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Bond Strength of Grouted Reinforcing Bars


by David Darwin and Shahin S. Zavaregh

The effects of hole preparation method, grout type, hole diameter, bar size, embedment length, cover, bar surface condition (epoxy-coated or uncoated), orientation of the installed bar, and concrete strength on the bond strength of grouted reinforcing bars are described. Hole preparation methods, using a high-speed vacuum drill or a hand-held electric hammer drill, and cleaning methods, using a fiber bottle brush with water, a fiber bottle brush without water, or compressed air only are compared. Two capsule systems, two two-component grout systems, and two nonshrink grout systems are evaluated. Hole diameters range from 3/4 to 1-1/2 in. (19 to 38 mm) for No. 5 (16 mm) bars; a hole diameter of 1-1/4 in. (32 mm) is used for No. 8 (25 mm) bars. Embedment lengths range from 4 to 12 in. (102 to 305 mm) for No. 5 (16 mm) bars and from 6 to 15 in. (150 to 380 mm) for No. 8 (25 mm) bars. 1-1/2 and 3 in. (38 and 75 mm) covers are used. Bar installations include vertical, sloped, and horizontal bars. Test results are used to develop rational design and construction requirements.

The bond strength of grouted reinforcing bars is not highly sensitive to differences in the hole preparation or cleaning methods studied. Grouts that provide strong bond at the grout-concrete interface provide higher bond strengths than grouts that undergo failure at the grout-concrete interface. With the exception of bars anchored by capsule systems, the bond strength provided by grouts is not sensitive to hole diameter. Bond strength increases with increasing embedment length, cover, and bar size. The bond strength of grouted reinforcement is insensitive to the presence of epoxy coating. Vertically and horizontally anchored bars may exhibit different bond strengths, depending on the grout used.

Keywords: adhesives; bond (concrete to reinforcement); coatings; embedment; grout; reinforcing steels; structural engineering.

Grouting reinforcement into holes drilled in existing concrete is commonly specified in the repair and retrofit of reinforced concrete structures. The procedure is widely used in highway construction to attach barriers and widen existing bridges, applications that involve relatively low cover on the grouted bars. In spite of its widespread use, little data exists on the bond strength of grouted reinforcement to concrete, and no data exists for bars with low cover. This lack of data has prevented the development of rational anchorage design procedures. Designers usually make use of proprietary design tables provided by grout manufacturers. These tables provide strengths that are based on highly confined pullout specimens. The strengths are then typically reduced by a factor of safety to establish "allowable" anchorage strengths. The strengths and modes of failure exhibited by highly confined specimens do not, however, match those obtained by grouted bars loaded under realistic conditions.[1]

Prior to the current study, there have been limited efforts to establish the strength of grouted reinforcement.[2,3] This earlier work has involved reinforcing bars with very high cover, such as those used for concrete anchors. The use of high cover is not representative of highway bridge construction, in which covers as low as 1-1/2 in. (38 mm) are used for grouted reinforcement. Thus, the previous work is not only limited, but because of the high cover provides unconservative values of strength. In addition, the previous work has used uncoated reinforcement rather than epoxy-coated reinforcement as used in most transportation structures today. The effect of epoxy coating on the bond strength of grouted reinforcement is thus largely unknown.

The behavior and design of both cast-in-place and retrofit concrete anchors have been thoroughly studied by Cook et al.[4,5] Although that research does not specifically address grouted reinforcing bars, it provides a wealth of information on the subject of anchorage to concrete.

The purpose of this study is to develop a pool of data on the bond strength of grouted reinforcing bars and to use that data to develop rational design and construction requirements. The experimental program addresses the effects of hole preparation method, grout type, hole diameter, bar size, embedment length, cover, bar surface condition (epoxy-coated or uncoated), orientation of the installed bar, and concrete strength. This paper describes the overall experimental program, evaluates test results, and presents design and construction recommendations that will improve both the safety and the economy of grouted reinforcing bars. Details not covered in this paper are presented in Reference 1.

EXPERIMENTAL PROGRAM

Test specimens

The experimental program consisted of 492 reinforcing bars grouted or cast-in-place in beam-end specimens designed to provide realistic degrees of concrete confinement to match the behavior of grouted bars as used in practice (Fig. 1). The test specimens were cast in 23 groups of six to 12 concrete specimens each.

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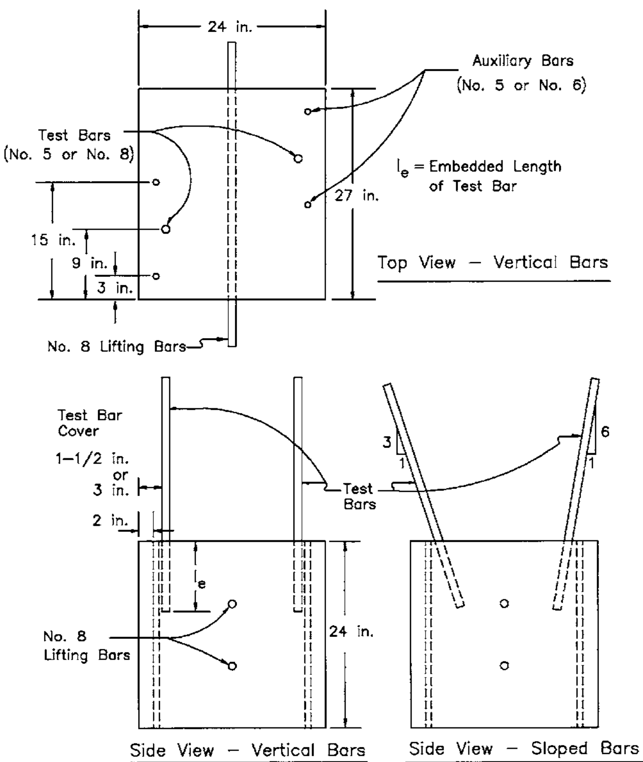


Fig. 1(a)—Test specimen with vertical or sloped bars as cast.

The basic test specimen consisted of a block of concrete 24-in. (610-mm) long by 27-in. (686-mm) wide by 24-in. (610-mm) high and contained two vertical or two sloped bars anchored on the upper surface [Fig. 1(a)] or two horizontal bars anchored on a vertical surface [Fig. 1(b)]. Some specimens contained as many as six test bars. As constructed and tested, the failure of individual bars was unaffected by other bars in the test specimen. No. 5 and No. 8 bars were used in this study.

Most bars had a 3 in. (75 mm) cover; selected bars had a 1-1/2 in. (38 mm) cover. Embedment lengths of 4, 6, 9, and 12 in. (100, 150, 230, and 305 mm) were used for No. 5 (16 mm) bars, while embedment lengths of 6, 9, 12, and 15 in. (150, 230, 305, and 380 mm) were used for No. 8 (25 mm) bars.

Based on experience with narrower test specimens,[6,7] auxiliary reinforcement was added parallel to the test bars to provide additional tensile capacity to the concrete (Fig. 1). Two No. 5 (16 mm) auxiliary bars were used for No. 5 (16 mm) test bars, and two No. 6 (19 mm) auxiliary bars were used for No. 8 (25 mm) test bars. Auxiliary bars had 2 in. (51 mm) of

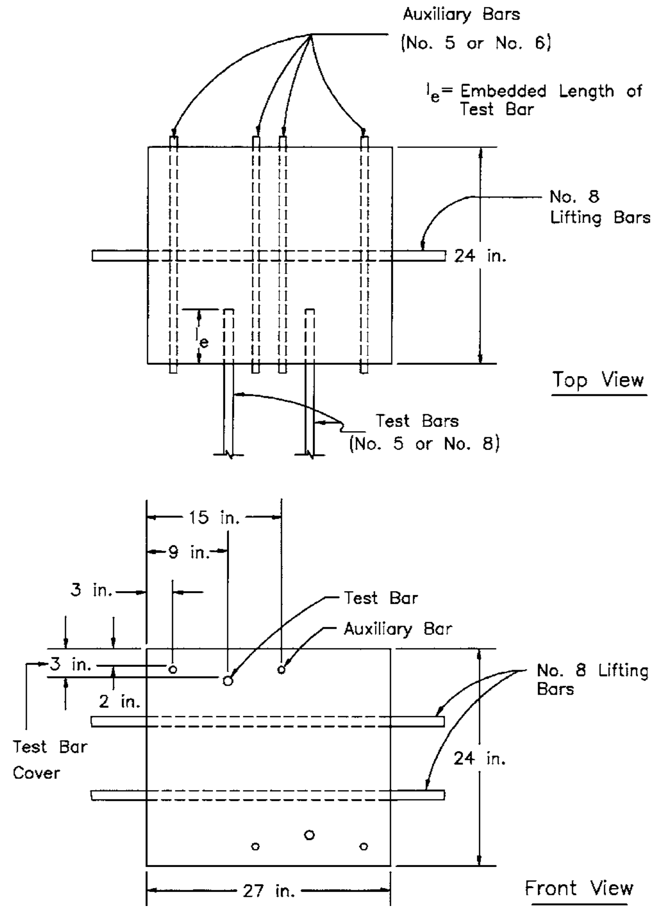


Fig. 1(b)—Test specimen with horizontal bars as cast.

cover and were centered 6 in. (152 mm) on either side of the test bars. Some test specimens, however, did not contain auxiliary reinforcement, and an analysis of the data later demonstrated that auxiliary reinforcement was not required and played no measurable role in specimen behavior or strength.[1] Both epoxy-coated and uncoated bars were evaluated. Epoxy-coated reinforcement was used in most of the tests due to its wide application in transportation structures.

Grouted No. 5 (16 mm) bars were anchored in holes with diameters of 3/4, 13/16, 7/8, and 1-1/2 in. (19, 21, 22, and 38 mm), while grouted No. 8 (25 mm) bars were anchored exclusively in holes with diameters of 1-1/4 in. (32 mm). Most tests involved holes with diameters 1/4 in. larger than the bar diameter [7/8 and 1-1/4 in. (22 and 32 mm) for No. 5 and No. 8 (16 and 25 mm) bars, respectively].

Materials

Reinforcing steel—ASTM A 615[8] Grade 60 No. 5, No. 6, and No. 8 (16, 19, and 25 mm) bars were used for the tests. Epoxy coating was commercially applied in accordance with ASTM A 775.[9]

Concrete—Air-entrained concrete was supplied by a local ready-mixed plant. Type I portland cement, 3/4 in. nominal maximum size crushed limestone, and river sand were used to produce concretes with nominal strengths of 2700 or 5000 psi (18.6 or 34.5 MPa). The majority of the tests were carried out at 5000 psi (34.5 MPa).

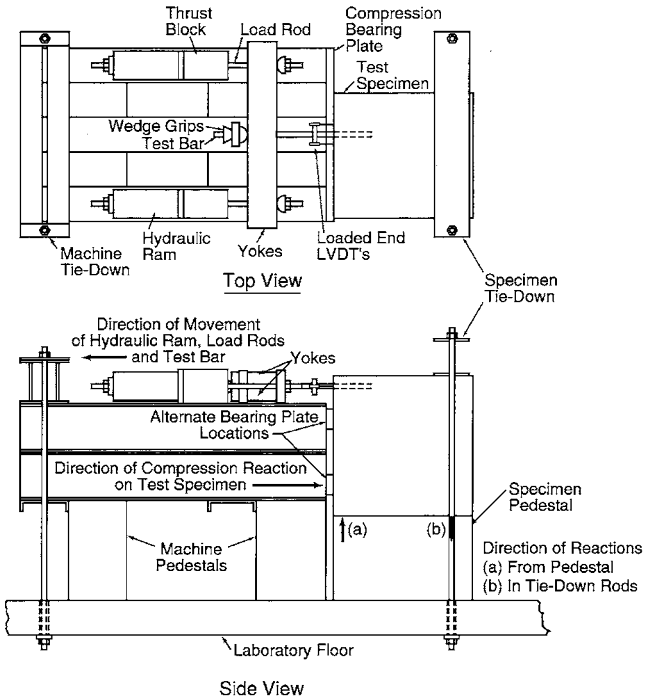


Fig. 2—Schematic of test setup.

Grout—Six grouts were evaluated in the study: two capsule systems (designated CPA, CPB); two two-component systems (TCA, TCB); and two nonshrink grouts (NSA, NSB). CPA consisted of a vinyl ester resin system, and CPB consisted of a polyester resin system. The capsule systems contained microaggregate, and the size of the capsules depended on the size of the bar being anchored. TCA consisted of a vinyl ester resin system, while TCB consisted of an epoxy resin system. NSA and NSB consisted of nonmetallic cementitious nonshrink grout systems. The study placed major emphasis on four of the grouting systems: CPA, TCA, TCB, and NSA.

Bar installation

A high-speed, hydraulic, truck-mounted vacuum drill and a hand-held electric rotary hammer drill were used to place holes in the specimens. The self-cleaning vacuum drill has been used for over 15 years by the Kansas Department of Transportation to add shear reinforcement to bridges.[10,11] It was evaluated to see if it provided any advantages over the more traditional hand-held drill, which was used to prepare most of the test specimens. A shop vacuum cleaner was used in conjunction with the hand-held drill to remove cutting debris at the top of the hole.

Four cleaning methods were evaluated in the study: 1) using the truck-mounted vacuum drill, with no additional hole preparation (V); 2) vacuuming the bottom of the hole with a shop vacuum cleaner with a 1/2 in. outside diameter nozzle, followed by thorough scrubbing with a fiber bottle brush and water and blowing out the hole with compressed air (BW); 3) vacuuming with the shop vacuum cleaner, brushing with the fiber bottle brush (no water), and blowing out the hole with compressed air (BA); and 4) vacuuming the hole with the shop vacuum cleaner and blowing out the hole with compressed air (A). An in-line filter removed oil and water from the compressed air. Methods BW, BA, and A were used for holes made with the hand-held drill.

Grouts and reinforcing bars were placed according to the manufacturer's instructions.[1] A manual dispenser provided by the manufacturer was used to place TCA grout, which was prepackaged for automatic proportioning during installation. TCB grout was batched by volume (two parts A to one part B) and mixed for 3 min according to the manufacturer's instructions. In the plastic state, TCA had the consistency of toothpaste and set rapidly, while TCB had the consistency of honey and set slowly. As a result, TCA could be used in both vertical and horizontal holes, while TCB, without the addition of a filler or special provision to prevent leakage in horizontal holes, could be used only in vertical holes.

The capsule systems, CPA and CPB, contained two components sealed in glass tubes. The individual capsules were placed in holes, and the reinforcing bar, with a chisel point (45 deg angle), was attached to the hammer drill with a special drive socket and drilled to the bottom of the hole.

The nonshrink grouts were mixed until uniform. The NSA and NSB grouts were combined with 1.5 and 2.55 gal. (5.7×10^{-3} and 9.7×10^{-3} m^3) of water, respectively, per 55 lb (25 kg) bag of material to produce grout with a fluid consistency.

To avoid air pockets and insure complete filling of a hole, grouts were poured down one side of the hole and placement was completed without interruption. Bars were inserted by hand after placement of the two-component and nonshrink grouts. Following insertion of the reinforcing bar, exposed surfaces were sealed with duct tape. Grouts were cured for a minimum of 3 days.

Test procedure

The test system, illustrated in Fig. 2, was used to apply load at approximately 3 kips (13 kN) per min for No. 5 (16 mm) bars and 6 kips (27 kN) per min for No. 8 (25 mm) bars. The tensile force on the test bar was counteracted by a compressive force imposed on the concrete specimen through a 4 in. (102 mm) deep steel bearing plate. The edge of the plate was located 4-1/2 in. (114 mm) below the center of the test bars, except for selected specimens for which the spacing was increased to 12 in. (305 mm) to evaluate the effects of changes in degree of confinement provided to the test bar based on the proximity of the bearing plate. Loaded-end slip was measured using two spring-loaded linear variable differential transformers (LVDTs) attached to an aluminum block mounted on the test bar 4 in. (102 mm) from the face of the concrete. The orientation of specimens with sloped bars [Fig. 1(a)] was adjusted and shims were used to adjust the bearing plate so that the test bars could be placed in direct tension.

SPECIMEN BEHAVIOR AND ANALYSIS OF TEST RESULTS

To account for differences in concrete strength, experimental bond strengths are multiplied by $(5000/f_c')^{1/2}$ [f_c' in psi] to obtain "modified bond strengths" that are used for comparison and analysis. The term "bond strength" represents the maximum tensile force T_e attained during a test.

Failure modes

The test specimens exhibited five failure modes. In many cases, failure involved a combination of these modes. Most of the test specimens exhibited a splitting failure (tensile cracks in the concrete parallel to the reinforcing bar), shown in Fig. 3(a), or a failure at the interface between the grout and the concrete (IGC failure), shown in Fig. 3(b). These failure modes often occurred in conjunction with the formation of a shallow angle concrete cone surrounding the reinforcing bar on the face of the specimen, also shown in Fig. 3(b). Some specimens exhibited a tensile failure mode in which the concrete test specimen failed due to tensile/flexural cracks perpendicular to the direction of loading, while some specimens exhibited no sign of failure other than bar pullout.

Splitting failure is the type of bond failure exhibited by most cast-in-place reinforcing bars in structural applications[12-15] and was the primary mode of failure for bars anchored with Capsule B (CPB), Two-Component Grout B (TCB), Nonshrink Grout A (NSA), Nonshrink Grout B (NSB), and No. 8 bars anchored with Capsule A (CPA). For cast-in-place bars, splitting failures are governed primarily by the strength of the concrete and any confining reinforcement, such as stirrups or ties[16,17] (confining reinforcement was not used in this study). For grouted bars, a splitting failure indicates close interaction between the grout and the surrounding concrete and is usually accompanied by failure at the reinforcing bar-grout interface, not the grout-concrete interface.

Failure at the interface between grout and concrete (IGC) indicates a low bond strength between the two materials. This type of failure generally results in a lower anchorage strength than a splitting failure. IGC was the primary mode of failure for bars anchored with Two-Component Grout A (TCA).

Pullout was the primary mode of failure for No. 5 bars anchored with CPA.

The failure modes obtained for bars for which the steel bearing plate was moved from 4-1/2 to 12 in. (114 to 305 mm) below the center of the test bars showed no significant differences from those obtained in the balance of the tests, indicating little difference in the degree of confinement provided to the bars based on the two bearing plate positions.

The following sections cover the effects of bar surface condition, hole diameter, hole preparation method, bonding system, embedment length, bar diameter, cover, bar orientation, and concrete strength. The full test results[1] are summarized in Appendix A.*

Bar surface condition, hole diameter, hole preparation method, and bonding method system

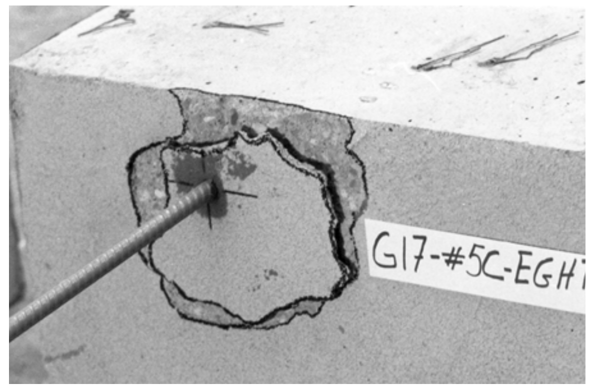
Six test groups (three each for vertically anchored No. 5 and No. 8 [16 and 25 mm] bars) were selected to evaluate the effects of bar surface condition, hole diameter, hole preparation method, and bonding system on bond strength. The bars had a nominal cover of 3 in. (75 mm) and embedded lengths of 6 and 9 in. (150 and 330 mm) for No. 5 and No. 8 bars, respectively. No. 5 bars were used to evaluate the effects of hole diameter. The results are summarized in Tables 1 and 2. The mean bond strengths listed in the tables are averages for three specimens, each of the three taken from a different test group.

Surface condition—Results indicate no significant effect of epoxy coating on the bond strength of grouted reinforcement. Comparisons of coated and uncoated bars are made in Table 1 for No. 5 bars with Nonshrink Grout A (NSA) and Two-Component Grout A (TCA). Of the four comparisons shown in the table, the uncoated bars (marked M for mill scale surface) provide a higher bond strength in one case, the epoxy-coated bars (marked E) provide a higher bond strength in two cases, and the two surface conditions provide nearly identical strengths in the fourth case.

Hole diameter—Increased hole diameter is often considered to result in a decreased bond strength.[18] To determine the effect of hole diameter on bond strength, No. 5 (16 mm) bars were grouted in 7/8 in. (22 mm) diameter and 1-1/2 in. (38 mm) diameter holes using the two nonshrink grouts (NSA and NSB) and the two two-component grouts (TCA and TCB). The capsule systems were not used in the comparison due to their dependence on a small hole diameter for proper performance.

For the six comparisons shown in Table 1, the small diameter hole produced a higher strength in two cases, and the large diameter hole produced a higher strength in three cases. The results were nearly identical in the sixth case. The overall

(a)



(b)

Fig. 3—Test specimens at failure: (a) splitting failure; (b) combined cone failure and failure at interface between grout and concrete (IGC).

*The Appendix is available in xerographic or similar form from ACI headquarters, where it will be kept permanently on file, at a charge equal to the cost of reproduction plus handling at time of request.

Table 1—Mean bond strength* (kips) as affected by bar surface condition, hole diameter, and hole preparation method for grouted No. 5 (16 mm) bars

Bar surface grout†	Hole preparation method: rotary hammer drill	Hole diameter‡	
		Small	Large
E-CPA	BW§	11.0	—
E-CPB	BW	9.7	—
M-NSA	BW	15.1	14.2
	BA	—	15.3
	A	—	15.5
E-NSA	BW	13.1	14.9
E-NSB	BW	14.2	14.1
M-TCA	BW	10.3	12.4
E-TCA	BW	11.7	12.5
E-TCB	BW	15.8	15.0

*Average of three tests; nominal concrete strength = 5000 psi (34.4 MPa); embedded length = 6 in. (150 mm); vertical placement.
†E = epoxy-coated; CPA = capsule grout system; NSA = nonshrink grout; NSB = nonshrink grout; TCA = stiff two-component grout; TCB = fluid two-component grout.
‡Small = 7/8 in. (22 mm), except = 13/16 in. (21 mm) for CPA and 3/4 in. (19 mm) for CPB; large = 1-1/2 in. (38 mm).
§BW = brush with water followed by compressed air; BA = brush and compressed air; A = compressed air only.
Note: 1 kip = 4.45 kN.

Table 2—Mean bond strength* (kips) as affected by hole preparation for grouted No. 8 (25 mm) bars

Bar surface grout†	E-CPA	E-NSA	E-TCA	E-TCB
Hole preparation method‡				
Vacuum drill V	25.7	24.8	23.4	24.9
Rotary hammer drill				
BW	26.7	25.2	16.6	24.7
BA	28.2	23.2	14.6	24.9
A	27.5	23.9	16.8	24.8

*Average of three tests; nominal concrete strength = 5000 psi (34.4 MPa); embedded length = 9 in. (230 mm); vertical placement.
†E = epoxy-coated; CPA = capsule grout system; NSA = nonshrink grout; NSB = nonshrink grout; TCA = stiff two-component grout; TCB = fluid two-component grout.
‡V = truck-mounted vacuum drill; BW = brush with water followed by compressed air; BA = brush and compressed air; A = compressed air only.
Note: 1 kip = 4.45 kN.

conclusion is that for the four grouting systems evaluated, hole diameter does not play a role in bond strength. It is, of course, important to remember that an increased hole diameter requires a greater amount of grout, reducing the economy of the system, and that the bond strength of capsule systems can be very sensitive to hole diameter, as will be demonstrated later in the paper.

Hole preparation—Hole preparation involved the use of either a vacuum drill or a hand-held rotary hammer drill. When the vacuum drill (V) was used, no additional hole preparation was used. With the hand-held drill, the holes were first cleaned with a shop vacuum. The openings were then cleaned with 1) a fiber brush and water, allowed to dry, and then cleaned with compressed air (BW); 2) a fiber brush without water, followed by compressed air (BA); or 3) with compressed air only (A). Bond strengths, as affected by preparation method, are compared in Table 1 for uncoated No. 5 (16 mm) bars with Nonshrink Grout A (M-NSA), cast in 1-1/2 in. (38 mm) diameter holes, and in Table 2 for epoxy-coated No. 8 (25 mm) bars cast with Capsule System A (E-CPA), Nonshrink Grout System A (E-NSA), and Two-Component Grout Systems A and B (E-TCA and E-TCB). The vacuum drilling system (V) was used only for the No. 8 bars.

As shown in Table 1, the brush with water (BW) cleaning system provides a slightly lower bond strength for the NSA grout than does either the brush with air (BA) or compressed air (A) alone, which provide nearly identical strengths. However, the differences are not significant.

The comparisons in Table 2 for No. 8 (25 mm) bars show no statistically significant differences based on hole preparation method, with the exception of the bars anchored with Two-Component System A (TCA). The TCA grout is a stiff, rapid-setting polymer system that does not readily wet (penetrate) concrete surfaces. It provides a bond strength comparable to that provided by the other grouts when used in holes prepared with the vacuum drill. However, its bond strength drops about one-third when anchored in holes prepared with the hand-held drill and cleaned with one of the other three methods. The lower strength may be due to the presence of residual drilling debris on the concrete surface, not removed by the BW, BA, or A cleaning methods. This observation is reinforced by the failure modes of the test specimens. The TCA bars anchored in holes prepared using the hand-held drill and the BW, BA, or A cleaning method exhibited a failure at the interface between the grout and the concrete (IGC). The bars anchored with the TCA system in the holes prepared with the vacuum drill and all three of the other anchoring systems for all hole preparation methods exhibited a splitting failure, indicating a better bond between grout and concrete.

These results show that for most systems a reasonable effort to clean the hole will provide adequate bond between the grout and the concrete. However, some grout systems are sensitive to the hole preparation method and should be evaluated based on the preparation specified for use in the field.

Bonding system—A review of Tables 1 and 2 indicates that, for the systems evaluated, there can be measurable differences in bond strength. In the case of the No. 5 (16 mm) bars, the two capsule systems provided generally lower strengths than the other systems. In contrast, for the No. 8 (25 mm) bars, the capsule system (CPA) provided the highest strengths, although in the latter case the differences in strength between CPA and the NSA or TCB grouts are not statistically significant. As will be demonstrated next, however, the accurate evaluation of a grout system requires an understanding of the bond strength produced by the system as a function of embedment length, bar diameter, and concrete cover.

Embedment length, bar diameter, and cover

A prime goal of this study is to determine the effects of the key structural parameters, embedment length, bar diameter, and cover, on the bond strength of grouted reinforcing bars. It is generally acknowledged that the bond strength of cast-in-place reinforcing bars decreases as cover decreases.[16,17] The majority of the tests in the current study were carried out with 3 in. (75 mm) cover, the minimum recommended for grouted reinforcing bars in most bridge installations.[19] A small number of tests were carried out with 1-1/2 in. (38 mm) cover. The comparisons that follow are based on bars grouted in vertical holes prepared using the BA cleaning method.

Embedment length—The effect of embedment length ℓ_e on the modified bond strength T_e of vertically anchored No. 5 and No. 8 (16 and 25 mm) bars is illustrated in Fig. 4. Embedment lengths of 4, 6, 9, and 12 in. (100, 150, 230, and 305 mm) are used for No. 5 (16 mm) bars. Embedment lengths of 6, 9, 12, and 15 in. (150, 230, 305, and 380 mm) are used for No. 8 (25 mm) bars. The figure shows the modified bond strengths and the best-fit lines for uncoated (M) and epoxy-coated (E) cast-in-place bars and epoxy-coated TCA and TCB-grouted bars. The relationships between bond strength and embedment length are nearly linear.

Overall, uncoated cast-in-place bars provide the highest strengths, followed by coated cast-in-place bars, bars anchored with TCB grout, and, finally, bars anchored with TCA grout, although the epoxy-coated (E) cast-in-place (CIP) No. 5 bars exhibit higher strengths than the uncoated (M) CIP No. 5 bars for ℓ_e = 9 to 12 in. (230 to 305 mm).

For both No. 5 and No. 8 (16 and 25 mm) bars, the bond strength of the TCB-anchored bars is similar to the strength of the epoxy-coated cast-in-place (E-CIP) bars. Based on best-fit lines, the TCB/E-CIP strength ratio ranges from 1.10 to 0.91 with increasing embedment length for No. 5 bars, and from 0.985 to 0.975 for No. 8 bars.

The bond strength of TCA-anchored bars is significantly lower than the bond strengths of TCB-anchored bars. Based on the best-fit lines, the TCA/E-CIP strength ratio is nearly constant, 0.73 to 0.74, for No. 5 bars and ranges from 0.67 to 0.79 for No. 8 bars.

Bar diameter—The effect of bar diameter on bond strength is also illustrated in Fig. 4, which shows that the No. 5 (16 mm) bars have lower bond strengths than the No. 8 (25 mm) bars. The effect of bar diameter is greater for the cast-in-place and TCB-grouted bars than for the TCA-grouted bars. For embedment lengths of 6 and 12 in. (150 and 305 mm), respectively, the No. 5/No. 8 strength ratios are 0.82 and 0.76 for uncoated (M) cast-in-place bars, 0.88 and 0.94 for epoxy-coated (E) cast-in-place bars, 0.90 and 0.87 for TCB-grouted bars, and 0.97 and 0.90 for TCA-grouted bars, based on the best-fit lines. This effect of bar size on bond strength is similar to that observed for spliced cast-in-place bars.[16,17]

Cover—The effect of cover on bond strength is evaluated for uncoated and epoxy-coated cast-in-place and epoxy-coated TCA and TCB-anchored No. 5 (16 mm) bars in Fig. 5. The reduction in concrete cover from 3 to 1-1/2 in. (75 to 38 mm) results in a reduction in bond force in all cases. For embedment lengths of 6 and 12 in. (150 and 305 mm) (as represented by the best-fit lines), the 1-1/2 in./3 in. (38 mm/75 mm) cover strength ratios are, respectively, 0.86 and 0.99 for uncoated (M) cast-in-place bars, 0.81 and 0.85 for epoxy-coated (E) cast-in-place bars, 0.86 and 0.91 for TCB-grouted bars, and 0.74 and 0.78 for TCA-grouted bars. In none of these cases, however, is bond strength as sensitive to cover as it is for the splice strength of cast-in-place bars.[17]

Horizontal bars

Top-cast and bottom-cast No. 5 and No. 8 bars with 3 in. (75 mm) cover were used to evaluate the bond strength of

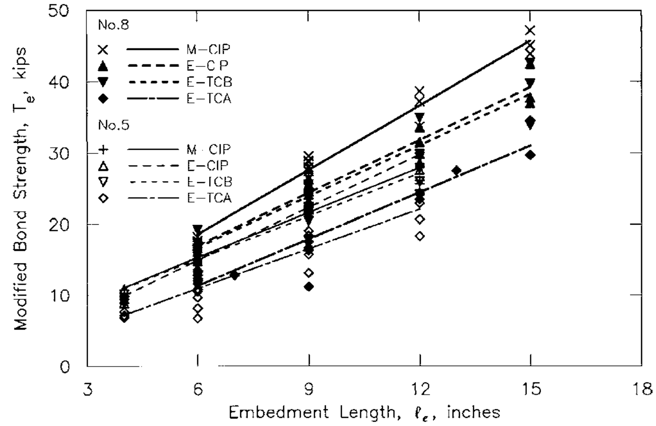


Fig. 4—Modified bond strength T_e *versus embedment length* ℓ_e *for vertical No. 5 and 8 (16 and 25 mm) bars with 3 in. cover (1 kip = 4.45 kN; 1 in. = 25.4 mm).*

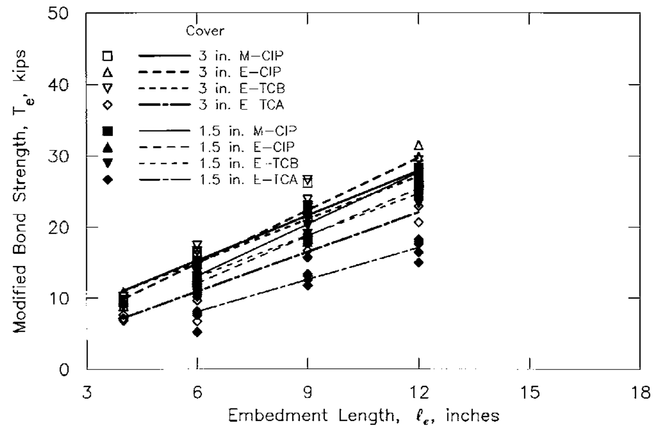


Fig. 5—Modified bond strength T_e *versus embedment length* ℓ_e *for vertical No. 5 (16 mm) bars with 1-1/2 and 3 in. cover (1 kip = 4.45 kN; 1 in. = 25.4 mm).*

bars grouted in horizontal holes. The No. 8 bars were cast-in-place or anchored in 1-1/4 in. (32 mm) diameter holes with CPA, NSA, and TCA grouts, while the No. 5 bars were cast-in-place or anchored in 7/8 in. (22 mm) holes with CPA and TCA grouts. All bars were epoxy-coated. The results are illustrated in Fig. 6 for the top-cast bars.

Fig. 6 shows that the cast-in-place and CPA-grouted No. 8 (25 mm) bars have similar strengths. In fact, the CPA bars have higher strengths for embedment lengths of 9 in. (230 mm) or more. The No. 8 (25 mm) NSA and TCA-grouted bars exhibit significantly lower strengths, with the NSA-grouted bars exhibiting higher strengths than the TCA-grouted bars. For ℓ_e = 6 and 15 in. (150 and 380 mm), the grouted-to-cast-in-place strength ratios are, respectively, 0.96 and 1.05 for CPA, 0.70 and 0.92 for NSA, and 0.65 and 0.84 for TCA.

For No. 5 (16 mm) bars, Fig. 6 shows that the cast-in-place bars are significantly stronger than the TCA-grouted bars, which are stronger than the CPA-grouted bars. The CPA-grouted bars actually decrease in strength with increasing ℓ_e. As with vertically placed bars, horizontal No. 5 bars provide lower bond strengths than horizontal No. 8 bars with the same embedment length and anchoring method.

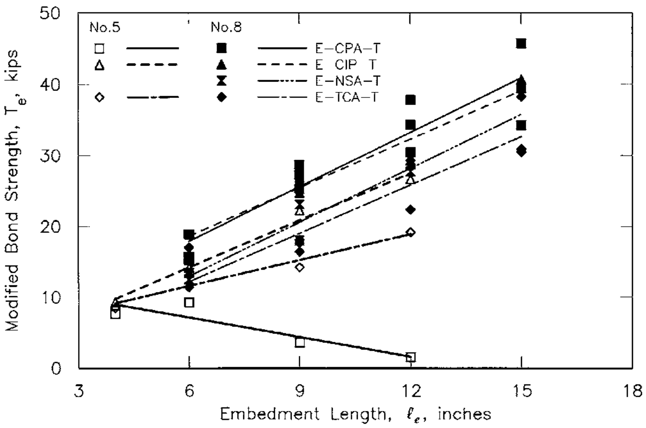


Fig. 6—Modified bond strength T_e *versus embedment length* ℓ_e *for top-cast horizontal No. 5 and 8 (16 and 25 mm) bars with 3 in. cover (1 kip = 4.45 kN; 1 in. = 25.4 mm).*

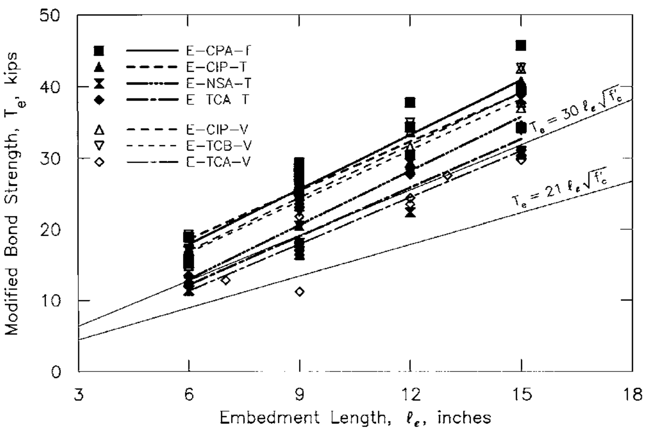


Fig. 7—Modified bond strength T_e *versus embedment length* ℓ_e *for vertical and top-cast horizontal No. 8 (25 mm) bars with 3 in. cover and expressions defining minimum strength class requirements for* f_c' *= 5000 psi (1 kip = 4.45 kN; 1 in. = 25.4 mm; 1000 psi = 6.89 MPa).*

The behavior of the CPA-grouted No. 5 (16 mm) bars (Fig. 6) represents a significant departure from the behavior observed for any other bars. The CPA No. 5 bars exhibit nearly equal strengths for ℓ_e = 4 and 6 in. (100 and 150 mm), but progressively lower strengths for ℓ_e = 9 and 12 in. (230 and 305 mm). The strength for ℓ_e = 6 in. (150 mm) is below that observed for the vertically placed No. 5 bars anchored with CPA grout (Table 1). The low strength (at all embedment lengths) may be due to the fact that the 7/8 in. (22 mm) hole diameter used for the CPA bars is greater than the value of 13/16 in. (21 mm) recommended by the manufacturer and used for the vertical bars. Since CPA grout contains micro-aggregate particles, the size of which may play an important role in interlock as bond failure occurs, the greater gap between the reinforcing bar and the wall of the hole may have resulted in the lower capacity. This was not a factor for the No. 8 (25 mm) bars, since the hole diameter used for the No. 8 bars, 1-1/4 in. (32 mm), was that recommended by the manufacturer. For the No. 5 bars with ℓ_e = 4 and 12 in. (100 and 305 mm), the grouted-to-cast-in-place strength ratios are, respectively, 0.94 and 0.69 for TCA and 0.92 and 0.05 for CPA based on the best-fit lines. The trends observed for top-cast bars were also exhibited by the bottom-cast bars.[1]

Top-bar effect—The bottom-cast No. 8 bars in this study exhibited higher bond strengths than the corresponding top-cast bars for all values of ℓ_e. The higher capacity is likely due to the higher quality of the concrete at the bottom of the placement. Overall, the top-bar effect (ratio of bond strengths of bottom-cast bars to top-cast bars) based on the best-fit lines ranges from 1.08 to 1.10 for cast-in-place No. 8 (25-mm) bars, from 1.00 to 1.06 for cast-in-place No. 5 (16 mm) bars, from 1.06 to 1.15 for CPA-grouted No. 8 bars, from 1.06 to 1.08 for NSA-grouted No. 8 bars, from 1.03 to 1.06 for TCA-grouted No. 8 bars, and from 0.96 to 1.02 for TCA-grouted No. 5 bars [the top-bar effect for the CPA-grouted No. 5 bars, which ranges from 0.85 to 3.13, is not of much practical interest, but is reported for completeness]. These values compare to top-bar factors of 1.3 and 1.4 used by the ACI Building Code[20] and AASHTO Bridge Specifications,[21] respectively.

Comparison with vertically anchored bars—Fig. 7 compares the bond strengths for vertical and top-cast horizontal No. 8 (25 mm) bars and demonstrates that for the cast-in-place (CIP) and TCA-anchored No. 8 bars the top-cast horizontal bars, on average, provide slightly higher strengths than the vertical bars (maximum difference in best-fit lines = 1.7 kips [7.6 kN] in both cases). Comparisons for the CPA and NSA-grouted bars must be made based on a single embedded length, since vertically anchored No. 8 bars using these grouts were tested only with 9 in. (230 mm) embedment lengths. In these cases, bond strength is more sensitive to bar orientation. For ℓ_e = 9 in. (230 mm), the CPA and NSA-grouted top-cast horizontal bars have lower average strengths than the corresponding vertical bars, 25.6 versus 28.2 kips (114 versus 125 kN) for the CPA-grouted bars and 20.6 versus 23.2 kips (92 versus 103 kN) for the NSA-grouted bars.

As shown in Fig. 8, the horizontal No. 5 (16 mm) cast-in-place and TCA-grouted bars have lower strengths than the corresponding vertical bars for most values of ℓ_e. The low strength of the top-cast horizontal CPA-grouted bars was discussed earlier in the paper.

Sloped bars

Grouted reinforcing bars are often inserted at an angle rather than perpendicular to the surface. To evaluate the effect of bar slope on bond strength, 15 No. 5 (16 mm) bars were inserted at a slope—six with a slope of 1:3 and nine with a slope of 1:6 [Fig. 1(a)]. The bars were oriented so that the cover increased with increasing embedment.

The sloped bars exhibited strengths that were equal to or greater than the strengths of bars that were placed with uniform cover equal to the minimum cover on the sloped bar in all but two tests (two NSA-grouted bars with ℓ_e = 6 in. [150 mm] and a 1:6 slope). Considering the fact that the preponderance of that data indicates improved performance, it appears that it would be safe to consider sloped reinforcement as equivalent to reinforcement placed with a constant cover equal to the minimum cover on the sloped bar.

Concrete strength

One test group was used to provide some insight into the effect of concrete strength on the bond capacity of anchored bars. The group consisted of nine vertically anchored No. 5 bars, with 6-in. embedment. Three bars each were anchored with NSA, CPA, and TCA grouts. The concrete had a strength of 2700 psi (18.6 MPa) at the time of the test, producing bond strengths significantly below those provided by bars with nominal concrete strengths of 5000 psi (34.5 MPa). However, when the bond strengths are multiplied by $(5000/f_c')^{1/2}$ [f_c' in psi], the modified bond strengths overlap the test results provided by the vertically anchored No. 5 bars in 5000 psi (34.5 MPa) concrete. For NSA grout, the modified bond strengths range from 13.1 to 15.2 kips (58 to 68 kN), compared to a range of 10.9 to 17.4 kips (48 to 77 kN) for the earlier (5000 psi [34.5 MPa] concrete) tests at a 6 in. (150 mm) embedment; for CPA grout, modified bond strengths range from 7.0 to 13.5 kips (31 to 60 kN), compared to 10.0 to 18.5 kips (44 to 82 MPa) for earlier tests; and for TCA grout, modified bond strengths range from 8.7 to 12.3 kips (39 to 55 kN), compared to 6.8 to 15.4 kips (30 to 69 kN) for earlier tests.

This limited comparison suggests that using the square root of the compressive strength is a reasonable way to account for the effect of concrete strength on the capacity of grouted reinforcing bars. The limited nature of the data also suggests that additional tests would be worthwhile.

RECOMMENDATIONS FOR DESIGN AND CONSTRUCTION

The design procedures that follow recognize that: 1) different grouts exhibit different strengths; 2) individual grouts may provide different strengths when used to anchor bars in horizontal and vertical holes; 3) the bond strength provided by grouted bars drops with decreasing cover; and 4) the bond strength of a sloped bar can be conservatively represented by the strength of a bar with a constant concrete cover equal to the minimum cover on the sloped bar. Although not evaluated in this study, it is assumed that the bond strength of grouted bars will drop with decreasing center-to-center spacing, as occurs for cast-in-place bars.[16,17]

The approach defines three strength classes of grout: Strength Class A, Strength Class B, and a Special Strength Class. Strength Classes A and B are based on minimum strength requirements, while the Special Strength Class is provided to allow for the use of the actual test results.

Definitions

Strength class—A category of grout based on the bond strength it provides for anchoring embedded reinforcement. The strength class of a grout should be established separately, and need not be the same, for horizontal and vertical bar installations, since it is observed that grouts can perform differently based on bar orientation. The procedures for establishing the strength class should match those used in this study and are spelled out in ASTM format in Reference 1 and summarized below.

Strength Class A Grout—A grout that provides a minimum average bond strength $T_e = A_b f_s = 30\ell_e\sqrt{f_c'}$ for $\ell_e = 9d_b$ and $\ell_e = 15d_b$, in which T_e = tensile force in grouted

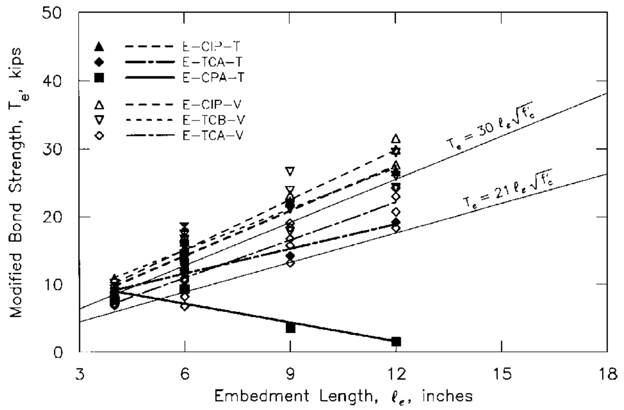


Fig. 8—Modified bond strength T_e *versus embedment length* ℓ_e *for vertical and top-cast horizontal No. 5 (16 mm) bars with 3 in. cover and expressions defining minimum strength class requirements for* f_c' *= 5000 psi (1 kip = 4.45 kN; 1 in. = 25.4 mm; 1000 psi = 6.89 MPa).*

reinforcement at bond failure, lb; A_b = area of an individual bar, in.^{2}; f_s = tensile stress in reinforcement, psi; ℓ_e = embedded length of grouted reinforcement, in.; $\sqrt{f_c'}$ = square root of concrete compressive strength, psi.

Strength Class B Grout—A grout that provides a minimum average bond strength = 70 percent of that required of a Strength Class A grout.

Special Strength Class Grout—A grout that provides a minimum average bond strength = $T_e = A_b f_s = \gamma\ell_e\sqrt{f_c'}$ for $\ell_e = 9d_b$ and $\ell_e = 15d_b$, in which γ = factor obtained in evaluating grout strength = $T_e(avg)/\ell_e\sqrt{f_c'}$.

Grout Strength Classes A and B were established using the test results for top-cast horizontal and vertical bars. The specific strength requirements defining the classes were selected primarily based on the strength properties of grouted No. 5 bars, since these provide lower bond strengths than larger bars with the same embedment length.

Two primary strength classes, A and B, were selected to both allow economical use of the highest strength grouts without preventing the use of lower strength grouts that may have desirable construction properties, such as rapid curing, but require longer embedment lengths. The Special Strength Class allows any grout to be used based on its actual performance. The strength of a Special Strength Class grout may be above or below that of Strength Classes A or B. The proposed requirements for evaluating the strength of a grout[1] require a minimum of three tests each at embedment lengths equal to 9 and 15 bar diameters, and a cover of 3 in. (75 mm). General qualification as a Strength Class A, Strength Class B, or Special Strength Class grout would require the use of No. 5 bars. However, a Special Strength Class grout could be qualified using a bar size other than No. 5, but the application of that Special Strength Class would be limited to the bar size used in the test.

The requirements for Strength Class A and Strength Class B are compared with the test results for vertical and top-cast horizontal No. 5 and No. 8 (16- and 25-mm) bars in Fig. 8 and 7, respectively. As illustrated in Fig. 8, TCB grout in vertical holes would qualify as a Strength Class A grout, while TCA in both vertical and top-cast horizontal holes would qualify as a Strength Class B grout. CPA grout, as applied with a single capsule and oversize holes (not in accordance with the manufacturer's recommendations), would not meet the requirements of a standard strength class grout.

The No. 8 bars provide higher strengths than the No. 5 bars, as illustrated in Fig. 7. CPA grout and NSA grout in top-cast horizontal holes and TCB grout in vertical holes meet the requirements of a Strength Class A grout, while TCA grout in both horizontal top-cast and vertical holes provides strengths that place it in the upper range of Class B grouts. Under these proposed design procedures, the engineer would have the option of using the lower strengths obtained with the No. 5 bars to establish the strength class or treating the grouts used with the No. 8 bars as belonging to a Special Strength Class to take advantage of the higher strengths obtained with the larger bars.

Design

Strength reduction factors

1. Steel yield strength: $\phi = 0.90$
2. Bond strength: $\phi = 0.65$

A strength reduction factor of 0.90 is commonly used when strength is governed by tensile yielding of reinforcing steel.[20-22] A strength reduction factor of 0.65 is commonly used when strength is governed by the tensile strength of concrete or the anchorage provided by a grout.[5,22]

Design tensile strength—The design tensile strength of grouted reinforcement ϕT_n must exceed the factored tensile force in the reinforcement. ϕT_n is equal to the smaller of the design tensile force based on the yield strength of the bar, given by Eq. (1), and the design tensile force based on the bond strength of the grout, given by Eq. (2), (3), or (4)

$$\phi T_n = \phi A_b f_y = 0.9 A_b f_y \tag{1}$$

in which f_y = specified yield strength of reinforcement, psi.

Strength Class A Grout

$$\phi T_n = \phi 30 l_e \sqrt{f_c'} = 19.5 l_e \sqrt{f_c'} \tag{2}$$

Strength Class B Grout

$$\phi T_n = \phi 21 l_e \sqrt{f_c'} = 13.7 l_e \sqrt{f_c'} \tag{3}$$

Special Strength Class Grout

$$\phi T_n = \phi \gamma l_e \sqrt{f_c'} = 0.65 \gamma l_e \sqrt{f_c'} \tag{4}$$

Eq. (2) and (3) produce predicted strengths equal to 78 and 55 percent, respectively, of the strength that would be calculated for cast-in-place bars using the expression for basic development length in the 1989 ACI Building Code[20] and the 1992 AASHTO Bridge Specifications.[21]

Modification factors based on cover and bar spacing—For bars with covers less than 3 in. (75 mm) or clear spacings less than 6 in. (150 mm), the value of design strength ϕT_n, calculated using Eq. (2), (3), or (4), should be modified by a factor of 0.85 for bars anchored with a grout that meets the requirements of a Strength Class A grout and 0.75 for bars anchored with grouts that do not. These requirements are based on observations made earlier in the paper indicating that the bond strengths of bars anchored with Strength Class B grouts are more sensitive to low covers than the bond strengths of bars anchored with Strength Class A grouts. Both modification factors are less severe than the corresponding factors in ACI 318-89,[20] reflecting the lower cover sensitivity of bars that are grouted compared to bars that are spliced or developed. Covers less than 1-1/2 in. (38 mm) and clear spacings less than 3 in. (75 mm) should not be permitted unless justified by tests. For bars with cover that changes along the embedded length, cover should be interpreted as minimum cover.

Construction requirements

The principal construction considerations are hole size and cleanliness. The only case in which hole diameter appears to affect strength is when capsules are used. To cover this case, construction requirements should require the use of "hole diameters that have been demonstrated to provide adequate strength."

To insure adequate surface properties, holes should be vacuumed (as with a shop vacuum) after drilling, brushed with a fiber brush, and then blown out with compressed air (filtered for oil and water). If another less stringent cleaning method is used, the grout bond strength should be qualified using the alternate cleaning method.

CONCLUSIONS

The following conclusions are based on the tests and evaluations presented in this paper.

1. For the techniques evaluated in this study, the bond strength of grouted reinforcing bars is not highly sensitive to differences in hole preparation method. Drilling methods that do not damage the surrounding concrete and most hole-cleaning methods are satisfactory for most grouts. Grouts that tend to exhibit a bond failure at the interface between grout and concrete (IGC) may provide higher strengths with more thorough cleaning methods. The vacuum drilling procedure appears to provide the best strength for grouts that exhibit IGC failures. However, this method is not required, nor does it give the highest strength for most other grout installations. Vacuuming, followed by cleaning with a fiber bottle brush and compressed air, is recommended.

2. There can be significant differences in grout strength. Grouts that provide a strong bond at the grout-concrete interface provide higher bond strengths than grouts that undergo failure at the grout-concrete interface.

3. The bond strength provided by most grouts is not sensitive to the hole diameter. However, bond strength may be severely decreased for bars anchored with capsules if the hole diameter is larger than recommended by the manufacturer.

4. Bond strength increases with increasing embedment length, bar size, and cover. The bond strength of both cast-in-place and grouted reinforcing bars subjected to tension at the surface of concrete appears to be less sensitive to cover

than is the strength of cast-in-place spliced reinforcement within reinforced concrete members.

5. Cast-in-place epoxy-coated reinforcement provides a lower bond strength than cast-in-place uncoated reinforcement. Grouted epoxy-coated reinforcement and grouted uncoated reinforcement provide similar bond strengths.

6. Grouted vertically anchored bars and grouted top-cast horizontally anchored bars provide similar strengths for some grouts and different strengths for other grouts. Therefore, it is recommended that grouts be qualified separately for anchorage at each orientation. Grouted bottom-cast horizontal reinforcement provides a higher bond strength than grouted top-cast reinforcement.

7. The bond strength of a sloped bar can be conservatively represented by the bond strength of a bar with a constant concrete cover equal to the minimum cover on the sloped bar.

8. For the grouts tested, bond strength increases approximately with the square root of concrete compressive strength.

ACKNOWLEDGMENTS

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NOTATION

A	=	air cleaning method
A_b	=	area of individual bar, in.^{2}
B	=	bottom-cast horizontal bar
BA	=	brush with air-cleaning method
BW	=	brush with water-cleaning method
CIP	=	cast-in-place
CPA, CPB	=	Capsule A, Capsule B
E	=	epoxy-coated
f_c'	=	compressive strength of concrete, psi
f_s	=	tensile stress in reinforcement, psi
H	=	horizontal bar
IGC	=	failure at interface between grout and concrete
ℓ_e	=	embedded length of grouted reinforcement, in.
M	=	mill scale (uncoated)
NSA, NSB	=	Nonshrink Grout A, Nonshrink Grout B
T	=	top-cast horizontal bar
TCA, TCB	=	stiff two-component Grout A, fluid two-component Grout B
T_e	=	bond strength of grouted reinforcement = maximum tensile force attained during a test, lb
T_n	=	nominal tensile force in grouted reinforcement, lb
V	=	vacuum-drilled or vertical bar
γ	=	factor obtained in evaluating grout strength = $T_e(\text{avg})/\ell_e\sqrt{f_c'}$
ϕ	=	strength reduction factor

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93-S45

Supplement to:

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Appendix to:

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"Bond Strength of Grouted Reinforcing Bars" by D. Darwin and S.S. Zavaregh

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APPENDIX A

to

BOND STRENGTH OF GROUTED REINFORCING BARS

by

David Darwin and Shahin S. Zavaregh

TEST DATA

Table A.1: Test Bar Data

Bar Size No.	Def Pattern	Yield Strength (ksi)	Def. Height (in.)	Def. Spacing (in.)	Def. Gap (in.)	Def. Angle (deg.)
5*	C	72.3	0.041	0.413	0.116	60
5**	C	72.3	0.040	0.413	0.140	60
5***	C	65.5	0.041	0.403	0.182	60
5	S	70.6	0.031	0.423	0.159	90
8***	C	69.0	0.062	0.654	0.165	60
8+	C	67.6	0.064	0.590	0.285	60
8++	C	+++	0.062	0.656	0.195	60

* Used for epoxy-coated (E) bars; except as noted
** Used for uncoated (mill scale surface = M) bars, except as noted
*** Used for uncoated (M) bars in Groups 15-17, 19
\+ Used for uncoated (M) bars in Groups 12-14
++ Used for horizontal bars in Group 24
+++ Yield strength is greater than 70.0 ksi

Table A.2: Concrete Mixture Proportions (Cubic Yard Batch Weights)

Group	Nominal Strength (psi)	W/C ratio	Cement (lb)	Water (lb)	Aggregate Fine+ (lb)	Aggregate Coarse++ (lb)
1	5000	0.46	520	240	1525	1525
2	5000	0.42	544	230	1595	1595
4-22,24	5000	0.43	520	225	1545	1545
23	2500	0.46	496	228	1508	1565

\+ Kansas River Sand - Lawrence Sand Co., Lawrence, KS, bulk specific gravity (ssd) = 2.62, absorption = 0.5%, fineness modulus = 3.0.
++ Crushed limestone - Fogel's Quarry, Ottawa, KS, bulk specific gravity (ssd) = 2.57 absorption = 3.0%, nominal maximum size = 3/4 in., unit weight = 90.5 lb/cu. ft.

Table A.3: Concrete Properties

Group	Slump (in.)	Concrete Temperature (F)	Age at Test (days)	Grout Age at Test (days)	Air Content %	Average Compressive Strength (psi)
1	3 1/2	78	69	3-4	*	5340
2	4	78	41	5-6	3.1	5350
			42			5500
4	2	72	78	3-4	1.9	5460
5	2 1/2	74	56	4-5,7	5.6	5570
6	3	63	33	7	5.8	5250
			34	8		5530
7	3 1/2	51	16	3	5.8	4460
8	3	52	24	3	5.9	4710
9	3 1/4	45	27	3	6.4	5360
10	3 1/2	52	20	3	5.5	4970
11	3 1/2	52	31	4	6.4	5230
12	2 3/4	64	25	3	6.2	5270
13	3	59	21	3	5.2	5600
14	4 5/8	60	22	3	6.6	4550
15	1 3/4	62	25	3	5.0	5360
			26	4		5480
			46	24		5870
16	4 3/4	68	39	3-4	6.2	4610
17	3 1/4	70	27	3	5.3	4980
18	3 1/4	67	35	3	5.6	5400
			45	3		5600
19	6 1/2	68	26	5	6.4	3960
			31	3		4270
20	2 1/2	69	47	3	4.9	5230
			57	3		5490
21	3	66	26	3	5.8	4410
			27			4660
			44	3		5270
22	2 3/4	67	24	3	4.8	4980
23	4 3/4	62	5	3	6.8	2700
24	3 1/2	59	22	3	5.8	4600
			29	7		4740
			53	31		4980
			53	6-7		4980**

* Not measured

** Horizontal Bars

Table A.4: Grout Data

Grout Symbol:	CPA*
Manufacturer:	Hilti, Inc. 5400 S. 122nd East Avenue Tulsa, OK 74146
Grout Trade Name and Description:	HEA Adhesive Capsule Vinyl ester resin system packed in sealed glass tubes. Part A is in the outer tube and Part B is in the inner tube.
Ingredients:	Part A: Styrene, vinyl ester resin Part B: Dibenzoyl peroxide, silica sand

Appropriate diameter capsule ($^5/_8$ x 5 in. or 1 in. x $8^1/_4$ in.) was inserted into a predrilled hole. Recommended hole diameter = $^{13}/_{16}$ in. for No. 5 bars and 1 $^1/_4$ in. for No. 8 bars. The rebar was inserted in setting tool mounted on a TE-72 Hilti rotary hammer drill. The end of the rebar with a 45° cut on it was placed on top of the capsule. The drill was switched on, and the rebar was drilled to the bottom of the hole with rotary hammer drill set in the hammer/rotation mode. The curing time varied based on the temperature of the base concrete.

Grout Symbol:	CPB
Manufacturer:	RAWLPLUG CO., Inc. P.O.Box 641 New Rochelle. NY 10802-9978
Grout Trade Name and Description:	Chem-Stud Capsule The Chem-Stud adhesive is packaged in single use (outer & inner) glass capsules which have premeasured components.
Ingredients:	Outer Capsule: Polyester resin, quartz aggregate Inner Capsule: Benzol peroxide hardening agent

A $^5/_8$ in. capsule was inserted into a predrilled hole. The rebar was inserted in setting tool mounted on a TE-72 Hilti rotary hammer drill. The end of the rebar with a 45° cut on it was placed on top of the capsule. The drill was switched on, and the rebar was drilled to the bottom of the hole with rotary hammer drill set in the hammer/rotation mode. The curing time varied based on the temperature of the base concrete.

Grout Symbol:	TCA*
Manufacturer:	Hilti, Inc. 5400 S. 122nd East Avenue Tulsa, OK 74146
Grout Trade Name and Description:	HIT C-100 Adhesive Material is packed in two tubes joined together. Part A is located in the larger tube, part B is located in the smaller tube.
Ingredients:	Part A: Vinyl ester resin, unsaturated polyester resin styrene, fumed silica, silica sand Part B: Dibenzoyl peroxide, fumed silica, paraffin wax, micro hollow balls

HIT C-100 adhesive was injected into the hole using a Hilti P-2000 manual dispenser. Rebar was rotated by hand during installation to insure proper adhesion between grout and rebar. The gel time and cure time of the grout varied based on the temperature of the base concrete.

Grout Symbol:	TCB
Manufacturer:	The Carter-Waters Corporation 2440 West Pennway P. O. Box 412676 Kansas City, MO 64141
Grout Trade Name and Description:	CWC 202, Type I A two component 100% solids, moisture insensitive, multipurpose structural epoxy bonding agent.
Ingredients:	Component A (epoxy resin) - Bisphenol A diglycidyl ether resin Component B - Polysulfied polymer, dimethylaminomethylphenol, 2,4,6, - Tri (Dimethylaminomethyl) phenol

Bonding Agent designed for application temperatures between 68°F and 104°F. Two component bonding agent was mixed in a 2:1 ratio by volume (two parts part A-resin, one part B-curing agent) for three minutes using a paint mixer blade mounted on a $^1/_4$ in. drill. Blending took place at low speed to avoid the formation of air bubbles in the mix. The grout, having a honey consistency, was poured directly into the hole, and rebar was rotated by hand during installation to insure proper adhesion. The grout had a pot life of 30 min. and a cure time of 24 hours at 75° F.

Grout Symbol:	NSA*
Manufacturer:	Cormix Construction Chemicals P. O. Box 190970 Dallas, TX 75219-0970
Grout Trade Name and Description:	Non-shrink Supreme Grout. A non-metallic grout, packaged in 55 lb. poly-lined bags.
Ingredients:	Silica aggregates, cements, a shrinkage compensating system, and plasticizing agents.

The non-shrink grout had a water requirement of 1 $^1/_4$ - 1 $^1/_2$ gal. per 55 lb. bag for a fluid state and a yield of $^1/_2$ ft^3 per bag. For fluid consistency, $^3/_4$ of the required water was placed in the container, grout was added slowly while mixing using the drill mounted mixer blade to the point of stalling the mixer. Grout was mixed to a doughy state until all dry material was thoroughly wet. After all lumps had disappeared, the remaining water was added. Mixing continued for a total of 3-5 min. or until a uniform consistency was achieved.

Since small batches were mixed at each placement, grout and water required were carefully measured based on 1 $^1/_2$ gal. per bag requirement. To avoid air pockets and insure complete filling of the hole, the grout was placed from one side of the hole only. Rebar was rotated by hand during installation to insure proper adhesion between grout and rebar. Care was exercised not to overwork the grout in order to avoid segregation or bleeding. Exposed grout surfaces around the rebar were sealed with duct tape for a minimum of 3 days. Working time was approximately 20 min. Setting time was approximately 25-30 min.

Grout Symbol:	NSB
Manufacturer:	Master Builders, Inc. 23700 Chagrin Boulevard Cleveland, Ohio 44122-5554
Grout Trade Name and Description:	MASTERFLOW 814 Cable Grout A one component cement-based grout packaged in 55 lb moisture-resistant bags.
Ingredients:	Portland Cement and other cementituous materials and materials that protect against stress corrosion and hold to a minimum all components including chlorides and sulfides.

Grout had a 2.55 gal. water requirement per 55 lb. bag, producing approximately 0.65 ft^3 of fluid grout. Required water and grout were carefully measured. Water was placed in a container. With the drill mounted mixer blade operating, grout was added steadily and mixed for 2-3 minutes until the grout was uniform and essentially free of lumps. To avoid air pockets and insure complete filling of the hole, the grout was placed from one side of the hole only. Rebar was rotated by hand during installation to insure proper adhesion between grout and rebar. Care was exercised not to overwork the grout in order to avoid segregation or bleeding. Exposed surfaces were moist cured for 24 hours and sealed thereafter for a minimum of 3 days.

*Horizontal Rebar Placement, CPA, NSA and TCA only:

For CPA and TCA, same procedure as described above.

For NSA, all of the required water was placed in the mixer (rather than $^3/_4$ as described above) and the grout was mixed to a doughy state. This produced a slightly stiffer grout. The only other difference compared to vertical bars was the method of grout placement in the horizontal hole. A dessert decorator with plastic tubing fitted at the end was custom made so that the grout could flow smoothly into the hole by means of injection. Care was exercised to fill up the hole as fully as possible prior to rebar placement.

Rebars were supported using a special bracing fitted around the concrete block.

Table A.5: Test Results

Group No.	Specimen label*	Anchorage method**	Cover in.	Concrete strength psi	Bond strength kips	Mod. bond strength*** kips	Failure mode****
			Groups 1 and 2				
1	5VC-M-6-7/8BW	NSA-NTR	3	5310	17.95	17.42	Pullout
2	5VC-M-6-7/8BW	NSA-NTR	2-15/16	5360	16.61	16.05	T
Avg						16.74	
1	5VC-M-6-13/16BV	CPA-NTR	3	5310	18.75	18.20	S
2	5VC-M-6-13/16BV	CPA-NTR	3-1/8	5360	19.17	18.52	S/T
Avg						18.36	
1	5VC-M-6-3/4BW	TCA-NTR	2-15/16	5310	14.38	13.96	IGC
2	5VC-M-6-3/4BW	TCA-NTR	3-1/16	5360		15.43	IGC/Cone
Avg						14.69	
1	5VC-M-6-7/8BA	NSA-NTR	3	5310	16.03	15.56	S
2	5VC-M-6-7/8BA	NSA-NTR	3-1/8	5510	15.25	14.53	Cone
Avg						15.05	
1	5VC-M-6-13/16BA	CPA-NTR	2-15/16	5390	14.85	14.30	Pullout
2	5VC-M-6-13/16BA	CPA-NTR	2-7/8	5360	18.48	17.86	S
Avg						16.08	
1	5VC-M-6-3/4BA	TCA-NTR	2-3/4	5310	8.16	7.92	IGC
2	5VC-M-6-3/4BA	TCA-NTR	3	5360	12.75	12.32	IGC/Cone
Avg						10.12	
1	5VC-M-6-7/8A	NSA-NTR	3	5390	13.30	12.81	IGC
2	5VC-M-6-7/8A	NSA-NTR	3-1/16	5510	17.91	17.07	S
Avg						14.94	
1	5VC-M-6-13/16A	CPA-NTR	3-1/8	5310	18.56	18.02	Pullout
2	5VC-M-6-13/16A	CPA-NTR	2-15/16	5360	17.00	16.43	Pullout
Avg						17.22	
1	5VC-M-6-3/4A	TCA-NTR	2-15/16	5390	9.69	9.33	IGC/Cone
2	5VC-M-6-3/4A	TCA-NTR	2-7/8	5360	10.93	10.56	IGC/Cone
Avg						9.95	
1	5VC-M-6-1.5BW	NSA-NTR	2-3/4	5310	15.65	15.19	S
2	5VC-M-6-1.5BW	NSA-NTR	2-5/8	5360	14.22	13.74	S/T
Avg						14.47	
1	5VC-M-6-1.5BW	TCA-NTR	3	5390	9.52	9.17	IGC
2	5VC-M-6-1.5BW	TCA-NTR	2-5/8	5360	9.22	8.91	IGC/S/Cone
Avg						9.04	
1	5VC-M-6-1.5BA	NSA-NTR	2-3/4	5390	16.05	15.46	IGC/S
2	5VC-M-6-1.5BA	NSA-NTR	3	5360	19.10	18.46	T
Avg						16.96	
1	5VC-M-6-1.5BA	TCA-NTR	3	5310	11.25	10.92	IGC
2	5VC-M-6-1.5BA	TCA-NTR	2-15/16	5510	12.51	11.92	IGC

Table A.5: Test Results, continued

Group No.	Specimen label*	Anchorage method**	Cover in.	Concrete strength psi	Bond strength kips	Mod. bond strength*** kips	Failure mode****
Avg						11.42	
1	5VC-M-6-1.5A	NSA-NTR	2-13/16	5310	15.80	15.34	T
2	5VC-M-6-1.5A	NSA-NTR	2-11/16	5360	15.24	14.73	S/T
Avg						15.03	
1	5VC-M-6-1.5A	TCA-NTR	2-7/8	5360	13.71	13.25	IGC
2	5VC-M-6-1.5A	TCA-NTR	2-11/16	5510	9.87	9.40	IGC
Avg						11.33	
1	5VC-M-6	CIP-NTR	3	5310	15.31	14.86	T
2	5VC-M-6	CIP-NTR	3-1/16	5510	14.56	13.87	S/T
Avg						14.37	
1	5VC-E-6	CIP-NTR	3	5310	15.40	14.95	T
2	5VC-E-6	CIP-NTR	3-1/16	5510	14.63	13.94	S/T
Avg						14.44	
			Groups 4, 5 and 6				
4	5VC-M-6-7/8BW	NSA	3	5460	17.15	16.41	S
5	5VC-M-6-7/8BW	NSA	2-15/16	5570	15.74	14.91	T
6	5VC-M-6-7/8BW	NSA	2-15/16	5410	14.46	13.90	S
Avg						15.08	
5	5VC-E-6-7/8BW	NSA	3	5570	16.14	15.29	S
6	5VC-E-6-7/8BW	NSA	2-3/4	5410	11.36	10.92	S
Avg						13.11	
4	5VC-E-6-7/8BW	NSB	2-7/8	5460	14.88	14.24	S/Cone
5	5VC-E-6-7/8BW	NSB	3-1/16	5570	15.26	14.46	S/Cone
6	5VC-E-6-7/8BW	NSB	3	5410	14.38	13.82	S
Avg						14.17	
4	5VC-E-6-7/8BW	TCB	3-1/16	5460	18.77	17.96	S
5	5VC-E-6-7/8BW	TCB	2 13/16	5570	16.91	16.02	S
6	5VC-E-6-7/8BW	TCB	2-7/8	5410	14.00	13.46	S
Avg						15.81	
4	5VC-E-6-3/4BW	CPB	3	5460	11.59	11.09	S/Cone
5	5VC-E-6-3/4BW	CPB	2-7/8	5520	11.25	10.66	S/Cone
6	5VC-E-6-3/4BW	CPB	3	5410	7.64	7.34	IGC/Cone
Avg						9.70	
4	5VC-E-6-13/16BW	CPA	3	5460	13.44	12.86	S
5	5VC-E-6-13/16BW	CPA	2-13/16	5570	10.51	9.96	S
6	5VC-E-6-13/16BW	CPA	3-1/16	5410	10.70	10.29	S
Avg						11.04	
4	5VC-M-6-7/8BW	TCA	3-1/16	5460	11.20	10.72	IGC/S
5	5VC-M-6-7/8BW	TCA	2-15/16	5570	13.35	12.65	S/T

Table A.5: Test Results, continued

Group No.	Specimen label*	Anchorage method**	Cover in.	Concrete strength psi	Bond strength kips	Mod. bond strength*** kips	Failure mode****
6	5VC-M-6-7/8BW	TCA	2-15/16	5410	7.61	7.32	T
Avg						10.23	
4	5VC-E-6-7/8BW	TCA	2-15/16	5460	13.49	12.91	IGC/S/Cone
5	5VC-E-6-7/8BW	TCA	2-7/8	5570	12.79	12.12	IGC/S/Cone
6	5VC-E-6-7/8BW	TCA	2-7/8	5410	10.59	10.18	IGC/T/Cone
Avg						11.74	
4	5VC-M-6-1.5BW	NSA	2-11/16	5460	16.20	15.50	S
5	5VC-M-6-1.5BW	NSA	2-5/8	5570	15.03	14.24	S/T/Cone
6	5VC-M-6-1.5BW	NSA	2-7/8	5410	13.38	12.86	S
Avg						14.20	
4	5VC-E-6-1.5BW	NSA	3-1/16	5460	16.74	16.02	S
5	5VC-E-6-1.5BW	NSA	2-3/4	5570	15.90	15.06	S
6	5VC-E-6-1.5BW	NSA	3-1/16	5410	14.28	13.73	S/Cone
Avg						14.94	
4	5VC-E-6-1.5BW	NSB	2-13/16	5460	14.98	14.34	Cone
5	5VC-E-6-1.5BW	NSB	2-13/16	5570	14.94	14.15	S
6	5VC-E-6-1.5BW	NSB	3-1/16	5410	14.21	13.66	S
Avg						14.05	
4	5VC-E-6-1.5BW	TCB	2-3/4	5460	16.26	15.56	S
5	5VC-E-6-1.5BW	TCB	2-7/8	5570	16.05	15.21	S
6	5VC-E-6-1.5BW	TCB	2-7/8	5410	14.76	14.19	T
Avg						14.99	
4	5VC-M-6-1.5BW	TCA	2-7/8	5460	12.30	11.77	IGC/Cone
5	5VC-M-6-1.5BW	TCA	3	5570	14.67	13.90	IGC/S
6	5VC-M-6-1.5BW	TCA	2-15/16	5410	12.08	11.61	IGC/S/Cone
Avg						12.43	
4	5VC-E-6-1.5BW	TCA	2-5/8	5460	12.65	12.11	IGC/Cone
5	5VC-E-6-1.5BW	TCA	2-11/16	5570	14.52	13.76	IGC/S/Cone
6	5VC-E-6-1.5BW	TCA	2-13/16	5410	12.27	11.80	IGC/S/Cone
Avg						12.52	
4	5VC-M-6-1.5BA	NSA	3	5460	17.79	17.02	S
5	5VC-M-6-1.5BA	NSA	2-13/16	5570	15.49	14.68	S
6	5VC-M-6-1.5BA	NSA	2-7/8	5410	14.90	14.32	S
Avg						15.34	
4	5VC-M-6-1.5A	NSA	2-7/8	5460	16.84	16.12	T
5	5VC-M-6-1.5A	NSA	3	5570	16.52	15.65	IGC/S
6	5VC-M-6-1.5A	NSA	2-7/8	5410	15.32	14.73	S
Avg						15.50	
4	5VC-M-6	CIP	3-1/16	5460	16.82	16.10	S
5	5VC-M-6	CIP	3	5570	17.50	16.58	S/Cone

Table A.5: Test Results, continued

Group No.	Specimen label*	Anchorage method**	Cover in.	Concrete strength psi	Bond strength kips	Mod. bond strength*** kips	Failure mode****
6	5VC-M-6	CIP	3	5410	16.34	15.71	S
Avg						16.13	
4	5VC-E-6	CIP	3	5460	17.73	16.97	S
5	5VC-E-6	CIP	3	5570	17.16	16.26	S/Cone
6	5VC-E-6	CIP	3	5410	15.57	14.97	S
Avg						16.06	
			Group 7				
7	5VC-E-6-7/8BW	TCB	3-3/16	4460	9.92	10.50	IGC/Cone
7	5VC-E-6-7/8BW	TCB	3-3/16	4460	8.29	8.78	IGC/Cone
7	5VC-E-6-7/8BW	TCB	3-5/16	4460	11.06	11.17	IGC/Cone
Avg						10.33	
7	5VC-E-6-7/8BA	TCB	3-1/16	4460	8.36	8.85	Cone
7	5VC-E-6-7/8BA	TCB	3-1/8	4460	13.18	13.96	S/Cone
7	5VC-E-6-7/8BA	TCB	3-1/4	4460	11.61	12.29	S/Cone
Avg						11.70	
7	5VC-E-6-7/8A	TCB	3-1/4	4460	13.70	14.51	S/Cone
7	5VC-E-6-7/8A	TCB	3-1/8	4460	13.74	14.55	S
7	5VC-E-6-7/8A	TCB	3-1/4	4460	14.65	15.51	S/Cone
Avg						14.86	
			Groups 8, 9 and 10				
8	8VC-E-9-1.25V	NSA	3	4710	24.62	25.37	S
9	8VC-E-9-1.25V	NSA	2-7/8	5360	24.96	24.11	S
10	8VC-E-9-1.25V	NSA	3	4970	24.89	24.97	S
Avg						24.81	
8	8VC-E-9-1.25BW	NSA	3	4710	24.89	25.64	S
9	8VC-E-9-1.25BW	NSA	3	5360	22.86	22.08	S
10	8VC-E-9-1.25BW	NSA	3-1/4	4970	27.79	27.87	S
Avg						25.20	
8	8VC-E-9-1.25BA	NSA	3	4710	23.35	24.06	S
9	8VC-E-9-1.25BA	NSA	3-3/16	5360	21.16	20.44	S
10	8VC-E-9-1.25BA	NSA	3-1/16	4970	25.07	25.15	S
Avg						23.21	
8	8VC-E-9-1.25A	NSA	3	4710	21.66	22.32	S
9	8VC-E-9-1.25A	NSA	2-7/8	5360	24.14	23.32	S
10	8VC-E-9-1.25A	NSA	3	4970	26.13	26.21	S
Avg						23.95	

Table A.5: Test Results, continued

Group No.	Specimen label*	Anchorage method**	Cover in.	Concrete strength psi	Bond strength kips	Mod. bond strength*** kips	Failure mode****
8	8VC-E-9-1.25V	TCB	3-3/16	4710	24.24	24.98	S
9	8VC-E-9-1.25V	TCB	2-7/8	5360	28.41	27.44	S
10	8VC-E-9-1.25V	TCB	3	4970	22.22	22.29	S
Avg						24.90	
8	8VC-E-9-1.25BW	TCB	3	4710	21.53	22.18	S
9	8VC-E-9-1.25BW	TCB	3-1/16	5360	28.40	27.43	S
10	8VC-E-9-1.25BW	TCB	3-1/16	4970	24.52	24.59	S
Avg						24.74	
8	8VC-E-9-1.25BA	TCB	3-1/16	4710	25.80	24.06	S
9	8VC-E-9-1.25BA	TCB	3	5360	25.76	20.44	S
10	8VC-E-9-1.25BA	TCB	2-7/8	4970	23.20	25.15	S
Avg						24.91	
8	8VC-E-9-1.25A	TCB	3-1/16	4710	23.62	24.34	S
9	8VC-E-9-1.25A	TCB	3-1/8	5360	26.20	25.30	S
10	8VC-E-9-1.25A	TCB	3	4970	24.81	24.88	S
Avg						24.84	
8	8VC-E-9-1.25V	CPA	3	4710	26.12	26.91	S
9	8VC-E-9-1.25V	CPA	2-15/16	5360	26.06	25.17	S
10	8VC-E-9-1.25V	CPA	3-1/8	4970	24.97	25.05	S
Avg						25.71	
8	8VC-E-9-1.25BW	CPA	3	4710	27.30	28.13	S
9	8VC-E-9-1.25BW	CPA	2-7/8	5360	25.15	24.29	S
10	8VC-E-9-1.25BW	CPA	2-15/16	4970	27.60	27.68	S
Avg						26.70	
8	8VC-E-9-1.25BA	CPA	3-1/8	4710	27.81	28.65	S
9	8VC-E-9-1.25BA	CPA	3-1/16	5360	27.63	26.69	S
10	8VC-E-9-1.25BA	CPA	2-7/8	4970	29.26	29.35	S
Avg						28.23	
8	8VC-E-9-1.25A	CPA	3-1/16	4710	27.25	28.08	S
9	8VC-E-9-1.25A	CPA	3-1/8	5360	28.46	27.49	S
10	8VC-E-9-1.25A	CPA	3	4970	26.84	26.92	S
Avg						27.49	
8	8VC-E-9-1.25V	TCA	2-7/8	4710	23.86	24.58	S/Cone
9	8VC-E-9-1.25V	TCA	2-15/16	5360	23.07	22.28	S
10	8VC-E-9-1.25V	TCA	2-15/16	4970	23.34	23.41	S
Avg						23.43	
8	8VC-E-9-1.25BW	TCA	3	4710	15.47	15.94	S
9	8VC-E-9-1.25BW	TCA	3-1/8	5360	18.11	17.49	S
10	8VC-E-9-1.25BW	TCA	3-1/16	4970	16.41	16.46	IGC/S
Avg						16.63	

Table A.5: Test Results, continued

Group No.	Specimen label*	Anchorage method**	Cover in.	Concrete strength psi	Bond strength kips	Mod. bond strength*** kips	Failure mode****
8	8VC-E-9-1.25BA	TCA	2-15/16	4710	15.81	16.29	S/Cone
9	8VC-E-9-1.25BA	TCA	2-7/8	5360	11.55	11.16	IGC/Cone
10	8VC-E-9-1.25BA	TCA	3-1/16	4970	16.34	16.39	IGC/S
Avg						14.61	
8	8VC-E-9-1.25A	TCA	3	4710	19.86	20.46	IGC/S
9	8VC-E-9-1.25A	TCA	3	5360	16.57	16.00	IGC/Cone
10	8VC-E-9-1.25A	TCA	3	4970	13.77	13.81	IGC/T
Avg						16.76	
8	8VC-M-9-1.25	CIP	3-1/16	4710	27.14	27.96	S
9	8VC-M-9-1.25	CIP	3-1/16	5360	27.45	26.51	S
10	8VC-M-9-1.25	CIP	3-1/16	4970	28.78	28.87	S
Avg						27.78	
8	8VC-E-9-1.25	CIP	3	4710	26.89	27.71	S
9	8VC-E-9-1.25	CIP	3	5360	27.18	26.25	S
10	8VC-E-9-1.25	CIP	3-1/16	4970	24.02	24.09	S
Avg						26.02	
			Group 11				
11	5VC-E-6-13/16BA	CPA-1CPS	2-7/8	5230	15.61	15.26	S
11	5VC-E-6-13/16BA	CPA-1CPS	2-15/16	5230	13.60	13.30	IGC/S
11	5VC-E-6-13/16BA	CPA-1CPS	3-1/16	5230	11.35	11.10	IGC
Avg						13.22	
11	5VC-E-6-13/16BA	CPA-2CPS	2-7/8	5230	15.33	14.99	S
11	5VC-E-6-13/16BA	CPA-2CPS	3	5230	14.08	13.77	S/Cone
11	5VC-E-6-13/16BA	CPA-2CPS	3-1/8	5230	14.23	13.91	S/Cone
Avg						14.22	
11	5VC-E-6-13/16BA	CPA-1CPE	3-1/16	5230	17.20	16.82	S
11	5VC-E-6-13/16BA	CPA-1CPE	3-1/16	5230	16.72	16.35	S
11	5VC-E-6-13/16BA	CPA-1CPE	2-15/16	5230	13.33	13.03	S
Avg						15.40	
11	5VC-E-6-13/16BA	CPA-2CPE	2-7/8	5230	14.83	14.50	S
11	5VC-E-6-13/16BA	CPA-2CPE	3	5230	14.65	14.32	S
11	5VC-E-6-13/16BA	CPA-2CPE	3-1/8	5230	14.44	14.12	S
Avg						14.31	
11	5VC-E-6-7/8V	TCA	2-15/16	5230	9.86	9.64	IGC
11	5VC-E-6-7/8V	TCA	3	5230	12.28	12.01	IGC/S/Cone
11	5VC-E-6-7/8V	TCA	3-3/16	5230	11.86	11.60	IGC/S
Avg						11.08	
11	5VC-E-6-7/8BA	TCA	3-1/16	5230	6.86	6.71	IGC
11	5VC-E-6-7/8BA	TCA	3	5230	13.09	12.80	IGC/S/Cone

Table A.5: Test Results, continued

Group No.	Specimen label*	Anchorage method**	Cover in.	Concrete strength psi	Bond strength kips	Mod. bond strength*** kips	Failure mode****
11	5VC-E-6-7/8BA	TCA	3-1/8	5230	10.73	10.49	IGC/S
Avg						10.00	
			Groups 12, 13 and 14				
12	8VC-E-6-1.25BA	TCB	2-7/8	5270	17.69	17.23	S
13	8VC-E-6-1.25BA	TCB	2-15/16	5600	16.97	16.04	S
14	8VC-E-6-1.25BA	TCB	3-1/8	4550	18.33	19.22	S
Avg						17.50	
12	8VC-E-9-1.25BA	TCB	3-1/8	5270	24.59	23.95	S
13	8VC-E-9-1.25BA	TCB	2-15/16	5600	23.69	22.38	S
14	8VC-E-9-1.25BA	TCB	2-3/4	4550	22.76	23.86	S
Avg						23.40	
12	8VC-E-12-1.25BA	TCB	3	5270	28.59	27.85	S
13	8VC-E-12-1.25BA	TCB	2-7/8	5600	31.56	29.82	S
14	8VC-E-12-1.25BA	TCB	3	4550	33.34	34.95	S
Avg						30.87	
12	8VC-E-15-1.25BA	TCB	2-13/16	5270	34.78	33.88	S
13	8VC-E-15-1.25BA	TCB	3-1/16	5600	42.03	39.71	S
14	8VC-E-15-1.25BA	TCB	3-1/8	4550	40.63	42.59	S
Avg						38.73	
12	8VC-E-6-1.25BA	TCA	2-7/8	5270	13.57	13.22	IGC/S
13	8VC-E-6-1.25BA	TCA	3-1/4	5600	14.16	13.38	IGC/S
14	8VC-E-6-1.25BA	TCA	3	4550	11.69	12.25	IGC/Cone
Avg						12.95	
12	8VC-E-9-1.25BA	TCA	2-3/4	5270	17.98	17.51	S
13	8VC-E-9-1.25BA	TCA	3	5600	13.53	12.78	IGC/T/S
14	8VC-E-9-1.25BA	TCA	3	4550	20.71	21.71	IGC/T/Cone
Avg						17.33	
12	8VC-E-12-1.25BA	TCA	3-1/8	5270	24.07	23.45	IGC/S/T
13	8VC-E-12-1.25BA	TCA	3	5600	25.75	24.33	IGC/Cone
Avg						23.89	
12	8VC-E-13-1.25BA	TCA	3-1/16	5270	28.23	27.50	IGC/S/T
13	8VC-E-15-1.25BA	TCA	3	5600	31.41	29.68	IGC/S/Cone
14	8VC-E-15-1.25BA	TCA	3	4550	32.96	34.55	IGC/S/Cone
Avg						32.11	
12	8VC-M-6-1.25	CIP	3-1/16	5270	18.09	17.62	S
13	8VC-M-6-1.25	CIP	3	5600	18.57	17.55	S
14	8VC-M-6-1.25	CIP	3-1/8	4550	17.33	18.17	S
Avg						17.78	

Table A.5: Test Results, continued

Group No.	Specimen label*	Anchorage method**	Cover in.	Concrete strength psi	Bond strength kips	Mod. bond strength*** kips	Failure mode****
12	8VC-M-9-1.25	CIP	3-1/16	5270	29.50	28.73	S
13	8VC-M-9-1.25	CIP	3	5600	28.97	27.37	S
14	8VC-M-9-1.25	CIP	3-1/16	4550	28.17	29.53	S
Avg						28.54	
12	8VC-M-12-1.25	CIP	3	5270	38.20	37.21	S
13	8VC-M-12-1.25	CIP	3	5600	35.67	33.70	S
14	8VC-M-12-1.25	CIP	3-1/16	4550	36.86	38.64	S
Avg						36.52	
12	8VC-M-15-1.25	CIP	3-1/16	5270	45.04	43.87	S
13	8VC-M-15-1.25	CIP	3-1/16	5600	47.67	45.04	S
14	8VC-M-15-1.25	CIP	3	4550	44.96	47.13	S
Avg						45.35	
12	8VC-E-6-1.25	CIP	3-1/8	5270	16.53	16.10	S
13	8VC-E-6-1.25	CIP	3	5600	15.67	14.81	S
14	8VC-E-6-1.25	CIP	3-1/16	4550	16.42	17.21	S
Avg						16.04	
12	8VC-E-9-1.25	CIP	3	5270	25.20	24.55	S
13	8VC-E-9-1.25	CIP	3	5600	24.45	23.10	S
14	8VC-E-9-1.25	CIP	3	4550	24.31	25.48	S
Avg						24.38	
12	8VC-E-12-1.25	CIP	3-1/16	5270	34.47	33.58	S
13	8VC-E-12-1.25	CIP	3	5600	30.18	28.52	S
14	8VC-E-12-1.25	CIP	3-1/8	4550	30.04	31.49	S
Avg						31.20	
12	8VC-E-15-1.25	CIP	3	5270	43.58	42.45	S
13	8VC-E-15-1.25	CIP	3	5600	39.11	36.96	S
14	8VC-E-15-1.25	CIP	3-1/16	4550	35.98	37.72	S
Avg						39.04	
			Groups 15, 16 and 17				
15	5VC-E-4-7/8BA	TCB	3	5480	10.11	9.66	S
16	5VC-E-4-7/8BA	TCB	2-15/16	4610	9.72	10.12	S
17	5VC-E-4-7/8BA	TCB	3-1/16	4980	9.34	9.36	S
Avg						9.71	
15	5VC-E-6-7/8BA	TCB	2-7/8	5360	15.00	14.49	S/Cone
16	5VC-E-6-7/8BA	TCB	2-7/8	4610	15.06	15.68	S
17	5VC-E-6-7/8BA	TCB	2-7/8	4980	14.24	14.27	S/Cone
Avg						14.81	
15	5VC-E-9-7/8BA	TCB	2-7/8	5360	18.36	17.73	S/Cone
16	5VC-E-9-7/8BA	TCB	3-1/16	4610	22.86	23.81	S/Cone

Table A.5: Test Results, continued

Group No.	Specimen label*	Anchorage method**	Cover in.	Concrete strength psi	Bond strength kips	Mod. bond strength*** kips	Failure mode****
17	5VC-E-9-7/8BA	TCB	2-7/8	4980	21.06	21.10	S/Cone
Avg						20.88	
15	5VC-E-12-7/8BA	TCB	2-13/16	5360	26.92	26.00	Cone
16	5VC-E-12-7/8BA	TCB	2-7/8	4610	28.23	29.40	IGC/S/Cone
17	5VC-E-12-7/8BA	TCB	2-3/4	4980	25.92	25.97	S/Cone
Avg						27.12	
15	5VS-E-4-7/8BA	TCB	3	5480	9.13	8.72	S
16	5VS-E-4-7/8BA	TCB	2-13/16	4610	8.81	9.18	S/Cone
17	5VS-E-4-7/8BA	TCB	2-7/8	4980	8.91	8.93	S/Cone
Avg						8.94	
15	5VS-E-6-7/8BA	TCB	2-3/4	5870	15.32	14.14	S
16	5VS-E-6-7/8BA	TCB	3-1/8	4610	11.94	12.43	S/Cone
17	5VS-E-6-7/8BA	TCB	3-1/16	4980	13.75	13.78	S/Cone
Avg						13.45	
15	5VS-E-9-7/8BA	TCB	2-3/4	5870	21.10	19.47	S/Cone
16	5VS-E-9-7/8BA	TCB	3	4610	21.34	22.22	S/Cone
17	5VS-E-9-7/8BA	TCB	2-15/16	4980	21.24	21.28	S/Cone
Avg						20.99	
15	5VS-E-12-7/8BA	TCB	2-7/8	5480	29.51	28.19	S/Cone
16	5VS-E-12-7/8BA	TCB	2-13/16	4610	25.17	26.21	S/Cone
17	5VS-E-12-7/8BA	TCB	3-1/16	4980	22.76	22.81	S/Cone
Avg						25.74	
15	5VC-E-4-7/8BA	TCA	2-15/16	5870	7.74	7.14	Cone
16	5VC-E-4-7/8BA	TCA	2-7/8	4610	7.34	7.64	Cone
17	5VC-E-4-7/8BA	TCA	3-1/16	4980	6.82	6.83	IGC/Cone
Avg						7.21	
15	5VC-E-6-7/8BA	TCA	3	5870	11.69	10.79	IGC/Cone
16	5VC-E-6-7/8BA	TCA	2-15/16	4610	11.79	12.28	IGC/Cone
17	5VC-E-6-7/8BA	TCA	2-7/8	4980	8.11	8.13	IGC/Cone
Avg						10.40	
15	5VC-E-9-7/8BA	TCA	2-3/4	5870	14.20	13.11	Cone
16	5VC-E-9-7/8BA	TCA	2-1/2	4610	16.02	16.68	IGC/Cone
17	5VC-E-9-7/8BA	TCA	2-7/8	4980	15.67	15.70	IGC/Cone
Avg						15.16	
15	5VC-E-12-7/8BA	TCA	2-15/16	5870	19.80	18.27	IGC/Cone
16	5VC-E-12-7/8BA	TCA	3-1/16	4610	23.17	24.13	S/Cone
17	5VC-E-12-7/8BA	TCA	3	4980	24.15	24.20	IGC/Cone
Avg						22.20	
15	5VC-M-4	CIP	3-1/4	5360	10.12	9.77	S/Cone
16	5VC-M-4	CIP	3	4610	9.37	9.76	S

Table A.5: Test Results, continued

Group No.	Specimen label*	Anchorage method**	Cover in.	Concrete strength psi	Bond strength kips	Mod. bond strength *** kips	Failure mode****
17	5VC-M-4	CIP	3-1/16	4980	10.21	10.23	S
Avg						9.92	
15	5VC-M-6	CIP	3	5360	15.68	15.14	S/Cone
16	5VC-M-6	CIP	3	4610	15.35	15.99	S
17	5VC-M-6	CIP	3-1/16	4980	16.38	16.41	S
Avg						15.85	
15	5VC-M-9	CIP	3	5360	22.14	21.38	Pullout
16	5VC-M-9	CIP	3	4610	25.11	26.15	Cone
17	5VC-M-9	CIP	3	4980	22.74	22.79	S
Avg						23.44	
15	5VC-M-12	CIP	3	5360	26.99	26.07	Cone
16	5VC-M-12	CIP	3	4610	24.62	25.64	Cone
17	5VC-M-12	CIP	3	4980	28.09	28.15	S/Cone
Avg						26.62	
15	5VC-E-4	CIP	3	5480	9.29	8.87	S
16	5VC-E-4	CIP	3	4610	10.41	10.84	S
17	5VC-E-4	CIP	3	4980	9.42	9.44	S
Avg						9.72	
15	5VC-E-6	CIP	3-1/16	5480	15.82	15.11	S
16	5VC-E-6	CIP	3-1/16	4610	14.20	14.79	S
17	5VC-E-6	CIP	2-15/16	4980	15.30	15.33	S
Avg						15.08	
15	5VC-E-9	CIP	3-1/16	5480	23.18	22.14	S
16	5VC-E-9	CIP	3-1/16	4610	21.09	21.96	S
17	5VC-E-9	CIP	3	4980	23.03	23.08	S
Avg						22.40	
15	5VC-E-12	CIP	3	5480	28.88	27.59	S/Cone
16	5VC-E-12	CIP	3-1/16	4610	30.26	31.51	S/Cone
17	5VC-E-12	CIP	3	4980	29.78	29.84	Cone
Avg						29.65	
15	5VS-E-4	CIP	3	5870	8.72	8.05	S/Cone
16	5VS-E-4	CIP	3	4610	9.04	9.41	S
17	5VS-E-4	CIP	3	4980	8.74	8.76	S
Avg						8.74	
15	5VS-E-6	CIP	3-1/8	5870	14.73	13.59	S
16	5VS-E-6	CIP	3	4610	13.23	13.78	S
17	5VS-E-6	CIP	3-1/16	4980	14.57	14.60	S
Avg						13.99	
15	5VS-E-9	CIP	3-1/8	5870	23.38	21.58	S
16	5VS-E-9	CIP	3	4610	19.46	20.27	S

Table A.5: Test Results, continued

Group No.	Specimen label*	Anchorage method**	Cover in.	Concrete strength psi	Bond strength kips	Mod. bond strength*** kips	Failure mode****
17	5VS-E-9	CIP	3	4980	21.55	21.59	S/Cone
Avg						21.15	
15	5VS-E-12	CIP	3	5870	25.50	23.53	Pullout
16	5VS-E-12	CIP	3-1/16	4610	27.59	28.73	S
17	5VS-E-12	CIP	3-1/16	4980	26.61	26.66	S/Cone
Avg						26.31	
			Groups 18 and 20				
18	8HC-T-E-6-1.25BA	NSA	2-15/16	5400	12.96	12.47	T
18	8HC-T-E-9-1.25BA	NSA	3-1/16	5400	18.68	17.97	S
18	8HC-T-E-12-1.25B	NSA	3	5400	29.78	28.66	S
18	8HC-T-E-6-1.25BA	CPA	3	5400	19.60	18.86	S
20	8HC-T-E-6-1.25BA	CPA	2-15/16	5230	15.53	15.18	S
Avg						17.02	
18	8HC-T-E-9-1.25BA	CPA	3-1/16	5400	28.23	27.16	S
20	8HC-T-E-9-1.25BA	CPA	3	5230	29.25	28.6	S
Avg						27.88	
18	8HC-T-E-12-1.25B	CPA	2-15/16	5400	35.64	34.29	S
20	8HC-T-E-12-1.25B	CPA	2-13/16	5230	31.09	30.4	S
Avg						32.35	
20	8HC-T-E-15-1.25B	CPA	2-7/8	5230	35	34.22	Pullout
20	8HC-T-E-15-1.25B	CPA	3-1/16	5230	46.75	45.71	S
Avg						39.97	
18	8HC-T-E-6-1.25BA	TCA	2-15/16	5400	17.64	16.97	IGC/S
20	8HC-T-E-6-1.25BA	TCA	3	5230	11.61	11.35	IGC/T
Avg						14.16	
18	8HC-T-E-9-1.25BA	TCA	2-3/4	5400	17.02	16.38	S
20	8HC-T-E-9-1.25BA	TCA	3-1/16	5230	18.43	18.02	IGC/T
Avg						17.2	
18	8HC-T-E-12-1.25B	TCA	2-15/16	5400	30.42	29.27	S/Cone
20	8HC-T-E-15-1.25B	TCA	2-15/16	5230	31.15	30.46	IGC/S
20	8HC-T-E-15-1.25B	TCA	3-1/8	5230	31.52	30.87	IGC/T
Avg						30.67	
18	8HC-T-E-9	CIP	3	5400	25.58	24.61	S
18	8HC-T-E-9	CIP	3-1/8	5400	27.38	26.35	S
18	8HC-T-E-9	CIP	3-3/16	5400	27.89	26.84	S
Avg						25.93	
20	8HC-T-E-12	CIP	3-1/16	5230	29.87	29.21	S
20	8HC-T-E-15	CIP	3-1/4	5230	41.55	40.63	S

Table A.5: Test Results, continued

Group No.	Specimen label*	Anchorage method**	Cover in.	Concrete strength psi	Bond strength kips	Mod. bond strength*** kips	Failure mode****
18	8HC-B-E-6-1.25BA	NSA	2-7/8	5400	11.01	10.59	T
18	8HC-B-E-9-1.25BA	NSA	3-1/4	5400	24.59	23.66	Pullout
18	8HC-B-E-12-1.25B	NSA	3-1/16	5400	32.48	31.25	S
18	8HC-B-E-6-1.25BA	CPA	2-3/4	5400	20.32	19.55	S
20	8HC-T-E-6-1.25BA	CPA	3-1/4	5230	18.73	18.31	S
Avg						18.93	
18	8HC-B-E-9-1.25BA	CPA	3-1/16	5400	31.67	30.47	S
20	8HC-T-E-9-1.25BA	CPA	3	5230	31.05	30.36	S
Avg						30.42	
18	8HC-B-E-12-1.25B	CPA	3	5400	40.14	38.62	S
20	8HC-T-E-12-1.25B	CPA	3-1/16	5230	35.2	34.91	Pullout
Avg						36.77	
20	8HC-T-E-15-1.25B	CPA	3	5230	43.49	42.52	Pullout
20	8HC-T-E-15-1.25B	CPA	3-1/16	5230	42.51	41.56	Pullout
Avg						42.04	
18	8HC-B-E-6-1.25BA	TCA	2-7/8	5400	11.15	10.73	T
20	8HC-T-E-6-1.25BA	TCA	3-1/16	5230	14.37	14.05	IGC/Cone
Avg						12.39	
18	8HC-B-E-9-1.25BA	TCA	2-3/4	5400	19.92	19.17	IGC/S/Cone
20	8HC-B-E-9-1.25BA	TCA	3	5230	18.36	17.95	IGC
Avg						18.56	
18	8HC-B-E-12-1.25B	TCA	3-1/16	5400	28.78	27.69	IGC/Cone
20	8HC-B-E-12-1.25B	TCA	2-15/16	5230	28.45	22.82	IGC/Cone
Avg						25.26	
20	8HC-B-E-13-1.25B	TCA	2-7/8	5230	27.54	26.92	IGC/S
20	8HC-B-E-15-1.25B	TCA	2-13/16	5230	32.65	31.92	IGC/T
18	8HC-B-E-6	CIP	3-3/16	5400	30.75	29.59	S
18	8HC-B-E-9	CIP	2-3/4	5400	28.51	27.43	S
18	8HC-B-E-12	CIP	2-7/8	5400	29.05	27.95	S
20	8HC-B-E-12	CIP	3-1/8	5230	31.72	31.01	S
Avg						29.48	
20	8HC-B-E-15	CIP	2-4/5	5230	45.28	44.22	T
			Group 19				
19	5VC-E-6-7/8BA	TCB	1-1/2	3960	10.70	12.02	S
19	5VC-E-6-7/8BA	TCB	1-7/16	3960	10.88	12.23	T
Avg						12.13	

Table A.5: Test Results, continued

Group No.	Specimen label*	Anchorage method**	Cover in.	Concrete strength psi	Bond strength kips	Mod. bond strength*** kips	Failure mode****
19	5VC-E-9-7/8BA	TCB	1-3/8	3960	18.02	20.25	S
19	5VC-E-9-7/8BA	TCB	1-1/2	3960	19.16	21.53	T
Avg						20.89	
19	5VC-E-12-7/8BA	TCB	1-3/8	3960	22.84	25.66	T
19	5VC-E-12-7/8BA	TCB	1-1/2	3960	20.85	23.43	Pullout
Avg						24.55	
19	5VC-E-6-7/8BA	TCA	1-1/2	3960	6.99	7.85	IGC
19	5VC-E-6-7/8BA	TCA	1-7/16	3960	4.62	5.19	IGC/Cone
Avg						6.52	
19	5VC-E-9-7/8BA	TCA	1-1/2	3960	11.90	13.37	IGC/Cone
19	5VC-E-9-7/8BA	TCA	1-3/8	3960	10.48	11.78	IGC/Cone
Avg						12.58	
19	5VC-E-12-7/8BA	TCA	1-1/2	3960	15.68	17.62	IGC/Cone
19	5VC-E-12-7/8BA	TCA	1-5/8	3960	14.62	16.43	IGC/Cone
Avg						17.03	
19	5VC-M-6	CIP	1-9/16	3960	11.64	13.08	T
19	5VC-M-6	CIP	1-7/8	3960	11.50	12.92	T
Avg						13.00	
19	5VC-M-9	CIP	1/9/16	3960	16.19	18.19	T
19	5VC-M-9	CIP	1-7/16	3960	20.46	22.99	T
Avg						20.59	
19	5VC-M-12	CIP	1-1/2	3960	25.16	28.27	T
19	5VC-M-12	CIP	1-1/2	3960	23.96	26.92	S
Avg						27.60	
19	5VC-E-6	CIP	1-1/2	3960	11.08	12.45	T
19	5VC-E-6	CIP	1-1/2	3960	10.56	11.87	S
Avg						12.16	
19	5VC-E-9	CIP	1-1/2	3960	17.11	19.23	S
19	5VC-E-9	CIP	1-9/16	3960	15.93	17.90	S
Avg						18.57	
19	5VC-E-12	CIP	1-1/2	3960	22.66	25.46	S
19	5VC-E-12	CIP	1-1/2	3960	22.74	25.55	S
Avg						25.51	
			Group 21				
21	5HC-T-E-4-7/8BA	CPA	2-15/16	4410	7.63	8.12	Pullout
21	5HC-T-E-6-7/8BA	CPA	3-1/8	4410	9.25	9.85	Pullout
21	5HC-T-E-9-7/8BA	CPA	2-15/16	4670	3.53	3.65	Pullout
21	5HC-T-E-12-7/8B/	CPA	3	4410	1.50	1.60	Pullout
21	5HC-T-E-4-7/8BA	TCA	2-15/16	4410	8.41	8.95	IGC/S/Cone

Table A.5: Test Results, continued

Group No.	Specimen label*	Anchorage method**	Cover in.	Concrete strength psi	Bond strength kips	Mod. bond strength*** kips	Failure mode****
21	5HC-T-E-6-7/8BA	TCA	3	4410	13.01	13.85	IGC/Cone
21	5HC-T-E-9-7/8BA	TCA	3	4670	14.18	14.67	IGC/Cone
21	5HC-T-E-12-7/8B/	TCA	3-5/8	4410	19.14	20.38	Cone
21	5HC-T-E-4	CIP	3	4670	9.26	9.58	S
21	5HC-T-E-6	CIP	3	4670	14.13	14.62	S/Cone
21	5HC-T-E-9	CIP	3-1/16	4410	22.17	23.61	S/Cone
21	5HC-T-E-12	CIP	3-1/16	4410	26.6	28.32	T
21	5HC-B-E-4-7/8BA	CPA	3	4410	7.14	7.60	Pullout
21	5HC-B-E-6-7/8BA	CPA	3	4410	7.2	7.67	Pullout
21	5HC-B-E-9-7/8BA	CPA	3	4670	6.41	6.63	Pullout
21	5HC-B-E-12-7/8B/	CPA	3	4410	4.18	4.45	Pullout
21	5HC-B-E-4-7/8BA	TCA	2-7/8	4410	8.04	8.56	IGC/Cone
21	5HC-B-E-6-7/8BA	TCA	2-7/8	4410	13.6	14.48	Pullout
21	5HC-B-E-9-7/8BA	TCA	3	4670	12.97	13.42	IGC/Cone
21	5HC-B-E-12-7/8B/	TCA	3	4410	20.25	21.56	Cone
21	5HC-B-E-4	CIP	2-7/8	4670	9.23	9.55	S
21	5HC-B-E-6	CIP	3-1/8	4670	14.74	15.25	S
21	5HC-B-E-9	CIP	2-7/8	4410	23.06	24.55	S/Cone
21	5HC-B-E-12	CIP	3	4410	28.39	30.23	T
21	5VC-E-6-7/8BA	TCB-NTR	2-15/16	5270	14.54	14.16	IGC/T/Cone
21	5VC-E-6-7/8BA	TCB-NTR	2-15/16	5270	15.17	14.78	IGC/T/Cone
Avg						14.47	
21	5VC-E-9-7/8BA	TCB-NTR	2-7/8	5270	19.89	19.37	S/T
21	5VC-E-9-7/8BA	TCB-NTR	3-1/16	5270	24.01	23.39	IGC/S/Cone
Avg						21.38	
21	5VC-E-12-7/8BA	TCB-NTR	3-1/16	5270	28.00	27.27	IGC/T
21	5VC-E-12-7/8BA	TCB-NTR	2-15/16	5270	27.27	26.56	IGC/T/Cone
Avg						26.92	
			Group 22				
22	5VC-E-6-7/8BA	TCB	3	4980	16.57	16.60	S
22	5VC-E-6-7/8BA	TCB	3-1/8	4980	17.37	17.40	S
Avg						17.00	
22	5VC-E-9-7/8BA	TCB	2-3/4	4980	21.61	21.65	S
22	5VC-E-9-7/8BA	TCB	3	4980	26.54	26.59	S/Cone
Avg						24.12	
22	5VC-E-12-7/8BA	TCB	3-1/16	4980	24.11	24.16	T
22	5VC-E-12-7/8BA	TCB	3	4980	25.88	25.93	T
Avg						25.05	

Table A.5: Test Results, continued

Group No.	Specimen label*	Anchorage method**	Cover in.	Concrete strength psi	Bond strength kips	Mod. bond strength*** kips	Failure mode****
22	5VC-E-6-7/8BA	TCA	2-15/16	4980	11.97	11.99	IGC/Cone
22	5VC-E-6-7/8BA	TCA	2-15/16	4980	13.42	13.45	IGC/Cone
Avg						12.72	
22	5VC-E-9-7/8BA	TCA	2-15/16	4980	18.32	18.36	IGC/Cone
22	5VC-E-9-7/8BA	TCA	3-1/16	4980	18.97	19.01	IGC/Cone
Avg						18.68	
22	5VC-E-12-7/8BA	TCA	2-15/16	4980	20.61	20.65	IGC/T
22	5VC-E-12-7/8BA	TCA	3-1/8	4980	22.85	22.90	IGC
Avg						21.77	
22	5VC-E-6-7/8BA	TCB	1-9/16	4980	13.64	13.67	T
22	5VC-E-6-7/8BA	TCB	1-1/2	4980	11.62	11.64	S/T
Avg						12.66	
22	5VC-E-9-7/8BA	TCB	1-9/16	4980	19.00	19.04	S
22	5VC-E-9-7/8BA	TCB	1-1/2	4980	19.01	19.05	T
Avg						19.04	
22	5VC-E-12-7/8BA	TCB	1-9/16	4980	24.06	24.11	S/Cone
22	5VC-E-12-7/8BA	TCB	1-1/2	4980	23.26	23.31	S/T
Avg						23.71	
22	5VC-E-6-7/8BA	TCA	1-1/2	4980	7.59	7.59	T/Cone
22	5VC-E-6-7/8BA	TCA	1-5/8	4980	10.17	10.19	IGC/Cone
Avg						8.89	
22	5VC-E-9-7/8BA	TCA	1-5/8	4980	15.68	15.71	IGC/Cone
22	5VC-E-9-7/8BA	TCA	1-3/8	4980	12.47	12.50	S/T/Cone
Avg						14.10	
22	5VC-E-12-7/8BA	TCA	1-5/8	4980	14.94	14.97	IGC/Cone
22	5VC-E-12-7/8BA	TCA	1-3/4	4980	17.88	17.92	IGC/T
Avg						16.44	
			Group 23				
23	5VC-E-6-7/8BA	NSA	2-3/4	2700	10.90	14.83	S
23	5VC-E-6-7/8BA	NSA	2-13/16	2700	9.61	13.08	T
23	5VC-E-6-7/8BA	NSA	2-15/16	2700	11.17	15.20	S
23	Avg					14.37	
23	5VC-E-6-7/8BA	CPA	2-15/16	2700	9.93	13.51	Pullout
23	5VC-E-6-7/8BA	CPA	3-1/16	2700	7.73	10.52	Pullout
23	5VC-E-6-7/8BA	CPA	2-15/16	2700	5.13	6.98	Pullout
23	Avg					10.34	
23	5VC-E-6-7/8BA	TCA	3	2700	8.64	11.76	IGC/Cone
23	5VC-E-6-7/8BA	TCA	3-3/16	2700	9.03	12.29	IGC/Cone
23	5VC-E-6-7/8BA	TCA	3-3/16	2700	6.41	8.72	IGC/T/Cone

Table A.5: Test Results, continued

Group No.	Specimen label*	Anchorage method**	Cover in.	Concrete strength psi	Bond strength kips	Mod. bond strength*** kips	Failure mode****
23	Avg					10.92	
			Group 24				
24	8HC-T-E-6-1.25BA	NSA-NTR	2-7/8	4980	13.39	13.42	S
24	8HC-T-3-9-1.25BA	NSA-NTR	2-15/16	4980	22.98	23.03	S
24	8HC-T-E-12-1.25B	NSA-NTR	3-1/8	4980	27.63	27.69	S
24	8HC-T-E-6-1.25BA	CPA-NTR	2-7/8	4980	15.67	15.70	S/T
24	8HC-T-E-9-1.25BA	CPA-NTR	2-7/8	4980	25.19	25.24	S/T
24	8HC-T-E-12-1.25B	CPA-NTR	2-7/8	4980	37.67	37.75	T
24	8HC-T-E-15-1.25B	CPA-NTR	2-3/4	4980	39.65	39.43	S
24	8HC-T-E-6-1.25BA	TCA-NTR	2-3/4	4980	11.37	11.39	IGC/S
24	8HC-T-E-9-1.25BA	TCA-NTR	3	4980	17.56	17.60	IGC/S/Cone
24	8HC-T-E-12-1.25B	TCA-NTR	2-11/16	4980	22.25	22.29	IGC/Cone
24	8HC-T-E-15-1.25B	TCA-NTR	3-1/8	4980	38.17	38.25	T/Cone
24	8HC-B-E-6-1.25BA	NSA-NTR	2-7/8	4980	15.15	15.18	S
24	8HC-B-E-9-1.25BA	NSA-NTR	3-1/8	4980	21.79	21.83	S
24	8HC-B-E-12-1.25B	NSA-NTR	3-1/8	4980.	31.52	31.58	S
24	8HC-B-E-15-1.25B	NSA-NTR	3-1/8	4980	36.68	36.75	S
24	8HC-B-E-6-1.25BA	TCA-NTR	3-1/8	4980	14.06	14.09	IGC/Cone
24	8HC-B-E-6-1.25BA	TCA-NTR	3	4980	12.27	12.29	S/T/Cone
Avg						13.19	
24	8HC-B-E-9-1.25BA	TCA-NTR	3	4980	20.88	20.92	IGC/Cone
24	8HC-B-E-12-1.25B	TCA-NTR	3	4980	30.73	30.79	IGC/Cone
24	8HC-B-E-12-1.25B	TCA-NTR	3-1/16	4980	25.40	25.45	IGC/Cone
Avg						28.12	
24	8HC-B-E-15-1.25B	TCA-NTR	3-1/16	4980	34.33	34.40	S/Cone
24	5VC-E-9-7/8BA	NSA-1:3	3-1/16	4740	23.35	23.98	Cone
24	5VC-E-12-7/8BA	NSA-1:3	2-3/4	4980	28.35	28.41	S/Cone
24	5VC-E-12-7/8BA	TCB-1:3	2-13/16	4980	30.08	30.14	S/T
24	5VC-E-6-7/8BA	CPA-1:3	3	4740	7.68	7.89	Pullout
24	5VC-E-9-7/8BA	CPA-1:3	2-3/4	4740	8.10	8.32	Pullout
24	5VC-E-12-7/8BA	CPA-1:3	3-1/8	4980	6.25	6.26	Pullout
24	5VC-E-6-7/8BA	NSA-1:6	2-15/16	4600	9.17	9.56	S/T
24	5VC-E-6-7/8BA	NSA-1:6	3	4600	5.00	5.21	S/T
Avg						7.39	

Table A.5: Test Results, continued

Group No.	Specimen label*	Anchorage method**	Cover in.	Concrete strength psi	Bond strength kips	Mod. bond strength*** kips	Failure mode****
24	5VC-E-12-7/8BA	NSA-1:6	2-13/16	4740	33.52	34.43	S/T##
24	5VC-E-6-7/8BA	TCB-1:6	2-5/8	4600	13.35	13.92	T
24	5VC-E-9-7/8BA	TCB-1:6	2-7/8	4740	18.90	19.41	S/Cone
24	5VC-E-12-7/8BA	TCB-1:6	3-1/8	4740	30.03	30.84	Cone##
24	5VC-E-9-7/8BA	CPA-1:6	2-15/16	4600	8.14	8.49	Pullout
24	5VC-E-9-7/8BA	CPA-1:6	3-1/8	4600	9.40	9.80	Pullout
Avg						9.15	
24	5VC-E-12-7/8BA	CPA-1:6	2-7/8	4740	10.99	11.29	Pullout

##Rebar failed in tension also

* Specimen Label: #ab-c-def or #ab-L-c-def

= Bar Size, No. 5 or No. 8

a = Bar Orientation, H - horizontal or V - vertical

b = Bar Pattern, C or S

c = Bar Surface, M - mill scale (uncoated), E - epoxy-coated

d = Embedment length, in.

e = Hole diameter, in.

f = Cleaning method, V - vacuum drilled, A - air, BA - brush with air, BW - brush with water

L = Level of Placement for horizontal bars, B - bottom-cast or T - top-cast

** Anchorage Method:

CIP = Cast-in-place;

CPA = Capsule A;

CPB = Capsule B;

TCA = Two-component grout A;

TCB = Two-compontent grout B;

NSA = Nonshrink grout A;

NSB = Nonshrink grout B;

1CPS = One capsule with standard number of rotations

2CPS = Two capsules with standard number of rotations

1CPE = One capsule with extra rotations

2CPE = Two capsules with extra rotations

NTR = No parallel tensile reinforcement

1:3 and 1:6 = Change in cover: change in embedded length for sloped bars

*** Mod. bond strength = (Bond strength) (5000/f)

**** Failure Mode: S = Splitting; T = Tensile; IGC = Interface between grout and concrete; Cone; Pullout. S, T and Cone failures were accompanied by a failure at the interface between the grout and the reinforcing bars (or between the concrete and the reinforcing bar in the case of cast-in-place bars) unless the failure mode includes an IGC designation