solution of 3M NaOH, and in a solution saturated with  $Ca(OH)_2$ ,  $CaSO_4 \cdot 2H_2O$ , and 0.5M  $CaCl_2$ . However, because it was impossible to fabricate this type of specimen from epoxy powders, this method of test is not recommended for prequalification of organic coatings for steel reinforcing bars.

As shown in a previous report, which gives a detailed description of the test method and results (8), some materials are highly unsatisfactory. One material, after 31 weeks of exposure, showed an increase in weight of 17 percent in water, 20 percent in 3M CaCl<sub>2</sub>, 15 percent in 3M NaOH, and 18 percent in Ca(OH)<sub>2</sub>, CaSO<sub>4</sub>•2H<sub>2</sub>O, and 0.5M CaCl<sub>2</sub>. Another coating, after 31 weeks of exposure, showed a decrease in weight of 6.8 percent in water, 10 percent in 3M CaCl<sub>2</sub>, and 14 percent in a saturated solution of Ca(OH)<sub>2</sub>, CaSO<sub>4</sub>•2H<sub>2</sub>O, and 0.5M CaCl<sub>2</sub> and an increase in weight of 9.3 percent in 3M NaOH.

#### Chloride Permeability

Cured films 3 to 7 mils (0.08 to 0.2 mm) thick were clamped in a permeability cell (Fig. 1), and the rate of passage of chloride ions was determined. This method and the results obtained have also been described in detail previously (8). All but 2 films (13 and 16) tested appeared to be sufficiently impervious to chloride penetration.

### Immersion Tests of Coated Reinforcing Bars

Coated No. 6 reinforcing steel bars were immersed in an aqueous solution of 3M NaOH and in a solution saturated with  $Ca(OH)_2$  and examined periodically for evidences of softening, color changes, disbonding, and changes in film integrity. Table 2 gives the appearance of some of the bars after 270 days of exposure. The effects after 45 days of exposure have been described (8). Rusting occurred on some of the coated bars in  $Ca(OH)_2$  after 15 days, but the uncoated bar showed no corrosion after 45 days. Bars 39 and 40 showed no change after 270 days when they were sandblasted before coating, but showed rusting during the first 15 days of exposure to  $Ca(OH)_2$  when they were sandblasted and phosphatized. The corrosion of the uncoated bar in  $Ca(OH)_2$  at some period after 45 days is unexplained.

## Effect of Impressed Voltage

Stresses that can destory the bond of coatings to steel can be induced by cathodic protection devices, stray currents, or corrosion. The effects of such stresses were evaluated by a modification of the disbonding tests (ASTM G 8-69T). Duplicate 6-in. (152.4mm) coated bars were used as both the cathode and anode. They were immersed in a 7 percent solution of NaCl, and a potential of 2 V was applied. The electrodes were observed periodically for evidence of hydrogen gas evolving at the cathode and for corrosion products of iron forming at the anode. Results of these tests were previously reported ( $\underline{8}$ ). Coatings (applied in the indicated thicknesses) that permit the evolution of hydrogen gas within 15 minutes are of doubtful value.

#### **Electrical Potential and Resistance in Solutions**

The electrical potential and electrical resistance of the coated bars were compared with those of uncoated bars, and the results are also recorded in the interim report (8). As discussed more fully below, these results could not be satisfactorily rationalized.

#### Electrical Potential and Resistance of Bars Embedded in Concrete

The corrosion potential of bars embedded in concrete was determined by fabricating "lollypops," similar to those described by Stratfull (9, 10). The coated bars were embedded in concrete prisms  $2^{7}_{8}$  by  $4^{7}_{8}$  by 15 in. (7.5 by 12.5 by 38 cm) coincident with the longitudinal axis of the prism. A terminal was inserted into one end of each bar for making connections to a voltmeter or conductivity bridge. The other exposed end of the bar was covered with a thick coating of silicone sealant. The lollypops were then placed vertically in a tank containing enough 3.5 percent sodium chloride solution to

## Table 2. Results of immersion tests of coatings on reinforcing bars.

Number	3N NaOH	Saturated CA(OH)
22	No change	No change
25	No change	No change <sup>a</sup>
29	No change	Slightly rusted
30	No change	No change
31	No change	No change
32	No change	No change
Sandblasted by		
ore coating Sandblasted and	No change	Rusted <sup>▶</sup>
before coating	No change	Rusted <sup>b</sup>
39	0	
Sandblasted by		
ore coating Sandblasted and	No change	No change
before coating	No change	Rusted <sup>b</sup>
40	ino unungo	ALLOCOL .
Sandblasted by		
ore coating	No change	No change
Sandblasted and phosphatized		
before coating	No change	Rusted <sup>b</sup>
41	No change	No change
Uncoated	No change	Rusted

<sup>a</sup>No rust, but numerous small blisters formed apparently by water penetrating through coating.

<sup>b</sup>During the first 15 days of immersion; afterward rusting lifted most of epoxy from bar.

## Table 3. Electrical potential and resistance of bars embedded in concrete.

	24 Hours		3,480 Hours		
Coating <sup>*</sup>	Potential (MV)	Resistance (Ω)	Potential (MV)	Resistance (Ω)	Protective Rating <sup>b</sup>
1A	345.0	$3.8 \times 10^{2}$	283.0	$3.9 \times 10^{2}$	3
1B	408.8	$7.0 \times 10^{2}$	362.4	$8.2 \times 10$	
1-1	337.0	$2.5 \times 10^{2}$	215.0	$2.5 \times 10^{2}$	-
1-S	484.5	$4.8 \times 10^{2}$	371.5	$4.2 \times 10^{2}$	-
3A	285.6	$3.1 \times 10^{2}$	432.4	$2.2 \times 10^{2}$	3
3B	260.3	$2.7 \times 10^{2}$	365.5	$2.4 \times 10^{2}$	
4A	339.2	$2.4 \times 10^{4}$	142.3	$1.1 \times 10^{5}$	3
4B	130.0	$1.0 \times 10^{5}$	115.5	$1.4 \times 10^{4}$	
18	575.6	$6.0 \times 10^{3}$	003.0°	$1.0 \times 10^{4}$	3
19A	484.0	$5.6 \times 10^{2}$	399.5	$5.4 \times 10^{2}$	2
19B	438.0	$6.1 \times 10^{2}$	282.0	$6.0 \times 10^{2}$	
25	542.7	$4.1 \times 10^{2}$	271.4°	$5.1 \times 10^{2}$	1
27A	654.6	$1.3 \times 10^{4}$	167.0°	$7.2 \times 10^{4}$	3
27B	571.5	$6.8 \times 10^{3}$	542.0	$1.1 \times 10^{4}$	
28	461.5	$5.2 \times 10^{2}$	262.8°	$5.4 \times 10^{2}$	3
29A	376.3	$6.4 \times 10^{2}$	163.0°	$7.8 \times 10^{2}$	2
29B	403.4	$6.6 \times 10^{2}$	360.5	$5.4 \times 10^{2}$	
30A	058.0	$1.0 \times 10^{5}$	N.C.d	$2.1 \times 15^{5}$	1
30B	448.2	$1.5 \times 10^{5}$	127.4°	$1.6 \times 10^{5}$	
31A	359.8	$1.5 \times 10^{3}$	038.5°	$9.8 \times 10^{4}$	1
31B	092.2	$9.8 \times 10^{3}$	013.5	$6.2 \times 10^{4}$	1
38	392.7	$3.2 \times 10^{2}$	165.7	$4.1 \times 10^{2}$	3
39A <sup>a</sup>	513.0	$4.9 \times 10^{2}$	348.0	$4.7 \times 10^{2}$	3
39B*	536.2	$5.0 \times 10^{2}$	402.0	$4.8 \times 10^{2}$	
40A <sup>a</sup>	282.2	$2.5 \times 10^{2}$	256.6	$2.2 \times 10^{2}$	2
40B <sup>a</sup>	382.5	$3.4 \times 10^{2}$	325.5	$2.7 \times 10^{2}$	
40A	431.8	$2.9 \times 10^{2}$	398.0	$3.1 \times 10^{2}$	3
40B	377.0	$2.8 \times 10^{2}$	316.9	$2.3 \times 10^{2}$	
41A	540.5	$6.0 \times 10^{3}$	432.2	$1.3 \times 10^{4}$	2
41B	575.9	$5.4 \times 10^{2}$	324.4	$2.5 \times 10^{4}$	
Uncoated A	334.2	$2.7 \times 10^{2}$	206.6	$2.3 \times 10^{2}$	4
Uncoated B	264.0	$2.6 \times 10^{2}$	180.3	$2.2 \times 10^{2}$	

<sup>a</sup>A and B denote duplicate specimens.
<sup>b</sup>From reference 8, Table 8.
<sup>c</sup>Large shifts in electrical potential attributed to self-sealing of small holes in the silicone seal.
<sup>d</sup>No current flow and, therefore, no voltage reading.

cover the lower 13 in. (33 cm) of the concrete prism. Provided the silicone sealant did not leak, the bars were exposed only to those chloride ions penetrating the protective layer of concrete and nonmetallic coating. The specimens were inspected regularly for evidence of cracking, products of corrosion, or other signs of failure. Periodic measurements were made of the electrical potential in relation to the saturated calomel half-cell (9, 10) and of the electrical resistance between a platinum electrode in the solution and the bar. The results, given in Table 3, should be compared with those given in the earlier report (8, Table 5) for coated bars immersed in salt solution rather than embedded in concrete. The reason that the bars in solution had higher resistances than those embedded in concrete has not been explained. Furthermore, why the uncoated bars showed a passive potential of -296 mV while many of the coated bars showed a highly active potential is also unexplained. For these reasons, this method of evaluation has not been recommended in the prequalification tests, and some other method should be developed to determine the condition of coated bars in actual use.

#### **Physical Properties**

Tests were performed to determine the ability of coatings to resist rough handling during fabrication and placement in the deck. Before these tests were started, the film thicknesses and the number of holidays (pinholes not visible to the naked eye) were determined, and the bars were examined for evidence of damage or faulty application of the coating. These measurements were reported previously (8).

Impact Resistance—The impact resistance of the coatings was determined by a method similar to that of ASTM G 14-69T. In this test, a 4-lb (1.81-kg) tup terminating in a hemispherical nose  $\frac{5}{6}$  in. (15.9 mm) in diameter was dropped 30 in. (762 mm) onto the area between the deformations of the bar. [Based on the  $\frac{5}{6}$ -in. (15.9-mm) nose diameter, the maximum area struck was 0.31 in.<sup>2</sup> (2 cm<sup>2</sup>).] The area of impact was visually examined, and the area of damage measured. With an impact of 120 in.-lb (13.6 N-m) not more than 0.15 in.<sup>2</sup> (0.96 cm<sup>2</sup>) should be damaged. Only 3 of the materials tested exceeded this value (Table 4).

<u>Resistance to Abrasion</u>—The abrasive resistance of the various coatings has been described previously (8). An abrasion loss of less than 100 mg/1000 cycles in the Tabor abraser (ASTM D 1044-56) with a 1,000-gram load per wheel should indicate satisfactory abrasive resistance.

<u>Hardness</u>—Five of the materials were tested according to ASTM D 1474-68. A 10gram load was used. The Knoop hardness number (KHN) of each of these materials is given below. A KHN of 16 will give a satisfactory coating.

Code	KHN		
22	20.7		
29	19.8		
30	6.7		
31	20.7		
39	21.2		

Bend Tests—The coating materials were also evaluated by bending the coated bars to an angle of 120 deg over a mandrel with a 3-in. (76-mm) radius and examining the coating for cracking, chipping, scaling, or other damage. These results are also recorded in the earlier report ( $\underline{8}$ , Table 8). Coated bars subjected to this test should show no visible cracks in the coating. Even if the coatings pass this test, they will not necessarily withstand the sharp bending and rough handling received during fabrication of the steel. However, the test is perhaps the simplest and most valuable for quality control purposes because insufficient curing of the coating, inadequate surface preparation (sandblasting) of the bar, excessive film thickness, or even use of the wrong epoxy may all become evident during this test.

<u>Pullout Tests</u>—One of the major items for concern in using coated reinforcing bars is that the bond between the steel and concrete may be reduced. Bond was evaluated by comparing the pullout strength of coated bars with that of uncoated bars. A procedure described by Mathey and Watstein  $(\underline{11})$  was used. Descriptions and results of those tests have already been reported  $(\underline{8}, \text{Table 9})$ . Selected values from the earlier report are given in Table 5. The average bond strength of the uncoated bars with horizontal deformations at a slip of 0.002 in. (0.05 mm) at the free end of the bar is 1,008 lb/in.<sup>2</sup> (6.9 MPa), whereas the strengths of 3 of the materials recommended for use are slightly above this value. The highest value obtained was for a bar coated with a coal tar epoxy (code 18) at 1,352 lb/in.<sup>2</sup> (9.3 MPa). For comparison, a polyvinyl chloride coated bar (code 23) had a bond strength of only 25 lb/in.<sup>2</sup> (0.17 MPa).

<u>Creep</u>—The creep or long-time slippage of the coated reinforcing bars in concrete under tensile stress can also be a matter for concern. Therefore, the creep of coated bars was compared with that of uncoated bars. Typical results are shown in Figures 2 and 3; bars coated with epoxy (code 31) exhibited even less creep than the uncoated bars. As might be expected, the bars heavily coated with polyvinyl chloride (code 30) show creep values several magnitudes greater than the uncoated bars. Also, coal tar epoxy had an excessive creep.

As far as we are aware, no such creep determinations of reinforcing steel in direct tension have been made; therefore, a brief description of the procedure will be given here.

The No. 6 reinforcing bars were embedded in the center of concrete prisms 10 by 10 by 12 in. (25.4 by 25.4 by 305 mm). These were mounted in frames as shown in Figure 4. The creep at the free end of the bar was measured by a dial gauge reading directly to 0.0001 in. (0.0025 mm) and mounted on a support attached to the top face of the concrete by bolts screwed into inserts cast in the concrete. The gauge was thus bearing on the exposed end of the reinforcing steel. At the loaded end of the specimen, 2 similar gauges were attached to a steel bar fastened to the lower face of the concrete by bolts secured to inserts cast in the concrete. These gauges bore on a steel yoke fastened to the reinforcing bar about 1 in. (25 mm) below the face of the concrete. This yoke was free to move in a recess in the base plate. The slippage (creep) of the loaded end of the reinforcing bar is then taken as the average reading of the 2 gauges.

The load on the bars was developed through large steel coil springs, also shown in Figure 4, which were first calibrated by measuring the load applied by a 60,000-lb (27,000-kg) capacity electromechanical universal testing machine versus the compressive displacement of the springs measured with dial gauges reading directly to 0.0001 in. (0.0025 mm). The setup for calibrations is shown in Figure 5. The compressive displacement versus load was nearly the same for all 24 springs tested as is shown in Figure 6.

The constancy of the stress in the rods was monitored by resistance strain gauges stated by the manufacturer to have negligible creep during a 1-year period.

#### CONCLUSIONS

This research shows that some powdered epoxy coatings applied by electrostatic spray techniques can prevent or greatly delay the corrosion of reinforcing bars in concrete. Many of the coated bars can give bond strengths under short-time and sustained loads equivalent to bond strengths of similar uncoated bars.

#### **IMPLEMENTATION**

From this research, specifications for the prequalification of any type of organic coating have been developed. Many of the manufacturers who submitted materials for this investigation may wish to modify those materials that failed to meet certain of the requirements by changing the composition of the coating material or some procedures such as curing methods or bar preparation.

Simple tests based on this research have also been developed for use as quality control specifications.

The Federal Highway Administration has suggested that states use coated bars on an experimental basis to determine the feasibility of such coatings, and portions of several bridge decks are now being constructed with epoxy-coated bars from 2 suppliers.

## Table 4. Impact resistance of coatings on bars.

Code	Film Thickness (mils)	Damaged Area (in. <sup>2</sup> )	Type and Severity of Damage
		0.440	
2	5 to 15	0.110	Shattering and disbonding of coating propagating from area of impact
3	2 to 5	0.028	Only indention in coating and bar at impact area
4	10 to 20	0.082	Shattering and disbonding of coating propagating from area of impact
5	10 to 15	0.383	Large amount of shattering and disbonding of coating surrounding area of impact
10	10	0.079	Shattering and disbonding of coating at impact area
11	10 to 12	0.188	Shattering and disbonding of coating propagating from area of impact
16	2 to 4	0.038	Slight shattering and disbonding of coating at impact area
17	4	0.028	Slight shattering and disbonding of coating at impact area
18	4	0.038	Slight shattering and disbonding of coating at impact area
19	1	0.028	Only indention in coating and bar at impact area
22	25	0.234	Large amount of shattering and disbonding of coating surrounding area of impact
23	25	0.077	Large indention in coating
24	35	0.110	Large indention in coating
25	6 to 11	0.049	Shattering and disbonding of coating at impact area
27	8	0.077	Coating shattered at area of impact with slight propagating of shattering from impact region
28	1 to 2	0.038	Slight shattering and disbonding of coating at impact area
29	1 to 2	0.028	Slight shattering and disbonding of coating at impact area
30	15 to 18	0.110	Large indention in coating accompanied by slight cracking at impact area
31	8 to 9	0.110	Shattering and some disbonding of coating at impact area
32	4 to 6	0.049	Cracking in coating at impact area; slight cracking extending from impact region
33	3 to 4	0.028	Shattering of coating at impact area
38	2 to 4	0.038	Shattering of coating at impact area; slight cracking extending from impact region
39	2 to 4	0.028	Only indention in coating and bar at impact area
40	2 to 4	0.079	Shattering of coating at impact area; slight disbonding extending from impact region
41	3 to 7	0.038	Shattering of coating at impact area; slight cracking extending from impact region
42	3 to 4	0.028	Only indention in coating and bar at impact area
43	3 to 4	0.038	Smashing of coating at impact area; slight cracking extending from impact region

Note: 1 mil = 0.0254 mm, and 1 in,<sup>2</sup> = 6,54 cm<sup>2</sup>,

# Table 5. Results of pullout tests.

Code	Avg Bond Strength (lb/in. <sup>2</sup> )	Code	Avg Bond Strength (lb/in. <sup>2</sup> )
Uncoated-H	1,008	31-H	1,056
18-II	1,352	39-H	1,121
23-H	25	41-H	1,046
25-D	986		

Note: 1 lb/in.<sup>2</sup> = 0.07 kg/cm<sup>2</sup>,

# Figure 2. Creep at free end under 30,000 lb/in.<sup>2</sup> load.



Figure 3. Creep at loaded end under 30,000 lb/in.<sup>2</sup> load.



Figure 4. Assembly for measuring creep of bars in concrete.



# Figure 5. Spring calibration apparatus.



Figure 6. Range of compressive development versus load of all 24 springs used in tests.



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The contents of this report reflect the views of the Office of Research of the Federal Highway Administration, which is responsible for the facts and the accuracy of the data presented. The contents do not necessarily reflect the official views or policy of the Department of Transportation. This report does not constitute a standard, specification, or regulation.

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