BOND OF EPOXY-COATED REINFORCEMENT TO CONCRETE: COVER, CASTING POSITION, SLUMP, AND CONSOLIDATION

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ABSTRACT

The effects of concrete cover, casting position, concrete slump, and degree of consolidation on the reduction in bond strength between reinforcing bars and concrete caused by epoxy coating are described. Tests include beam-end specimens containing No. 5, No. 6, No. 8, and No. 11 bars. Bottom-cast and top-cast bars with 1, 2, or 3 bar diameters of cover are evaluated. Concrete slump ranges from $2\,^1/_4$ to 8 in. Some specimens containing high slump concrete are not vibrated. The results of the study are used to develop improved development length modification factors for epoxy-coated bars.

Epoxy coatings significantly reduce bond strength. However, the extent of the reduction is less than used to select the development length modification factors in the 1989 ACI Building Code and the 1989 AASHTO Bridge Specifications for bars with cover $<$ 3 bar diameters or a clear spacing $<$ 6 bar diameters. The development length modification factor can be reduced from 1.5 to 1.35 for these bars. The relative bond strength of epoxy-coated reinforcement increases as cover increases. In most cases, the bond strength of coated bars exceeds the bond strength of uncoated bars that have one bar diameter less cover. As a result, the current provisions of ACI 318-89 are realistic as they are applied to epoxy-coated bars with a cover $\geq$ 3 bar diameters and a clear spacing $\geq$ 6 bar diameters. However, the provisions of the 1989 AASHTO Bridge Specifications are somewhat unconservative for these bars and should be modified. The ratio of bond strength of bottom-cast bars to the bond strength of top-cast bars, B/T, is about the same for coated and uncoated bars cast in low slump concrete. The ratio increases significantly for uncoated bars and decreases slightly for coated bars as slump increases. The results indicate that the upper limit on the product of the epoxy-coating factor and the top-bar factor can be reduced from 1.7 to 1.5. A lack of vibration has a negative effect on the bond strength of both coated and uncoated reinforcement in high slump concrete.

This is the fifth in a series of reports describing research at the University of Kansas on epoxy-coated reinforcement. The research is aimed at gaining a better understanding of the bond of epoxy-coated reinforcement to concrete and developing design procedures that accurately reflect the changes in bond strength caused by epoxy coating.

INTRODUCTION

The development length provisions of the 1989 ACI Building Code (ACI 318-89) and the 1989 AASHTO Bridge Specifications require the use of considerably longer development lengths for epoxy-coated reinforcement than for uncoated steel. Under these provisions, a development length modification factor of 1.5 is required for coated bars with less than 3 bar diameters of concrete cover or less than 6 bar diameters of clear spacing. The provisions also reflect the belief that (1) the detrimental effects of epoxy coating on bond will decrease with increased cover and spacing and (2) the detrimental effects of epoxy-coating and bar position are not fully additive for top bars (bars with more than 12 in. of concrete cast below the bar). Thus, factors of 1.2 (ACI 1989) or 1.15 (AASHTO 1989) are used for bars with 3 bar diameters or more concrete cover and 6 bar diameters or more of clear spacing between bars, and although top-bar factors of 1.3 (ACI 1989) and 1.4 (AASHTO 1989) are applied for all top bars, an upper limit of 1.7 is placed on the product of the epoxy-bar and top-bar factors.

The current provisions are based on tests of 21 splice specimens, 12 of which contained epoxy-coated reinforcement, by Treece and Jirsa (1987, 1989) and their interpretation of tests of beam-end specimens with confined reinforcement by Johnston and Zia (1982). Although limited in scope, the study by Treece and Jirsa (1987, 1989) provided experimental justification for a 1.5 factor for epoxy-coated bars with low cover and spacing. There were, however, no specific experimental data to support the lower factor (1.2 or 1.15) for bars with higher cover and spacing or the limit of 1.7 on the product of the epoxy-bar and top-bar factors. Subsequent work at the University of Kansas (Choi et al. 1990a, 1990b, 1991; Hadje-Ghaffari et al. 1991; Hester et al. 1991) and by Cleary and Ramirez (1989, 1991) indicates that, while epoxy coating significantly reduces bond strength, the reduction is less than reflected by the development length modification factors in ACI 318-89 and the AASHTO Bridge Specifications (1989). Specifically, work by Choi et al. (1991) and Hester (1991) indicates that a basic development length modification factor of 1.35 is satisfactory for coated bars with less than 3 bar diameters of cover or less than 6 bar diameters of clear spacing between bars for coated reinforcement both with and without transverse reinforcement. This report, the fifth in a continuing series describing research at the University of Kansas, describes research to characterize the effects of cover, casting position (top or bottom-cast bars), slump, and degree of consolidation on the bond strength of epoxy-coated reinforcement. Prior reports (Choi et al. 1990a, 1990b, 1991, Hadje-Ghaffari et al. 1991, Hester et al. 1991) have dealt with effects of coating thickness, deformation pattern, bar size, and transverse reinforcement on the development and splice strength of deformed reinforcing bars. Additional details on the tests presented in this report are available in Choi et al. (1990b) and Hadje-Ghaffari et al. (1991).

EXPERIMENTAL PROGRAM

The overall experimental program (Choi et al. 1990b, 1991, Hadje-Ghaffari et al. 1991, Hester et al. 1991) involved 637 beam-end specimens. This report presents the results obtained from 376 specimens used to evaluate the effects of cover, casting position, slump, and consolidation. The tests involved No. 5, No. 6, No. 8, and No. 11 bars with three deformation patterns.

Test Specimens

Beam-end specimens containing No. 5, No. 6, and No. 8 bars were 9 in. wide x 24 in. long (Fig. 1). The width was increased to 10 in. for specimens containing No. 11 bars. Most of the tests used specimens with 15 in. of concrete above or below the bars for bottom-cast and top-cast bars, respectively, and 1, 2, or 3 bar diameters of cover. Selected tests used deep specimens with 36 in. of concrete below top-cast or above bottom-cast bars for No. 8 bars (Fig. 1). Specimen dimensions were based on the work of Brettmann, Darwin, and Donahey (1984, 1986).

Test bars extended 22 in. out from the face of the specimens. Two polyvinyl chloride (PVC) pipes were used as bond breakers to control the bonded length of the bar and to avoid a localized cone-type failure of the concrete at the loaded end of the specimen (Brettmann, et al. 1984, 1986). Bonded lengths (length of test bars in contact with concrete) of $3^1/_2$, $4^1/_2$, 8, and 9 in. were used for No. 5, No. 6, No. 8, and No. 11 bars, respectively. The corresponding lengths of bond breaking PVC pipe in front of the bars (lead lengths) were $2^3/_8$, $2^3/_4$, $3^3/_4$, and $1^1/_2$ in., respectively. Two auxiliary bars, parallel to the test bar, were used to prevent the specimen from failing in flexure (Fig. 1). The size of the auxiliary bars depended on the test bar size. No. 4 auxiliary bars were used for No. 5 and No. 6 test bars. No. 5 and No. 6 auxiliary bars were used for No. 8 and No. 11 bars, respectively.

Materials

Reinforcing Steel–ASTM A 615 (1987) Grade 60 No. 5, No. 6, No. 8, and No. 11 bars were used. Bars with three deformation patterns, designated S, C, and N, were tested (Fig. 2). Deformation pattern S consists of ribs perpendicular to the axis of the bar. Deformation pattern C consists of ribs inclined at 60° with respect to the axis of the bar. Deformation pattern N consists of ribs inclined at 70° with respect to the axis of the bar. Bars of each size and deformation pattern were from the same heat of steel. Yield strengths and deformation properties are shown in Table 1. The bearing areas and face angles of the deformations were determined using methods presented by Choi et al. (1990b) and Hadje-Ghaffari et al. (1991).

The epoxy-coating was commercially applied in accordance with ASTM A 775 (1988) and ranged in thickness from 3 to 17 mils, as measured by a pull-off type thickness gauge. Readings were taken at six points around the circumference of the bar between each set of deformations within the bonded length. Average readings within the bonded lengths are reported.

Concrete–Non-air entrained concrete was supplied by a local ready mix plant. Type I portland cement, $^3/_4$ in. nominal maximum size crushed limestone, and Kansas River sand were used. A high-range water-reducer was added to some mixes to obtain a high slump. Water-cement ratios ranging from 0.55 to 0.41 were used to obtain concrete with nominal strengths of 5000 and 6000 psi. 6000 psi was used for the majority of the specimens. Mix proportions are shown in Table 2. Concrete properties for individual specimen groups are given in Table 3.

Placement Procedure

Concrete was placed in two lifts in the standard beam-end specimens and in three lifts in the deep beam-end specimens. The first lift was placed in all specimens in a group before any specimen received a second lift. Except in specimens that were deliberately not vibrated, each lift was vibrated at 6 evenly spaced points. All deep specimens in a group received the second lift before any specimen received a third lift.

Standard 6 x 12 in. test cylinders were cast in steel molds and cured in the same manner as the test specimens. Forms were stripped after the concrete had reached a strength of at least 3000 psi.

Test Procedure

Tests were made at nominal concrete strengths of 5000 or 6000 psi. Flexural bond strength was measured using an apparatus developed by Donahey and Darwin (1983, 1985) and modified by Brettmann et al. (1984, 1986) (Fig. 1c). Specimens from a group were tested within a 12 hour period (except for groups 18-20, for which tests were completed over a 48 hour period) at ages ranging from 3 to 11 days. Specimens containing No. 5 and No. 6 bars were loaded at about 3.0 kips/min., while specimens containing No. 8 and No. 11 bars were tested at about 6.0 kips/min. (Brettmann et al. 1984, 1986, Choi et al. 1990b).

Results and Observations

The test variables and ultimate bond forces of the bars are listed in Table 4. Details of load-slip behavior are provided by Choi et al. (1990a, 1990b, 1991) and Hadje-Ghaffari et al. (1991). Overall, uncoated bars provided higher bond strengths than coated bars. At a given load, coated bars exhibited greater slip than uncoated bars, and in most cases coated bars failed at greater values of slip than uncoated bars.

As observed in earlier studies (Johnston and Zia 1982, Treece and Jirsa 1987, 1989, Choi et al. 1990a, 1990b, 1991, Hester et al. 1991), after failure, concrete exhibited good adhesion to uncoated bars and virtually no adhesion to epoxy-coated bars.

EVALUATION OF EXPERIMENTAL RESULTS

This report emphasizes the role of bar placement and construction procedures on the bond strength of epoxy-coated reinforcement. Specifically, the roles of cover, casting position, concrete slump, and degree of consolidation are studied. The effect of epoxy-coating on bond strength is evaluated by calculating the ratio of the bond strength of coated bars to the bond strength of uncoated bars, C/U.

To compare the individual tests on an equitable basis, the ultimate bond strengths are corrected for variations in concrete strength by normalizing the test results with respect to a nominal concrete strength of 6000 psi, using the assumption that, within the concrete strength range used, bond strength is proportional to the square root of the compressive strength. Thus, bond strengths are multiplied by $(6000/f'_c)^{1/2}$.

For data reported in tabular form, the bond strengths of individual specimens are also corrected for variations in the actual cover from nominal values of 1, 2, and 3 bar diameters (d_b), as described by Choi et al. (1991). A similar correction should be made for the effects of variations in epoxy-coating thickness. However, work by Choi et al. (1990a, 1990b, 1991) showed that, of the bars tested in this study, only No. 5 bars are sensitive to coating thickness. Thus, a correction for coating thickness (9 mils taken as the standard) is made only for No. 5 bars (Hadje-Ghaffari et al. 1991).

Concrete Cover

Cover affects the confinement provided to reinforcing bars. Its effect on the normalized, ultimate bond forces for No. 5, No. 8, and No. 11 bars is shown in Figs. 3, 4, and 5, respectively. These figures show that, regardless of bar position, bar size, or deformation pattern, there is a nearly linear increase in bond force with increasing concrete cover. The best fit lines for coated and uncoated bars are nearly parallel, but the absolute magnitude of the increase in bond strength with cover is slightly greater for uncoated bars than for coated bars.

As a result of the relationships illustrated in Figs. 3-5, C/U increases as cover increases. These trends are illustrated in greater detail in Table 5, which provides a summary of the C/U ratios for No. 5, No. 8, and No. 11 bars from test groups that had specimens with different covers. Values of C/U provided in the tables are based on both the best fit lines illustrated in Figs. 3-5 and the average strengths for bars of each deformation pattern at each nominal value of cover. The improvement in the relative bond strength of coated bars with increasing cover is illustrated by bottom-cast N-pattern No. 8 bars, for which C/U (based on the best fit lines) increases from 0.85 to 0.91 as the concrete cover increases from 1 to 3 bar diameters. Similarly, for bottom-cast N-pattern No. 11 bars, C/U increases from 0.75 to 0.82.

The results illustrated in Figs. 3-5 and Table 5 can be used to select a development length modification factor for epoxy-coated bars as a function of cover. Table 6 summarizes the U/C ratios (inverse of C/U ratios in Table 5) for bars with different covers in beam-end specimens, as a function of bar size, along with the current ACI (1989) and AASHTO (1989) modification factors for epoxy-coated bars. Table 6 shows that the largest value of U/C for bars with a cover of 3 d_b or greater, 1.22 for No. 11 bars (based on the best fit line), is in agreement with the current ACI modification factor, 1.2, for bars with $\geq 3\ d_b$ of cover. The highest value of U/C for bars with a 3 d_b cover based on the average of actual test results is only 1.16 (also for No. 11 bars). For No. 8 and smaller bars, the highest U/C ratio for bars with a 3 d_b cover is 1.10, based on a best fit of data (top-cast S-pattern and N-pattern No. 8 bars and bottom-cast N-pattern No. 8 bars), and 1.14, based on an average of actual test results (top-cast S-pattern No. 8 bars). These results suggest that the ACI 1.2 factor might be reduced slightly for No. 8 and smaller bars. The maximum U/C ratio for bars with 2 d_b cover and less, 1.35 for bottom-cast N-pattern No. 11 bars, matches the values of development length modification factor recommended earlier by Choi et al. (1990a, 1990b, 1991) and Hester et al. (1991).

A particularly clear picture of the combined effects of epoxy coating and cover on bond strength is provided in Table 5 using the term C′/U, the ratio of the bond strength of coated bars to the bond strength of uncoated bars with 1 d_b less cover. With but one exception, (C′/U = 0.91 based on average test values for No. 11 N-pattern coated bars with 2 d_b cover), the C′/U ratios in Table 5 are greater than 1.0. For coated bars with 3 d_b cover, the C′/U ratio is always greater than 1.0, i.e., these bars consistently exhibit greater bond strength than uncoated bars with 2 d_b cover. Thus, the combined effects of the higher C/U ratio and improved bond strength with increased cover overcome the reduced bond strength caused by epoxy coating. The implication for design is that no increase in development length is needed for coated bars with covers $\geq 3\ d_b$, if the beneficial effect of covers $> 2\ d_b$ are not already considered for uncoated bars. This is, in fact, the case in ACI 318-89 and the 1989 AASHTO Bridge Specifications. However, the beneficial effect of increased spacing is considered for both uncoated and coated bars in ACI 318-89 and the 1989 AASHTO Bridge Specifications (0.8 factor for bars with clear spacing $\geq 5\ d_b$ or center-to-center spacing $\geq$ 6 in., respectively), and it is well established (Orangun et al. 1975, 1977) that bond strength is controlled by the smaller of the cover, C_b, or one-half of the clear spacing between bars, C_s (if $C_s < C_b$, C_s plays the role of cover in governing bond strength). Thus, current observations suggest that, for bars with covers $\geq 3\ d_b$ and clear spacings $\geq 6\ d_b$, the development length modification factor for epoxy-coated bars can be lowered to 1.0 as long as the 0.8 factor is *not* applied for coated bars. An alternative would be to retain the current 0.8 factor for wide spacing and a 1.2 factor for epoxy-coated bars with at least 3 d_b cover and 6 d_b clear spacing (0.8 x 1.2 = 0.96).

The combination of the 0.8 factor with the AASHTO (1989) factor of 1.15 for epoxy-coated bars with cover $\geq 3\ d_b$ and clear spacings $\geq 6\ d_b$ (0.8 x 1.15 = 0.92) corresponds to a C′/U ratio of 1/0.92 = 1.09, which is justified for No. 8 and smaller bars (Table 5) but not for No. 11 bars (C′/U = 1.03 – 1.07).

Casting Position, Concrete Slump, and Consolidation

The casting position of a bar affects its bond strength. The greater the amount of concrete cast below a bar, the greater the effects of settlement and bleeding and the lower the bond strength. The ACI Building Code (1989) and the AASHTO Bridge Specifications (1989) recognize these effects for "top bars" by increasing the required development lengths by 30 and 40 percent, respectively, for reinforcement with more than 12 in. of concrete cast below the bar. Luke et al. (1981) and Brettmann et al. (1984, 1986) demonstrated that the top-bar effect is greatest for "top-cast" bars, that is, bars cast near the upper surface of a placement, and that this effect increases as concrete slump increases. Brettmann et al. (1984, 1986) also demonstrated that the bond strength of bars in high slump concrete is reduced if the concrete is not vibrated. Thus, concrete slump and consolidation, as well as casting position, play a role in the "top-bar" effect.

The effects of casting position (top or bottom-cast), concrete slump, and degree of consolidation (vibration) of plastic concrete for bars in the current study are shown in Fig. 6, which provides a summary of normalized ultimate bond strengths obtained from standard beam-end specimens with slumps below 6 in. and deep beam-end specimens with slumps both below and above 6 in. Of the 52 data points shown, 48 represent the average of at least 3 tests. Some of the specimens made with high slump concrete were vibrated and some were not. The effects of casting position are also illustrated in Fig. 4.

For the tests illustrated, top-cast bars exhibit a lower bond strength than the corresponding bottom-cast bars, and bars cast in high slump concrete exhibit a reduced bond strength if the concrete is not vibrated. The top-cast bars in high slump concrete, whether vibrated or not, have a lower bond strength than the top-cast bars in lower slump concrete.

Casting position and concrete slump–The effects of casting position and slump on bond strength are illustrated in Figs. 7-9 for deep beam-end specimens containing N-pattern No. 8 bars. In Figs. 7 and 8, normalized bond strengths are plotted versus concrete slump for vibrated bottom and top-cast N-pattern No. 8 bars (groups 23 and 24), respectively. These figures show that, with the exception of the bottom-cast uncoated bars, the ultimate bond strength decreased with increased slump.

The ratio of bottom to top-cast bar bond strength (B/T), commonly referred to as the "top-bar effect," is plotted versus slump in Fig. 9. The curves in Fig. 9 represent the ratios of the best fit lines for the bond strengths of bottom and top-cast bars from Figs. 7 and 8. Fig. 9 illustrates that, for low slump concrete, uncoated and coated bars exhibit similar top-bar effects, with B/T $\cong$ 1.07. However, there is little similarity for high slump concrete. As expected (Menzel et al. 1952, Luke et al. 1981, Brettmann et al. 1984, 1986), B/T for uncoated bars increases (to about 1.2) as the concrete slump increases to 8 in. In contrast, B/T for coated bars actually decreases slightly as slump increases, showing that the top-bar effect is lower for coated bars than for uncoated bars.

A more detailed look at this behavior is provided by Table 7, which summarizes the normalized bond strengths, C/U ratios, and B/T ratios for all groups containing specimens with both top and bottom-cast bars (groups 9-11, 15, 17, 18, 23, and 24). As illustrated in Table 7, bottom-cast bars are, with one exception (coated No. 8 bars in group 23), stronger in bond than the companion top-cast bars. For the one exception, B/T = 1.00.

In Table 8, the B/T and C/U ratios from Table 7 are averaged based on bar size and concrete slump. In addition, the average B/T ratios for uncoated and coated bars, the average C/U ratios for bottom and top-cast bars, and the average bottom-cast uncoated to top-cast coated bar bond strength ratios (U_b/C_t) for all bars and concrete slumps are statistically analyzed, using the technique of hypothesis testing (Harnett 1975), to see if the differences in bond strengths represented by these ratios are statistically significant [for example, in the case of No. 6 bars, does the average B/T ratio for uncoated bars, 1.34, represent a significant difference in bond strength (due to the top-bar effect) or is the value of B/T due to the scatter in the data? And is the difference between the B/T ratios for uncoated bars, 1.34, and coated bars, 1.11, significant (due to the coating) or is it not significant (due to scatter in the data)?].

The hypothesis testing summarized in Table 8 indicates that, with at least a 97.5 percent level of confidence (probability of making an error in the determination ≤ 2.5 percent), the differences obtained in the bond tests as represented by B/T and C/U are statistically significant (not due to scatter), with the exception of the B/T ratio for No. 8 coated bars in vibrated high slump concrete (1.05) and the C/U ratios for No. 6 (1.00) and No. 8 (0.94) top-cast bars in vibrated high slump concrete.

Table 8 also shows that for low slump concrete (slump ≤ 5 in.), B/T is virtually the same for uncoated and coated bars for both standard and deep specimens. The average B/T ratios for low slump concrete are 1.13 and 1.14 (actually 1.132 and 1.137) for uncoated and coated bars, respectively. Also for low slump concrete, the average C/U ratios are virtually the same, at 0.89, for bottom and top-cast bars, respectively.

For high slump concrete (slump > 5 in.), however, the B/T ratios are significantly different for uncoated and coated bars. The average B/T ratio in high slump concrete is 1.28 for uncoated bars compared to 1.08 for coated bars. This reduction in the top-bar effect can be attributed to the fact that the epoxy coating and the weakened concrete at the interface caused by bleeding and settlement have similar, non-additive effects on bond strength. Thus, while the average B/T ratio for uncoated bars increases from 1.13 to 1.28 as slump increases, the average B/T ratio for coated bars *decreases* from 1.14 to 1.08. It follows from these observations that C/U is significantly different for bottom and top-cast bars in high slump concrete. The average value of C/U for bars in vibrated high slump concrete is 0.82 for bottom-cast bars, compared to 0.97 for top-cast bars. In fact, with increased slump, C/U decreases, from 0.89 to 0.82, for bottom-cast bars but increases, from 0.89 to 0.97, for top-cast bars.

The trends observed for B/T are important because the value of the top-bar development length modification factor used in the ACI Building Code (1989), 1.3, is based on a worst case assumption, i.e., bars cast in high slump concrete. The average B/T obtained in the current study for uncoated bars cast in high slump concrete, 1.28, agrees well with the ACI factor. Since coated bars do not appear to be affected as greatly as uncoated bars at higher slumps, it can be argued that a top-bar factor below 1.3 can be used for epoxy-coated bars. The results in Table 8 indicate that a value close to 1.14 (the average value of B/T for coated bars in low slump concrete) would be appropriate. This value compares favorably with the defacto top-bar factor for epoxy-coated bars in ACI 318-89, 1.13, which is obtained by dividing the upper limit on the combined effects of bar position and epoxy coating, 1.7, by the epoxy-bar factor, 1.5. Rounding up slightly gives a factor of 1.15 for epoxy-coated top bars.

The values of U_b/C_t, ratio of uncoated bottom-cast bar strength to coated top-cast bar strength, in Tables 7 and 8 show the combined effects of coating and bar position on the bond strength of coated top bars. Average U_b/C_t ratios of 1.29, 1.32 and 1.45 (Table 8) for low slump, high slump vibrated, and high slump non-vibrated concrete, respectively, demonstrate that the ACI upper limit on the combined factors, 1.7, can be conservatively decreased to 1.5 for coated top bars. A value of 1.5 also agrees closely with 1.55, the product of 1.35, the recommended epoxy-bar factor for bars with cover $< 3\ d_b$ or clear spacing $< 6\ d_b$, and 1.15, the top-bar factor for coated bars developed in this section.

Overall, it appears that a top-bar factor of 1.15 for coated bars, applied to the development length of bottom-cast coated bars and/or an upper limit of 1.5 on the combined factors, applied to the development length of bottom-cast uncoated bars, will provide safe, satisfactory designs.

Consolidation–As shown in Fig. 6 and Table 7 (group 24), the lack of vibration has a negative effect on bond strength in high slump concrete, regardless of casting position, for both coated and uncoated bars. In the case illustrated in Fig. 6, a lack of vibration of the 8 in. slump concrete caused normalized bond strengths to drop by 2.7 and 2.6 percent (Table 7) for uncoated bottom and top-cast bars, respectively. The differences were greater for coated bars, where a lack of vibration caused reductions of 9.2 and 13.1 percent for bottom and top-cast bars, respectively.

As seen in Table 7 for the bars in group 24, B/T remains nearly constant (about 1.22) for uncoated bars but rises from 1.05 to 1.16 for coated bars when the concrete is not vibrated. In addition, C/U drops from 0.81 to 0.77 for bottom-cast bars and from 0.94 to 0.84 for top-cast bars when the concrete is not vibrated. Thus, a lack of vibration appears to be more detrimental for coated bars than for uncoated bars.

As observed for vibrated high slump concrete, C/U for bars in non-vibrated high slump concrete is higher for top-cast bars, 0.84, than for bottom-cast bars, 0.77.

DESIGN RECOMMENDATIONS

This study points the way to a number of modifications in the development length provisions for epoxy-coated bars in the ACI Building Code (1989) and the AASHTO Bridge Specifications (1989).

Current Provisions

The current provisions consist of a 1.5 development length modification factor for epoxy-coated bars with a cover $< 3\ d_b$ or a clear spacing $< 6\ d_b$; a 1.2 (ACI) or 1.15 (AASHTO) modification factor for epoxy-coated bars with a cover $\geq 3\ d_b$ or more and a clear spacing $\geq 6\ d_b$; a top-bar factor of 1.3 (ACI) or 1.4 (AASHTO) for both coated and uncoated bars; and an upper limit of 1.7 on the product of the epoxy-coating factor and the top-bar factor.

Proposed Provisions

As shown here and in an earlier work by Choi et al. (1990a, 1990b, 1991) and Hester et al. (1991), the development length modification factor of 1.5 for epoxy-coated bars with a cover $< 3\ d_b$ or a clear spacing $< 6\ d_b$ can be reduced to 1.35.

For epoxy-coated bars with a cover $\geq 3\ d_b$ and a clear spacing $\geq 6\ d_b$, the current study supports the application of a development length modification factor of 1.0, if the beneficial effects of covers $> 2\ d_b$ and clear spacings $> 4\ d_b$ are not otherwise accounted for in the design provisions, as they are now (ACI 1989, AASHTO 1989) through application of the 0.8 factor for widely spaced bars. If the 0.8 factor is retained, the current ACI (1989) epoxy-coating factor of 1.2 should be retained for bars with cover $\geq 3\ d_b$ and clear spacing ≥ 6 db, and the 1.15 factor used by AASHTO (1989) should be increased to 1.2.

The relative insensitivity of coated bars to the top-bar effect, especially when high slump concrete is used, strongly supports a reduction in the development length modification factor for coated top bars from 1.3 to 1.15 and a reduction in the upper limit on product of the epoxy-coating factor and the top-bar factor from 1.7 to 1.5. While both steps are justified, an upper limit on the combined factors would be easier to apply than different top-bar factors for coated and uncoated bars.

SUMMARY AND CONCLUSIONS

This study continues earlier research (Choi et al. 1990a, 1990b, 1991, Hester et al. 1991) on the bond strength of epoxy-coated reinforcement to concrete. The current effort evaluates the effect of concrete cover, casting position, slump, and degree of consolidation on the bond strength of epoxy-coated reinforcement using beam-end specimens containing No. 5, No. 6, No. 8, and No. 11 bars. Bottom-cast and top-cast bars with 1, 2, or 3 bar diameters of cover were evaluated. Concrete slump ranged from 2¼ to 8 in., and some specimens containing high-slump concrete were not vibrated.

Based on the tests and evaluations presented in this report, it may be concluded that:

1. Epoxy coating reduces the bond strength of reinforcing steel to concrete. However, for bars with a cover $< 3\ d_b$ or a clear spacing $< 6\ d_b$, the extent of the reduction is less than that used to establish the development length modification factors in the 1989 ACI Building Code and the 1989 AASHTO Bridge Specifications.
2. The bond strength of both coated and uncoated bars increases as cover increases, regardless of casting position, bar size, or deformation pattern. This results in an increase in the relative bond strength of coated bars, C/U, as cover increases.
3. In most cases, the bond strength of coated bars exceeds the bond strength of uncoated bars that have $1\ d_b$ less cover. This is true in all cases in the current study for coated bars with 3

3. In most cases, the bond strength of coated bars exceeds the bond strength of uncoated bars that have 1 d_b less cover. This is true in all cases in the current study for coated bars with 3 d_b of cover. As a result, the current provisions of the 1989 ACI Building Code are realistic as they are applied to epoxy-coated bars with a cover $\geq 3\ d_b$ and a clear spacing $\geq 6\ d_b$. The provisions of the 1989 AASHTO Bridge Specifications are somewhat unconservative for these bars and should be modified.
4. As the depth of concrete below a bar increases, the bond strength decreases, regardless of bar size, deformation pattern, or bar surface condition.
5. Bars cast in low slump concrete are stronger in bond than bars cast in high slump concrete of the same compressive strength.
6. The ratio of the bond strength of bottom-cast bars to the bond strength of top-cast bars, B/T, (a measure of the top-bar effect) increases significantly for uncoated bars and decreases slightly for coated bars as slump increases.
7. In low slump concrete, B/T is about the same for uncoated and coated bars, and C/U is about the same for bottom and top-cast bars.
8. In high slump concrete that is adequately vibrated, B/T is lower for coated bars than for uncoated bars, and C/U is greater for top-cast bars than for bottom cast bars.
9. For coated bars, the relative insensitivity of B/T to increasing slump allows the use of a reduced top-bar factor for epoxy-coated bars and/or a decrease in the upper limit of the product of the epoxy-bar factor and the top-bar factor.
10. Lack of vibration of high slump concrete has a negative effect on the bond strength of all bars, coated and uncoated, bottom and top-cast. Lack of vibration is more detrimental for coated bars than for uncoated bars.

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Table 1: Average Test Bar Data

Bar size	Def. pat.	Yield str. (ksi)	Def. height* (in.)	Def. spac. (in.)	Def. gap (in.)	Def. angle (deg.)	Def. face angle (deg.)	Bearing area per inch** (in.)	Related rib area+	Bearing area ratio++ (in.-1)
5	S	70.6	0.031	0.423	0.159	90	47	0.112	0.057	0.361
5	C	72.3	0.040	0.413	0.140	60	45	0.146	0.074	0.471
5	N	68.4	0.041	0.379	0.158	70	51	0.169	0.086	0.545
6	S	63.8	0.040	0.502	0.154	90	45	0.141	0.060	0.320
6	C	70.9	0.047	0.467	0.122	60	57	0.185	0.079	0.420
6	N	64.2	0.051	0.462	0.151	70	49	0.197	0.084	0.448
8	S	67.0	0.053	0.674	0.176	90	50	0.202	0.064	0.256
8	C	***	0.062	0.656	0.195	60	56	0.241	0.077	0.305
8	N	63.8	0.057	0.602	0.160	70	55	0.250	0.080	0.316
11	S	64.6	0.076	0.945	0.217	90	55	0.315	0.071	0.202
11	C	63.1	0.074	0.840	0.196	60	45	0.306	0.069	0.196
11	N	64.3	0.077	0.914	0.195	70	43	0.289	0.065	0.185

* Per ASTM A 615

** Bearing area of the deformations divided by the spacing of deformations. Bearing area based on closely spaced measurements of ribs.

\+ Ratio of bearing area of deformations to shearing area between deformations (bearing area per inch divided by nominal perimeter of bar)

++Ratio of bearing area of deformations to area of the bar (bearing area divided by nominal area of bar)

***Yield strength is greater than 70.0 ksi.

Table 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	0.55	509	280	1537	1575
2	6000	0.41	756	310	1245	1575
4,6	6000	0.45	622	280	1437	1575
8-17,21,22	6000	0.45	733	330	1213	1575
18-20,23, 24*	5000	0.55	600	330	1324	1575

\+ Kansas River Sand - Lawrence Sand Co., Lawrence, KS, bulk specific gravity = 2.62, absorption = 0.5%, fineness modulus = 3.0.

++ Crushed limestone - Hamm's Quarry, Perry, KS, bulk specific gravity = 2.52, absorption = 3.5%, maximum size = 3/4 in., unit weight = 97.2 lb/cu. ft.

* 10000 cc Master Builders "Rheobuild 1000" added

Table 3: Concrete Properties

Group	Slump (in.)	Concrete Temperature (F)	Age at Test (days)	Average Compressive Strength (psi)
1	1	58	4	4150
			5	4450
			6	4750
2	$2^{1}/_{2}$	60	3	5700
4	$1^{1}/_{2}$	73	4	6130
6	$1^{1}/_{2}$	70	5	5870
8	3	80	4	5800
9	4	89	6	5650
10	$4^{1}/_{2}$	85	7	5990
11	$3^{1}/_{4}$	89	6	5970
12	$3^{1}/_{4}$	92	7	5940
13	$3^{1}/_{4}$	93	9	5840
15	$4^{1}/_{4}$	74	8	6000
17	$5^{3}/_{4}$	78	9	5850
18	$4^{1}/_{4}$	57	3	4790
			4	5010
			5	5430
19	$3^{3}/_{4}$	68	4	5070
			5	5270
20	$2^{3}/_{4}$	89	9	5290
			10	5260
23	$2^{1}/_{4}$	75	3	5120
			4	5580
24	$2^{1}/_{2}$	70	5	4980
			6	5240
	8	71	5	5680
			6	5980

Table 4: Beam-end specimen test results

Group No.	Specimen label	Average coating thickness (mils)	Cover ** (in.)	Concrete strength (psi)	Ultimate bond force (lbs)	Modified bond ++ force (lbs)	Lead length (in.)
1	8TS-E 5-8.0	4.9	1.000	4480	23090	26721	3.75
1	8TS-E 9-8.0	8.5	1.000	4820	21910	24445	3.75
1	8TS-E12-8.0	13.8	1.000	4820	23640	26375	3.75
1	8TS-B 0-8.0	0.0	1.000	4420	24180	28172	3.75
1	8TS-M 0- 8.0	0.0	1.000	4410	27090	31598	3.75
1	8TS-E 5- 8.0	4.1	2.000	4750	33680	37853	3.75
1	8TS-E 9- 8.0	7.9	2.000	4720	33360	37612	3.75
1	8TS-E12- 8.0	12.5	2.000	4710	36000	40631	3.75
1	8TS-B 0- 8.0	0.0	2.000	4770	39000	43740	3.75
1	8TS-M 0- 8.0	0.0	2.000	4780	38410	43033	3.75
1	8TS-E 5- 8.0	3.5	3.000	4110	43730	52836	3.75
1	8TS-E 9- 8.0	7.7	3.000	4080	40000	48507	3.75
1	8TS-E12- 8.0	11.0	3.000	4060	41450	50389	3.75
1	8TS-B 0- 8.0	0.0	3.000	4910	53420	59052	3.75
1	8TS-M 0- 8.0	0.0	3.000	4910	52170	57670	3.75
2	8BC-E12- 8.0	11.0	1.000	5700	24840	25485	3.75
2	8BC-E 9- 8.0	9.1	1.000	5700	25660	26326	3.75
2	8BC-E 5- 8.0	5.4	1.000	5700	25000	25649	3.75
2	8BC-B 0- 8.0	0.0	1.000	5700	33020	33877	3.75
2	8BC-M 0- 8.0	0.0	1.000	5700	31040	31846	3.75
2	8BC-E12- 8.0	13.3	2.000	5700	38300	39294	3.75
2	8BC-E 9- 8.0	10.0	2.000	5700	36760	37714	3.75
2	8BC-E 5- 8.0	5.3	2.000	5700	35990	36924	3.75
2	8BC-B 0- 8.0	0.0	2.000	5700	40000	41039	3.75
2	8BC-M 0- 8.0	0.0	2.000	5700	45990	47184	3.75
4	8BN-E 9- 8.0	8.6	2.000	6130	35820	35438	3.75
4	8BN-E 9- 8.0A	8.5	2.000	6130	42030	41581	3.75
4	8BN-E 9- 8.0B	8.8	2.000	6130	34970	34597	3.75
4	8BN-B 0- 8.0	0.0	2.000	6130	46630	46132	3.75
4	8BN-B 0- 8.0A	0.0	2.000	6130	41620	41176	3.75
4	8BN-B 0- 8.0B	0.0	2.000	6130	41920	41473	3.75
4	8BN-M 0- 8.0	0.0	2.000	6130	45220	44737	3.75
4	8BN-M 0- 8.0A	0.0	2.000	6130	50000	49466	3.75
4	8BN-M 0- 8.0B	0.0	2.000	6130	44580	44104	3.75
6	8BS-E 9- 8.0	7.9	2.000	5870	35430	35820	3.75
6	8BS-E 9- 8.0A	10.8	2.000	5870	32840	33201	3.75
6	8BS-B 0- 8.0	0.0	2.000	5870	47530	48053	3.75
6	8BS-B 0- 8.0A	0.0	2.000	5870	35930	36325	3.75
6	8BS-M 0- 8.0	0.0	2.000	5870	46500	47012	3.75
6	8BS-M 0- 8.0A	0.0	2.000	5870	42710	43180	3.75
6	8BC-E 9- 8.0	10.7	2.000	5870	33790	34162	3.75
6	8BC-E 9- 8.0A	9.1	2.000	5870	36630	37033	3.75

Table 4 : Beam-end specimen test results, continued

Group No.	Specimen label	Average coating thickness (mils)	Cover ** (in.)	Concrete strength (psi)	Ultimate bond force (lbs)	Modified bond ++ force (lbs)	Lead length (in.)
6	8BC-B 0- 8.0	0.0	2.000	5870	51430	51996	3.75
6	8BC-B 0- 8.0A	0.0	2.000	5870	42510	42978	3.75
6	8BC-M 0- 8.0	0.0	2.000	5870	43930	44413	3.75
6	8BC-M 0- 8.0A	0.0	2.000	5870	46820	47335	3.75
6	8BN-E 9- 8.0	9.2	2.000	5870	36620	37023	3.75
6	8BN-E 9- 8.0A	10.4	2.000	5870	45070	45566	3.75
6	8BN-B 0- 8.0	0.0	2.000	5870	50810	51369	3.75
6	8BN-B 0- 8.0A	0.0	2.000	5870	39150	39581	3.75
6	8BN-M 0- 8.0	0.0	2.000	5870	38000	38418	3.75
6	8BN-M 0- 8.0A	0.0	2.000	5870	47670	48194	3.75
8	5BN-M 0- 3.5	0.0	0.656	5800	13860	14096	3.75
8	5BN-E 9- 3.5	6.1	0.656	5800	13440	13669	3.75
8	5BN-M 0- 3.5	0.0	0.656	5800	10180	10228	2.38
8	5TN-M 0- 3.5	0.0	0.719	5800	10610	10346	2.38
8	5BN-E 9- 3.5	5.7	0.687	5800	11780	11185	2.38
8	5TN-E 9- 3.5	6.5	0.687	5800	9160	8767	2.38
8	5BN-M 0- 3.5	0.0	0.625	5800	10270	10445	1.50
8	5TN-M 0- 3.5	0.0	0.687	5800	8340	8482	1.50
8	5BN-E 9- 3.5	6.5	0.656	5800	7850	7984	1.50
8	5TN-E 9- 3.5	8.3	0.687	5800	8420	8563	1.50
8	5BN-M 0- 3.5	0.0	0.687	5800	8500	8645	0.75
8	5BN-M 0- 3.5	0.0	1.250	5800	18110	18419	3.75
8	5BN-E 9- 3.5	5.6	1.281	5800	15860	16131	3.75
8	5BN-M 0- 3.5	0.0	1.313	5800	14580	14577	2.38
8	5TN-M 0- 3.5	0.0	1.250	5800	12700	12917	2.38
8	5BN-E 9- 3.5	7.0	1.344	5800	14100	13633	2.38
8	5TN-E 9- 3.5	5.9	1.281	5800	12700	12455	2.38
8	5BN-M 0- 3.5	0.0	1.250	5800	10850	11035	1.50
8	5TN-M 0- 3.5	0.0	1.313	5800	10990	11177	1.50
8	5BN-E 9- 3.5	5.1	1.250	5800	11180	11371	1.50
8	5TN-E 9- 3.5	6.0	1.250	5800	10330	10506	1.50
9	5BS-E 5- 3.5	6.9	1.313	5650	11160	10902	2.38
9	5BS-E 5- 3.5A	5.5	1.313	5650	11910	11444	2.38
9	5BS-E 5- 3.5B	4.4	1.313	5650	13590	12994	2.38
9	5BS-E12- 3.5	14.5	1.313	5650	10520	11494	2.38
9	5BS-E12- 3.5A	17.1	1.375	5650	11340	12516	2.38
9	5BS-E12- 3.5B	11.8	1.313	5650	10630	11163	2.38
9	5BS-B 0- 3.5	0.0	1.313	5650	12440	12567	2.38
9	5BS-B 0- 3.5A	0.0	1.344	5650	13690	13729	2.38
9	5BS-B 0- 3.5B	0.0	1.313	5650	13890	14061	2.38
9	5BS-M 0- 3.5	0.0	1.313	5650	14770	14968	2.38
9	5BS-M 0- 3.5A	0.0	1.313	6310	14870	14248	2.38
9	5BS-M 0- 3.5B	0.0	1.344	5650	13220	13245	2.38

Table 4 : Beam-end specimen test results, continued

Group No.	Specimen label	Average coating thickness (mils)	Cover ** (in.)	Concrete strength (psi)	Ultimate bond force (lbs)	Modified bond ++ force (lbs)	Lead length (in.)
9	5TS-E 5- 3.5	5.8	1.438	5650	12080	11235	2.38
9	5TS-E 5- 3.5A	6.9	1.375	5650	11300	10839	2.38
9	5TS-E 5- 3.5B	5.9	1.344	5650	10410	9969	2.38
9	5TS-E12- 3.5	14.3	1.281	5650	10470	11175	2.38
9	5TS-E12- 3.5A	15.6	1.375	5650	10800	11202	2.38
9	5TS-E12- 3.5B	12.2	1.375	5650	9820	9849	2.38
9	5TS-B 0- 3.5	0.0	1.375	5650	11220	10969	2.38
9	5TS-B 0- 3.5A	0.0	1.438	5650	12520	12012	2.38
9	5TS-B 0- 3.5B	0.0	1.438	5650	12590	12084	2.38
9	5TS-M 0- 3.5	0.0	1.281	5650	10770	10950	2.38
9	5TS-M 0- 3.5A	0.0	1.406	5650	11860	11480	2.38
9	5TS-M 0- 3.5B	0.0	1.313	5650	12060	12131	2.38
10	5BC-E 9- 3.5	9.3	1.188	5990	12660	12971	2.38
10	5BC-E 9- 3.5A	10.1	1.250	5990	12950	13141	2.38
10	5BC-E 9- 3.5B	8.7	1.250	5990	12880	12841	2.38
10	5BC-E 5- 3.5	3.0	1.313	5990	14700	13472	2.38
10	5BC-E 5- 3.5A	4.5	1.250	5990	13370	12640	2.38
10	5BC-E 5- 3.5B	3.7	1.313	5990	14110	12996	2.38
10	5BC-B 0- 3.5	0.0	1.281	5990	13370	13255	2.38
10	5BC-B 0- 3.5A	0.0	1.250	5990	14560	14572	2.38
10	5BC-B 0- 3.5B	0.0	1.250	5990	13850	13861	2.38
10	5BC-M 0- 3.5	0.0	1.281	5990	13660	13545	2.38
10	5BC-M 0- 3.5A	0.0	1.250	5990	13340	13351	2.38
10	5BC-M 0- 3.5B	0.0	1.375	5990	14340	13847	2.38
10	5TC-E 9- 3.5	9.7	1.313	5990	11460	11243	2.38
10	5TC-E 9- 3.5A	7.7	1.406	5990	12070	11207	2.38
10	5TC-E 9- 3.5B	8.9	1.375	5990	11980	11386	2.38
10	5TC-E 5- 3.5	3.4	1.313	5990	12620	11768	2.38
10	5TC-E 5- 3.5A	4.0	1.313	5990	12390	11599	2.38
10	5TC-E 5- 3.5B	3.9	1.344	5990	11990	11040	2.38
10	5TC-B 0- 3.5	0.0	1.281	5990	12020	11881	2.38
10	5TC-B 0- 3.5A	0.0	1.250	5990	12060	12070	2.38
10	5TC-B 0- 3.5B	0.0	1.313	5990	12090	11803	2.38
10	5TC-M 0- 3.5	0.0	1.344	5990	12080	11645	2.38
10	5TC-M 0- 3.5A	0.0	1.313	5990	12210	11923	2.38
10	5TC-M 0- 3.5B	0.0	1.313	5990	12510	12223	2.38
10	5BC-M 0- 3.5	0.0	1.875	5990	17330	17344	2.38
10	5TC-M 0- 3.5	0.0	1.875	5990	14430	14442	2.38
11	5BN-E 9- 3.5	9.6	1.219	5970	12180	12435	2.38
11	5BN-E 9- 3.5A	10.0	1.250	5970	11630	11823	2.38
11	5BN-E 9- 3.5B	9.9	1.344	5970	11930	11730	2.38
11	5BN-B 0- 3.5	0.0	1.344	5970	12700	12353	2.38
11	5BN-B 0- 3.5A	0.0	1.344	5970	12870	12524	2.38

Table 4 : Beam-end specimen test results, continued

Group No.	Specimen label	Average coating thickness (mils)	Cover ** (in.)	Concrete strength (psi)	Ultimate bond force (lbs)	Modified bond ++ force (lbs)	Lead length (in.)
11	5BN-B 0- 3.5B	0.0	1.250	5970	14220	14255	2.38
11	5BN-M 0- 3.5	0.0	1.281	5970	12180	12084	2.38
11	5BN-M 0- 3.5A	0.0	1.250	5970	12800	12832	2.38
11	5BN-M 0- 3.5B	0.0	1.250	5970	13940	13974	2.38
11	5TN-E 9- 3.5	9.0	1.375	5970	11980	11416	2.38
11	5TN-E 9- 3.5A	9.5	1.313	5970	9010	8786	2.38
11	5TN-E 9- 3.5B	10.6	1.313	5970	8980	8867	2.38
11	5TN-B 0- 3.5	0.0	1.313	5970	11910	11643	2.38
11	5TN-B 0- 3.5A	0.0	1.313	5970	11710	11442	2.38
11	5TN-B 0- 3.5B	0.0	1.219	5970	11060	11236	2.38
11	5TN-M 0- 3.5	0.0	1.281	5970	11790	11671	2.38
11	5TN-M 0- 3.5A	0.0	1.250	5970	12080	12110	2.38
11	5TN-M 0- 3.5B	0.0	1.313	5970	11680	11412	2.38
11	5BN-M 0- 3.5	0.0	1.281	6090	7050	6997	0.00
11	5BN-M 0- 3.5A	0.0	1.188	6090	7000	6948	0.00
11	5TN-M 0- 3.5	0.0	1.313	6090	6770	6719	0.00
11	5TN-M 0- 3.5A	0.0	1.313	6090	6720	6670	0.00
12	5BN-M 0- 3.5	0.0	1.250	5940	15320	15397	2.38
12	5BN-M 0- 3.5A	0.0	1.250	5940	13830	13899	2.38
12	5BN-M 0- 3.5B	0.0	1.250	5940	12650	12713	2.38
12	5BN-E 9- 3.5	9.8	1.188	5940	12080	12524	2.38
12	5BN-E 9- 3.5A	10.5	1.188	5940	12570	13132	2.38
12	5BN-E 9- 3.5B	9.3	1.344	5940	11890	11621	2.38
12	5BN-M 0- 3.5	0.0	1.250	5940	10460	10512	1.50
12	5BN-M 0- 3.5A	0.0	1.250	5940	11250	11306	1.50
12	5BN-E 9- 3.5	8.3	1.250	5940	10690	10743	1.50
12	5BN-E 9- 3.5A	9.8	1.125	5940	11350	11407	1.50
12	5BN-M 0- 3.5	0.0	1.250	5940	9550	9598	1.00
12	5BN-M 0- 3.5A	0.0	1.313	5940	10730	10784	1.00
12	5BN-E 9- 3.5	9.0	1.281	5940	9260	9306	1.00
12	5BN-E 9- 3.5A	9.4	1.219	5940	10520	10572	1.00
12	5BN-M 0- 3.5	0.0	1.281	5940	9930	9980	0.50
12	5BN-M 0- 3.5A	0.0	1.063	5940	8720	8763	0.50
12	5BN-M 0- 3.5B	0.0	1.188	5940	9290	9336	0.50
12	5BN-E 9- 3.5	9.2	1.219	5940	8310	8351	0.50
12	5BN-E 9- 3.5A	9.6	1.313	5940	8360	8402	0.50
12	5BN-E 9- 3.5B	8.8	1.438	5940	8150	8191	0.50
12	5BN-M 0- 3.5	0.0	1.281	5940	7980	8020	0.00
12	5BN-M 0- 3.5A	0.0	1.188	5940	7980	8020	0.00
12	5BN-E 9- 3.5	9.8	1.313	5940	6870	6904	0.00
12	5BN-E 9- 3.5A	8.1	1.219	5940	7950	7990	0.00
13	5BN-M 0- 3.5	0.0	0.625	5844	10420	10558	2.38
13	5BN-M 0- 3.5A	0.0	0.625	5844	10130	10264	2.38

Table 4 : Beam-end specimen test results, continued

Group No.	Specimen label	Average coating thickness (mils)	Cover ** (in.)	Concrete strength (psi)	Ultimate bond force (lbs)	Modified bond ++ force (lbs)	Lead length (in.)
13	5BN-M 0- 3.5B	0.0	0.656	5844	11160	11181	2.38
13	5BN-E 5- 3.5	6.2	0.625	5844	9960	9630	2.38
13	5BN-E 5- 3.5A	5.7	0.625	5844	9970	9558	2.38
13	5BN-E 5- 3.5B	6.8	0.656	5844	10520	10171	2.38
13	5BN-M 0- 3.5	0.0	1.281	5844	12170	12205	2.38
13	5BN-M 0- 3.5A	0.0	1.250	5844	13660	13841	2.38
13	5BN-M 0- 3.5B	0.0	1.188	5844	12850	13272	2.38
13	5BN-E 5- 3.5	7.1	1.281	5844	13110	12844	2.38
13	5BN-E 5- 3.5A	6.2	1.250	5844	12000	11697	2.38
13	5BN-E 5- 3.5B	6.2	1.250	5844	11700	11393	2.38
13	5BN-M 0- 3.5	0.0	1.875	5844	14580	14773	2.38
13	5BN-M 0- 3.5A	0.0	1.938	5844	14650	14592	2.38
13	5BN-M 0- 3.5B	0.0	1.875	5844	16090	16303	2.38
13	5BN-E 5- 3.5	5.8	1.844	5844	14600	14392	2.38
13	5BN-E 5- 3.5A	6.4	1.875	5844	16080	15864	2.38
13	5BN-E 5- 3.5B	6.2	1.906	5844	14810	14419	2.38
15	8BS-M 0- 8.0	0.0	1.938	6000	41800	42650	3.75
15	8BS-M 0- 8.0A	0.0	2.000	6000	42700	42700	3.75
15	8BS-E 5- 8.0	4.1	2.000	6000	29050	29050	3.75
15	8BS-E 5- 8.0A	4.7	2.000	6000	33340	33340	3.75
15	8BS-E 5- 8.0B	6.8	1.938	6000	34730	35580	3.75
15	8BS-E12- 8.0	16.5	2.000	6000	30500	30500	3.75
15	8BS-E12- 8.0A	11.7	2.063	6000	29100	28249	3.75
15	8BS-E12- 8.0B	14.1	1.938	6000	32000	32850	3.75
15	8TS-E12- 8.0	7.0	2.063	6000	27400	26634	3.75
15	8TS-E12- 8.0A	12.1	2.000	6000	30200	30200	3.75
15	8BN-M 0- 8.0	0.0	2.000	5830	40600	41187	3.75
15	8BN-M 0- 8.0A	0.0	2.000	5830	42800	43419	3.75
15	8BN-M 0- 8.0B	0.0	2.000	5830	45140	45793	3.75
15	8TN-M 0- 8.0	0.0	2.063	5830	38900	38697	3.75
15	8TN-M 0- 8.0A	0.0	2.063	5830	43020	42876	3.75
15	8TN-M 0- 8.0B	0.0	2.125	5830	38900	37931	3.75
15	8TN-E 5- 8.0B	4.2	2.125	5830	33000	31945	3.75
17	6BC-M 0- 4.5	0.0	1.500	5850	17900	18128	2.75
17	6BC-M 0- 4.5A	0.0	1.563	5850	19800	19679	2.75
17	6BC-M 0- 4.5B	0.0	1.438	5850	17870	18470	2.75
17	6BC-E 5- 4.5	7.1	1.563	5850	16020	15851	2.75
17	6BC-E 5- 4.5A	5.9	1.500	5850	16740	16953	2.75
17	6BC-E 5- 4.5B	6.5	1.500	5850	16100	16305	2.75
17	6BC-E12- 4.5	9.3	1.500	5850	15890	16092	2.75
17	6BC-E12- 4.5A	10.5	1.500	5850	14570	14755	2.75
17	6BC-E12- 4.5B	10.9	1.500	5850	16160	16365	2.75
17	6BS-M 0- 4.5	0.0	1.469	5850	17400	17808	2.75

Table 4 : Beam-end specimen test results, continued

Group No.	Specimen label	Average coating thickness (mils)	Cover ** (in.)	Concrete strength (psi)	Ultimate bond force (lbs)	Modified bond ++ force (lbs)	Lead length (in.)
17	6BS-M 0- 4.5A	0.0	1.438	5850	18300	18905	2.75
17	6BS-M 0- 4.5B	0.0	1.500	5850	19200	19444	2.75
17	6BS-E 5- 4.5	5.7	1.500	5850	15130	15322	2.75
17	6BS-E 5- 4.5A	3.8	1.531	5850	15800	15814	2.75
17	6BS-E 5- 4.5B	3.6	1.531	5850	14900	14903	2.75
17	6BS-E12- 4.5	12.9	1.469	5850	15900	16288	2.75
17	6BS-E12- 4.5A	11.5	1.531	5850	16900	16928	2.75
17	6BS-E12- 4.5B	11.1	1.531	5850	13900	13890	2.75
17	6TS-M 0- 4.5	0.0	1.594	5850	13600	13189	2.75
17	6TS-M 0- 4.5A	0.0	1.656	5850	14200	13407	2.75
17	6TS-M 0- 4.5B	0.0	1.625	5850	15900	15323	2.75
17	6TS-E12- 4.5	13.2	1.438	5850	14400	14972	2.75
17	6TS-E12- 4.5A	10.4	1.656	5850	13700	12901	2.75
18	8BN-M 0- 8.0	0.0	0.937	5060	29200	32647	3.75
18	8BN-M 0- 8.0A	0.0	1.063	5060	29500	31272	3.75
18	8BN-M 0- 8.0B	0.0	1.063	5060	28660	30357	3.75
18	8BN-E12- 8.0	13.4	0.937	5060	23600	26549	3.75
18	8BN-E12- 8.0A	11.7	1.063	5060	27190	28757	3.75
18	8BN-E12- 8.0B	13.5	0.969	5060	27400	30262	3.75
18	8TN-M 0- 8.0	0.0	1.063	5060	25200	26675	3.75
18	8TN-M 0- 8.0A	0.0	1.156	5060	27200	27704	3.75
18	8TN-M 0- 8.0B	0.0	1.156	5060	27180	27682	3.75
18	8TN-E12- 8.0	11.1	1.063	5060	22800	24061	3.75
18	8TN-E12- 8.0A	12.6	1.094	5060	21840	22633	3.75
18	8TN-E12- 8.0B	14.2	1.063	5060	21300	22428	3.75
18	8BN-M 0- 8.0	0.0	1.875	5060	45600	51357	3.75
18	8BN-M 0- 8.0A	0.0	1.938	5060	42400	47021	3.75
18	8BN-M 0- 8.0B	0.0	1.875	5060	41040	46391	3.75
18	8BN-E12- 8.0	12.2	1.969	5060	33700	37122	3.75
18	8BN-E12- 8.0A	9.3	1.969	5060	35700	39300	3.75
18	8BN-E12- 8.0B	8.6	1.938	5060	35950	39997	3.75
18	8TN-M 0- 8.0	0.0	2.063	5060	32900	35059	3.75
18	8TN-M 0- 8.0A	0.0	1.938	5060	38600	41264	3.75
18	8TN-M 0- 8.0B	0.0	2.000	5060	35800	38983	3.75
18	8TN-E12- 8.0	11.8	2.000	5060	32630	35531	3.75
18	8TN-E12- 8.0A	13.7	2.063	5060	29800	31684	3.75
18	8TN-E12- 8.0B	12.7	2.063	5060	31530	33568	3.75
18	8BN-M 0- 8.0A	0.0	3.188	4790	58400	62808	3.75
18	8BN-M 0- 8.0B	0.0	3.000	4790	49600	55512	3.75
18	8BN-E12- 8.0	9.7	3.031	4790	47100	52288	3.75
18	8BN-E12- 8.0A	10.3	2.938	4790	51600	58601	3.75
18	8BN-E12- 8.0B	12.0	3.031	4790	50600	56206	3.75
18	8TN-M 0- 8.0A	0.0	3.063	4790	47110	51959	3.75
18	8TN-E12- 8.0	12.6	3.063	4790	42400	46688	3.75

Table 4 : Beam-end specimen test results, continued

Group No.	Specimen label	Average coating thickness (mils)	Cover ** (in.)	Concrete strength (psi)	Ultimate bond force (lbs)	Modified bond ++ force (lbs)	Lead length (in.)
18	8TN-E12- 8.0A	9.8	3.063	4790	43300	47695	3.75
18	8TN-E12- 8.0B	12.4	3.094	4790	43200	47200	3.75
18	8BS-M 0- 8.0	0.0	1.969	5440	36920	39199	3.75
18	8BS-M 0- 8.0A	0.0	2.031	5440	43540	45300	3.75
18	8BS-M 0- 8.0B	0.0	2.031	5440	37940	39419	3.75
18	8BS-E12- 8.0	8.1	2.063	5440	32660	33448	3.75
18	8BS-E12- 8.0A	9.7	1.906	5440	29510	32268	3.75
18	8BS-E12- 8.0B	11.6	1.906	5440	33510	36468	3.75
18	8TS-M 0- 8.0	0.0	2.094	5440	32120	32583	3.75
18	8TS-M 0- 8.0A	0.0	2.156	5440	34270	34075	3.75
18	8TS-M 0- 8.0B	0.0	2.063	5440	36490	37556	3.75
18	8TS-E12- 8.0	12.7	2.094	5440	29010	29317	3.75
18	8TS-E12- 8.0A	13.5	2.125	5440	29000	28924	3.75
18	8TS-E12- 8.0B	12.9	2.063	5440	29650	30372	3.75
19	11BN-M 0- 9.0	0.0	2.883	5070	36000	38666	1.50
19	11BN-M 0- 9.0A	0.0	2.945	5270	46100	48195	1.50
19	11BN-M 0- 9.0B	0.0	2.633	5270	36100	40009	1.50
19	11BN-E 9- 9.0	10.3	2.820	5270	32000	34144	1.50
19	11BN-E 9- 9.0A	8.5	2.820	5070	29600	32200	1.50
19	11BN-E 9- 9.0B	8.1	2.820	5270	28200	30089	1.50
19	11BN-M 0- 9.0	0.0	4.230	5070	48300	52543	1.50
19	11BN-M 0- 9.0A	0.0	4.230	5270	47500	50683	1.50
19	11BN-M 0- 9.0B	0.0	4.355	5270	42900	44781	1.50
19	11BN-E 9- 9.0	9.6	4.355	5070	37000	39257	1.50
19	11BN-E 9- 9.0A	9.4	4.293	5270	44200	46665	1.50
19	11BN-E 9- 9.0B	12.2	4.293	5270	40900	43144	1.50
19	11BS-M 0- 9.0	0.0	2.758	5270	38600	41683	1.50
19	11BS-M 0- 9.0A	0.0	2.851	5270	36300	38484	1.50
19	11BS-M 0- 9.0B	0.0	2.883	5070	34400	36925	1.50
19	11BS-E 9- 9.0	11.0	2.820	5270	27600	29449	1.50
19	11BS-E 9- 9.0A	10.9	2.695	5070	27700	31127	1.50
19	11BS-E 9- 9.0B	12.6	2.820	5270	36400	38839	1.50
19	11BC-M 0- 9.0	0.0	2.570	5070	37500	42781	1.50
19	11BC-M 0- 9.0A	0.0	2.789	5270	37800	40581	1.50
19	11BC-M 0- 9.0B	0.0	2.758	5270	35100	37948	1.50
19	11BC-E 9- 9.0	12.1	2.820	5070	29000	31547	1.50
19	11BC-E 9- 9.0A	13.1	2.820	5270	27700	29556	1.50
19	11BC-E 9- 9.0B	12.4	2.883	5270	29100	30553	1.50
20	11BN-M 0- 9.0	0.0	1.410	5290	34120	36337	1.50
20	11BN-M 0- 9.0A	0.0	1.160	5260	31260	35373	1.50
20	11BN-M 0- 9.0B	0.0	1.410	5260	32480	34689	1.50
20	11BN-E 9- 9.0	10.5	1.285	5290	23570	26095	1.50
20	11BN-E 9- 9.0A	7.9	1.410	5260	27900	29797	1.50

Table 4 : Beam-end specimen test results, continued

Group No.	Specimen label	Average coating thickness (mils)	Cover ** (in.)	Concrete strength (psi)	Ultimate bond force (lbs)	Modified bond ++ force (lbs)	Lead length (in.)
20	11BN-E 9- 9.0B	6.9	1.348	5260	25690	27934	1.50
20	11BN-M 0- 9.0	0.0	2.883	5290	47380	49962	1.50
20	11BN-M 0- 9.0A	0.0	3.070	5260	39500	40200	1.50
20	11BN-M 0- 9.0B	0.0	2.758	5260	41330	44638	1.50
20	11BN-E 9- 9.0	10.4	2.945	5290	29300	30210	1.50
20	11BN-E 9- 9.0A	8.7	3.008	5260	33700	33012	1.50
20	11BN-E 9- 9.0B	9.2	2.883	5260	32910	34652	1.50
20	11BN-M 0- 9.0	0.0	4.136	5260	58550	63278	1.50
20	11BN-M 0- 9.0A	0.0	4.230	5260	48300	51585	1.50
20	11BN-M 0- 9.0B	0.0	4.168	5260	58610	63093	1.50
20	11BN-E 9- 9.0	9.0	4.230	5260	48660	51970	1.50
20	11BN-E 9- 9.0A	9.1	4.043	5260	44680	49209	1.50
20	11BN-E 9- 9.0B	8.9	4.230	5260	46280	49428	1.50
20	11BS-M 0- 9.0	0.0	2.883	5290	36480	38354	1.50
20	11BS-M 0- 9.0A	0.0	2.883	5260	43990	46485	1.50
20	11BS-M 0- 9.0B	0.0	2.758	5260	38060	41145	1.50
20	11BS-E 9- 9.0	10.9	2.883	5290	41780	43998	1.50
20	11BS-E 9- 9.0A	9.4	2.820	5260	36030	38481	1.50
20	11BS-E 9- 9.0B	9.7	2.820	5260	39560	42251	1.50
20	11BC-M 0- 9.0	0.0	2.945	5290	41580	43289	1.50
20	11BC-M 0- 9.0A	0.0	2.883	5260	34500	36350	1.50
20	11BC-M 0- 9.0B	0.0	2.883	5260	39440	41626	1.50
20	11BC-E 9- 9.0	9.4	2.820	5290	28320	30160	1.50
20	11BC-E 9- 9.0A	8.2	2.758	5260	38600	41722	1.50
20	11BC-E 9- 9.0B	8.4	2.758	5260	33800	36596	1.50
23+	8BN-M 0- 8.0	0.0	1.938	5580	42200	44610	3.75
23	8BN-M 0- 8.0A	0.0	1.938	5580	37850	40099	3.75
23	8BN-M 0- 8.0B	0.0	2.063	5120	41000	43532	3.75
23	8BN-E12- 8.0	12.5	2.000	5120	30870	33417	3.75
23	8BN-E12- 8.0A	10.2	1.875	5580	35270	38275	3.75
23	8BN-E12- 8.0B	11.3	2.000	5580	36210	37548	3.75
23	8TN-M 0- 8.0	0.0	2.031	5580	42800	43998	3.75
23	8TN-M 0- 8.0A	0.0	1.969	5580	39280	41114	3.75
23	8TN-M 0- 8.0B	0.0	2.000	5120	38100	41244	3.75
23	8TN-E12- 8.0	12.4	2.000	5120	33580	36351	3.75
23	8TN-E12- 8.0A	11.7	2.063	5580	37400	38016	3.75
23	8TN-E12- 8.0B	11.9	2.063	5580	34690	35205	3.75
24+	8BN-M 0- 8.0	0.0	2.125	4980	37520	42886	3.75
24	8BN-M 0- 8.0A	0.0	2.031	5240	37830	40055	3.75
24	8BN-M 0- 8.0B	0.0	1.969	5240	40840	44126	3.75
24	8BN-E12- 8.0	11.1	1.938	4980	36400	40805	3.75
24	8BN-E12- 8.0A	10.4	1.938	5240	35430	38763	3.75
24	8BN-E12- 8.0B	12.4	1.875	5240	37560	41893	3.75

Table 4 : Beam-end specimen test results, continued

Group No.	Specimen label	Average coating thickness (mils)	Cover ** (in.)	Concrete strength (psi)	Ultimate bond force (lbs)	Modified bond ++ force (lbs)	Lead length (in.)
24	8TN-M 0- 8.0	0.0	2.063	4980	35810	38540	3.75
24	8TN-M 0- 8.0A	0.0	2.156	5240	34790	35312	3.75
24	8TN-M 0- 8.0B	0.0	2.000	5240	36020	38543	3.75
24	8TN-E12- 8.0	11.6	2.094	4980	34680	36917	3.75
24	8TN-E12- 8.0A	8.7	2.125	5250	34190	35018	3.75
24	8TN-E12- 8.0B	8.8	2.063	5240	30430	31796	3.75
24	8BN-M 0- 8.0	0.0	1.906	5680	41650	44083	3.75
24	8BN-M 0- 8.0A	0.0	1.813	5980	43610	46235	3.75
24	8BN-M 0- 8.0B	0.0	1.938	5980	40310	41228	3.75
24	8BN-E12- 8.0	11.8	1.875	5680	35830	38527	3.75
24	8BN-E12- 8.0A	12.3	1.906	5980	31640	32969	3.75
24	8BN-E12- 8.0B	10.8	1.938	5980	34090	34997	3.75
24	8TN-M 0- 8.0	0.0	2.000	5680	33760	34697	3.75
24	8TN-M 0- 8.0A	0.0	2.094	5980	38350	37265	3.75
24	8TN-M 0- 8.0B	0.0	2.063	5980	36780	36075	3.75
24	8TN-E12- 8.0	11.5	2.031	5680	32650	33174	3.75
24	8TN-E12- 8.0A	12.0	1.906	5980	36930	38140	3.75
24	8TN-E12- 8.0B	8.3	2.031	5980	30340	30007	3.75
24	8BN-M 0- 8.0	0.0	1.813	5680	38290	41906	3.75
24	8BN-M 0- 8.0A	0.0	1.813	5980	41570	44192	3.75
24	8BN-M 0- 8.0B	0.0	1.875	5980	40100	41868	3.75
24	8BN-E12- 8.0	12.2	1.938	5680	32940	34706	3.75
24	8BN-E12- 8.0A	8.2	1.938	5980	34260	35168	3.75
24	8BN-E12- 8.0B	12.4	1.844	5980	26200	28370	3.75
24	8TN-M 0- 8.0	0.0	2.031	5680	34820	35404	3.75
24	8TN-M 0- 8.0A	0.0	2.094	5980	36330	35241	3.75
24	8TN-M 0- 8.0B	0.0	2.063	5980	35300	34593	3.75
24	8TN-E12- 8.0	10.3	1.938	5680	27260	28783	3.75
24	8TN-E12- 8.0A	11.6	2.031	5980	31340	31009	3.75
24	8TN-E12- 8.0B	8.9	2.063	5980	28960	28242	3.75

\+ Deep specimens

** Measured cover before testing. Cover was not measured for specimens in groups 1-6. For these groups cover is assumed to be equal to the nominal cover.

++ Modified bond force is the ultimate bond force corrected for variations in the concrete cover from 1, 2, or 3 d_b, coating thickness from 9 mils (for No. 5 bars only), and concrete strength from 6000 psi.

Specimen label:

#PD-SC-LR

# : Bar size : 5, 6, 8, 11	S : Bar surface condition : M = uncoated, C = coated
P : Bar position : B = bottom, T = top	C : Nominal coating thickness : 0, 5, 9, 12 mils
D : Deformation pattern : S, C, N	L : Bonded length of the test bar
	R : Replication I.D. : blank, A, B

Table 5: Relative bond strengths, C/U and C′/U,
versus bar size and concrete cover

Bar size	Def. pat.	Group no.	Casting position*	Cover (d_b)*	C/U+		C′/U++	
					BF*	AV*	BF*	AV*
5	N	8, 13	B	1	0.92	0.96		
		8,11-13		2	0.93	0.91	1.26	1.16
		13		3	0.94	0.98	1.19	1.11
		13		4.8	0.95	0.93		
8	S	1	T	1	0.85	0.82		
		1,15,18		2	0.89	0.89	1.29	1.04
		1		3	0.91	0.88	1.19	1.37
	N	18	B	1	0.85	0.91		
		4,6,15,18,23,24		2	0.89	0.87	1.28	1.23
		18		3	0.91	0.94	1.19	1.25
	N	18	T	1	0.83	0.84		
		15,18		2	0.88	0.86	1.27	1.23
		18		3	0.91	0.91	1.19	1.21
11	N	20	B	1	0.75	0.79		
		19,20		2	0.79	0.74	1.06	0.91
		19,20		3	0.82	0.86	1.03	1.07

* Casting position:
B = bottom-cast, T = top-cast
d_b: bar diameter
BF: based on best fit line
AV: based on average test data
\+ Ratio of bond force of coated bar to bond force of uncoated bar with same cover
++Ratio of bond force of coated bar to bond force of uncoated bar with 1 d_b less cover

Table 6: Comparison of experimental and design epoxy-bar development length modification factors

Bar size	Def. pat.	Casting position*	Cover (d_b)*	Exp.U/C+ BF*	Exp.U/C+ AV*	Design U/C++ ACI	Design U/C++ AASHTO
5	N	B	1	1.09	1.04	1.5	1.5
			2	1.07	1.10	1.5	1.5
			3	1.06	1.02	1.2	1.15
			4.8	1.05	1.05	1.2	1.15
8	S	T	1	1.18	1.22	1.5	1.5
			2	1.12	1.12	1.5	1.5
			3	1.10	1.14	1.2	1.15
	N	B	1	1.18	1.10	1.5	1.5
			2	1.12	1.15	1.5	1.5
			3	1.10	1.06	1.2	1.15
	N	T	1	1.20	1.19	1.5	1.5
			2	1.14	1.16	1.5	1.5
			3	1.10	1.10	1.2	1.15
11	N	B	1	1.34	1.27	1.5	1.5
			2	1.26	1.35	1.5	1.5
			3	1.22	1.16	1.2	1.15

* Casting position:
B = bottom-cast, T = top-cast
d_b: bar diameter
BF: based on best fit line
AV: based on average test data
\+ Ratio of bond force of uncoated bar to bond force of coated bar
++ Development length modification factor (ACI 1989, AASHTO 1989)

Table 7: Summary of beam-end tests with bottom and top-cast bars in standard and deep specimens with different slump concretes and degrees of consolidation

Bar size	Group No.	Def. pattern	Slump (in.)	Cover (d_b)	No. of uncoated bars	Uncoated bars modified bond force (lbs.)	No. of coated bars	Coated bars modified bond force (lbs.)	CP*	B/T*			C/U*
										U/U*	C/C*	U_b/C_t*	group
5	9	S	4	2	3	14154	6	11753	B	1.228	1.097	1.321	0.830
					3	11522	6	10714	T				0.930
5	10	C	4 1/2	2	3	13580	6	13010	B	1.138	1.144	1.194	0.958
					3	11932	6	11375	T				0.953
5	11	N	3 1/4	2	3	12964	3	11998	B	1.105	1.238	1.338	0.925
					3	11732	3	9688	T				0.826
Average of No. 5 bars =										1.157	1.160	1.284	
6	17	S	5 3/4	2	3	18720	6	15525	B	1.340	1.114	1.343	0.829
					3	13973	2	13941	T				0.998
Average of No. 6 bars =										1.340	1.114	1.343	
8	5	N	4 1/4	2	3	43464	-	-	B	1.091	-	-	-
					3	39832	-	-	T				-
8	15	S	4 1/4	2	2	42680	6	31600	B	-	1.112	1.502	0.740
					-	-	2	28416	T				
8	18	N	4 1/4	1	3	31424	3	8520	B	1.149	1.238	1.364	0.908
					3	27352	3	23040	T				0.842
8	18	N	4 1/4	2	3	48256	3	38800	B	1.256	1.155	1.437	0.804
					3	38432	3	33592	T				0.874
8	18	N	4 1/4	3	2	59160	3	55696	B	1.139	1.180	1.254	0.941
					1	51960	3	47192	T				0.908
8	18	S	4 1/4	2	3	41312	3	34064	B	1.189	1.153	1.399	0.825
					3	34736	3	29536	T				0.850
Average of No. 8 bars in standard specimens =										1.165	1.168	1.391	

Table 7: Summary of beam-end tests with bottom and top-cast bars in standard and deep specimens with different slump concretes and degrees of consolidation, continued

Bar size	Group No.	Def. pattern	Slump (in.)	Cover (d_b)	No. of uncoated bars	Uncoated bars modified bond force (lbs.)	No. of coated bars	Coated bars modified bond force (lbs.)	CP*	B/T*			C/U*
										U/U*	C/C*	U_b/C_t*	group
8+	23	N	2 1/4	2	3	42744	3	36416	B	1.015	0.997	1.170	0.852
					3	42120	3	36520	T				0.867
8+	24	N	2 1/2	2	3	42360	3	40488	B	1.131	1.170	1.225	0.956
					3	37464	3	34592	T				0.923
Average of No. 8 bars in deep specimens (low slump vibrated) =										1.073	1.084	1.198	
8+	24	N	8	2	3	43848	3	35504	B	1.218	1.051	1.298	0.810
					3	36008	3	33776	T				0.938
Average of No. 8 bars in deep specimens (high slump vibrated) =										1.218	1.051	1.298	
8+$	24	N	8	2	3	42656	3	32752	B	1.216	1.116	1.454	0.768
					3	35080	3	29344	T				0.836
Average of No. 8 bars in deep specimens (high slump non-vibrated) =										1.216	1.116	1.454	
Average of No. 8 bars in deep specimens =										1.145	1.084	1.287	
Average of all No. 8 bars =										1.156	1.130	1.345	
AVERAGE OF ALL BARS =										1.170	1.136	1.331	

\+ Deep specimens
$ Non-vibrated specimens

* CP : Casting position
B = bottom-cast, T = top-cast
B/T : Ratio, bottom-cast bars to top-cast bars
U/U : Ratio, uncoated bottom-cast bars to uncoated top-cast bars
C/C : Ratio, coated bottom-cast bars to coated top-cast bars
U_b/C_t : Ratio, uncoated bottom-cast bars to coated top-cast bars
C/U : Ratio, coated bars to uncoated bars

Table 8: Summary of hypothesis testing for average values from Table 7

Bar size	Slump (in.)	Consolidation *	Spec. type **	Bottom / Top (B/T)					Coated / Uncoated (C/U)					U_b/C_t	
				Uncoated		Coated		U&C$ H test	Bottom		Top		B&T + H test	ratio	H test*
				ratio	H test*	ratio	H test*		ratio	H test*	ratio	H test*			
5	$3\frac{1}{4}$ - $4\frac{1}{2}$	V	ST	1.157	S	1.160	S	NS	0.904	S	0.903	S	NS	1.284	S
8	$4\frac{1}{2}$	V	ST	1.165	S	1.168	S	NS	0.870	S	0.869	S	NS	1.391	S
8	$2\frac{1}{4}$ - $2\frac{1}{2}$	V	D	1.073	S	1.084	S	NS	0.904	S	0.895	S	NS	1.200	S
Average - low slump				1.132		1.137			0.893		0.889			1.292	
6	$5\frac{3}{4}$	V	ST	1.340	S	1.114	S	S	0.829	S	0.998	NS	S	1.343	S
8	8	V	D	1.218	S	1.051	NS	S	0.810	S	0.938	NS	S	1.298	S
Average - high slump vibrated				1.279		1.083			0.820		0.968			1.321	
8	8	NV	D	1.216	S	1.116	S	S	0.768	S	0.836	S	S	1.454	S

* H test : Results of hypothesis testing
S = difference in bond strengths indicated by ratio is statistically significant with a confidence of 97.5 percent (significance level = 0.025)
NS = difference in bond strengths indicated by ratio is not statistically significant with a confidence of 97.5 percent (significance level = 0.025)
Consolidation:
V = Vibrated
NV = Not Vibrated

** Specimen type
ST = standard
D = deep

$ Hypothesis test for the difference in the B/T ratio for the uncoated and coated bars

\+ Hypothesis test for the difference in the C/U ratio for the bottom and top bars

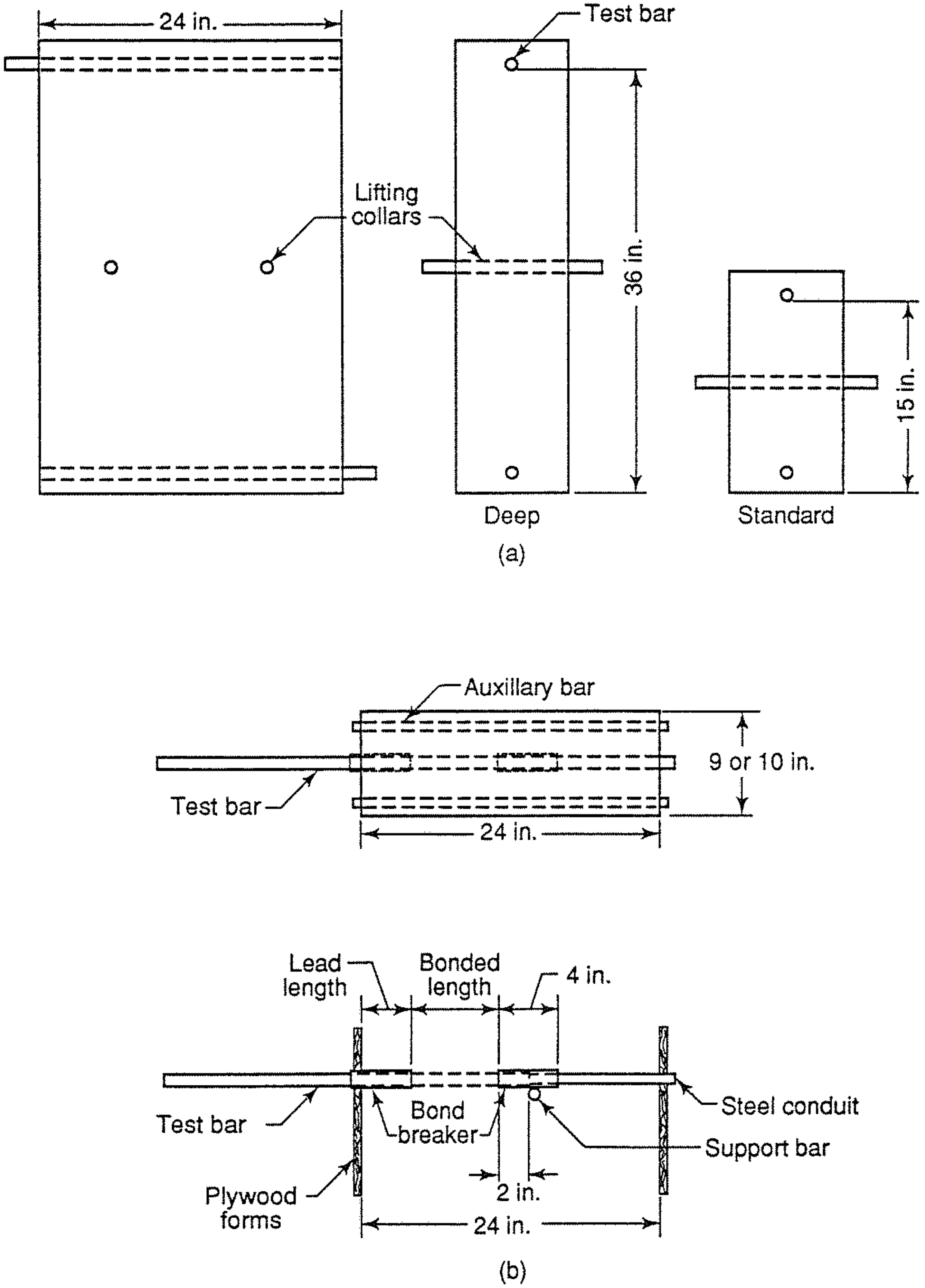

Fig. 1 (a) Beam-end specimen dimensions; (b) test bar installation

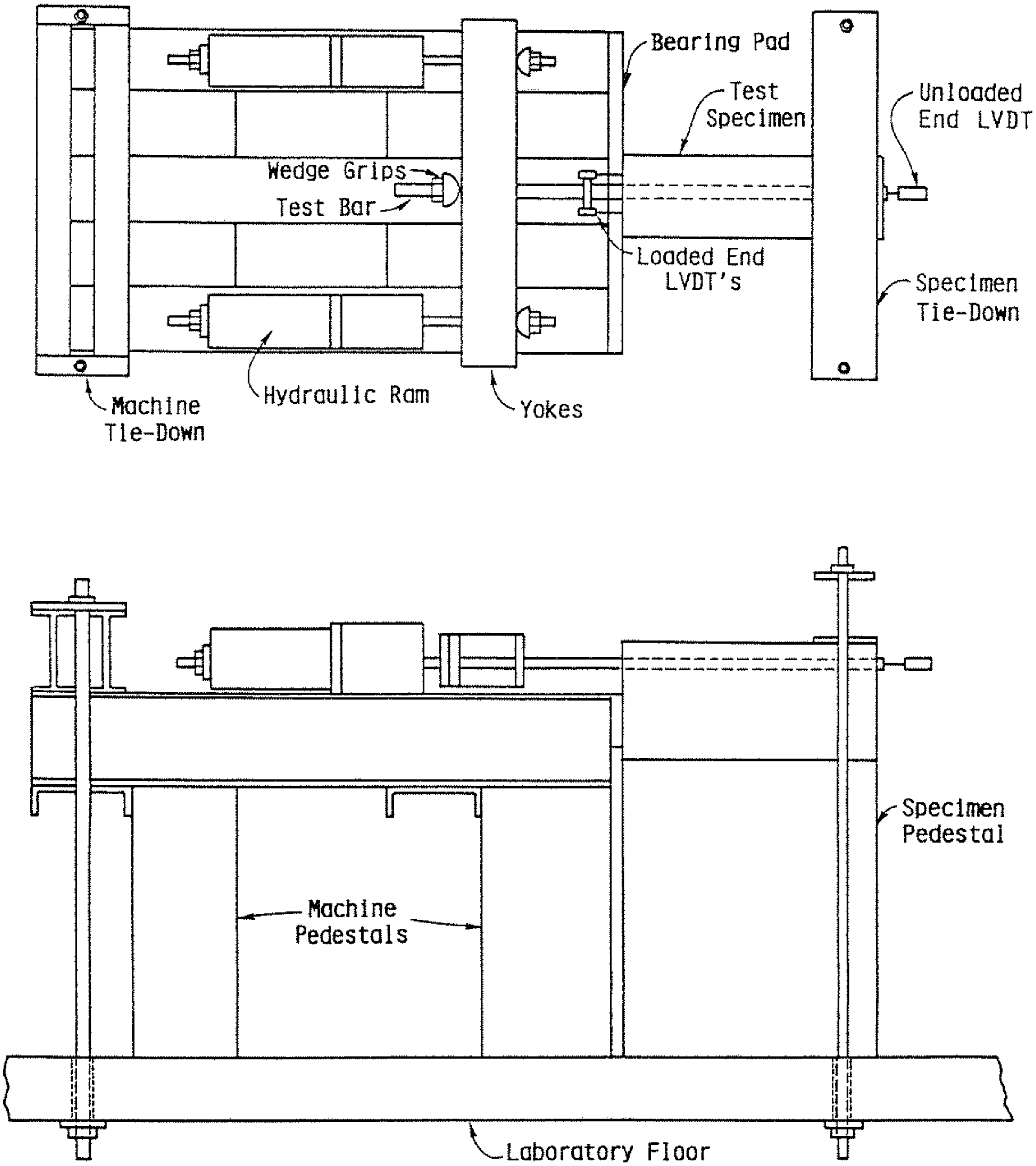

Fig. 1 (c) Schematic of test apparatus (Brettmann, Darwin and Donahey 1984)

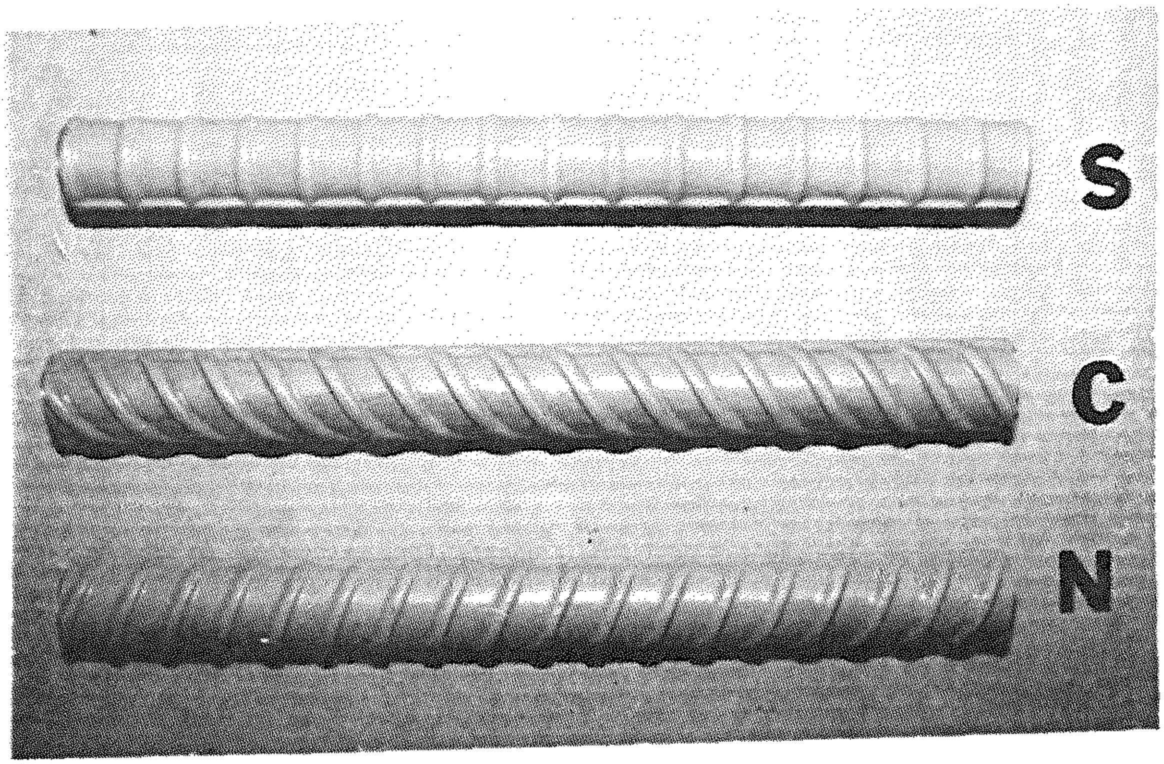

Fig. 2 Reinforcing bar deformation patterns

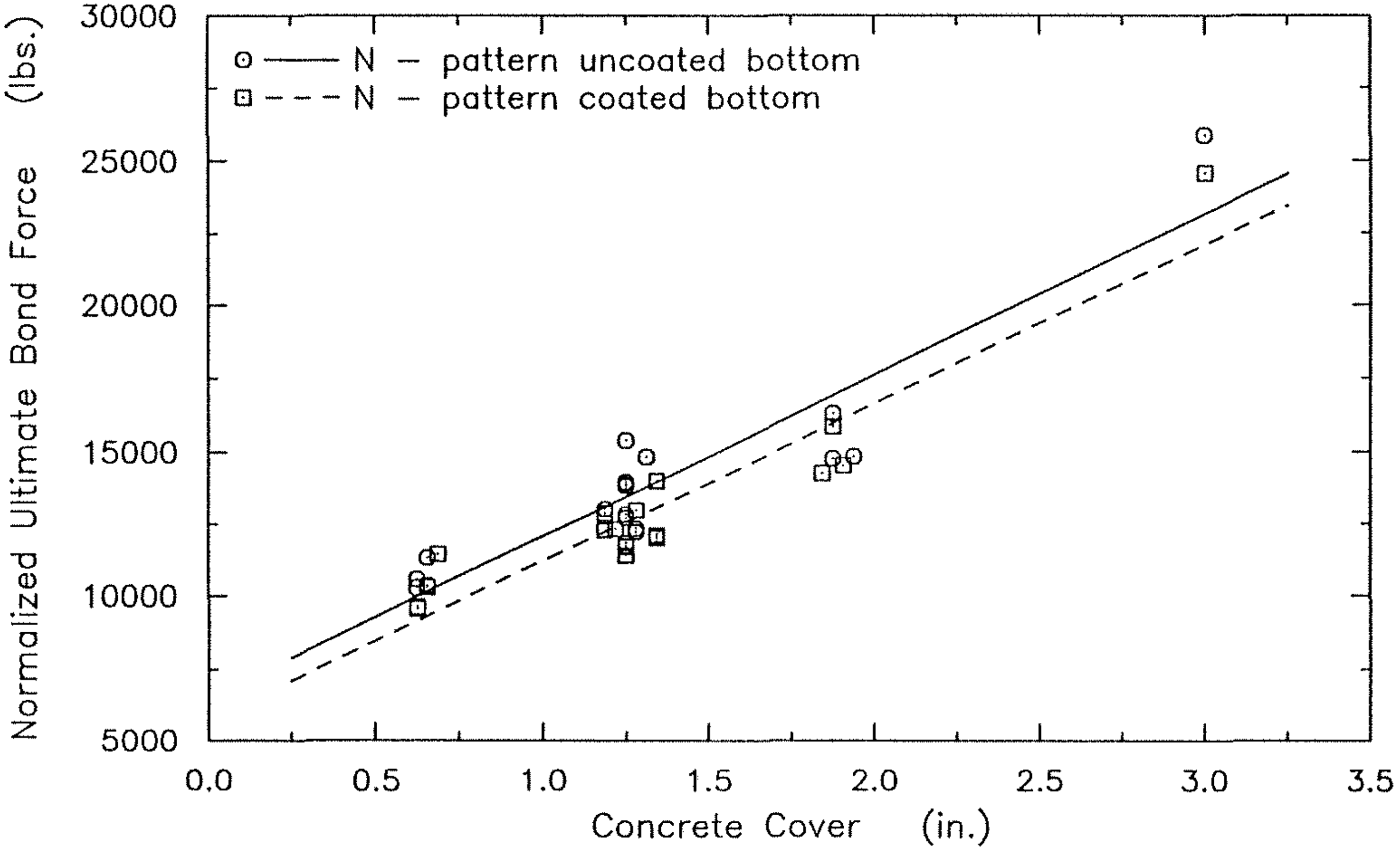

Fig. 3 Normalized ultimate bond force versus concrete cover for No. 5 bars

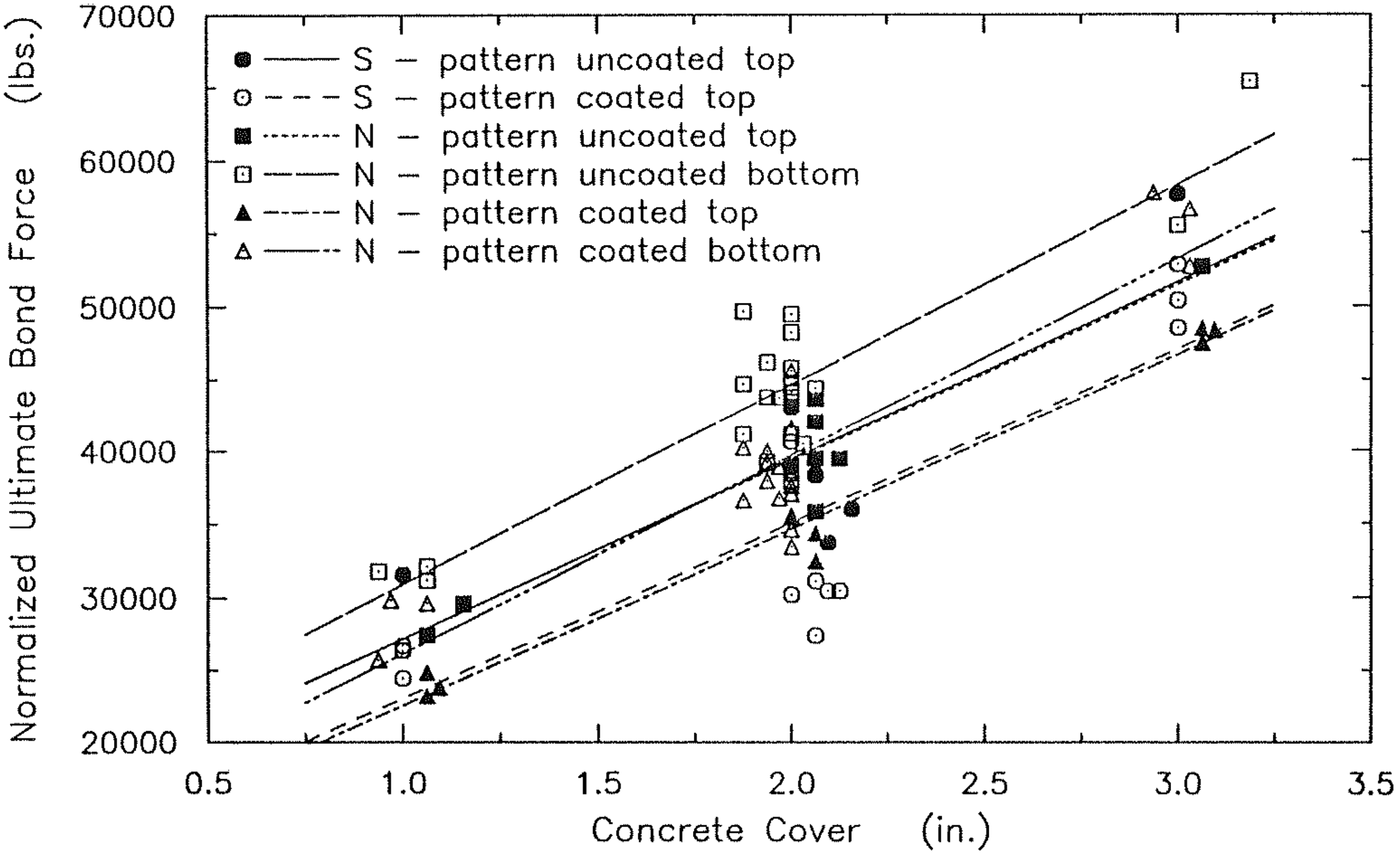

Fig. 4 Normalized ultimate bond force versus concrete cover for No. 8 bars

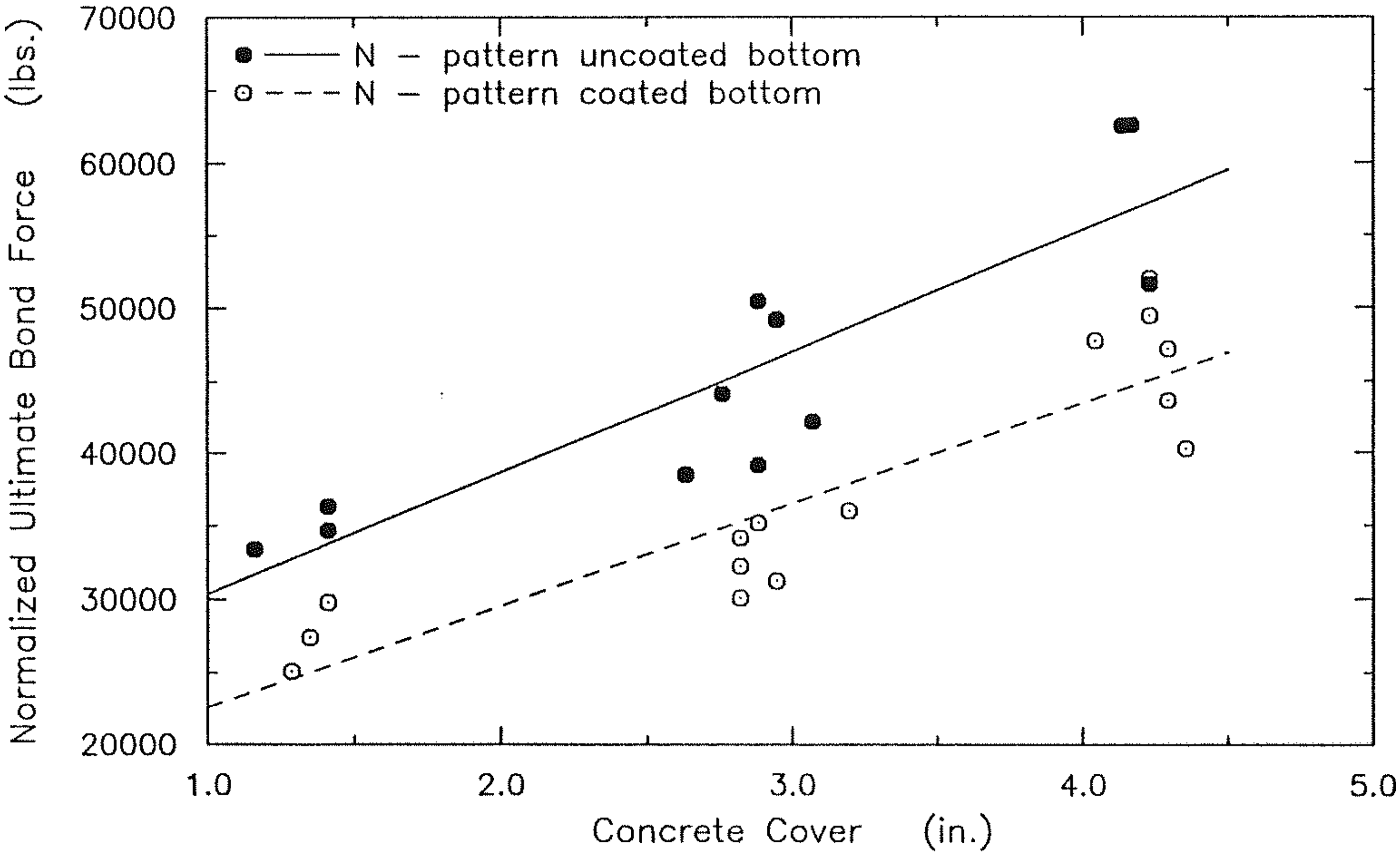

Fig. 5 Normalized ultimate bond force versus concrete cover for No. 11 bars

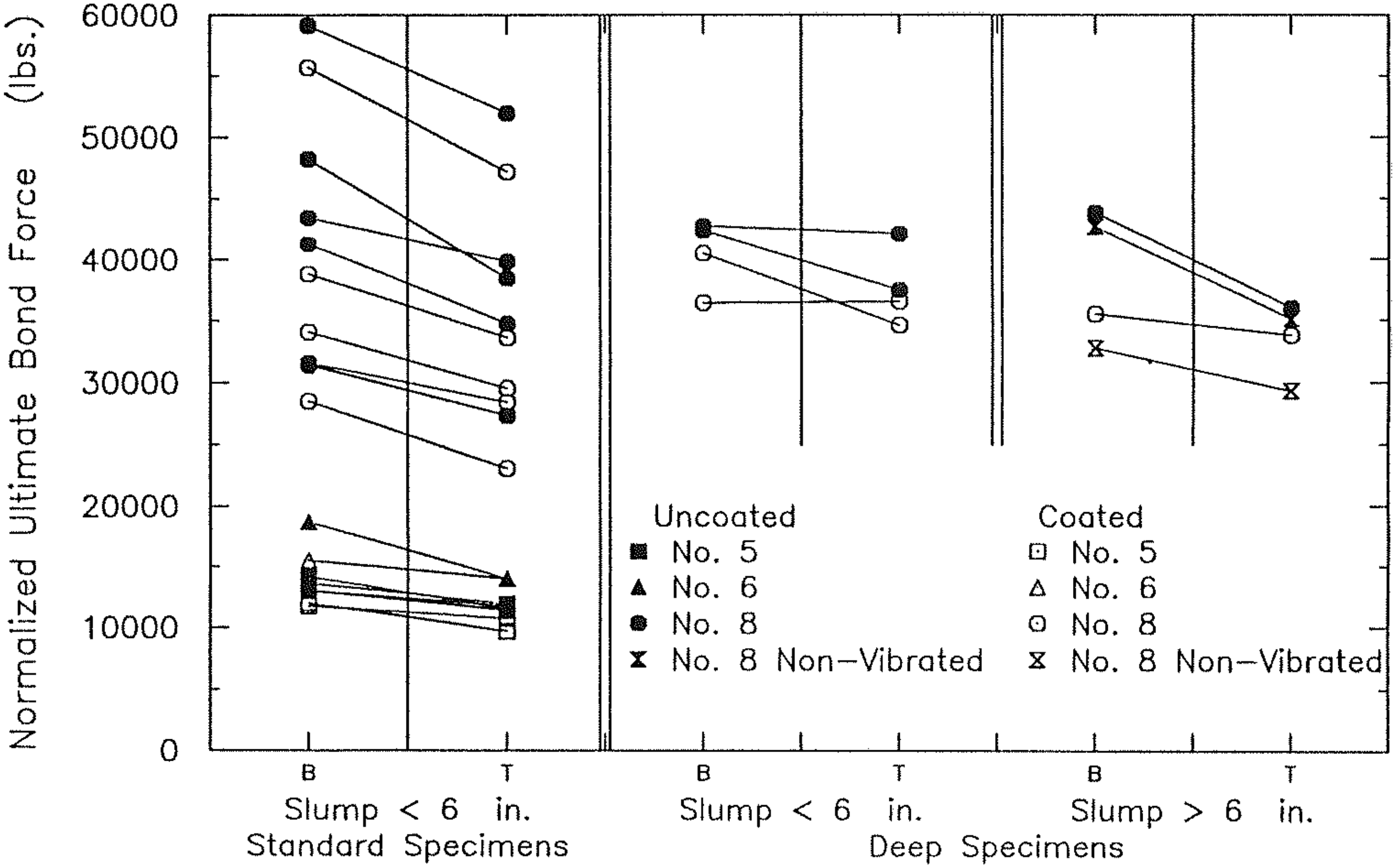

Fig. 6 Normalized ultimate bond force for bottom and top-cast bars for different slump concretes in standard and deep specimens

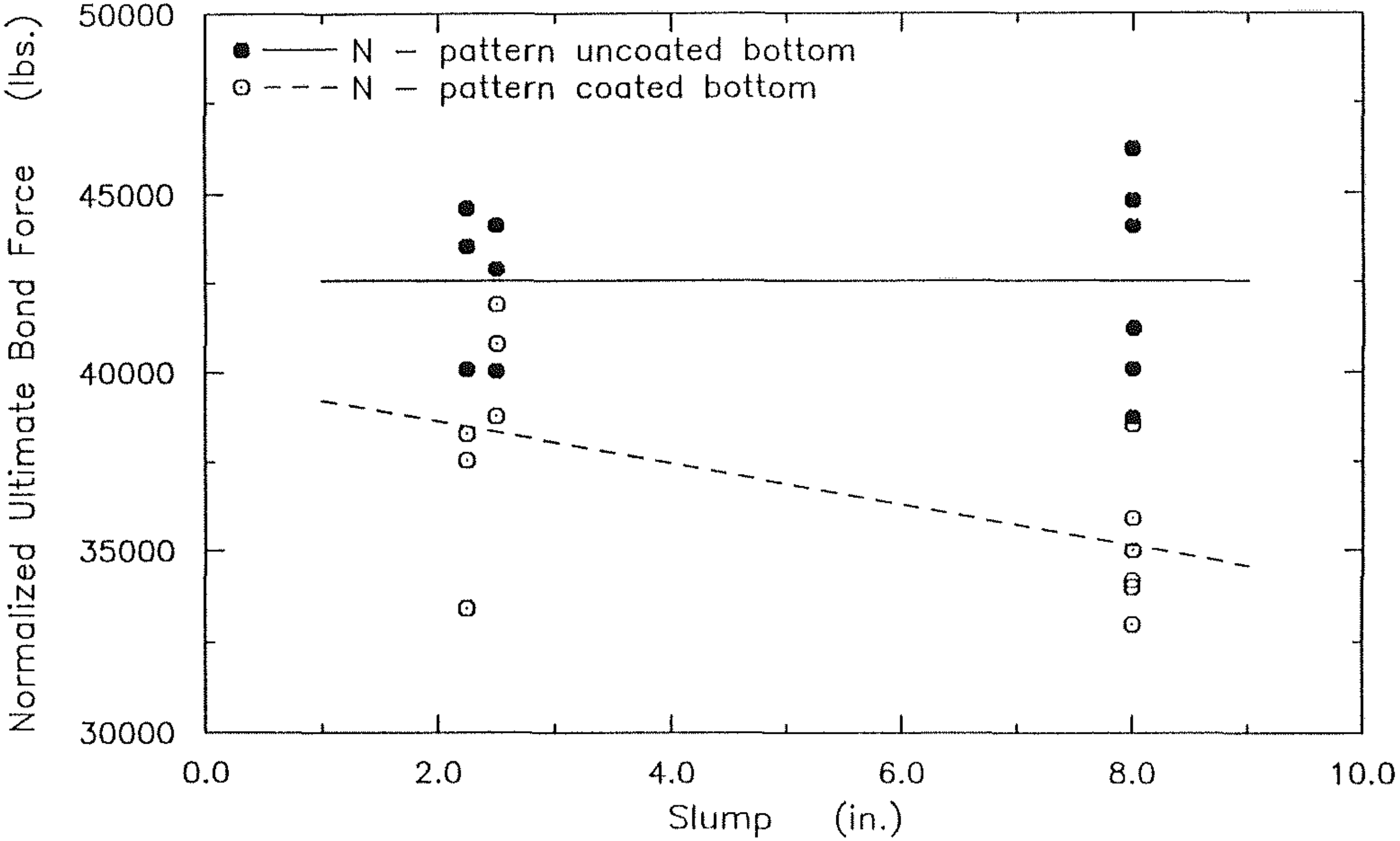

Fig. 7 Normalized ultimate bond force for bottom-cast bars versus slump for No. 8 bars in deep specimens

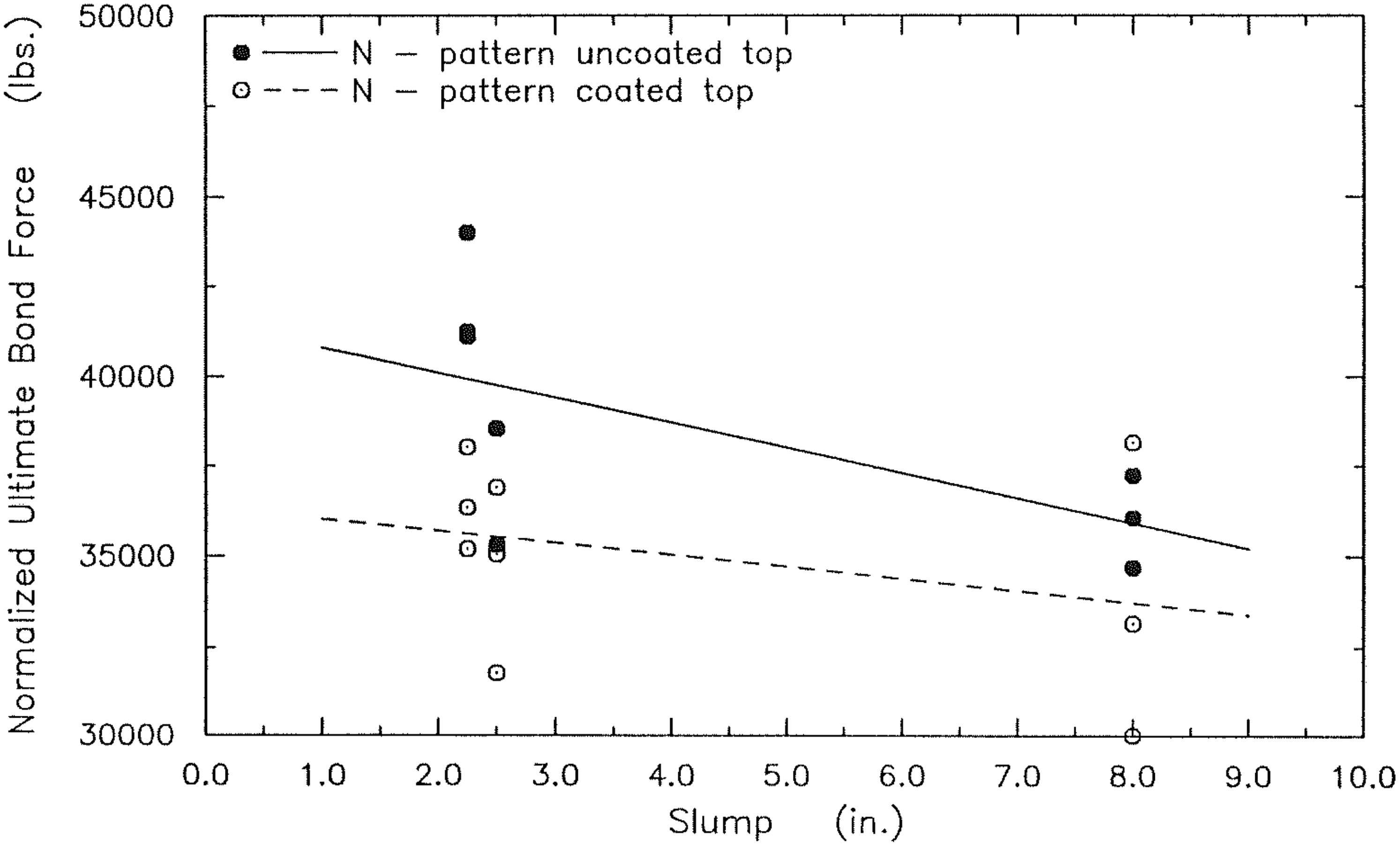

Fig. 8 Normalized ultimate bond force for top-cast bars versus slump for No. 8 bars in deep specimens

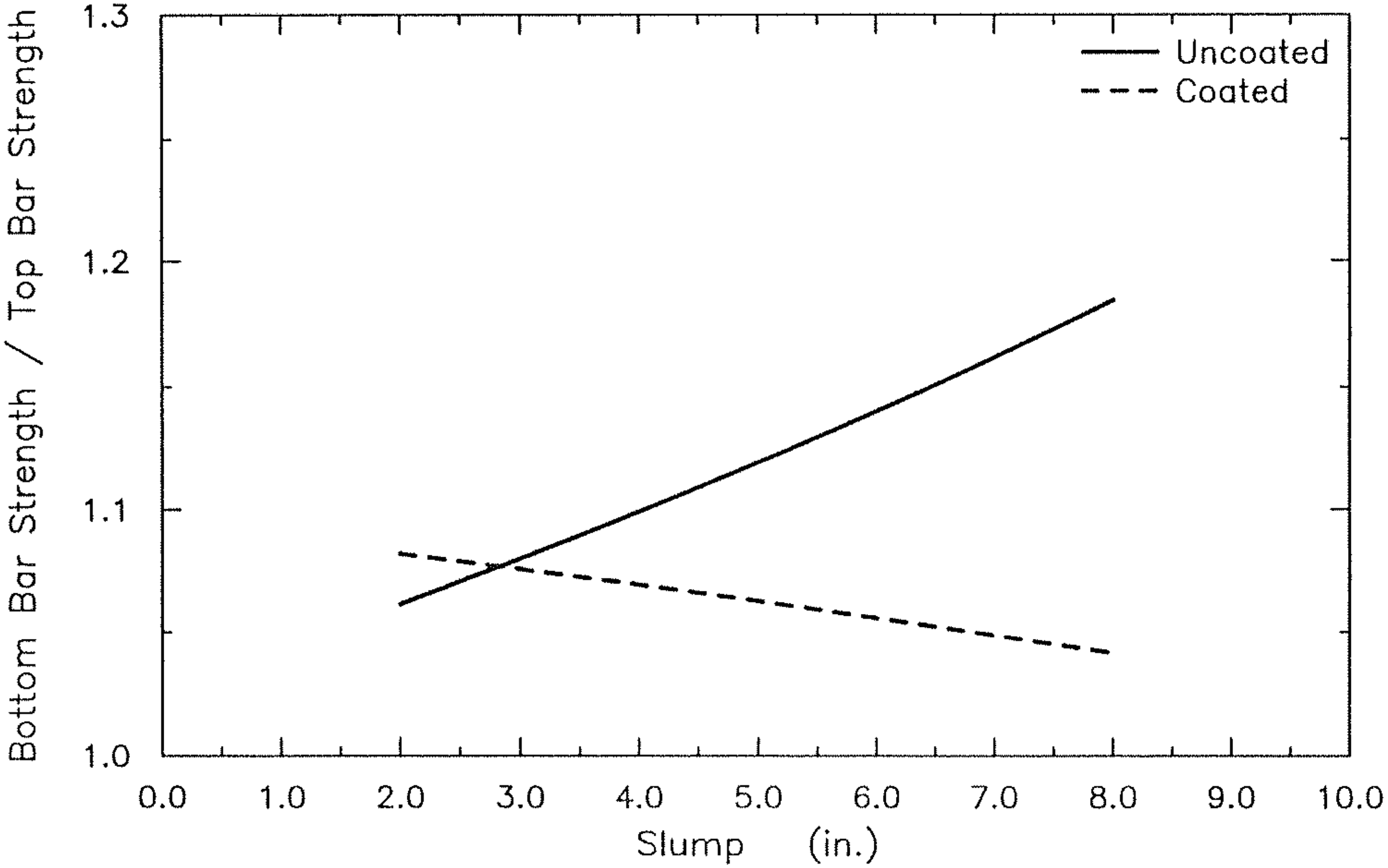

Fig. 9 Ratio of bottom-cast to top-cast bar bond strength, B/T, versus slump for No. 8 bars in deep specimens