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Nonmetallic Coatings for Concrete Reinforcing Bars.

Coating Materials

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Nonmetallic Coatings for Concrete Reinforcing Bars. Coating Materials

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Nonmetallic Coatings for Concrete Reinforcing Bars.

Coating Materials*

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Robert G. Mathey

This work was undertaken to determine the feasibility of using organic coatings, especially epoxies, to protect steel reinforcing bars embedded in concrete from the accelerated corrosion attributed to the depassivation of steel by chloride ions.

Coatings have been evaluated on the basis of their chemical and physical durabilities as well as their protective qualities. In this study, attention also has been directed to the following: application methods; surface preparation of the steel reinforcing bar; and site of application.

Key words: Chlorides; concrete; corrosion; epoxy coatings; organic coating; steel reinforcing bars.

1. INTRODUCTION

The premature deterioration of concrete bridge deckings, in 5-10 years, has become a major problem during the past decade [1-7]^{1/}. Often, this early deterioration has been attributed to accelerated corrosion of the steel reinforcing bars caused by chloride ions from deicing materials [8-9]. Use of the two more commonly applied deicing materials, sodium chloride and calcium chloride, has increased substantially during the past decade. Normally, steel is passive towards corrosion when in an environment of high basicity (pH of about 13) inherent in portland cement concretes [10]; chloride ions, however, are able to depassivate steel and thereby promote the active corrosion of steel [11]. Corrosion of reinforcing bars results in spalling and cracking of concrete, necessitating extensive and expensive repairs.

Coating reinforcing steel bars with protective materials has been considered as a practical method to obviate the rapid corrosion of the bars. Much attention has been given to the use of galvanized reinforcing bars [12-13]. Recent studies [14-15], however, indicate that zinc does not provide long term protection to steel in the presence of chloride ions. Cadmium [15] and nickel [16] have been reported to be satisfactory coatings for reinforcing steel. Their cost, however, may be prohibitively high. The use of organic types of barrier coatings for protecting reinforcing bars has been recommended [17-18]. Tripler and co-workers evaluated a few nonmetallic coatings and suggested that an epoxy - coal tar type of coating could have potential as protective coating for reinforcing steel [16].

The present study was undertaken to ascertain the feasibility of using organic coatings, especially epoxy systems, to protect reinforcing steel bars. The evaluation of the physical

*/ Work performed under auspices of the Federal Highway Administration.

1/ Figures in brackets indicate the literature references at the end of this paper.

and chemical durabilities of coatings has been completed, along with evaluation of their potential protective qualities, and the results are presented in this report.

2. MATERIALS

2.1 Selection of Coating Materials for Evaluation

The selection of the coating materials to be evaluated as protective coatings on steel reinforcing bars was done on a generic basis and was restricted essentially to organic formulations. Some of the most important criteria for selection were: inertness towards the constituents of cement paste and also chloride ions; creep characteristics; film integrity and protective qualities; as well as cost considerations.

The coatings selected for evaluation, listed in table 1 (also included, are a few unsolicited coatings submitted by the respective firms who handled them), are of commercial origin. The coating materials have been assigned code numbers, for identification purposes, which will be used in this paper, exclusively. The code number sequence has no significance other than indicating the chronological order in which the materials were received.

The polyurethanes and epoxies consist of two components and are classified as thermosetting materials because their cure is accelerated by heat. Once cured, they normally retain their shape up to their decomposition temperatures. The other coatings in table 1 are classified as thermoplastics as they soften and change shape when heated.

The emphasis has been on thermosetting materials and especially on epoxies because these materials seem to best satisfy the chosen criteria. Altogether 36 epoxy coatings, both powder and liquid systems, have been evaluated to some extent.

Some materials, especially powders, were submitted only in the form of cured films on steel reinforcing bars.

2.2 Curing Methods and Specimen Preparation

2.2.1 Two-Component Liquid Systems

The epoxy liquid systems consist of two components, an epoxy resin and a curing component. The curing of epoxies is attributed to chemical reactions between the resin and curing agents which lead to polymerization of the mixture.

In the present work, the ratio of curing component to epoxy resin and the mixing and curing times, were closely controlled and were the same as those specified by the manufacturers' accompanying instructions. The epoxy resins and curing components were mixed at room temperature, ca. 24°C, relative humidity of ca. 50 percent, using either an electric stirrer (solventless systems) or a metal spatula (solvent containing systems). The two component urethanes and zinc-filled coating were similarly mixed.

TABLE 1 COATING MATERIALS

Code Number	Type	Uncured State ^{1/}	Comments
1	Epoxy-Polyamide	Liquid - 100 percent solids	Used for concrete overlays
2	Epoxy-Polyamide	Liquid - 100 percent solids	Has been previously tested as coating for steel rebars
3	Epoxy-Polyamide	Liquid - 100 percent solids	Primer
4	Epoxy-Modified amine	Liquid - 100 percent solids	Primer
5	Epoxy-Polysulfide	Liquid - 100 percent solids	Used to bond fresh concrete to old concrete
6	Epoxy-Modified amine	Liquid - 100 percent solids	Topcoat
7	Epoxy	Liquid - 50 percent solids	Water emulsion activated system
8	Epoxy-Polyamide	Liquid - 60 percent solids	
9	Epoxy-Polyamide	Liquid - 50 percent solids	Primer
10	Epoxy-Ketamine	Liquid - 100 percent solids	High Viscosity
11	Epoxy-Ketamine	Liquid - 100 percent solids	
12	Epoxy	Liquid - ca. 100 percent solids	Cures at relative humidity above 50 percent
13	Epoxy	Liquid - ca. 100 percent solids	Limited flexibility
14	Vinyl	Liquid - 20 percent solids	Primer paint
15	Epoxy-Polyamide	Liquid - 50 percent solids	Epoxy paint
16	Epoxy-Polyamide	Liquid - 50 percent solids	Epoxy paint
17	Epoxy	Liquid - 100 percent solids	Low Viscosity
18	Coal tar epoxy	Liquid - 100 percent solids	Protective overlay on concrete pavements

TABLE 1 COATING MATERIALS (cont.)

Code Number	Type	Uncured State	Comments
19	Epoxy	Liquid - 46 percent solids	One component cures by heating
20	Epoxy	Powder	Only coated rebars have been received
21	Epoxy	Powder	Only coated rebars have been received
22	Epoxy	Powder	Only coated rebars have been received
23	Polyvinylchloride	Powder	Only coated rebars have been received
24	Polyvinylchloride-Plastisol	Powder	Only coated rebars have been received
25	Epoxy	Powder	Only coated rebars have been received
26	Polyvinylchloride	Powder	Only coated rebars have been received
27	Epoxy	Powder	
28	Epoxy	Powder	
29	Epoxy	Powder	
30	Polyvinylchloride	Powder	Only coated rebars have been received
31	Epoxy	Powder	Same material as No. 22, but coated rebars submitted from a different applicator and also the pure powder was submitted.
32	Epoxy	Powder	
33	Polyurethane	Liquid	Only coated rebars have been received
34	Phenolic nitrile	Liquid - 10 percent solids	Adhesive for metals
35	Polyurethane	Liquid - 100 percent solids	Elastomer, elongation - 600 percent

TABLE 1 COATING MATERIALS (cont.)

Code Number	Type	Uncured State	Comments
36	Polyurethane	Liquid - 100 percent solids	Elastomer, elongation - 550 percent
37	Epoxy	Liquid - 100 percent solids	Adhesive for metals
38	Epoxy	Powder	
39	Epoxy	Powder	
40	Epoxy	Powder	
41	Epoxy	Powder	Only coated rebars have been received
42	Epoxy	Powder	Only coated rebars have been received, same materials as number 41, but different application procedure.
43	Epoxy	Powder	
44	Zinc in a zinc silicate binder	Liquid - 80 percent solids	Metallic Zinc filler and liquid base are mixed, hardens by solvent evaporation
45	Coal tar epoxy	Liquid	One component, epoxy resin and coal tar, no curing components.
46	Epoxy-Polysulfide	Liquid	
47	Polypropylene	Powder	Only coated rebars have been received. Coating very brittle.

1/ Solvents comprised the unlisted percent of liquid materials of less than 100 percent solids.

Test specimens of the coating materials were cast and in addition steel plates and steel reinforcing bars were coated with thin films. Specimen discs of $2\frac{1}{4}$ ^{2/} inches diameter of thickness of ca. $\frac{3}{8}$ inches (thicknesses of solvent containing systems were reduced to $\frac{3}{16}$ inches) were cast using aluminum weighing dishes as molds. The molds were stripped after the mixture had cured for seven days. Wet films of 3-7 mils^{3/} thicknesses were formed immediately after mixing, by applying the coatings with a Baker roller film applicator to the gel side of photographic paper or to sheets of Teflon^{4/}. Then the cured films were stripped from the photographic paper by being immersed in water at room temperature for 16 hours. Cured films were easily stripped from Teflon sheets using a thin-bladed spatula. Coating materials were applied to 4 x 4 x 0.050 inch cold-rolled steel plates and to No. 6 steel reinforcing bars^{5/} using a paint brush. The steel plates had been degreased previously using mineral spirits, and the reinforcing bars had been sand blasted to a white surface [19].

2.2.2 One-Component Liquid Systems

The two one-component liquid systems, a polyvinyl chloride and a phenolic nitrile, were hardened by the evaporation of solvents. Test specimens were formed as described above.

2.2.3 Powder System

No mixing of the epoxy powders was necessary since the two components are contained within each powder particle. The powders were applied to steel and Teflon substrates preheated to ca. 200°C in an electric oven by immersing the substrates into a fluidized bed [20] of the powders. Then the coatings were cured in the electric oven under the conditions specified by the manufacturers. When allowed to cool to room temperature, the cured epoxy films were easily removed from the Teflon substrate by using a thin-bladed spatula. Both No. 6 steel reinforcing bars and 4 x 4 x 0.050 inch cold-rolled steel plates were coated with the powders.

Specimen discs were not fabricated from the epoxy powders because, when sufficient masses to make $\frac{3}{16}$ inch thick discs were heated to their specified curing temperatures, porous solids that had expanded over 100 percent were produced. Even four-fold reduction of the masses did not yield satisfactory specimens. Only one powder epoxy did not exhibit this expansion phenomenon. Possibly, some of the curing components are vaporized at the curing temperatures causing the formation of porous structures in the thick castings. No similar difficulties were encountered when films less than 20 mils were formed from the powder epoxies.

^{2/} One inch equals 0.0254 meter, exactly.

^{3/} One mil equals 0.001 inch, exactly.

^{4/} Certain instruments and materials are identified in this paper in order to adequately specify the experimental conditions. In no case does such identification imply recommendations or endorsement by the National Bureau of Standards nor does it imply that the material or instruments are necessarily the best available for the purpose.

^{5/} No. 6 steel reinforcing bars have nominal diameters of $\frac{3}{4}$ inch.

2.2.4 Reinforcing Bars Coated by Applicators

The coating materials that were judged (on the basis of preliminary screening tests which included: resistance to chemicals; length of cure; film integrity; and evaluation of relative brittleness) to have the most promise as potential protective coatings for steel reinforcing bars were applied by the applicators or manufacturers handling the respective coatings. No. 6 steel reinforcing bars, four feet in length having two different deformation patterns, were supplied to each applicator. The surfaces of the bars were cleaned, usually by sandblasting by the applicator; coatings applied; and the bars returned to the National Bureau of Standards for evaluation.

3. TESTING PROCEDURES AND RESULTS

Descriptions of the test methods used to evaluate coating materials are given in this section along with the experimental results.

Not all of the 47 coating materials were subjected to the same degree of testing as some were quickly judged not to be acceptable for such reasons as: gel times for two component systems longer than eight hours, coatings Nos. 10 and 11 (table 1); poor film integrity and excessive entrapped air in the cured state, Nos. 12 and 13; the tendency of some thermoplastics to soften at 60°C, Nos. 14 and 47; rubber-like expansion qualities (500 to 600 percent elongation) of two urethanes, Nos. 35 and 36 (obviously these two coatings would not pass the pull-out and creep requirements); and extreme brittleness of some epoxy systems, Nos. 5 and 13.

3.1 Immersion Testing

3.1.1 Epoxy Disc Specimens

Disc shape castings of cured epoxy specimens were immersed in water, in an aqueous solution of $3M\ CaCl_2$, in an aqueous solution of $3M\ NaOH$, and in a solution saturated with $Ca(OH)_2$ and $CaSO_4 \cdot 2H_2O$ and containing $0.5M\ CaCl_2$. These test chemicals were selected because they are, with the exception of $NaOH$, probably the major chemicals most potentially deleterious to epoxy coatings present in concrete of bridge deckings. $Ca(OH)_2$ is a reaction product of portland cement and water; it stabilizes the silicate gels which are important constituents of durable concretes. $CaSO_4$ is often added as a set-regulator to portland cement and also is frequently present in soil drainage water. $CaCl_2$ is one of the two most commonly used deicing materials. The solubility of $Ca(OH)_2$ is low ($0.2M$ at $25^\circ C$) and $3M\ NaOH$ was used in an accelerated-type of test to determine if hydroxide ions are detrimental to the long term embedment of epoxy coatings in concrete. Water, in itself, can have a deleterious effect on coating materials. It was felt that these test solutions are probably as aggressive or more so than those encountered in concrete. Therefore, materials performing well in the immersion tests will probably not be degraded by long term embedment in concrete. The specimens were immersed in water for one or two minutes and wiped dry before measuring the original weights prior to the immersion studies. Original weights of the discs varied from ca. 20 grams for solvent containing systems to ca. 50 grams for the solventless epoxy systems. The temperatures of the test solutions were $24 \pm 1^\circ C$.

TABLE 2. WEIGHT CHANGES OF CURED EPOXY DISCS IMMERSED IN AQUEOUS SOLUTIONS

Code Number	Immersion Time (Weeks)	PERCENT WEIGHT CHANGES			
		Water	3M CaCl ₂	3M NaOH	Saturated Ca(OH) ₂ Saturated CaSO ₄ ·2H ₂ O and 0.5M CaCl ₂
1	31 18	2.3 3.5	1.3 0.4	1.9 2.4	2.4 3.0
2	31 18	3.1 2.4	1.8 1.6	1.9 1.8	3.7 2.3
3	31 18	-1.9 -2.3	-2.1 -2.6	2.1 1.9	-2.0 -2.3
4	31 18	2.3 1.5	1.6 0.7	1.6 1.3	1.9 1.6
5	31 18	1.2 1.1	1.1 0.5	1.6 0.9	1.8 1.2
6	31 18	2.7 1.7	1.5 0.7	2.1 1.0	2.7 2.1
7	31	17	20	15	18
8	31	-4.8	-5.7	-2.7	-4.8
9	31	-6.8	-10	9.3	-14
12	29	1.2	0.0	1.3	1.5
13	29	1.3	1.2	1.8	2.5
16	22 18	-0.8 -3.1	-1.7 -3.1	- .7 - .5	-1.7 -3.4
17	24 18	2.1 1.5	0.7 0.7	1.6 2.0	2.4 1.7
18	24 18	0.6 0.9	0.0 0.4	0.1 0.7	0.8 0.8

TABLE 3 IMMERSION TESTING OF COATINGS ON REINFORCING BARS^{1/}

Code Number	3M NaOH ^{2/}	Saturated Ca(OH) ^{2/} ₂
19	No Change	A. Rusted ^{3/} _{4/} B. No Change ^{3/} _{3/}
22	No Change	No Change
23	No Change	No Change
24	No Change	No Change
27	No Change	No Change
28	No Change	No Change
29	No Change	No Change
30	No Change	No Change
31	No Change	No Change
32	No Change	No Change
38	No Change	B. Rusted ^{4/} _{5/} P. Rusted ^{4/} _{5/}
39	No Change	B. No Change ^{5/} _{5/} P. Rusted ^{4/} _{5/}
40	No Change	B. No Change ^{5/} _{5/} P. Rusted ^{4/} _{5/}
41	No Change	No Change
Uncoated Rebar	No Change	No Change

^{1/} No. 6 reinforcing bar coated by firms handling the respective coatings.

^{2/} Immersion time of 45 days.

^{3/} A and B are specimens from companion bars.

^{4/} Rusting took place during the first 15 days of immersion, afterwards no changes were visually observed.

^{5/} B denotes bars that were only sandblasted prior to application of the coating, while P indicates that their surfaces were also phosphatized prior to being coated.

The immersion data are presented in table 2. In some cases two separate castings were made, indicated by two sets of data with different immersion times. The epoxies which in their uncured state contained solvents, generally lost weight and had greater weight changes than the solventless epoxies. An exception is No. 7, a solvent containing epoxy, which had the largest weight increase. The surfaces of both No. 7 and No. 9 were converted from smooth to rough textures during the immersion period. No apparent deterioration was observed with the other epoxy specimens.

3.1.2 Coatings on Reinforcing Bars

The chemical resistances of powdered epoxy systems were investigated by immersing coated reinforcing bars, supplied by applicators, in aqueous solutions of 3M NaOH and of saturated Ca(OH)_2 . The coatings were visually inspected for evidences of softening, color changes, disbonding, and changes in film integrity. The data are presented in table 3, which includes three polyvinyl chloride coatings (Nos. 23, 24, and 30) as well as one one-component liquid epoxy (No. 19) and 10 powder epoxy coatings.

The rusting of some coated reinforcing bars in saturated Ca(OH)_2 solutions during the first two weeks of the immersion study is an interesting phenomenon, especially since the uncoated rebars were passive towards corrosion in a similar solution. Furthermore, the corrosion was only observed in the less alkaline solution, i.e. saturated Ca(OH)_2 (pH of 12.6) rather than 3M NaOH (pH of 14.5). The pH of saturated Ca(OH)_2 , however, is sufficient to passivate steel. Therefore, the cause of the corrosion apparently lies in either the surface preparation or the composition of the coatings. Note that the surfaces of the rusting specimens of Nos. 38, 39, and 40 were phosphatized, while the surfaces of the non-rusting specimens were only sand blasted. It is not obvious at this date why the same rusting phenomenon was not observed when the rebars were immersed in 3M NaOH.

3.2 Chloride Permeability

The chloride permeability characteristics of thin films of cured epoxies were measured using permeability cells of the type shown in figure 1. A cell consists of two glass compartments separated by the epoxy film sandwiched between two glass plates, each having centered one-inch diameter holes. One compartment contains 175 ml of 3M NaCl and the other has 115 ml of distilled water. The activities of chloride ions passing through an epoxy membrane was measured using an Orion Specific Ion Meter Model 401, along with an Orion Chloride Electrode Model 94-17, and an Orion Double Junction Reference Electrode Model 90-02. Activity readings have been converted into concentration values of moles per liter by using a conversion diagram, constructed by plotting measured chloride ion activities versus known chloride ion concentrations.

Films selected for the permeability studies were carefully handled, and examined for any defects before installation in the cell.

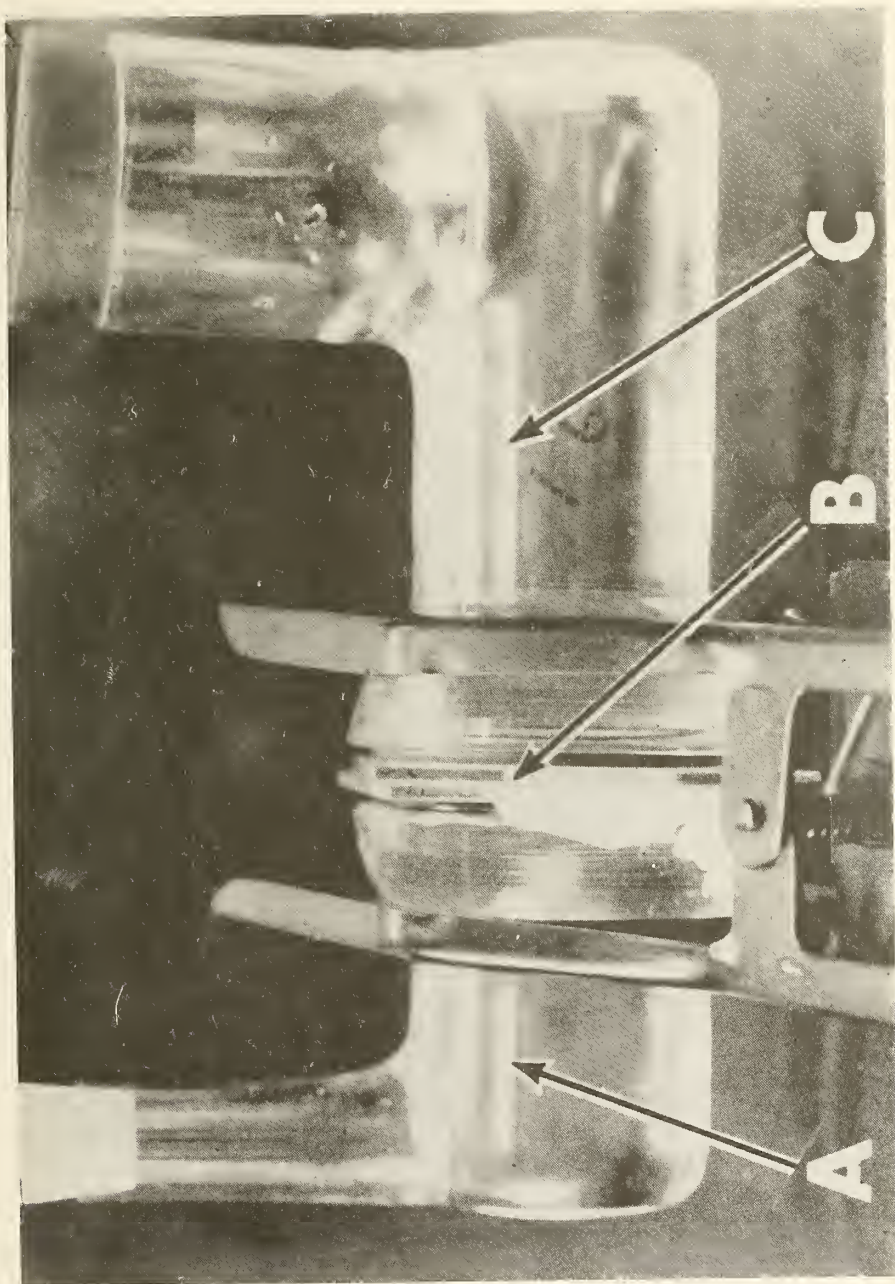


Figure 1. Permeability Cell

- Components:
- A. compartment containing distilled water;
 - B. epoxy film sandwich between two glass plates each having centered one-inch diameter holes;
 - C. compartment containing 3M NaCl.

TABLE 4 PERMEABILITY OF CHLORIDE IONS THROUGH EPOXY FILMS

Code Number	Film Thickness (mils)	Exposure Time (weeks)	Concentration $\frac{1}{2}$ (Moles per liter)	Permeability Units
1	3	16	$< 5 \times 10^{-5} \frac{3}{4}$	$< 8.5 \times 10^{-6}$
2	3	23	1×10^{-4}	9.7×10^{-6}
3	3	16	$< 5 \times 10^{-5} \frac{3}{4}$	$< 8.5 \times 10^{-6}$
4	3	23	1×10^{-4}	9.7×10^{-6}
6	3	23	1×10^{-4}	9.7×10^{-6}
11	3	12	4×10^{-3}	7.5×10^{-4}
13	3	21	1×10^{-2}	5×10^{-4}
16	7	23	2×10^{-3}	6.2×10^{-4}
	3	10	8×10^{-1}	2.3×10^{-1}
17	3	16	$< 5 \times 10^{-5} \frac{3}{4}$	$< 8.5 \times 10^{-6}$
19	7	6	N.C. $\frac{4}{4}$	
29	10	6	5×10^{-5}	1.8×10^{-5}
31	10	6	N.C. $\frac{4}{4}$	
38	2.5	6	N.C. $\frac{4}{4}$	
39	2.5	6	N.C. $\frac{4}{4}$	
40	2.5	6	5×10^{-5}	1.8×10^{-5}

 $\frac{1}{2}$ $\frac{2}{2}$ Concentration of chloride ions in the chamber originally containing only distilled water. $\frac{3}{3}$ Permeability units are: (grams per day)/exposed area (in^2)/film thickness (mils); i.e. theoretically the number of

grams of chloride ion passing per day through a film having an exposed area of one square inch and a thickness of one mil.

 $\frac{4}{4}$ Millivolt readings were near the region of distilled water and the lower limit of the chloride ion concentration was estimated. $\frac{5}{5}$ N.C. denotes that no changes from the original millivolt values were measured.

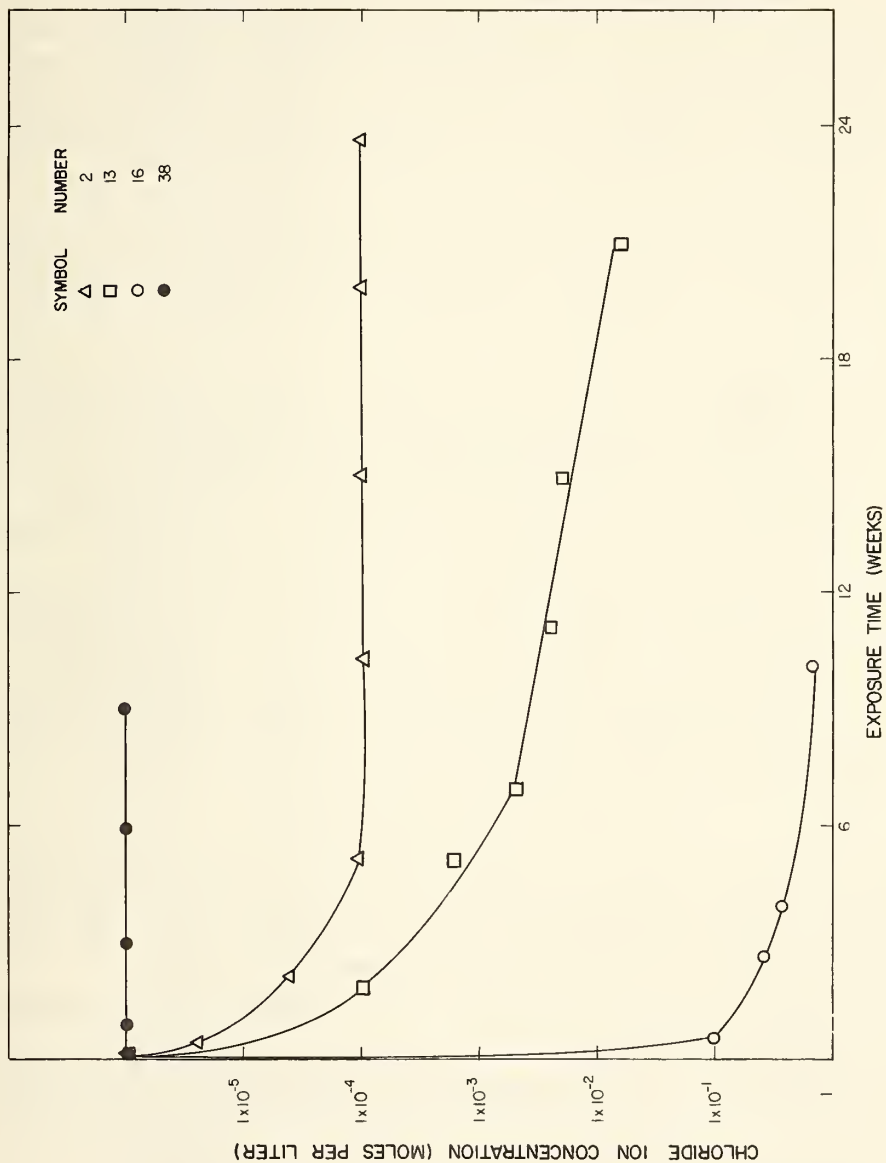


Figure 2. Concentration of chloride ions passing through epoxy films 2, 13, 16 and 38. Film thicknesses were 3 mils.

The permeability data (calculated at listed exposure times) are presented in table 4 in the form of both permeability units and concentrations. Many of the epoxy films appear to be essentially impervious to chloride ions. Only two films, No. 13 and 16, permitted chloride ions to migrate through so that the corrosion threshold concentration of 0.02M chloride ion was approached [21]. Diagrams of the accumulative permeating chloride ion concentrations versus time are reproduced in figure 2 for four epoxy films. These plots are representative of the varying degrees of impermeabilities. The permeability rates were largest during the first six weeks of testing, afterwards the values were lower and more constant.

3.3 Impact and Abrasion Resistances of Epoxy Coatings on Steel Plates

Both direct and reverse impact resistances of cured epoxy coatings on 4 x 4 x 0.050 in. cold-rolled steel plates were determined in accordance with ASTM Designation G14-69T [22]. A Gardner Laboratory impact tester was used along with a four pound hammer.

The impact data are presented in table 5. The reverse impact is more severe than the direct impact and probably gives a better indication of the flexibility of a coating (reverse impact values lower than 40 in. lb are indicative of brittle materials). However, it is felt that the impact values for the powder materials (Nos. 25, 28, 29, 31, and 38-40) are too low and are not reliable indicators of their properties. Possibly, the low values can be attributed to poor adherence to the particular steel substrate. The bend testing of coated reinforcing bars, discussed later, is considered to yield more reliable results.

The abrasion resistances of epoxy coatings on similar steel panels were determined in accordance with ASTM Designation D1044-56 [23] by using a Taber Abraser and Taber CS-10 wheels with 1000g load per wheel. After each 200 cycles the wheels and specimens were gently cleaned with a soft bristle brush. The abrasion data are given in table 5 in units of weight loss in mg per 1000 cycles. Two of the solvent containing materials, Nos. 3 and 16, had weight losses over 100 mg indicating poor abrasion resistances.

3.4 Inspection of Coated Reinforcing Bars

The film thicknesses, the number of holidays^{6/} (determined using a 67 1/2 volt holiday detector) per unit bar length (4 feet), and the visual evaluations of coated reinforcing bars submitted by the respective firm handling the materials, are given in table 6. The film thicknesses were measured with a Mikrotest Model 790000 Magnetic Gage.

The following tentative conclusions concerning the integrity of the coating films are implicit in the results given in table 6:

1. The effectiveness of the application methods in producing thin films free of defects decreases in the sequence; electrostatic spray gun > fluidized bed > dipping > brush.

^{6/} Holidays denotes film defects such as pinholes that are locations of potential corrosion.

TABLE 5 ABRASION AND IMPACT RESISTANCE OF CURED EPOXY COATINGS ON STEEL PANELS^{1/}

Code Number	Film Thickness (mils)	IMPACT RESISTANCE ^{2/}		ABRASION RESISTANCE ^{3/} Weight loss per 1000 cycles (mg)
		Reverse Impact (in lb.)	Direct Impact (in lb.)	
1	7	20	90	71
2	7	4	120 ^{4/}	56
3	8	40	160	107
4	5	4	40	70
5	7	8	20	58
6	6	4	20	71
11	6	--	--	89
16	5	8	50	148
17	6	7	50	58
18	7	12	110	52
19	1	>160	>160	51
	4	160	160	--
25	7	4	60	--
28	8	40	60	88
29	8	50	60	57
31	6	20	80	--
38	7	20	80	--
39	8	20	40	--
40	11	20	-- ^{5/}	--

^{1/} Epoxy coatings applied to 4 x 4 x .050 inch steel plates (cold rolled).^{2/} Four pound hammer used.^{3/} Taber CS-10 wheels, with 1000g load per wheel.^{4/} Bond at the steel-epoxy interface severed at 10 in-lb.^{5/} Coating shattered off of steel panel.

TABLE 6. INSPECTION OF COATED STEEL REINFORCING BARS^{1/}

Code Number	Color	Application Method	Film Thickness (mils)	No. of Holidays per 4 foot bar	Visual Inspection and comments
1	Reddish Brown	Brush	4-5	40	Deformation not well coated and slightly exposed. Accumulation of epoxy in low lying regions.
2	Clear	Brush	5-15	ca. 10	Deformations not well covered-long uncovered regions. Material is brittle.
3	Dull Green	Brush	2-5	ca. 30-40	Deformations appear to be well covered.
4	Orange	Brush	10-20	none	Deformation not well defined as the epoxy is concentrated in the low lying region between the deformations.
5	Dark Tan	Brush	10-15	too many to estimate	Longitudinal deformations are not well covered. Excess epoxy in regions between the deformations.
10	White	Brush	10	ca. 10	Susceptible to abrasion; coating easily comes off of rebars. Rough texture. Epoxy accumulated between deformations.
11	Orange	Brush	10-12	none	Coating easily chips off of rebar. Regions where deformations are not well covered. Evidence of epoxy dripping from bar.
16	White	Electrostatic spray gun	2-4	40	Deformations not well covered; accumulation of epoxy in low lying areas.
17	Gray	Brush	4	too many to estimate	Tops of deformations not well covered. Brittle material that easily chips off steel substrate.
18	Black	Brush	4	too many to estimate	Bad adhesion to steel. Abrades easily off of rebar.
19	Reddish Brown	Single dipping	1	40	Good coverage; well defined deformation pattern. Not bad dipping regions observed.

TABLE 6 INSPECTION OF COATED STEEL REINFORCING BARS^{1/} (cont.)

Code Number	Color	Application Method	Film Thickness (mils)	No. of holidays per 4 foot bar	Visual inspection and comments
22	Light Green	Fluidized bed	25	none except at ends	Uniform build-up film. Large thickness characteristic of fluidized bed application.
23	Dark Olive Green	Fluidized bed	25	none except at ends	Uniform build-up film. Thermoplastic coating.
24	Purplish Black	Fluidized bed	35	none	Deformation pattern is hidden. Thermoplastic.
25	Blue	Electrostatic spray gun	6-11	none	Good coating material. Some bad spraying techniques; bars were sprayed from one direction giving the underside of the deformations a thin coating.
26	Clear	Electrostatic spray gun	2-3	too many to estimate	Top of deformations not covered. When received, coated rebars were sticky. Thermoplastic.
27	Black	Electrostatic spray gun	8	ca. 1	High gloss coating. Even build-up. Very tough coating that did not chip off.
28	Black	Electrostatic spray gun	1-2	cannot estimate	Either very high number of holidays or electrical conducting pigments. Rough texture.
29	Yellow	Electrostatic spray gun	1-2	cannot estimate	Either very high number of holidays or electrical conducting pigment. Deformations do not appear to be well coated. Tough coating that is not susceptible to chipping.

TABEL 6 INSPECTION OF COATED STEEL REINFORCING BARS^{1/} (cont.)

Code Number	Color	Application Method	Film Thickness (mils)	No. of holidays per 4 foot bar	Visual inspection and comments
30	Dull Green	Fluidized bed	15-18	none	Thermoplastic coating. Deformation pattern hidden, possibly due to tendency of material to flow when cured at elevated temperatures.
31	Green	Electrostatic spray gun	8-9	none	Good even build-up film. Deformations well covered. Tough coating that is not susceptible to chipping.
32	White	Electrostatic spray gun	4-6	40	Mill scale was not removed and coating chips off easily due to disbonding between the mill scale and the steel rebars.
33	Orange	Brush	3-4	too many to estimate	Coating easily damaged and chips off of rebar.
38	Gray	Electrostatic spray gun	2-4	ca. 30-40	Deformation not well covered. Some bars were phosphatized.
39	Brown	Electrostatic spray gun	2-4	ca. 30-40	Holidays located on deformations. Some bars were phosphatized.
40	Red	Electrostatic spray gun	2-4	10	Tough coating that is not susceptible to chipping; some bars were phosphatized.
41	Red	Electrostatic spray gun	3-7	1	Good coverage. Bar heated prior to application of powder coating.
42	Red	Electrostatic spray gun	3-4	too many to estimate	Same material as No. 41, but powder applied to cold rebars.
43	Black	Electrostatic spray gun	3-4	too many to estimate	Material readily abrades off of rebar.

^{1/} Number 6 steel reinforcement bars coated by applicators or coating producers. Unless otherwise stated, the mill scale was removed by sand blasting.

2. Powder coatings yield films of more uniform thickness than most liquid coatings.
3. Good application practices, including proper surface preparation, are imperative if a coating material is to realize its fullest potential.

3.5 Physical Durabilities of Coated Reinforcing Bars

The physical durabilities of coated reinforcing bars were evaluated on the basis of bend tests, impact tests, and pencil hardness measurements (table 7). The tests were carried out on either the same specimens, or companion specimens, listed in table 6.

3.5.1 Bend Tests

No. 6 bars coated by applicators were bent at a 120° angle with a radius of curvature of ca. 3 in. using a Green Lee Tool Company Model 770 Bar Bender. Portions of the bars in contact with the bending machine were protected with rubber tubing of 1 1/2 in. o.d. and 3/4 i.d. to avoid mechanical damage to the coating so that any cracking in a coating occurring during the bend test could be attributed to stress failure of the coating.

Cracking and disbonding took place on the area of some bars that were under tension during the bending (table 7). The four different polyvinyl chloride coated rebars (Nos. 23, 24, 26, and 30) gave excellent performances even though their film thicknesses ranged from 2 to 35 mils. A greater variation was observed for the epoxy coated rebars as some performed well while a few were classified as failing. Generally, the epoxy coatings which did not perform well were either the most brittle epoxies or they were applied in film thicknesses over 10 mils. The effect of the film thickness is well illustrated by comparing the coated reinforcing bars Nos. 22 and 31, which were both coated with the same materials, but applied by different means. No. 22 has a film thickness of ca. 25 mils while the film thickness of No. 31 was ca. 8-9 mils. When bent, substantial cracking was observed in the film of No. 22, while No. 31 was completely free of cracking.

Another factor affecting the bending characteristics of coated reinforcing bars is the type of surface preparation of the substrate prior to application of the coatings. In two series of coated reinforcing bars, No. 28B and No. 32, epoxy coatings were applied to unprepared surfaces which were still covered with mill scale. Almost total disbondment was observed when both series of bars were bent; while the epoxy adhered tenaciously to the mill scale, the mill scale was disbonded from the steel substrate. A portion of the coated rebars Nos. 38, 39, and 40 were both sand blasted and phosphatized prior to being coated while the remainder were just sand blasted. The sand blasted coated rebars gave no indications of coating failures when bent while the phosphatized bars were susceptible to varying degrees of coating failures.

The temperature of the steel substrate, when being coated, can affect the flexibility of the cured epoxy coating. For example, Nos. 41 and 42 rebars were coated with the same material. However, No. 41 rebars were heated to 191°C and immediately coated, while No. 42 rebars were at ambient temperature when coated. The epoxy coating was then cured at 177°C on both sets of rebars. Excellent flexibility was exhibited by No. 41, whereas No. 42 cracked badly when bent.

TABLE 7 PHYSICAL TESTING OF COATED STEEL REINFORCING BARS^{1/}

Code Number	Film Thickness (mils)	Results of 120° bend ^{2/}	Impact ^{3/} Rating	Pencil ^{4/} Hardness
1	4-5	Slight cracking near edge of deformation, length of cracks were ca. 1/8 inch.	Good	>8H
2	5-15	Complete failure in bend area. Almost complete disbonding	Poor	>8H
3	2-5	Few small cracks ca. 1/8 in. long. Good performance.	Good	>8H
4	20-30	Severe cracking at almost every transverse deformation in bend area. Lengths of cracks were 1/2 to 3/4 in.	Poor	
5	40-50	Severe cracking at deformations. Cracks were ca. 1/8 in. wide and undercutting disbondment between the films and steel took place.	Poor	>8H
10	10	Severe cracking which extended from longitudinal deformation. Disbonding between the coating and steel was observed.	Poor	>8H
11	10-12	Same as No. 10	Poor	>8H
16	2-4	Very fine cracks, good performance	Fair	>8H
17	4	Cracking started at 20° bend. Total disbondment in area under tension. Complete failure.	Fair	>8H
18	4	No cracking, excellent performance	Fair	>8H
19	4	No cracks, excellent performance	Fair	>8H
22	25	Substantial cracking extending from longitudinal to longitudinal deformation, some disbonding between the coating and steel was observed.	Excellent	>8H

TABLE 7 PHYSICAL TESTING OF COATED STEEL REINFORCEMENT BARS^{1/} (cont.)

Code Number	Film Thickness (mils)	Results of 120° bend ^{2/}	Impact Rating	Pencil Hardness ^{4/}
23	25	No cracks, excellent performance.	Excellent	8H
24	35	No cracks, excellent performance.	Excellent	H
25	6-11	Many small (ca. 1/8 in. long) thin cracks, considered as moderate cracking.	Good	>8H
26	2-3	No cracks, excellent performance.		
27	8	Substantial cracking extending from longitudinal to longitudinal deformation. Some disbonding was observed.	Good	> 8H
28	1-2	A. Slight cracking, good performance. B. Substantial cracking and disbonding observed. ^{5/}	Fair	>8H
29	3-4	No cracks, excellent performance.	Good	> 8H
30	15-18	No cracks, excellent performance.	Poor	H
31	8-9	No cracks, excellent performance.	Excellent	>8H
32 ^{5/}	4-6	Complete failure as total disbonding in bend area; probably attributable to disbonding between mill scale and steel.	Fair	>8H
33	3-4	No cracks, excellent performance	Good	8H
38 A ^{6/} B ^{6/}	2-4 2-4	No cracks, excellent performance Severe cracking on every deformation in area under tension during bending	Excellent	> 8H
39 A ^{6/} B ^{6/}	2-4 2-4	No cracks, excellent performance Two or three small cracks. Good performance.	Excellent	>8H

TABLE 7 PHYSICAL TESTING OF COATED STEEL REINFORCEMENT BARS^{1/} (cont.)

Code Number	Film Thickness (mils)	Results of 120° bend ^{2/}	Impact ^{3/} Rating	Pencil Hardness ^{4/}
40 A ^{6/}	2-4	Excellent performance; no cracking. Failure. Phosphate coating adhered poorly to the steel substrate. Cracking of epoxy coating in complete area under tension during bending.	Excellent	>8H
41 ^{7/}	3-7	Excellent performance, no cracking	Good	>8H
42 ^{8/}	3-4	Substantial cracking	Good	>8H
43	3-4	Slight "popping off" of coating. Good performance.	Good	>8H

^{1/} Number 6 steel reinforcement bars coated by applicators or coating producers. Unless otherwise stated the mil was removed by sand blasting.

^{2/} Crack rating in order of decreasing performance: Excellent > Good > Moderate > Substantial > Severe > Complete failure.

^{3/} Relative rating: Excellent > Good > Fair > Poor.

^{4/} Lead hardness which imparts a mark to the coating.

^{5/} Mill scale was not removed.

^{6/} Surface of A sandblasted prior to application of coating material.
Surface of B sandblasted and phosphatized prior to coating application.

^{7/} Bars heated to 190°C prior to applying powder coating.

^{8/} Same coating material as 41, but applied to cold reinforcing bars.

3.5.2 Impact Tests

The impact resistances of coatings were evaluated by dropping an 18 in. length of coated No. 6 reinforcing bar on a slab of concrete so that impact occurred lengthwise as follows:

1. A single bar was dropped one meter from a horizontal position to the concrete.
2. The same bar was dropped from a height of two meters.
3. A companion specimen was taped loosely between two bare No. 7 bars of the same length and the assembly was dropped from a height of 2 meters to the concrete slab.
4. The bars were inspected after each drop for the following types of damages:
 - A. Shattering of the coating to expose bare metal.
 - B. Cutting of the coating to expose bare metal.
 - C. Cracking of the coating.
 - D. Disbonding of the coating from the steel substrate.

The coatings were rated on a relative basis (table 7). There is a fairly direct correlation between the results of the bend tests and the impact tests.

3.5.3 Pencil Hardness

The pencil hardness values (table 7) were determined using a series of lead pencils covering the hardness ranges from H to 8H with steps of one hardness increments. The hardness is designated as the softest lead that imparts a scratch in the coating. All of the epoxy coatings had ratings above 8H, while the polyvinyl chloride coatings were softer with ratings of H, Nos. 24 and 30, and 8H, No. 23.

3.6 Electrochemical Tests

Electrochemical tests were undertaken to quantitatively rate the relative performance of coatings exposed to solutions corrosive to steel.

3.6.1 Applied Voltage Studies

The effects of electrical and electrochemical stresses on the bond of barrier coatings to steel were assessed by modifying the disbonding test, ASTM Designation G8-69T [24]. These stresses can be induced by cathodic protection devices, stray currents, or by corrosion processes. The cathode and anode were No. 6 reinforcing bars, 6 inches long, both coated with the same material. The electrolyte was an aqueous solution of 7 percent NaCl. A potential of two volts was applied and the electrodes were visually observed periodically for evolution of hydrogen gas at the cathode and for evidence of corrosion products of iron at the anode. Before immersion, any bare ends or obvious mechanically damaged areas on the electrodes were covered with a film of silicone rubber, and no intentional holidays were induced. The source of any corrosion, therefore, were holidays in the films. Therefore, the applied voltage method serves as a sensitive holiday detector and can be used to ascertain if holidays are developing in a film because of degradation of the coating.

The results of the impressed voltage studies are listed in table 8. It is felt that coatings which permitted the evolution of hydrogen gas within 15 minutes are of doubtful value (when applied in the indicated thicknesses).

3.6.2 Electrical Potential and Resistance Measurements

Alternate means of assessing the protective qualities of barrier coatings are electrical potential measurements on coated rebars immersed in corrosive solution and the simultaneous measurements of the resistance of the coating films. Such measurements were made on coated reinforcing bars partially immersed in 3 1/2 percent aqueous solutions of NaCl. The electrode potentials of the coated reinforcing bars were measured using a Coleman Model 37A pH Meter with a standard calomel electrode as the reference electrode. Measurements of the resistance of the films on the coated reinforcing bars were made using a Yellow Springs Instrument Company Model 31 Conductivity Bridge along with a platinum electrode.

The electrical potential and resistance data are presented in table 8. Low resistance readings, below 500 ohms, are indicative of films which either have many holidays or are permeable towards water and/or chloride ions. Coated reinforcing bars which were visually observed to have several corrosion sites gave potential readings below -600 mV (the electrical potential of uncoated reinforcing bars was -634 mV after 1000 hours). The thicker films, above 15 mils, were free of holidays and had resistances higher than 24×10^5 ohm, which are beyond the range of the measuring device. The same films did not permit the passage of any measurable current; therefore, the potential of these bars could not be measured.

Potential and resistance data for three sets of reinforcing bars each set coated with a different epoxy, are reproduced in figures 3, 4, and 5. The wide variance in the initial millivolts and ohmic readings of duplicate and triplicate specimens decreased rapidly the first 200 hours of testing so that after 1000 hours of testing good agreements were obtained for companion specimens. A rapid decrease in the resistance of a coatings, probably, can be attributed to the emergence of holidays; while an increase in resistance is, probably, indicative of some type of healing mechanism.

The ratings of coatings, table 8, are based on their overall protective qualities. It is felt that adequate protection is provided by coatings with ratings of 1 or 2. The coatings with ratings 3 may have performed badly because of poor application techniques, improper curing or inadequate film thicknesses.

TABLE 8 CORROSION BEHAVIOR OF COATINGS ON REINFORCING BARS

Code Number	Film Thickness (mils)	Application Method	Time to Evolve H_2 (g) $\frac{1}{\text{Hour}}$ at Cathode (Hours)	Resistance (ohms) $\frac{2}{1000 \text{ hours}}$		Voltage (Millivolts) $\frac{2}{1000 \text{ Hours}}$		Rating $\frac{3}{-}$
				1 Hour		1 Hour		
1	4 - 5	Brush	$\angle 1/4$	537	200	-340	-570	3
2	5 - 15	Brush	$\angle 1/4$	250	190	-588	-576	3
3	2 - 5	Brush	$\angle 1/4$	400	180	-615	-604	3
4	20 - 30	Brush	$\angle 1/2$	700	260	-470	-555	3
5	40 - 50	Brush	$\angle 1/4$	1.1×10^3	$425 \frac{4}{\text{Hour}}$	-513	$-617 \frac{4}{\text{Hour}}$	3
10	10	Brush	$\angle 1/4$	--	--	--	--	3
11	10 - 12	Brush	$\angle 1/4$	9.6×10^3	800	-497	-560	3
16	8	Brush	1	400	250	-516	-593	2
17	4	Brush	$\angle 1/4$	1.5×10^3	700	-430	-545	3
18	4	Brush	$\angle 1/4$	98	240	-516	-604	3
19	4	Brush	24	435	225	-503	-568	2
22	25	Fluidized bed	$> 648 \frac{4}{\text{Hour}}$	$> 25 \times 10^5 \frac{5}{\text{Hour}}$	$> 25 \times 10^5 \frac{5}{\text{Hour}}$	N.R. $\frac{6}{\text{Hour}}$	N.R. $\frac{6}{\text{Hour}}$	1
23	25	Fluidized bed	$> 120 \frac{4}{\text{Hour}}$	$> 25 \times 10^5 \frac{5}{\text{Hour}}$	$> 25 \times 10^5 \frac{5}{\text{Hour}}$	N.R. $\frac{6}{\text{Hour}}$	N.R. $\frac{6}{\text{Hour}}$	1
24	25	Fluidized bed	$> 480 \frac{4}{\text{Hour}}$	13×10^5	$> 25 \times 10^5 \frac{5}{\text{Hour}}$	N.R. $\frac{6}{\text{Hour}}$	N.R. $\frac{6}{\text{Hour}}$	1
25	6 - 11	Electrostatic spray	6	2×10^5	$> 25 \times 10^5 \frac{5}{\text{Hour}}$	-613	-541	1
26	2 - 3	Electrostatic spray	$\angle 1/4$	--	--	--	--	3
27	8	Electrostatic spray	$\angle 1/4$	--	--	--	--	3
28	1 - 2	Electrostatic spray	$\angle 1/4$	250	240	-600	-606	3
29	3 - 4	Electrostatic spray	$\angle 1/4$	475	300	-518	-565	2

TABLE 8 CORROSION BEHAVIOR OF COATINGS ON REINFORCING BARS (cont.)

Code Number	Film Thickness (mils)	Application Method	Time to Evolve H ₂ (g) $\frac{1}{\text{at Cathode}}$ (Hours)	Resistance (ohms) $\frac{2}{\text{1000 Hours}}$		Voltage (millivolts) $\frac{2}{\text{1000 Hours}}$		Rating $\frac{2}{\text{3}}$
				1 Hour	5 5/ 25 x 10 ⁵ 5/	1 Hour	5 5/ 25 x 10 ⁵ 5/	
30	15 - 18	Fluidized bed	> 168 $\frac{4}{\text{hr}}$	25 x 10 ⁵ $\frac{5}{\text{hr}}$	25 x 10 ⁵ $\frac{5}{\text{hr}}$	N.R. $\frac{6}{\text{hr}}$	N.R. $\frac{6}{\text{hr}}$	1
31	8 - 9	Electrostatic spray	> 96 $\frac{4}{\text{hr}}$	25 x 10 ⁵ $\frac{5}{\text{hr}}$	1500	-532	-588	1
32	4 - 6	Electrostatic spray	< 1/4	800	540	-617	-573	3
33	2 - 4	Brush	< 1/4	550	400	-516	-565	3
38 B $\frac{7}{\text{hr}}$	2 - 4	Electrostatic spray	< 1/4	360 $\frac{8}{\text{hr}}$	210 $\frac{9}{\text{hr}}$	-51 $\frac{8}{\text{hr}}$	-589 $\frac{9}{\text{hr}}$	3
38 P $\frac{7}{\text{hr}}$	2 - 4	Electrostatic spray	< 1/4	380 $\frac{8}{\text{hr}}$	220 $\frac{9}{\text{hr}}$	-481 $\frac{8}{\text{hr}}$	-606 $\frac{9}{\text{hr}}$	3
39 B $\frac{7}{\text{hr}}$	2 - 4	Electrostatic spray	< 1/4	380 $\frac{8}{\text{hr}}$	240 $\frac{9}{\text{hr}}$	-610 $\frac{9}{\text{hr}}$	-610 $\frac{9}{\text{hr}}$	2
39 P $\frac{7}{\text{hr}}$	2 - 4	Electrostatic spray	3	410 $\frac{8}{\text{hr}}$	230 $\frac{9}{\text{hr}}$	-557 $\frac{9}{\text{hr}}$	-643 $\frac{9}{\text{hr}}$	2
40 B $\frac{7}{\text{hr}}$	2 - 4	Electrostatic spray	< 1/4	280 $\frac{8}{\text{hr}}$	200 $\frac{9}{\text{hr}}$	-513 $\frac{8}{\text{hr}}$	-608 $\frac{9}{\text{hr}}$	3
40 P $\frac{7}{\text{hr}}$	2 - 4	Electrostatic spray	1/2	290 $\frac{8}{\text{hr}}$	240 $\frac{9}{\text{hr}}$	-481 $\frac{8}{\text{hr}}$	-606 $\frac{9}{\text{hr}}$	2
41	3 - 7	Electrostatic spray	1/2	3.8 x 10 ⁵	3.0 x 10 ³	-451	-570	2
42 $\frac{10}{\text{hr}}$	3 - 4	Electrostatic spray	< 1/4	400	370	-526	-579	3
Uncoated bar			Immediate	200	370	-648	-634	4

$\frac{1}{\text{hr}}$ Potential of 2 volts was applied to coated bar.

$\frac{2}{\text{hr}}$ Bars partially immersed in 7 percent NaCl.

$\frac{3}{\text{hr}}$ Bars partially immersed in 3 1/2 percent NaCl.

$\frac{4}{\text{hr}}$ Ratings sequence in order of decreasing corrosion protection: 1 > 2 > 3 > 4.

$\frac{5}{\text{hr}}$ Test stopped after indicated time.

$\frac{6}{\text{hr}}$ Resistance values beyond capacity of measuring device. N.R. denotes no reading possible, i.e. no current flow because of holiday-free films.

$\frac{7}{\text{hr}}$ B represents sand blasted surfaces, only, while P indicates that the surfaces were phosphatized before applying the coatings.

$\frac{8}{\text{hr}}$ Initial measurement taken after immersion time of 120 hours.

$\frac{9}{\text{hr}}$ Measured after 696 hours.

$\frac{10}{\text{hr}}$ Same coating material as No. 41, however, applied to cold bars: coating applied to bars heated to 190°C in the case of No. 4.

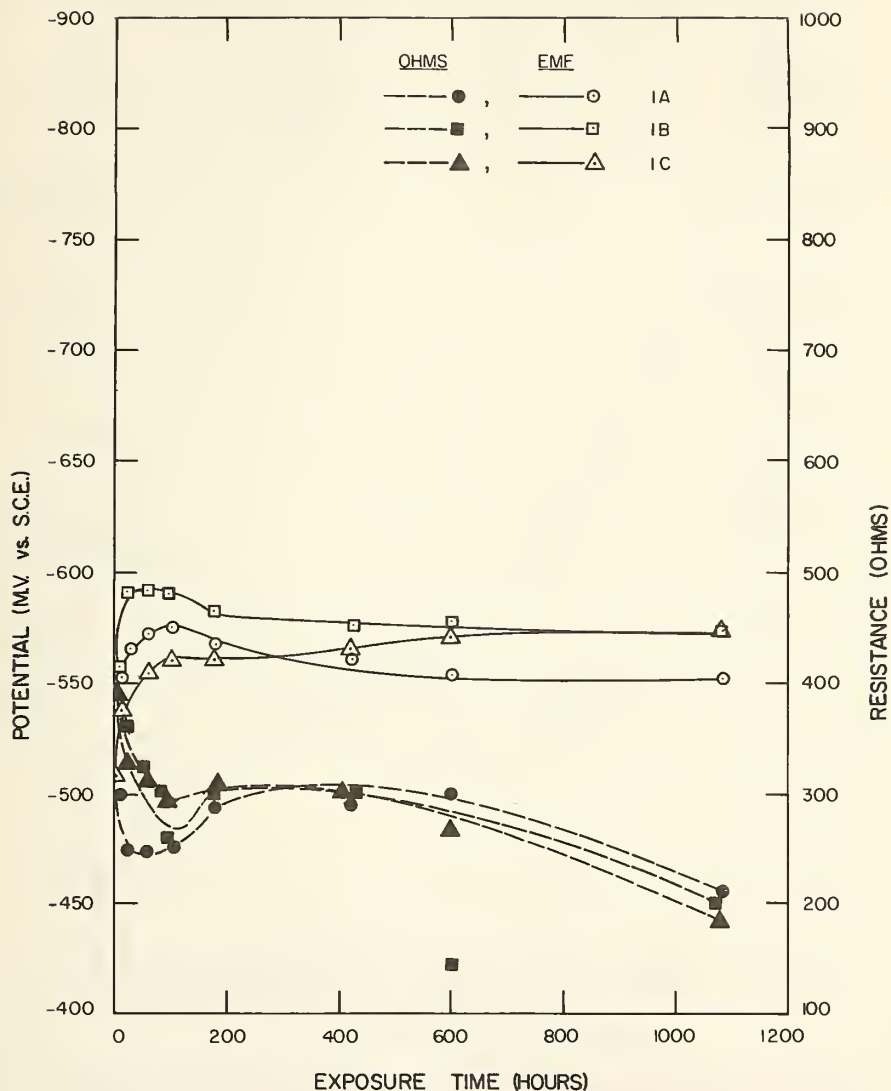


Figure 3. Electrical potential and resistance measurements of reinforcing bar coated with material No. 1 immersed in 3 1/2 percent NaCl. In the ordinate caption, M.V. vs. S.C.E. denotes millivolt reading taken using a saturated calomel electrode as the reference.

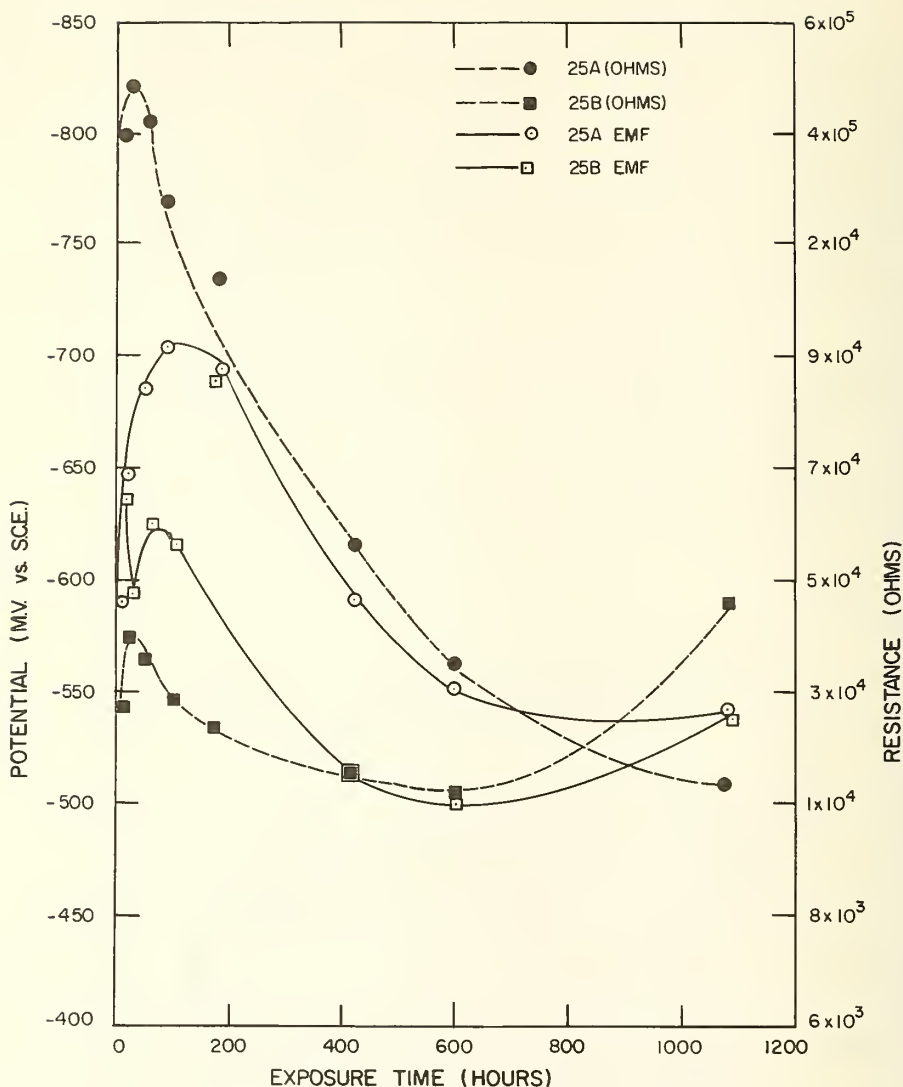


Figure 4. Electrical potential and resistance measurements of reinforcing bar coated with material No. 25 immersed in 3 1/2 percent NaCl. In the ordinate caption, M.V. vs. S.C.E. denotes millivolt reading taken using a saturated calomel electrode as the reference.

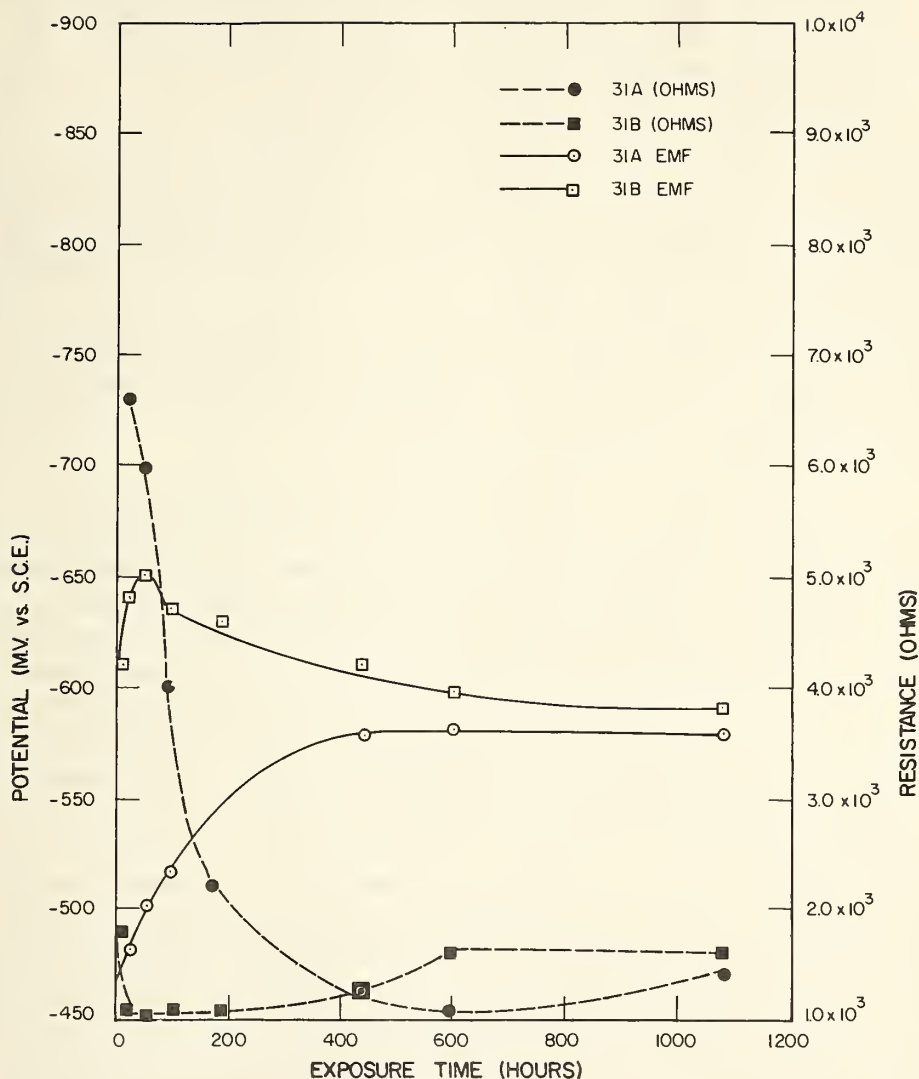


Figure 5. Electrical potential and resistance measurements of reinforcing bar coated with material No. 31 immersed in 3 1/2 percent NaCl. In the ordinate caption, M.V. vs. S.C.E. denotes millivolt reading taken using a saturated calomel electrode as the reference.

4. EVALUATION OF COATINGS

4.1 Evaluation Program

The evaluation program, conducted to select the best coatings for reinforcing bars embedded in concrete, was roughly separated into three general test categories:

1. chemical and physical durabilities of cured coatings;
2. corrosion protection of steel reinforcing bars by coatings;
3. structural characteristics of coated reinforcing bars.

Categories 1 and 2 have been essentially completed and the overall results will be discussed in this section. The structural characteristics denote creep and bond strengths of coated reinforcing bars embedded in concrete prisms. These tests are currently being performed and the results will be given in a future report.

The major emphasis has been devoted to epoxies because of anticipated unacceptable structural characteristics of reinforcing bars coated with thermoplastics. However, such coatings have been included in this study as they may serve well on dowel pins and other members of the steel frame work not subjected to high tensional forces.

4.2 Chemical and Physical Durabilities of Coatings

The resistance of coatings to chemicals was investigated by immersing both specimens of pure coatings (table 2), and coatings on steel substrates (table 3), in aqueous solutions containing aggressive salts similar to those in portland cement concrete. The weight changes listed in table 2 are in the range reported by others [25]. It is felt that with the exception of two solvent containing epoxy systems, Nos. 7 and 9, the epoxy coatings performed well and probably will not be degraded by long term embedment in concrete. The long term durability of polyvinyl chlorides when embedded in concrete, however, is thought to be of major concern for if considerable hydrolysis should take place sufficient amounts of chloride ions to induce corrosion of the rebars will be liberated.

Phosphatizing the surface of metal substrates has been considered advantageous to inhibition of corrosion [26]. In the present study, however, the coated bars with phosphatized steel surfaces, Nos. 38, 39, and 40, prematurely rusted when immersed in saturated Ca(OH)_2 (table 3). This corrosion terminated after about two weeks of exposure. No rusting took place with reinforcing bars coated with the same epoxies applied to sand blasted surfaces.

Reinforcing bars are normally subjected to harsh physical treatment while being shipped to the site of bridge construction and during the placement process. Furthermore, steel reinforcing bars are still being bent to form hooks, in accordance with the specifications of some state highway departments. Therefore, the abilities of coated bars to withstand such rough treatment with minimum coating damage is a necessary requirement.

The relative physical durabilities of coatings were ascertained by measuring the abrasion and impact resistance of coatings on steel plates (table 5), and by dropping and bending coated reinforcing bars (table 7). As discussed in section 3.3, the correlation between the relative impact resistance of coated plates and the relative drop and bend

ratings of coated rebars was not good. Results of the bend and drop tests are considered to provide the more reliable indications of the relative performances of the coating films.

The performance of a coating on a reinforcing bar when subjected to bend stresses can be related to: the flexibility of a coating; proper cure of the coating; surface preparation of the steel; and film thickness. Coatings with little flexibility will crack when under the tensional bend forces. Polyvinyl chlorides are inherently flexible materials and performed well, even with film thicknesses up to 35 mils (No. 24). Although epoxies are intrinsically more brittle than polyvinyl chlorides, the relative performance of epoxy films ranged from complete failure (e.g. No. 2) to excellent (e.g. No. 9). Interestingly, the flexibilities do not appear to be directly related to the type of epoxy system, i.e. powder or liquid. Flexibilities of epoxy coatings will often be decreased by improper cure caused by such factors as mixing incorrect ratios of resin to hardener or by curing powder epoxies at improper temperatures. The flexibilities of epoxy coatings decrease inversely with their film thickness. Based on the present study, it is recommended that the maximum allowable film thickness should be determined for each epoxy coating and in no case should it exceed 10 mils.

The importance of proper surface preparation cannot be over emphasized, as noted for the rebars coated with material No. 28. A set of bars was sand blasted prior to being coated and gave good performance in the bend test; while with the B set of bars the epoxy was applied to mill scale surfaces and these coated bars performed badly in the bend test. Similar results were obtained for Nos. 38, 39, and 40, when epoxies were applied to freshly sand blasted surfaces and to surfaces both sand blasted and phosphatized; the phosphatized sets were subject to varying degrees of cracking while the sand blasted bars were free of cracks.

The drop test does not merely supplement the bend test; some coatings have good bend characteristics but have a poor impact rating, for example, No. 18, and the reverse situation was observed for No. 22. Both the drop and bend test, therefore, should be included in future coating evaluation programs.

Some of the epoxies are of doubtful value as protective coating for reinforcing bars because of bad chipping characteristics when coated rebars were struck together, Nos. 2, 17, 32, 33 and 34 (table 6), and poor abrasion resistances, Nos. 10, 18, and 43 (table 6).

4.3 Corrosion Protection

The relative effectiveness of barrier organic coatings in protecting reinforcing bars from accelerated corrosion attributed to chloride ions can be associated with the following: physical and chemical durabilities of the coating (discussed in the previous section); intrinsic chloride ion permeability rates; film integrity; film thickness and corrosion inhibitors added to coating formulations [26, 27].

The present study confirms the results of others [25] that epoxies absorb measurable amounts of water and, therefore, thin epoxy films, ca. 2-10 mils, are not entirely impervious to moisture. However, chloride ion permeability rates may be much lower than those of pure water. Little if any data on the permeability rates of chloride ions through epoxy films have been previously reported. The data listed in table 4 and partially reproduced in figure 2, indicate a large range of permeabilities exist for epoxy coatings. Films of materials Nos. 1, 3, 17, 19, 31, 38, 39 were essentially impervious to chloride ions, during the listed exposure periods. Films of materials Nos. 13 and 15 permitted the accumulation of chloride ions in the originally distilled water compartment of the cell (figure 1) to approach, or reach, the chloride ion threshold concentration of 0.02M, i.e. the chloride concentration reported [21] to induce corrosion of steel embedded in concretes. At the present, unequivocal interpretations of the chloride permeability values are not possible, however, epoxy films with low values would probably provide the best protection for reinforcing bars.

The film integrity of coatings on reinforcing bars is an important consideration since holidays are potential sites of corrosion. In general, the coated rebars with few or no holidays (table 6) had acceptable corrosion ratings (rating of either 1 or 2). Holidays can be produced by solvent evaporation, poor flow characteristics of coatings, and mechanical damage. Note that in table 6, films of all of the solvent-containing systems had significant amounts of holidays, regardless of the application method. Liquid epoxies had the tendency to flow off the bar deformations leaving the high lying region exposed. The powdered epoxies, in many cases yielded films with few holidays and uniform film coverage. The large numbers of holidays in the powdered epoxy films Nos. 28, 29, 39, and 42, can be attributed to either poor coating practices or to low film thicknesses. Holiday-free films can also be obtained by thick film buildups, however, the maximum permissible film thickness must be consistent with good structural and flexibility characteristics.

Corrosion inhibitors can prevent the enlargement of small corrosion sites [27]. The apparent healing mechanisms previously noted for films Nos. 25 (figure 4) and 31 (figure 5) possibly, are associated with the presence of such corrosion inhibitors.

5. RECOMMENDATIONS AND CONCLUSIONS

Any recommendations concerning what type of coating to use, application methods, etc., must take into consideration the site of coating application; in the field or in an application plant. Bridge-construction-site application essentially limits the range of coating systems to those of the liquid type and restricts their application to the less desirable methods such as air spray, brushing or dipping. It is our opinion that in-plant application, soon after the reinforcing bars are fabricated, would yield the best quality of coated reinforcing bars.

The powder epoxies have, potentially, slightly better overall properties as barrier coatings for reinforcing bars than the liquid epoxies; within the liquid epoxy system the solvent free generally perform better than the solvent containing systems. However, in order for any coating to perform well, good application techniques are necessary.

Epoxy coatings should be applied to sand blasted steel surfaces as both phosphatized and mill scale surface are brittle and modest mechanical forces can cause disbondment.

The effectiveness of the application methods in producing thin films free of defects decrease in the sequence: electrostatic spray gun > fluidized bed > dipping > brushing.

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