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BOND OF COATED REINFORCING BARS IN CONCRETE

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INTRODUCTION

The premature deterioration of concrete bridge decks in 5 yr-10 yr has become a major problem during the past decade (5,6,7,8,9,11). Often, this early deterioration has been attributed to accelerated corrosion of steel reinforcing bars (rebars) caused by chloride ions from deicing materials (13,20). The use of the two more commonly applied deicing materials, sodium chloride and calcium chloride, has increased substantially during the past decade. Corrosion of reinforcing bars results in spalling and cracking of concrete, necessitating in many cases extensive and expensive repairs.

The possibility of protecting steel reinforcing bars from corrosion with organic-type coatings was investigated. Evaluations of the physical and chemical durabilities of 47 different coatings including epoxy and polyvinyl chloride materials were reported (4) in the earlier phase of the investigation. Assessments of the coatings protective qualities were made to determine their properties with regard to chemical resistance, film integrity, adhesion, chloride permeability, impact resistance, abrasion resistance, hardness, extensibility as determined from bar bend tests, and film thickness. It was concluded that among the organic materials, epoxy coatings had the most promise as a protective coating for reinforcing bars. The epoxies that had the best protective qualities and physico-chemical durabilities were selected for testing in a comprehensive evaluation program. The program included determining the structural characteristics, bond and creep strengths, of coated reinforcing bars embedded in concrete prisms. The bond strengths were measured in tests using pullout specimens and the results are reported herein. Creep studies of coated reinforcing bars are curently being performed and these results will be reported in the future.

Little attention has been previously devoted to epoxy materials as protective coatings for reinforcing bars because of the supposition that the coated bars

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will have unacceptable bond strengths (14). No reports were found in the literature of any type of structural testing performed on epoxy coated reinforcing bars embedded in concrete. In this investigation, 34 pullout specimens were tested,

FIG. 1.—View of No. 6D and No. 6B Reinforcing Bars

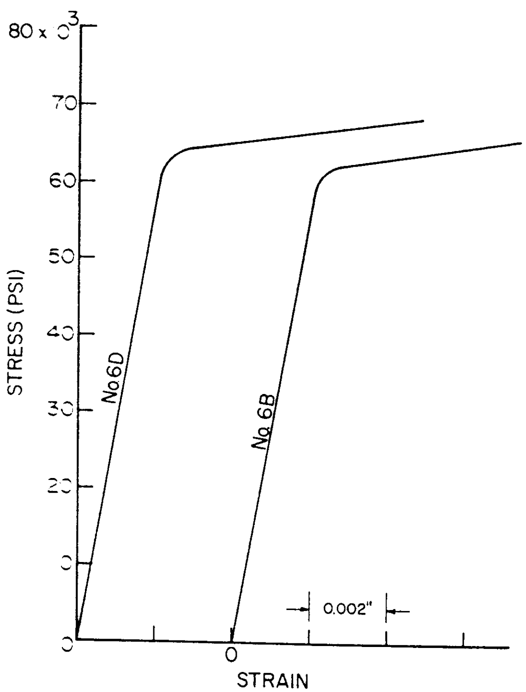

FIG. 2.—Typical Stress-Strain Characteristics of Reinforcing Bars

which were comprised of five specimens with uncoated reinforcing bars, 23 specimens with epoxy-coated bars, and six specimens with polyvinyl chloride-coated bars.

Materials and Specimens

Reinforcement.—The tensile reinforcement in the pullout tests consisted of No. 6 deformed bars, 3/4 in. (19 mm), nominal diameter, having either a barrel (B) or diamond (D) shaped deformation pattern, as shown in Fig. 1. These bars were randomly selected and may not have been from the same heat of steel. A 4-ft (1.2-m) length of each type of bar was tested to rupture in tension. The yield strengths determined by the "0.2% offset" (16) method were 67,600 psi (466 MN/m²) for No. 6 rebars (D) and 62,500 psi (431 MN/m²) for No. 6 rebars (B). These bars did not exhibit a well-defined yield point. However,

TABLE 1.—Properties of Reinforcing Bars

Bar size and type (1)	Area, A_s, in square inches (2)	Perimeter, Σ_o, in inches (3)	Yield[a] strength, f_y, in pounds per square inch (4)	Proportional limit, in pounds per square inch (5)	Tensile strength, in pounds per square inch (6)	Modulus of elasticity, E_s, in 10^6 pounds per square inch (7)	Elongation in 10 in., as a percentage (8)
No. 6D[b]	0.441	2.35	67,600	63,900	95,700	30.7	11.2
No. 6B[c]	0.434	2.34	62,500	61,800	95,200	28.4	8.2

[a]Yield strength was determined by the "0.2% offset" method.
[b]D denotes diamond deformation pattern.
[c]B denotes barrel deformation pattern.
Note: 1 in. = 25.4 mm; 1 psi = 0.0069 MN/m².

TABLE 2.—Properties of Deformations[a]

Bar size and type (1)	Width of gap, in inches (2)	Average spacing, in inches (3)	Average height, in inches (4)	Average projected length, in inches (5)	Bearing area, in square inches per inch (6)
No. 6D[b]	0.064	0.300	0.040	2.22	0.296
No. 6B[c]	0.047	0.402	0.038	2.25	0.212

[a]Methods of measuring properties of deformation and definition of terminology are given in Ref. 16.
[b]D denotes diamond deformation pattern.
[c]B denotes barrel deformation pattern.
Note: 1 in. = 25.4 mm.

their stress-strain relationships (Fig. 2) were linear up to a stress of about 64,000 psi (442 MN/m^2) for the (D) bars and approx 62,000 psi (427 MN/m^2) for the (B) rebars. Tensile properties of the bars are listed in Table 1. The properties of deformations were determined from three specimens from each type of bar and are given in Table 2.

Concrete.—The concrete was procured from a transit-mix concrete company. The mix proportions of portland cement (Type III), sand, and coarse aggregate were approx 1:1.7:2.5, by weight. The sand was a siliceous aggregate and the coarse aggregate was crushed stone. Maximum size of the coarse aggregate was 3/4 in. (19 mm). Water content of the concrete was about 5-1/2 gal per sack of cement and the slump ranged from 3 in.-5 in. (76 mm-130 mm). Three batches of concrete were used to cast 34 pullout specimens (12 specimens each from concrete batch No. 1 and No. 2, and 10 specimens from concrete batch No. 3).

TABLE 3.—Coated Reinforcing Bars[a]

Coating code number (1)	Type of coating materials (2)	Film thickness, in mils (3)	Application method (4)
U	No coating		
1	Epoxy, liquid	4-5	Brush
1-S	Material No. 1 mixed with sand	4-5	Brush
3	Epoxy, liquid	2-5	Brush
18	Coal tar epoxy, liquid	4	Brush
19	Epoxy, liquid	1	Dipping
22	Epoxy, powder	25	Fluidized bed
23	Polyvinylchloride, powder	23	Fluidized bed
24	Polyvinylchloride-plastisol, powder	35	Fluidized bed
25	Epoxy, powder	6-11	Electrostatic spray gun
29	Epoxy, powder	1-2	Electrostatic spray gun
30	Polyvinylchloride, powder	15-18	Fluidized bed
31	Epoxy, powder[b]	8-9	Electrostatic spray gun
38	Epoxy, powder	2-4	Electrostatic spray gun
38-Ph	Rebar surface phosphatized, then material No. 38 applied	2-4	Electrostatic spray gun
39	Epoxy, powder	2-4	Electrostatic spray gun
41	Epoxy, powder	3-7	Electrostatic spray gun

[a]No. 6 steel reinforcing bars coated by applicators or coating producers. Mill scale removed by sandblasting.

[b]Same material as No. 22, but applied by different method, by different applicator.

Note: 1 mil = 0.001 in. = 0.000254 m.

Six standard 6-in × 12-in. (150-mm × 305-mm) cylinders were cast from each batch of concrete along with the pullout specimens. The cylinders were stored and cured in the same manner as the pullout specimens; and their compressive strengths were measured at the same time as the specimens were tested. The compressive strength was determined in accordance with American Society for

Testing and Materials (ASTM) C39-71 (15). The average compressive stengths at 27 days-29 days were 6,170 psi (42.5 MN/m^2) for concrete batch No. 1, 6,620 psi (45.6 MN/m^2) for batch No. 2, and 5,730 psi (39.5 MN/m^2) for batch No. 3. The range and coefficient of variation (2) of the strength of the concrete cylinders was 226 psi (1.6 MN/m^2) and 1.5, 136 psi (0.9 MN/m^2) and 0.8, 355 psi (2.4 MN/m^2) for concrete batches numbered 1, 2, and 3 respectively.

Coatings on Reinforcing Bars.—Coating materials were applied to No. 6 reinforcing bars by the applicators or manufacturers handling the respective coatings. The National Bureau of Standards supplied the reinforcing bars used in the tests. The applicator or manufacturer blasted the surface of the bars to a white finish (19), applied and cured the coatings as recommended by the manufacturer, and then returned the bars to NBS for testing.

The coating materials and the methods by which they were applied are described in Table 3.

Pullout Specimens.—The pullout specimens were 10-in. × 10-in. × 12-in. (250-mm × 250-mm × 305-mm) concrete prisms with the 4-ft (1.2-m) length of reinforcing bar concentric with the longitudinal axis of the specimens, so that the length of embedment of the bar in concrete was 12 in. (305 mm). This length of embedment of the deformed bar was selected based on previous studies at NBS (12 and unpublished data) and because the current American Concrete Institute (ACI) Standard 318-71 states that the development length should not be less than 12 in. (305 mm) (3). The pullout specimen was designed so that the loaded-end slip reached a value of 0.01 in. (0.25 mm) corresponding to a steel stress of approximately one-half its tensile strength when uncoated bars were embedded in the specimen. Loaded-end slip is defined as the relative movement between a point on the loaded portion of the reinforcing bar and the surface of concrete. Splitting of the concrete was minimized by reinforcing the specimen with a cylindrical cage of 2-in. × 2-in.—12/12 (51-mm × 51-mm—2.7-mm diam) welded wire fabric. An instrumented pullout specimen is shown in Figure 3.

Fabrication and Curing of Specimens.—The pullout specimens were cast with the reinforcing bar in a horizontal position in wooden forms. The specimens were removed from the forms after 2 days, moist cured for 14 days with wet burlap, and room cured at 73° F (23° C) and 50% relative humidity until tested 27 days-29 days after being cast.

Two pullout specimens with uncoated (U) reinforcing bars were fabricated from each of concrete batch No. 1 and No. 2 and one such specimen was cast from batch No. 3. Two specimens were fabricated for each coating material from the same batch of concrete with the exception that only one pullout specimen was fabricated that contained coating No. 1-S.

Testing Procedure

Pullout specimens were tested in a 200,000-lb (90,700-kg) capacity universal electromechanical testing machine. A pullout specimen positioned on the testing machine is shown in Fig. 4. The pullout specimen shown in Fig. 3 is seated on leather cushions, on two segments of a 2-in. (51-mm) base plate attached to a spherical bearing block. Free-end and loaded-end slips of the reinforcing bar were measured with 1×10^{-4} in. (25.4×10^{-4} mm) micrometer dial gages. Free-end slip is defined as the relative movement between the unloaded end of the bar and the surface of concrete. At the loaded end of the specimen,

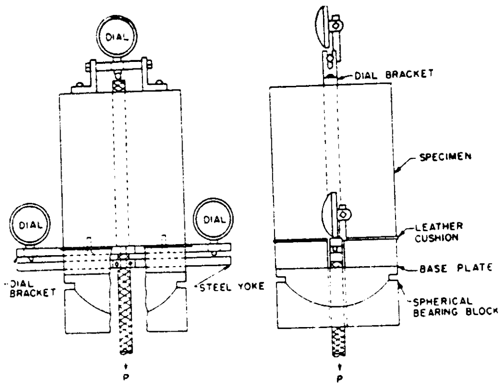

FIG. 3.—Schematic of Pullout Specimen

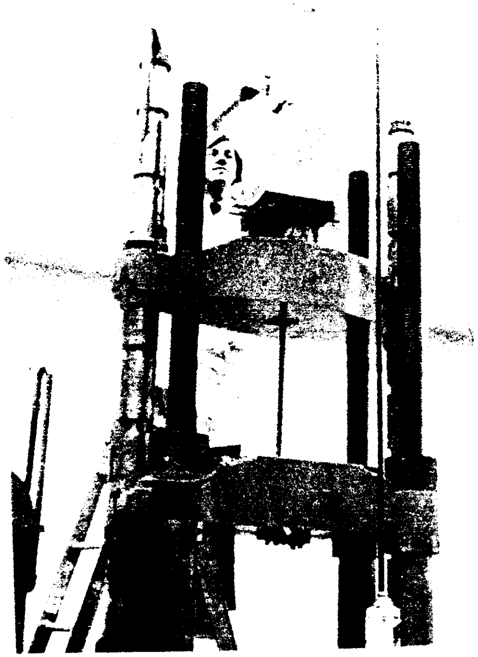

FIG. 4.—Pullout Specimen on Electromechanical Testing Machine Being Prepared for Testing

two dial gages were attached to a steel bar fastened to the face of the concrete by bolts secured into inserts cast in the concrete. The gages bore on a steel yoke fastened to the reinforcing bar about 1 in. (25.4 mm) below the face

of the concrete. The bar supporting the dial gages and the yoke was free to move in the recess in the base plate. The average of the two gage measurements gave the displacement of the point on the reinforcing bar where the yoke was attached, with reference to the face of the concrete. Slip at the free end was measured with a gage that bore on the exposed end of the reinforcing bar (any coating material on the exposed end of the reinforcing bar was removed

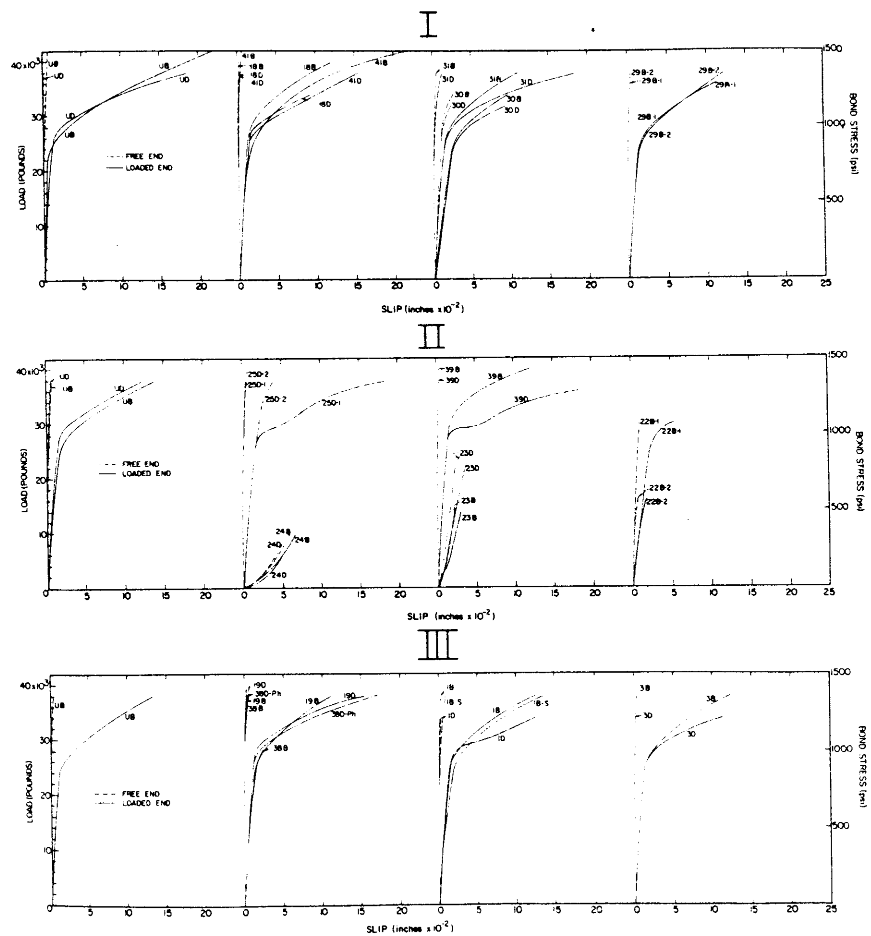

FIG. 5.—Applied Load to Reinforcing Bar in Pullout Specimens Versus Free-End and Loaded-End Slip

prior to testing). The gage was mounted on a support attached to the top face of the concrete by bolts secured into inserts cast in the concrete. Loads were applied in increments of 2,000 lb (907 kg) to the reinforcing bars in the pullout tests until failure occurred either by yielding of the steel or excessive slip between the bar and concrete was attained. At each load increment, measured displacement data were recorded.

TABLE 4.—Pullout Data

								Bond Stress Corresponding To			
Pull-out number (1)	Compressive strength of concrete, f'_c, in pounds per square inch (2)	Maximum applied load, P_{max}, in pounds (3)	Maximum computed steel stress, $f_{s\,max}$, in pounds per square inch (4)	Maximum computed bond stress, u_m, in pounds per square inch (5)	Load corresponding to critical bond strength, P_{cr}, in pounds (6)	Steel stress corresponding to critical bond strength, $f_{s\,cr}$, in pounds per square inch (7)	Maximum slip observed at free end, in inches (8)	Loaded-end slip of 0.01 in., u_1, in pounds per square inch (9)	Free-end slip of 0.002 in., u_2, in pounds per square inch (10)	$u_m/2$, in pounds per square inch (11)	Mode of failure (12)
U-B	6,170	40,000	92,100	1,423	20,300	46,800	0.006	723	978	712	Yielding of reinforcement; no cracks.
U-B	6,170	38,000	87,600	1,257	18,000	41,500	0.007	641	889	629	Yielding of reinforcement. Small longitudinal crack extending one-third length of one face. Small transverse crack at loaded end.
U-D	5,730	38,000	87,600	1,458	20,000	46,100	0.006	712	1,157	729	Yielding of reinforcement. small longitudinal crack extending one-half length of specimen on one face.
U-D	6,620	38,200	86,200	1,256	21,600	48,900	0.006	764	1,037	628	Yielding of reinforcement; no cracks.
U-D	6,170	40,600	92,100	1,328	21,400	48,500	0.002	755	—[a]	664	Yielding of reinforcement; no cracks.
1-B	5,730	38,000	87,800	1,455	21,200	48,800	0.003	751	1,185	727	Yielding of reinforcement; no cracks.
1-D	5,730	34,000	77,100	1,290	18,000	40,800	0.003	638	1,060	645	Yielding of reinforcement. Small longitudinal crack extending one-half length of specimen on two opposite faces.
1-B-S	5,730	38,000	87,600	1,455	17,100	39,400	0.01	609	925	727	Yielding of reinforcement; no cracks
3-B	5,730	38,000	87,600	1,455	20,000	46,100	0.006	712	1,210	727	Yielding of reinforcement; no cracks.
3-D	5,730	34,000	77,100	1,293	21,000	47,600	0.002	745	1,199	646	Yielding of reinforcement. Small longitudinal crack extending one-sixth of length of specimen on one face.
18-B	6,170	38,000	87,600	1,350	21,500	49,600	0.002	766	1,352	675	Yielding of reinforcement; no cracks.
18-D	6,170	38,000	86,200	1,347	18,800	42,600	0.003	677	1,089	727	Yielding of reinforcement. Small longitudinal crack extending one-sixth length of specimen on two faces.
19-B	5,730	38,000	86,600	1,455	19,000	43,700	0.004	759	1,277	726	Yielding of reinforcement; no cracks.
22-B-1	6,620	30,000	69,200	994	11,600	26,700	0.01	455	413	497	Bond failure. Small transverse crack extending one half length of loaded end.
22-B-2	6,620	15,800	36,300	—[b]	6,500	15,000	—[b]	363	231	—	—[b]
23-B	6,620	27,000	62,400	894	700	1,600	—[c]	107	25	447	Bond failure. Specimen badly cracked.
23-D	6,620	24,000	54,500	791	1,400	3,200	0.03	167	50	395	Bond failure. Specimen badly cracked.
24-B	6,620	8,000	18,500	266	100	300	0.05	18	5	133	Bond failure. Excessive free-end slip.
24-D	6,620	10,000	22,700	331	30	64	0.06	18	1	165	Bond failure. Excessive free-end slip.
25-D-1	6,620	38,600	87,600	1,276	18,500	41,900	0.003	656	1,050	638	Yielding of reinforcement. Small longitudinal crack extending one-half of length of specimen on two opposite faces.

TABLE 4.—Continued

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
25-D-2	6,620	38,000	86,200	1,256	17,800	40,400	0.005	631	922	628	Yielding of reinforcement. Small longitudinal crack extending one-half of length of specimen on two opposite faces.
29-B-1	6,170	38,000	87,600	1,347	17,000	39,200	0.004	605	979	673	Yielding of reinforcement. Small longitudinal crack extending one-third of length of specimen on two opposite faces.
29-B-2	6,170	35,400	81,600	1,276	18,200	41,900	0.004	648	1,033	638	Yielding of reinforcement. Small longitudinal crack extending one-third of length of specimen on two opposite faces.
30-B	6,170	34,000	78,300	1,210	6,000	13,800	0.03	410	214	605	Bond failure. Small longitudinal crack extending entire length of specimen on two opposite faces.
30-D	6,170	32,000	72,600	1,139	5,400	12,300	0.02	348	191	569	Bond failure. Numerous small longitudinal cracks on all faces.
31-D	6,170	38,000	86,200	1,350	19,500	44,200	0.012	670	1,056	675	Yielding of reinforcement. Small longitudinal crack extending one-third length of specimen on two opposite faces.
31-B	6,170	38,000	87,600	1,347	18,700	43,100	0.006	646	956	674	Yielding of reinforcement. Small longitudinal crack extending one-third length of specimen on two opposite faces.
38-B	5,730	40,000	92,100	1,533	19,700	45,400	0.008	702	1,129	766	Yielding of reinforcement; no cracks.
38-D-Ph	5,730	38,000	86,200	1,451	21,500	48,700	0.003	762	1,032	726	Yielding of reinforcement. Small longitudinal crack extending one-third length of specimen on two opposite faces.
39-D	6,620	38,600	87,600	1,276	20,000	45,400	0.004	709	1,177	638	Yielding of reinforcement. Small longitudinal crack extending one-sixth of specimen on two opposite faces.
39-B	6,620	37,400	86,200	1,256	17,500	40,300	0.004	623	1,122	628	Yielding of reinforcement. Small longitudinal crack extending one-sixth of specimen on two opposite faces.
41-D	6,170	38,600	87,600	1,350	18,500	42,200	0.004	656	1,046	675	Yielding of reinforcement. Small longitudinal crack extending entire length of two opposite faces.
41-B	6,170	37,400	86,200	1,347	17,000	39,200	0.004	605	1,068	673	Yielding of reinforcement; no cracks.

[a] Unreliable data due to sticking gage.
[b] Test stopped at f_s of 36,300 with free-end slip of 0.007.
[c] Not recorded, greater than 0.02 inch.
Note: 1 lbf = 4.45 N; 1 psi = 0.0069 MN/m^2.

Results and Examination

An important requirement for coated steel reinforcing bars is the necessity of having adequate bond strength when embedded in concrete. In the present study, the relative bond strengths of coated and uncoated bars were determined by testing pullout specimens.

In the bond study of the senior writer and Watstein (12) critical bond stresses were determined from bond stress-slip relationships. The critical bond stress was taken as the lower value of bond stress corresponding to a loaded-end slip of 0.01 in. (0.25 mm) or a free-end slip of 0.002 in. (0.051 mm). It was observed in general that significant changes in slope of the bond stress-slip relationship occurred at these values of the slip for various lengths of embedments in beams containing No. 4 or No. 8 bars. Comparison of bond strength data for beam pullout specimens in the study of the senior writer and Watstein (12) indicated that considerably lower critical bond strengths were developed in pullout specimens compared to beam specimens having the same length of embedment.

Load-Slip Relationships.—The relationships between applied load and the free-end and loaded-end slip are plotted in Fig. 5 for the 34 pullout specimens tested. Roman numerals denote the concrete batch number while the Arabic numbers next to the plots identify the coating materials (Table 3). The loaded-end slip was larger than the free-end slip for all specimens tested primarily because slipping initiates at the loaded-end and extends toward the free-end as the load is increased. Test results indicate that the critical bond stress is as important as the maximum load carried by the reinforcing bar in evaluating the performance of coated reinforcing bars in the pullout tests.

Bond Strength.—In comparison of the bond strengths developed in the pullout tests of uncoated and coated reinforcing bars the variation in the concrete strength, f'_c, was considered. Values of $\sqrt{\bar{f}'_c/f'_c}$ were 1.00, 0.97, and 1.04 for the three batches of concrete designated I, II, and III respectively. The average strength of concrete, $\bar{f}'_c$, for all three batches was 6,170 psi (42.5 MN/m^2). The values of all calculated bond stresses were adjusted for the differences in concrete strength by multiplying them by the ratio of $\sqrt{\bar{f}'_c/f'_c}$.

Yielding of the reinforcing bar was attributed as failure in most tests, with the exception being pullout specimens containing bars coated with materials Nos. 22, 23, 24, and 30. Although yielding of the reinforcing bar occurred in most tests, the critical bond strength corresponded to steel stresses well below the yield strength of the steel. The critical bond strength corresponded to applied loads ranging from 17,000 lb-21,600 lb (7,711 kg-9.797 kg) for uncoated bars and for coated bars, except those coated with materials Nos. 22, 23, 24, and 30 (Table 4). Material No. 22 is a powder epoxy applied by the fluidized bed method producing a cured film about 24 mils (0.0610 cm) thick. Coatings Nos. 23, 24, and 30 are polyvinyl chloride materials. The other coatings are epoxy coatings ranging from 1 mil-11 mils (0.0025 cm-0.0279 cm) thick. The applied load corresponding to the critical bond strength in the 19 pullout specimens with bars having epoxy coatings 1 mil-11 mils (0.0025 cm-0.0279 cm) thick ranged from 17.000 lb-21,500 lb (7,711 kg-9.752 kg) with an average value of 19,100 lb (8,663 kg). The applied load corresponding to the critical bond strength in the five pullout specimens with uncoated bars ranged from 18,000 lb-21,600 lb (8,164 kg-9.797 kg) with an average value of 20,300 lb (9,207 kg). Variability of the test results can allow acceptable bond strengths of coated rebars to be slightly less than the mean value of bond strengths of uncoated bars. Adequate mean bond strengths of coated bars denotes values comparable to those for uncoated bars. The average value of applied load corresponding to the critical bond strength in the 19 pullout specimens with the bars having epoxy coatings 1 mil-11 mils (0.00259 cm-0.0279 cm) thick was 6% less than for the pullout specimens containing the uncoated bars. Therefore, these particular coated bars

are concluded to have acceptable bond strengths.

The average applied loads corresponding to the critical bond strength in pullout specimens containing rebars with coatings Nos. 22, 23, 24, and 25 were 9,000 lb, 1,100 lb, 60 lb and 5,700 lb (4,082 kg, 499 kg, 27 kg and 2,585 kg), respectively. Critical bond strengths developed in pullout specimens containing rebars having these coatings were considerably less than the values of critical bond strengths determined from pullout specimens containing the uncoated bars.

A comparison of the bond strengths based on maximum load can also be made for coated and uncoated bars. Values of maximum applied loads are also presented in Table 4. Noted from this table that the maximum load for all pullout specimens except those containing bars having coatings Nos. 22, 23, 24, and 30 corresponded to yielding of the reinforcement. When the steel stresses considerably exceeded the yield strength of the bar, loading was halted. An evaluation of the pullout test results (Table 4) indicates that epoxy-coated reinforcing bars have bond strengths essentially equal to uncoated bars when the film thicknesses are approx 10 mils (0.025 cm) or less. Both liquid and powder epoxies performed equally well, and the application method did not significantly affect the bond strength of coated bars. The polyvinyl chloride coated bars had bond strengths considerably less than that for uncoated bars and bars with these coatings are not recommended for structural use. The lower bond strengths for polyvinyl coated bars are attributed in part to the viscoelastic nature of the polyvinyl chloride. The thicknesses of the polyvinyl chloride film were greater than most of the epoxy films, but thicker films are normal for thermoplastics (10).

Bond Stress.—Note that in a previous study (12) the average bond strength of pullout specimens was 75% of the average value for beam specimens. Although pullout test results are not recognized as being comparable to beam test results, the writers believe that bond characteristics of reinforcing bars can be determined from pullout tests. Pullout tests give reference bond values and the results do not imply actual development strength in reinforced concrete members. Bond stresses were computed from the formula

$$u = \frac{f_s A_s}{\Sigma_o L} \quad \text{or} \quad u = \frac{P}{\Sigma_o L} \qquad (1)$$

in which f_s = the stress in the reinforcing bar; P = the load or tensile force applied to the bar; A_s = the nominal cross-sectional area of the bar; Σ_o = the nominal perimeter of the bar; and L = the length of embedment, in inches, of the reinforcing bar in the pullout specimen. Values of A_s and Σ_o for each of the two types of rebars are given in Table 1.

Values of critical bond stress developed in the pullout specimens were greater than allowable values given in the American Concrete Institute Building Code 318-63 (1), and the Standard Specification for Highway Bridges adopted by the American Association of State Highway Officials (17).

The critical bond stresses and bond stresses corresponding to one half the maximum applied load, $u_m/2$, given in Table 4 for all pullout specimens except those having bars coated with materials 22, 23, 24, and 30 were greater than 600 psi (4.1 MN/m^2).

Summary and Conclusions

Bond strenths were determined in 34 pullout specimens with 23 epoxy coated (10 different epoxy coatings), six polyvinyl chloride coated (three different materials), and five uncoated No. 6 deformed reinforcing bars. In general, the comparable pullout tests indicated that bars with epoxy coatings approx 10 mils (0.025 cm) or less in thickness developed essentially the same bond strengths as the uncoated bars. When the film thickness of the epoxy coating was 25 mils (0.064 cm) or when polyvinyl coatings were used, the bond strength was considerably less for these coated bars than for the uncoated bars. It is recommended that thick epoxy coatings, greater than approx 10 mils (0.025 cm), and polyvinyl chloride coatings not be used as protective coatings for reinforcement in concrete flexural members.

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Appendix II.—Notation

The following symbols are used in this paper:

A_s = nominal cross-sectional area of reinforcing bar;
D = nominal diameter of reinforcing bar;
E_s = modulus of elasticity of reinforcing bar;
f'_c = concrete compressive strength;
$\bar{f}'_c$ = average compressive strength of concrete;
f_{scr} = steel stress corresponding to critical bond strength;
f_s = stress in steel reinforcement;
$f_{s\,max}$ = maximum computed stress in steel reinforcement;
f_y = yield strength of reinforcing bar;
L = length of embedment of steel reinforcing bar;
P = tensile force applied to reinforcing bar;
P_{cr} = load corresponding to critical bond strength;
P_{max} = maximum applied load;
u = bond stress;
u_m = bond stress corresponding to maximum load;
u_1 = bond stress corresponding to a loaded-end slip of 0.01 in;
u_2 = bond stress corresponding to a free-end slip of 0.002 in; and
Σ_o = nominal perimeter of reinforcing bar.