EFFECTS OF INNOVATIVE CONSTRUCTION PROCEDURES
ON CONCRETE BRIDGE DECKS
FINAL REPORT: PART I

EFFECTS OF CONSTRUCTION PROCEDURES ON BOND IN BRIDGE DECKS

By
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David Darwin

A Report on Research Sponsored by
THE KANSAS DEPARTMENT OF TRANSPORTATION
Project No. P 0255

Structural Engineering and Engineering Materials
SL Report 83-1
June 1983

THE UNIVERSITY OF KANSAS CENTER FOR RESEARCH, INC.
2291 Irving Hill Drive—Campus West Lawrence, Kansas 66045

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Contract Period: July 15, 1980 - June 30, 1983

University of Kansas
Lawrence, Kansas
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Abstract

Effects of Construction Procedures on Bond in Bridge Decks

The effects of consolidation method and two-course construction on concrete-steel bond in concrete bridge decks are studied as functions of slump, bleed, and depth of slab. The consolidation was varied by vibrator spacing and insertion time. Four top covers were studied: 3/4, 1, and 3 in. monolithic and 3 in. two-course. Bond test specimens were of two types: shallow, with 8 in. of concrete below the reinforcement, and deep, with 24 in. of concrete below the reinforcement. All specimens were modified cantilever beam specimens. Concrete densities were obtained using core samples.

Based on the experimental work, high density internal vibration provides improved bond over low density internal vibration. 3 in. monolithic cover provides higher bond strength than 3 in. two-course cover. Increased concrete slump has a negative effect on bond strength for top-cast reinforcement. Deep specimens made with stiff, well consolidated concrete can provide the same bond strengths as shallow specimens.

INTRODUCTION

Attempts to solve the problem of corrosion of reinforcing steel in bridge decks have led to the introduction of innovative procedures for new deck construction. Two of these procedures, two-course bonded deck construction and high density internal vibration are relatively untested for their effects on concrete-steel bond strength.

Two-course bonded deck construction places a high quality concrete wearing surface on a previously placed and cured first course. It has been found, however, that due to the low cover initially used over the top steel, a number of problems arise with the first course: the finishing equipment tends to work the coarse aggregate away from the reinforcing bars, while settlement cracks form in the first course over the reinforcing bars. These factors, may, in turn, affect the concrete-steel bond strength.

Bridge deck concrete in Kansas is currently consolidated using high density internal vibration, which limits maximum vibrator spacing to 1 ft. This method is intended to be an improvement over consolidation using hand held vibrators. Although it is generally accepted that good consolidation leads to good concrete, it is not clear what effect high density vibration has on concrete-steel bond.

This report presents the results of a study of the effects of consolidation method and two-course construction on bond strength in bridge decks as a function of concrete slump and bleed, and depth of slab. The results are analyzed and compared with predictions of the AASHTO Bridge Specifications (1) and the ACI Building Code (3).* Recommendations are made. Additional details of this study are presented in Reference 8.

EXPERIMENTAL INVESTIGATION

To study the effects of consolidation method and top cover on bond in bridge decks, test specimens, placement procedures, and test procedures were selected to reflect actual deck thicknesses, placement procedures, and loading.

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*The ACI Building Code is cited because it serves as the source document on most aspects of reinforced concrete design for the AASHTO Bridge Specifications, as well as the report by ACI Committee 343, "Analysis and Design of Reinforced Concrete Bridge Structures (ACI 343R-77)," American Concrete Institute, Detroit, 1977, 116 pp.

Test Specimens

The study used eighteen 4 ft x 8 ft shallow deck specimens, with 8 in. of concrete below the top reinforcement (Fig. 1), and six 3 ft x 4 ft deep deck specimens, with 24 in. of concrete below the top reinforcement (Fig. 2). Four top covers were studied, 3/4, 1 and 3 in. monolithic top covers and 3 in. two-course top covers. #5 and #8 deformed bars were used. A total of 117 bars were tested.

The shallow specimens were stepped down 2-1/4 in. in the third of the form containing the 3 in. monolithic cover in order to maintain a constant 8 in. depth below the reinforcement. Each shallow specimen contained six test bars. Twelve dummy deformed bars (not tested) were installed in the form to allow aggregate bridging, which tends to restrict settlement.

Each deep specimen contained two test bars and four dummy bars. Full information on the test variables, including embedment length, cover, thickness, and cover type are presented in Table 1.

Material Properties

Concrete: Air entrained concrete was supplied by a local ready mix plant for the first course. Type I cement and 3/4 in. nominal maximum size coarse aggregate were used. Concrete slump was varied using both water content and air content.

The overlay concrete was prepared in the laboratory using Type I cement and 3/4 in. maximum size aggregate. The coarse aggregate for the overlays was obtained by removing all material retained on a 3/4 in. sieve from the coarse aggregate used for the first course placement. A high-range water-reducer was used in the overlays for two slab groups (7 and 8). Mix designs, aggregate, and concrete properties are summarized in Table 2.

Steel: ASTM A615, Grade 60 reinforcing bars were used for all tests. Deformation dimensions and bearing areas are presented in Table 3.

Placement Procedure

Construction procedures were selected to be as consistent as possible within and between individual slab groups. The first course concrete was placed in the forms using a one cubic yard bucket and an overhead crane. Shallow forms were filled in one lift, and deep forms were filled in two lifts (each lift vibrated equally). The forms were filled with a 1 in. surcharge to allow for settlement during consolidation.

In the first two placements, consolidation was started as soon as the first form was filled. For the remaining placements, the filled forms were allowed to rest for 10 minutes before vibration was started.

Consolidation was obtained using frame mounted, 1-7/8 in. diameter pneumatic vibrators. The vibrators were rated by the manufacturer at 11,500 cycles per minute at 90 psi pressure in air. Vibrator amplitude was 0.04 inch (peak to peak).

High density vibration (vibrator radii of influence overlap) was obtained using either one or two vibrators inserted at 1 ft centers. Low density vibration (radii of influence do not overlap) was achieved using a single vibrator inserted at 2 ft centers. With the exception of Slab Group 6, low density vibration slabs were vibrated 1 ft from each side of the forms. The low density slab in Group 6 was vibrated at the slab center line only.

Vibrators were inserted rapidly, held in place for 10 seconds, and withdrawn slowly. The exception was the low density vibration slab in Group 7, in which the vibrator was held in place for seven seconds.

Slabs were hand screeded using a metal-edged screed. Two passes were made, with screed travel perpendicular to the top reinforcement in each pass.

Immediately upon completion of screeding, the specimens were floated using a magnesium bull float. Bleed and settlement tests were then started.

Special bleed tests were required, since standard bleed tests (4) yielded very little water from the air entrained concrete (Table 2b). The tests were performed on the surface of the slabs and used preweighed 5-1/2 in. square paper towels (from the same lot). The towels were placed on the surface of the concrete and covered with a glass plate to prevent evaporation. When fully saturated, the towels were replaced. The time on the surface was recorded for each slab. This provided data on the amount of bleed water reaching the slab surface as a function of the time after finishing. The tests were not solely a measure of bleed, because the towels drew water from the slab surface.

Bleed tests were conducted at both ends of the shallow specimens and at one end of the deep specimens.

Slab settlement was obtained by measuring the movement of 2 in. square balsa wood pads resting on the concrete surface, using linear variable differential transformers (LVDT's).

Bleed and settlement tests continued for a minimum of two hours after finishing. Following the tests, the slabs were covered with polyethylene until a strength of 3000 psi was obtained in companion test cylinders. The polyethylene sheet was then removed and the forms stripped.

At this point, the portions of the slabs to be overlayed were cleaned using a water blaster (rated at 3000 psi) until all traces of laitence and carbonation were removed. The surfaces were allowed to dry for two hours and a 50% sand - 50% cement (by weight) grout was applied using a stiff brush. The water-cement ratio of the grout was approximately the same as used for the overlay concrete. For Group 8, a high-range water-reducer was added to the grout to compensate for the low water-cement ratio. In all cases, the grout had the consistency of a thick cream.

The overlay concrete was placed on the wet grout and consolidated using a pneumatic vibratory screed. The screed rode on a 2-1/4 in. high form. The overlays were then hand floated using a magnesium float to remove local imperfections. The overlays were allowed to cure under plastic until a strength of 4000 psi was attained or until the overlay strength was as high as the first course strength (one exception to this practice was Group 6, where the overlay strength was only 2600 psi at the time of pullout tests). Curing material was removed at least five hours before the pullout tests started.

Test Procedure

The pullout apparatus shown in Fig. 3 was used for the bond tests. The equipment was designed so that the test bars in the "modified cantilever" slab specimens could be loaded in tension without placing the surrounding concrete in compression.

Each slab group was tested during a 24-hour period, at ages ranging from 6 to 43 days. 6 in. x 12 in. compression cylinders were tested at the time of the bond tests to determine the slab and overlay strengths.

The bars were loaded at approximately 3 kips per minute. Load, loaded end slip, and unloaded end slip were recorded as the tests progressed.

4 in. diameter cores were taken from Groups 6 and 7. Concrete density and void percentage were determined following ASTM C 642 (5) with the

following exceptions: dry weights were obtained using air dried specimens rather than oven dried specimens; saturated weights after immersion were used in place of saturated weights after boiling.

Results and Observations

Plastic concrete: Bleeding was initially rapid, but slowed substantially after 90 minutes. With the exception of Groups 1, 2, and 3, bleed did not vary significantly between individual slabs in a group. The differences in Groups 1, 2, and 3 were due to methods of placement, which were corrected in later work (8).

For the valid comparisons, the maximum difference in bleed occurred in Slab Group 5, with a ratio of bleed obtained with high density vibration to bleed obtained with low density vibration of 0.84. Ratios for Groups 4, 6 and 7 were 0.94, 1.01 and 1.01, respectively.

The settlements were extremely low for all specimens (maximum of 0.012 in.), and seemed to indicate that both consolidation densities were satisfactory from the point of view of settlement.

The results from the bleed and settlement tests are presented in Table 4.

Hardened Concrete: Settlement cracks were noted above the test bars with 3/4 in. cover in Slab Groups 2, 4, 5 and 6. Group 2 contained #8 bars and was placed with 8-1/2 in. slump concrete. The other three groups contained #5 bars.

Typical load versus unloaded end slip curves are presented in Fig. 4. The test results are summarized in Table 1.

For both bar sizes, the behavior and failure mode in the pullout tests depended upon the cover. All failures were splitting failures, except for the #5 bars with a 3 in. cover, which rarely displayed any cracking. Crack patterns for a shallow slab with #8 bars are shown in Fig. 5.

Bars with 3/4 in. cover failed at lower loads than bars with 3 in. cover, while bars with two-course cover normally failed at loads below the failure loads for 3 in. monolithic cover.

The cores showed extremely good bond between the overlay and the first course concrete.

The core density tests showed that density was increased about 3% and void percentage was reduced about 4%, where high density consolidation was used (8).

EVALUATION OF EXPERIMENTAL RESULTS

The test results are used to examine the effects of consolidation method and cover type on bond strength and to compare the values with those predicted by the AASHTO Bridge Specifications (1) and the ACI Building Code (3). These results are also used to examine the effects of slump, bleed, and slab depth on bond strength.

The ultimate loads listed in Table 1 represent the maximum recorded load for each test. Since some bars yielded before reaching the ultimate load, the criteria of unloaded end slip is also used for bond force comparison. Bond forces for unloaded end slips of 0.010 in. and 0.005 in. are shown for #5 and #8 bars, respectively.

In Slab Groups 1, 2 and 3, longitudinal splitting cracks crossed the slab center line for most #8 bars with 3 in. cover. In these groups, only the first #8 bar with 3 in. cover pulled from a slab is used for comparison. Additional transverse reinforcing was added to intercept splitting cracks in Groups 7 and 8, which allows the second 3 in. cover bar to be used in these groups.

To further assist in the comparisons, the bond forces are converted to bond force per unit length and normalized to a strength of 4000 psi and to embedment lengths of 10 in. and 3-1/2 in. for #8 and #5 bars, respectively.

The strength is normalized (9,11,14) using the assumption that the bond strength is proportional to the tensile strength of the concrete, which in turn is proportional to the square root of the compressive strength. Bond values are therefore multiplied by $(4000/f'_c)^{1/2}$.

The embedment length is modified utilizing a nonlinear relation between bond strength and bonded length. The equation developed by Jimenez, et al, (10) is used to determine an equivalent embedment length, L_e. The bond forces are divided by L_e obtained from the following expression:

$$L_e = \frac{L\,(35.4d_b + 0.573L_n)}{(35.4d_b + 0.573L)} \qquad [1]$$

in which L = actual embedment length, and d_b = bar diameter, and L_n = embedment to which results are normalized.

The normalized results are presented in Table 1.

Effect of Consolidation Method

The results indicate that high density vibration generally improves bond strength, and the amount of improvement is a function of concrete slump. In addition, improved consolidation provides higher unit weights and lower void contents.

The effects of consolidation on bond strength are illustrated in Table 5 and Fig. 6, which compare ratios of average bond forces obtained with high density vibration to bond forces obtained with low density vibration. At ultimate, the average ratios for #5 bars are 1.06, 1.23, and 1.05 for 3/4 in., 3 in. two-course, and 3 in. monolithic covers, respectively. The corresponding values for #8 bars are 1.03, 1.00, and 1.04.

Fig. 6 (bond forces at 0.005 in. slip) shows that the relative effectiveness of high density vibration appears to increase with increasing slump for #8 bars with monolithic cover. The ratios increased from 0.96 to 1.11 for bars with 3/4 in. cover as the slump increased from 1-3/4 in. to 8-1/2 in. Ratios for bars with 3 in. monolithic cover increased from 1.28 to 1.32 for the same slump range.

The fact that high density vibration provides a greater relative improvement in bond for higher slump concrete is of interest, since higher slump concrete should need less, not more, consolidation. This observation suggests that the improved consolidation may overcome some of the extra settlement that occurs with high slump concrete. Since low slump concrete settles less, the extra consolidation may be relatively less effective.

Fig. 6 also shows that high density vibration provides a much greater benefit for the #8 bars with the monolithic 3 in. cover than for the #8 bars with either the monolithic 3/4 in. cover or the two-course 3 in. cover.

This difference in behavior may be explained by the fact that while high density consolidation does provide increased concrete density, the formation of settlement cracks in the thin top cover may dominate the behavior of bars with a 3/4 in. initial cover, allowing early slip of the bars. The bars with the greater cover, therefore, benefit more from consolidation than bars with thinner cover.

A similar trend is obtained for the #8 bars at ultimate, with the relative strengths increasing from 0.99 to 1.05 for 3/4 in. cover and from 1.05 to 1.08 for 3 in. monolithic cover, as slump increases from 1-3/4 in. to 8-1/2 in.

The slump range (2-3/4 in. to 4-1/2 in.) was not wide enough to obtain a clear trend for the #5 bars.

Overall, high density vibration provided an improved average bond strength, with the exception of the #5 bars in Group 4, which were the only tests to exhibit any significant reduction in bond strength with increased consolidation. The concrete for Group 4 had the lowest cement content (555 lb./yd^3) used in the tests, but it is not clear why this would explain the 12% to 22% decreases in bond strength observed for this group.

Effect of Cover Thickness and Type

The effect of cover thickness on bond strength is illustrated in Fig. 7, which shows that the bars with 3/4 in. cover had a bond strength of only about 60% of the strength obtained with a 3 in. monolithic cover. This relative strength appears to be almost independent of bar size, slump, and vibration density.

The bond strengths in two-course and monolithic decks are compared in Fig. 8. The relative strengths are compared to the ratio of overlay to first-course concrete strength. Fig. 8 shows that a low strength overlay can reduce bond strength up to 20%, while high strength overlays can, at best, achieve a bond strength equal to that obtained with a monolithic cover. The slabs with a overlay strength in excess of the first course strength attained bond strengths ranging from 90% to 102% of the bonds strengths in the monolithic slabs, with most two-course slabs showing a reduced bond strength. However, a high strength overlay does not guarantee a high bond strength, as illustrated by the #8 bars in Group 2, in which the bond strengths for two-course decks were only 91% of those with monolithic decks, even though the overlay strength was 155% of the first course strength.

The reduction in bond strength in the two-course decks is probably due to problems associated with low top cover in the first course - the formation of settlement cracks, coupled with the tendency of the finishing equipment to remove the coarse aggregate from the concrete above the bars. The lower coarse aggregate content above the bars will aggrevate any shrinkage cracking that occurs. These longitudinal settlement and shrinkage cracks can then act as incipient bond cracks. This line of reasoning is strengthened by the observation that the bond strength reduction was the greatest for Groups 2 and

3, the groups with the highest slump first course concrete (8-1/2 in. and 5-1/2 in.); the higher the slump, the greater the settlement and shrinkage.

Should the bond between the first and second course concrete be unsatisfactory, then additional problems arise, as shown in Fig. 7.

Effect of Slump and Bleed

The results generally agree with earlier work (11,12,16) indicating that bond strength decreases with increasing slump (Fig. 9). However, no trend appears for #5 bars alone and the trends for #8 are not as strong as reported earlier (11), possibly because of the shallow specimens and high density consolidation used in this study.

For the #8 bars in Groups 2, 3 and 8 (similar first course concrete strengths), average bond strengths dropped a total of 4%, 15%, and 6%, as the slump increased from 2-1/4 in. to 8-1/2 in. for the 3/4 in., 3 in. two-course, and 3 in. monolithic covers, respectively.

A definite correlation between bleed and slump exists for this series of tests (Fig. 10), suggesting that the trends of decreased bond with increased slump may be trends of decreased bond with increased bleed. For air contents ranging from 4-1/2 to 10%, there is no apparent effect of air content on bleed.

Effect of Specimen Depth

Both AASHTO (1) and ACI (3) require a 40% increase in embedment length for top bars, i.e. horizontally cast bars with more than 12 in. of concrete below them. Following this reasoning, all of the test bars in the deep slabs should have significantly lower bond strengths than the bars in the shallow slabs. This was not the case in this study.

As illustrated in Table 6, the bond strengths in the deep slabs ranged from 96% to 124% of the bond strengths in the companion shallow slabs.

Earlier tests (12) have indicated that even for low slump, highly consolidated concrete, the depth of concrete below the top reinforcement should have at least some effect on bond. These earlier test specimens were, however, prepared so that they were the same size at the time of testing. It is possible then, that the geometry of the test specimens plays a role.

The vertical cracks that were observed below the #8 test bars often extended to the bottom of the shallow slabs. While the vertical cracks did not extend to the bottom of the deep slabs, they did grow to more than 8 in.

in length. Therefore the test bars in the deep slabs actually cracked more concrete. The additional energy required to crack the deep slabs may have been reflected in the high bond strength of the deep specimens. This fact does not reduce the validity of the results, since in practice, deeper bridge decks will have more concrete available to crack.

Design Equations

Ideally, the AASHTO and ACI bond requirements should be uniformly conservative when compared with experimental data. This is not the case for these tests.

The expressions for development length in the AASHTO Bridge Specifications (1) and ACI Building Code (3) can be used to obtain an ultimate bond force, T. The following equations are obtained for #11 bars and smaller:

$$T = 1.25 \cdot 25L\sqrt{f'_c} \qquad [2]$$

$$T = 1.25 \cdot 625\pi L d_b \qquad [3]$$

in which f'_c = the concrete compressive strength (psi). The 1.25 factor takes into account the 20% reduction in development length (equivalent to a 25% increase in bond strength) allowed for bars with a lateral spacing of at least 6 in.

Following the bond design requirements (1,3), Eq. 2 provides the minimum bond force for #8 bars, while Eq. 3 provides the minimum bond force for #5 bars.

The experimental bond strengths are compared to the predicted values (from Eq. 2 or Eq. 3) in Fig. 11 and Table 7. Table 7(a) includes only those bars that remained elastic, while Table 7(b) includes all valid tests. The predicted values are based on the first course concrete strength.

The comparisons for the #5 bars show a much greater scatter than the comparisons for the #8 bars, because Eq. 3 does not include the concrete strength.

The AASHTO and ACI requirements are generally conservative for the #8 bars. The requirements are less conservative for the #5 bars.

The #5 bars with the 3/4 in. cover are by far the least conservative, with an average strength which is 33% above the predicted value (Table (7a)).

The #8 bars with 3/4 in. cover average 38% above the predicted value. Coupled with the large scatter in the results, however, 20% of #5 bars with 3/4 in. cover can be expected to have bond strengths below the predicted value, compared to only 0.3% for the #8 bars. This relative lack of conservatism for the #5 bars agrees with earlier observations made with respect to top cast bars with low cover (13). 3.3% and 0.6% of the #5 bars within two-course and 3 in. monolithic covers, respectively, are expected to be below the predicted strengths. The corresponding values for #8 bars are essentially zero (less 0.01%).

RECOMMENDATIONS

The construction procedures currently in use for concrete bridge decks were implemented primarily to improve deck quality and to prolong deck life. These procedures have both positive and negative effects on the concrete-steel bond.

The use of high density internal vibration results in improved bond over low density consolidation in most cases. The procedure reduces the percentage of voids in the concrete and can provide reduced permeability when compared with low density consolidation (6). Continued use of the procedure is recommended.

The continued use of low slump concrete (maximum 2-1/2 in.) for the first course is also recommended, since increased slump is detrimental to bond strength. The use of thorough consolidation with relatively low slump concrete is an effective method of providing improved bond, especially in top-cast reinforcement.

In most cases, two-course construction results in lower bond strengths than monolithic construction. Although the bond strengths achieved with two-course construction are generally conservative when compared with ACI and AASHTO requirements, the data are based on tests using high-strength, well-bonded overlays. Low strength, or poorly bonded overlays will lead to much lower bond strengths. The current work indicates that the bond strengths for a significant percentage of reinforcement with only 3/4 in. cover will be less than the current design requirements (1,3). This can be a problem, both during the construction phase and during the service phase, if delamination of the overlay occurs.

Continued use of two-course bonded deck construction is warranted only if it can be shown that (1) high-strength, well bonded overlays are used and (2) the procedure results in more corrosion protection than provided by 3 in. monolithic cover.

Longitudinal settlement cracking, longitudinal depressions, and aggregate tears in the concrete have been noted above the top reinforcement in first-course placements. All of these can be detrimental, not only to the concrete-steel bond strength, but to the durability of the deck as well.

Longitudinal settlement cracking has been shown to be a function of top cover (7). Longitudinal depressions and aggregate tearing are brought about in the finishing operation and are probably both caused by the combination of a low cover with a relatively large maximum aggregate size. The current specified 3/4 in. first course top cover is the same as the specified nominal maximum aggregate size. The lack of adequate spacing between the top reinforcement and the finishing equipment causes the coarse aggregate to be worked away from the reinforcement, resulting in depressions. It also causes the aggregate particles to be trapped between the reinforcement and the finishing equipment, resulting in tearing of the concrete surface.

The first course cover should be increased to a 1 in. minimum, or 4/3 of the maximum size aggregate, as is recommended in ACI 211.1 (2). This would then allow the use of 3/4 in. maximum size aggregate. Field studies have shown that concrete cover has a standard deviation of about 3/8 in. (15). Therefore, using a standard deviation of 3/8 in. and assuming a normal distribution, a design first course cover of 1-1/2 in. is needed to insure that at least 90 percent of the top reinforcement has a 1 in. cover. The specified overlay thickness could then be decreased to 2 in., if required for economy.

SUMMARY AND CONCLUSIONS

Summary

The purpose of this investigation was to study the effects of high density vibration and two-course deck construction on concrete-steel bond in concrete bridge decks. 117 pullout tests were conducted using #5 and #8 deformed bars. The major variables in the study were the consolidation method, the top cover, and the specimen depth. The test results are used to evaluate the effects of the major variables and compared with the bond values predicted by the AASHTO Bridge Specifications (1) and the ACI Building Code (3).

Conclusions

The following conclusions are based on the tests and analysis described in this report:

1) High density internal vibration provides both improved bond and increased concrete density when compared to low density internal vibration.
2) 3 in. monolithic cover provides a higher bond strength than 3 in. two-course cover.
3) 3/4 in. cover provides approximately 60 percent of the bond strength of 3 in. monolithic cover.
4) The bond strengths for a significant percentage of top-cast reinforcement with 3/4 in. cover will be less than current design requirements (1, 3).
5) 3 in. two-course cover will provide adequate bond strength only if high strength, well bonded overlays are used. For this type of construction, increased overlay strength will increase the bond strength, but equivalence to bond strength in monolithic decks is difficult to attain.
6) Deep specimens made with stiff, well consolidated concrete can provide the same bond strengths as shallow specimens. However, the data is limited.
7) Increased concrete slump has a negative effect on the bond strength of top-cast reinforcement.

Recommendations for Future Study

Although the current design provisions use only the depth of the concrete below the reinforcement as a criterion in defining a "top bar", the data from this and other studies tend to support the use of two other criteria, slump and top cover.

The effects on bond of slump, top cover, and depth of concrete below the reinforcement are interactive and cannot be quantified without research considering all three simultaneously. Since the relative effects are of primary concern, it would be possible to determine the relationships using smaller specimens than were used in the current study.

Any relationships developed from a study considering all three parameters could be applied to data obtained from more realistic tests and specimens (for example, beam tests).

Much confusion exists in the literature in the area of the effect of revibration on bond in concrete. Available test data are very limited and quite dated. There is, therefore, a need for new research that will quantify the effects of revibration on bond, using current deformed bars and realistic construction procedures.

The linear relationship between bleed and slump, combined with the apparent independence of this relationship from air content, raises a number of important questions about one of the acknowledged major advantages of entrained air: i.e., that it reduces bleeding. Perhaps the reduced bleeding is attained with the first few percent of entrained air, and more entrained air results in no additional reduction in bleed. The ranges of water-cement ratios and cement contents used in this study were also quite limited. Some additional work on the effects of entrained air and slump on bleeding would be useful.

ACKNOWLEDGEMENTS

This report is based on a thesis presented by Rex C. Donahey in partial fulfillment of the requirements for the MSCE degree from the University of Kansas. Support for this project was provided by the State of Kansas Department of Transportation under a research contract with the University of Kansas Center for Research, Inc. Vibrating and finishing equipment was supplied by Allen Engineering Corporation. Reinforcing steel was provided by ARMCO, Inc. and Sheffield Steel. High-range water-reducer was supplied by Gifford-Hill and Company, Inc. The water blaster was supplied by District I of Kansas Department of Transportation. Additional support was provided by the University of Kansas Department of Civil Engineering. Special thanks are due Carl F. Crumpton and John B. Wojakowski of the Kansas Department of Transportation Bureau of Materials and Research for their careful reading and detailed comments on the report.

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Table 1 Bond Forces

Slab	Bar Number	Bar Size	Concrete Strength (Slump, in.) 1st Course psi	2nd Course psi	Consol-idation Type+	Embed-ment Length in.	Total Cover in.	Cover Type*	End Slip Load^ kips	Ult-imate Load kips	Normalized Bond Forces Per Unit Length End Slip Load kips/in.	Ultimate Load kips/in.
1c	4	#8	4510	N.A.	H2	12	3/4	1	29.3	35.3	2.36	2.48
	5		(2-1/2)				3/4	1	32.3	35.2	2.60	2.84
	6						3	1	45.8	56.4Y	3.69	4.55Y
	7						3	1	46.3	48.3	3.73	3.89
	8						3/4	1	29.4	31.4	2.37	2.53
1b	9	#8	4510	N.A.	H1	12	3/4	1	31.0	33.1	2.50	2.67
	10		(2-1/2)				3/4	1	37.0	37.8	2.98	3.05
	11						3	1	49.5Y	57.5YT	3.99Y	4.64YT
	12						3/4	1	33.5	34.3	2.70	2.76
	13						3/4	1	37.8	38.2	3.04	3.08
	14						3	1	46.6	47.9	3.76	3.86
1a	15	#8	4510	N.A.	H2	12	3/4	1	37.0	38.7	2.98	3.12
	16		(2-1/2)				3/4	1	31.3	33.3	2.52	2.69
	17						3/4	1	29.8	30.3	2.40	2.44
	18						3/4	1	37.0	38.0	2.89	3.06
	19						3	1	52.8Y	56.7YT	4.26Y	4.57YT
	20						3	1	43.8	51.3YT	3.53	4.13YT
2c	39	#8	3820	5920	L1	10	3/4	1	19.1	22.8	1.95	2.33
	40		(8-1/2)				3	2	25.3	39.1	2.58	3.99
	41						3	2	28.0	37.6	2.86	3.84
	42						3/4	1	21.3	27.1	2.17	2.77
	43						3	1	29.0	43.1	2.96	4.40
	44						3	1	22.0	35.2	2.24	3.59
2b	45	#8	3820	5920	H2	10	3/4	1	19.8	26.8	2.02	2.73
	46		(8-1/2)				3	2	24.8	40.1	2.53	4.09
	47						3	2	30.2	40.3	3.08	4.11
	48						3/4	1	24.8	28.5	2.53	2.91
	49						3	1	30.8	44.3	3.14	4.52
	50						3	1	35.0	38.8	3.57	3.96
2a	51	#8	3820	5920	H2	10	3/4	1	24.0	26.8	2.44	2.74
	52		(8-1/2)				3/4	1	22.0	25.9	2.24	2.64
	53						3/4	1	22.8	24.6	2.33	2.51
	54						3/4	1	21.6	24.3	2.20	2.47
	55						3	1	34.0	46.1	3.47	4.70
	56						3	1	33.8	40.0	3.45	4.08
3a	21	#8	3970	4380	H2	10	3/4	1	24.2	25.8	2.42	2.58
	22		(5-1/2)				3	2	30.8	42.9	3.08	4.29
	23						3	2	26.3	41.4	2.63	4.14
	24						3/4	1	23.5	29.7	2.35	2.97
	25						3	1	42.0	47.3	4.20	4.73
	26						3	1	38.5	43.6	3.85	4.36
3c	27	#8	3970	4380	L1	10	3/4	1	23.8	26.2	2.38	2.62
	28		(5-1/2)				3	2	29.3	43.8	2.93	4.38
	29						3	2	30.5	39.4	3.05	3.94
	30						3/4	1	28.5	30.0	2.85	3.00
	31						3	1	34.0	48.6	3.40	4.86
	32						3	1	29.8	41.5	2.98	4.15

Table 1 (continued)

Slab	Bar Number	Bar Size	Concrete Strength (Slump, in.) 1st Course psi	2nd Course psi	Consol- idation Type+	Embed- ment Length in.	Total Cover in.	Cover Type*	End Slip Load^ kips	Ult- imate Load kips	Normalized Bond Forces Per Unit Lengt End Slip Load kips/in.	Ultim Loa kips/i
3b	33	#8	3970	4380	H2	10	3/4	1	28.8	31.2	2.88	3.12
	34		(5-1/2)				3/4	1	28.0	31.3	2.80	3.13
	35						3/4	1	28.5	31.0	2.85	3.10
	36						3/4	1	28.5	29.4	2.85	2.94
	37						3	1	34.3	47.8	3.43	4.78
	38						3	1	39.0	45.5	3.90	4.55
4b	57	#5	3570	N.A.	H2	5	3/4	1	6.10	8.17	1.34	1.79
	58		(3)				3/4	1	5.50	7.00	1.21	1.54
	59						3/4	1	6.30	8.43	1.39	1.86
	60						3/4	1	7.33	8.55	1.61	1.88
	61						3	1	7.88	13.6	1.74	3.00
	62						3	1	5.75	11.8	1.27	2.59
4a	63	#5	3570	N.A.	L1	5	3/4	1	5.80	8.39	1.28	1.85
	64		(3)				3/4	1	6.55	8.03	1.44	1.77
	65						3/4	1	10.2	10.9	2.25	2.40
	66						3/4	1	8.00	9.40	1.76	2.07
	67						3	1	17.2	18.2Y	3.78	4.01Y
	68						3	1	8.00	14.4	1.76	3.17
5b	69	#5	4910	5670	H2	3.5	3/4	1	9.75	10.8	2.50	2.77
	70		(2-3/4)				3	2	10.3	17.6	2.64	4.54
	71						3	2	13.0	17.9	3.35	4.61
	72						3/4	1	10.9	11.1	2.80	2.86
	73						3	1	12.5	21.2Y	3.22	5.46Y
	74						3	1	8.40	14.9	2.16	3.83
5a	75	#5	4910	5670	L1	3.5	3/4	1	7.13	8.68	1.84	2.73
	76		(2-3/4)				3	2	8.55	13.9	2.20	3.58
	77						3	2	11.4	15.0	2.92	3.87
	78						3/4	1	8.20	9.24	2.11	2.38
	79						3	1	7.00	14.4	1.80	3.70
	80						3	1	10.0	15.5	2.57	3.98
6b	81	#5	4060	2600	L2	12	3/4	1	17.3	18.2	1.71	1.81
	82		(4-1/2)			3.5	3	2	5.60	8.93	1.58	2.53
	83					3.5	3	1	6.35	11.0	1.80	3.12
	84					12	3/4	1	19.0Y	20.4Y	1.88Y	2.02Y
	85					3.5	3	2	5.55	7.74	1.57	2.19
	86					3.5	3	1	6.75	9.50	1.91	2.68
6a	87	#5	4060	2600	H2	12	3/4	1	17.3	19.0Y	1.72	1.88Y
	88		(4-1/2)			3.5	3	2	7.00	10.9	1.98	3.09
	89					3.5	3	1	7.75	12.5	2.19	3.54
	90					12	3/4	1	21.5Y	22.5Y	2.13Y	2.23Y
	91					3.5	3	2	6.30	9.66	1.78	2.23
	92					3.5	3	1	9.40	13.2	2.65	3.74

Table 1 (continued)

Slab	Bar Number	Bar Size	Concrete Strength (Slump, in.) 1st Course psi	2nd Course psi	Consolidation Type+	Embedment Length in.	Total Cover in.	Cover Type*	End Slip Load^ kips	Ultimate Load kips	Normalized Bond Forces Per Unit Length End Slip Load kips/in.	Ultimate Load kips/in.
7a	93	#8	4950	5100	H2	15	3/4	1	40.5	41.3	2.62	2.66
	94		(1-3/4)			(10	3	2	40.0	47.5	3.60	4.28
	95					10	3	1	44.7	48.9Y	4.04	4.42Y
	96					15	3/4	1	30.3	34.0	1.95	2.19
	97					10	3	2	40.4	48.9Y	3.64	4.41Y
	98					10	3	1	41.3	47.7	3.72	4.30
7b	99	#8	4950	5100	L3	15	3/4	1	34.1	36.2	2.19	2.33
	100		(1-3/4)			10	3	2	35.2	50.1Y	3.17	4.51Y
	101					10	3	1	32.5	48.0	2.93	4.32
	102					15	3/4	1	40.0	40.1	2.57	2.58
	103					10	3	2	39.8	46.2I	3.59	4.16I
	104					10	3	1	38.3	43.6	3.45	3.93
7c	105	#8	4950	5100	H2	10	3	1	44.2	53.7Y	3.98	4.84Y(D)
	106		(1-3/4)				3	1	37.5	54.6Y	3.38	4.91Y(D)
7d	107	#8	4950	5100	H2	15	3/4	1	45.8	48.1	2.95	3.10(D)
	108						3/4	1	44.4	45.4	2.86	2.92(D)
8a	109	#8	3970	5350	H2	10	3/4	1	23.8	27.2	2.38	2.72
	110		(2-1/4)				3	2	33.3	48.3	3.33	4.83
	111						3	1	38.3	49.2E	3.83	4.92E
	112						3/4	1	27.0	28.4	2.70	2.84
	113						3	2	37.5	43.0	3.75	4.30
	114						3	1	38.3	46.3	3.83	4.63
8b	115	#8	3970	5350	H2	10	3	1	38.0	46.2	3.80	4.62(D)
	116		(2-1/4)				3	1	30.8	45.5	3.08	4.55(D)
8c	117	#8	3970	5350	H2	10	3	3	36.5	47.1	3.65	4.71(D)
	118		(2-1/4)				3	3	28.6	48.4	2.86	4.84(D)
	119	#8	3970	5350	H2	10	3	2	42.5	46.8	4.25	4.68(D)
	120		(2-1/4)				3	2	21.3	48.4	2.13	4.84(D)

^ End slip = 0.005 inches for #8 bars and 0.010 for #5 bars.
* Cover Type Designations:
1 = Monolithic.
2 = Two-course w/ 3/4 inch first course.
3 = Two-course w/ 1 inch first course.
+ Consolidation Type Designations:
H1 = High density vibration using one vibrator.
H2 = High density vibration using two vibrators.
L1 = Low density vibration at two foot centers.
L2 = Low density vibration at the slab centerline at two foot centers.
L3 = Low density vibration at two foot centers for seven seconds.
Y after load indicates pullout force exceeded yield strength.
YT is same as Y, but loading terminated before pullout.
I after load indicates loading rate ~ 10 times normal rate.
(D) after load indicates deep slab.
E after load indicates estimated value based on single load cell output.

Table 2(a) Concrete Mix Designs
(Cubic Yard Batch Weights)

	First Course Concrete					Second Course Concrete				
				Aggregate					Aggregate	
Slab Group	W/C Ratio	Cement #	Water #	Fine+ #	Coarse* #	W/C Ratio	Cement #	Water #	Fine+ #	Coarse* #
1	0.44	591	262	1470	1455	--	--	--	--	--
2	0.44	636	282	1381	1455	0.44	563	248	1491	1491
3	0.44	591	262	1470	1455	0.44	563	248	1491	1491
4	0.44	555	244	1545	1455	--	--	--	--	--
5	0.44	591	262	1470	1455	0.44	563	248	1491	1491
6	0.44	584	257	1484	1455	0.44	563	248	1491	1491
7	0.41	591	243	1515	1455	0.40	620	248	1447	1491
8	0.44	591	262	1470	1455	0.35	825	289	1316	1316

* Crushed limestone--Hamm's Quarry, Perry, KS
Bulk Specific Gravity = 2.52, Absorption = 3.5%,
Maximum size = 3/4 inch.
\+ Kansas River sand--Lawrence Sand Co., Lawrence, KS
Bulk Specific Gravity = 2.62, Absorption = 0.5%,
Fineness Modulus = 3.0.
Air entraining agent--vinsol resin
Design air entrainment = 6%.

Table 2(b) Concrete Properties

Slab Group	First Course Concrete				Second Course Concrete	
	Slump in.	Air %	Bleed* ml	f'_c psi	Slump in.	f'_c psi
1	2-1/2	4-1/2	0	4510	--	--
2	8-1/2	9	10.8	3820	1/2	5920
3	5-1/2	7	13.5	3970	1/2	4380
4	3	7	3.5	3570	--	--
5	2-3/4	5	0	4910	1/4	5670
6	4-1/2	10	2	4060	0	2600
7	1-3/4	5	0	4950	0	5100
8	2-1/4	7	0	3970	1/2	5350

* ASTM C 232, at 100 minutes.

Table 3 Average Test Bar Data

Bar Size	#8	#5
Deformation Spacing, in.	0.545	0.345
Deformation Height, in.	0.057	0.040
Deformation Angle, deg.	50	50
Deformation Gap, in.	0.313	0.125
Nominal Weight, #/ft.	2.650	1.010
Deformation		
Bearing Area, sq.in./in. length	0.239	0.162
Yield Strength, ksi	63.47	60.23
Tensile Strength, ksi	104.6	101.0
Deformation Pattern--Sheffield		

Table 4 Slab Bleed and Settlement at 2 Hours

Slab	Consolidation Type+	Avg. Total Bleed gm	Settlement in.
1a	H2	14.4	0.010
1b	H1	8.8	0.008
1c	H2	9.5	0.006
2a	H2	57.3	0.010
2b	H2	43.5	No Data
2c	L1	39.4	No Data
3a	H2	41.3	0.004
3b	H2	26.2	0.007
3c	L1	28.2	0.009
4a	L1	31.0	0.010
4b	H2	29.0	No Data
5a	L1	21.4	0.011
5b	H2	17.9	0.009
6a	H2	26.3	0.007
6b	L2	26.0	0.003
7a	H2	17.7	0.010
7b	L3	17.6	0.011
7c	H2(D)	18.3	0.005
7d	H2(D)	16.4	0.008
8a	H2	11.1	0.011
8b	H2(D)	10.6	0.012
8c	H2(D)	9.3	0.003
8d	H2(D)	11.6	0.005

+ See Table 1 for notation.

Table 5 Ratio of Bond Strengths for High Density Vibration to Bond Strengths for Low Density Vibration

Bar Size	Group #	Slump in.	End Slip Value+ Cover Type* 1	2	3	Ultimate Force Value Cover Type* 1	2	3
#5	4	3	0.83		0.54	0.88		0.78
	5	2-3/4	1.35	1.16	1.23	1.22	1.23	1.11
	6	4-1/2	1.06	1.19	1.32	1.07	1.23	1.25
	Average		1.08	1.18	1.03	1.06	1.23	1.05
#8	2	8-1/2	1.11	1.03	1.32	1.05	1.02	1.08
	3	5-1/2	1.03	.95	1.20	1.05	.98	.98
	7	1-3/4	.96	1.08	1.28	.99	1.00	1.05
	Average		1.04	1.02	1.27	1.03	1.00	1.04

+ End slip = 0.005 inches for #8 bars and 0.010 for #5 bars.
* Cover Type Designations:
1 = 3/4 inch monolithic cover.
2 = 3 inch two-course cover.
3 = 3 inch monolithic cover.

Table 6 Comparison of Bond Strengths for Deep Slabs and Shallow Slabs

Group Number	Bar Size	Embedment Length in.	Cover in.	Average Ultimate Bond Force Deep kips	Shallow kips	Deep/Shallow Ratio
7	#8	15	3/4	46.8	37.7	1.24
7	#8	10	3	54.2	48.3	1.12
8	#8	10	3/4+2-1/4	47.6	45.7	1.04
8	#8	10	3	45.9	47.8	0.96

Table 7 Comparison of Experimental Bond Strengths to AASHTO (1) and ACI (3) Bond Strengths

(a) Bars That Remained Elastic

	3/4 in. Cover	3/4in.+2-1/4in. Cover	3 in. Cover
#5 Bars			
Number of Bars in Sample	13	8	10
Average $\frac{T\ (test)}{T\ (Eq.\ 3)}$	1.329	2.349	2.197
Sample Standard Deviation	0.390	0.731	0.473
Estimated Percentage* T < T (Eq. 3)	20	3.3	0.6
#8 Bars			
Number of Bars in Sample	34	10	12
Average $\frac{T\ (test)}{T\ (Eq.\ 2)}$	1.380	2.224	2.296
Sample Standard Deviation	0.138	0.155	0.137
Estimated Percentage* T < T (Eq. 2)	0.3	0	0

(b) All Valid Tests**

	3/4 in. Cover	3/4in.+2-1/4in. Cover	3 in. Cover
#5 Bars			
Number of Bars in Sample	16	8	12
Average $\frac{T\ (test)}{T\ (Eq.\ 3)}$	1.288	2.349	2.354
Sample Standard Deviation	0.362	0.731	0.654
Estimated Percentage* T < T (Eq. 3)	21	3.3	2
#8 Bars			
Number of Bars in Sample	34	12	16
Average $\frac{T\ (test)}{T\ (Eq.\ 2)}$	1.380	2.283	2.308
Sample Standard Deviation	0.138	0.141	0.134
Estimated Percentage T < T (Eq. 2)	0.3	0	0

* Assuming normal distribution.
** Y bars included; YT bars excluded (see Table 1).

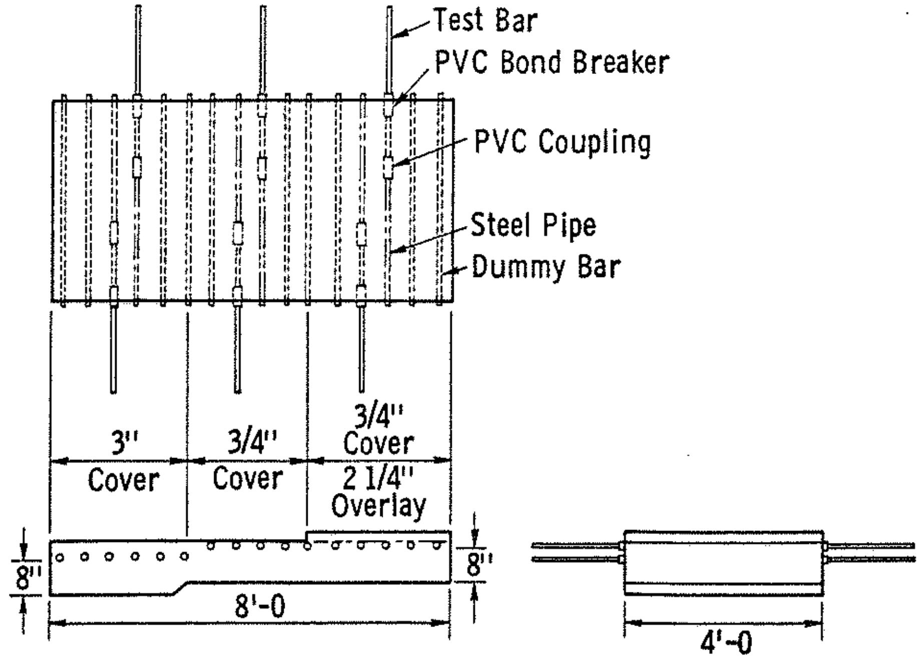


Fig. 1 Shallow Slab.

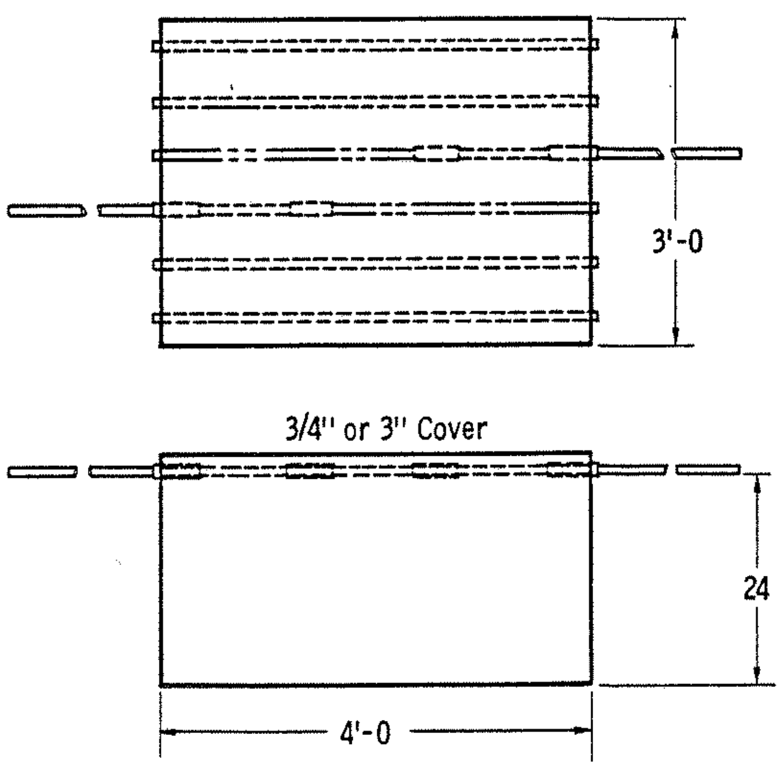


Fig. 2 Deep Slab.

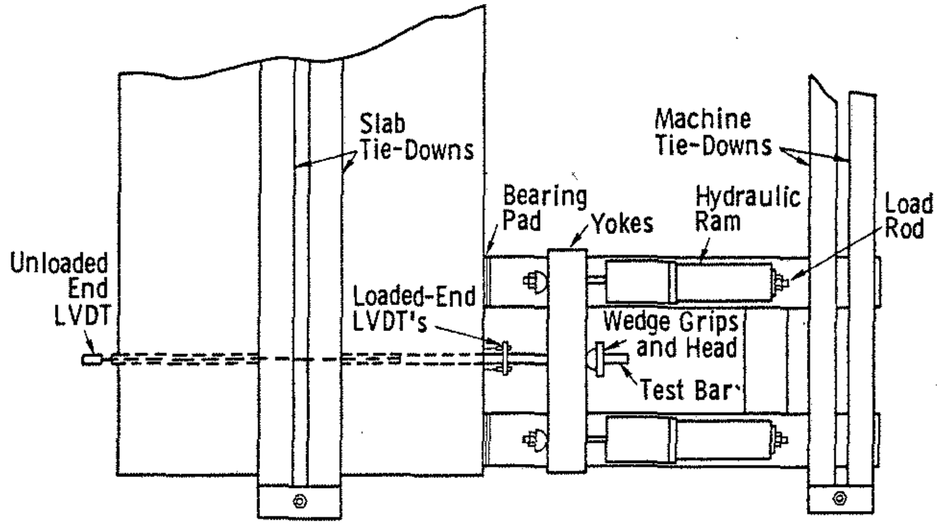


Fig. 3 Schematic of Bond Test.

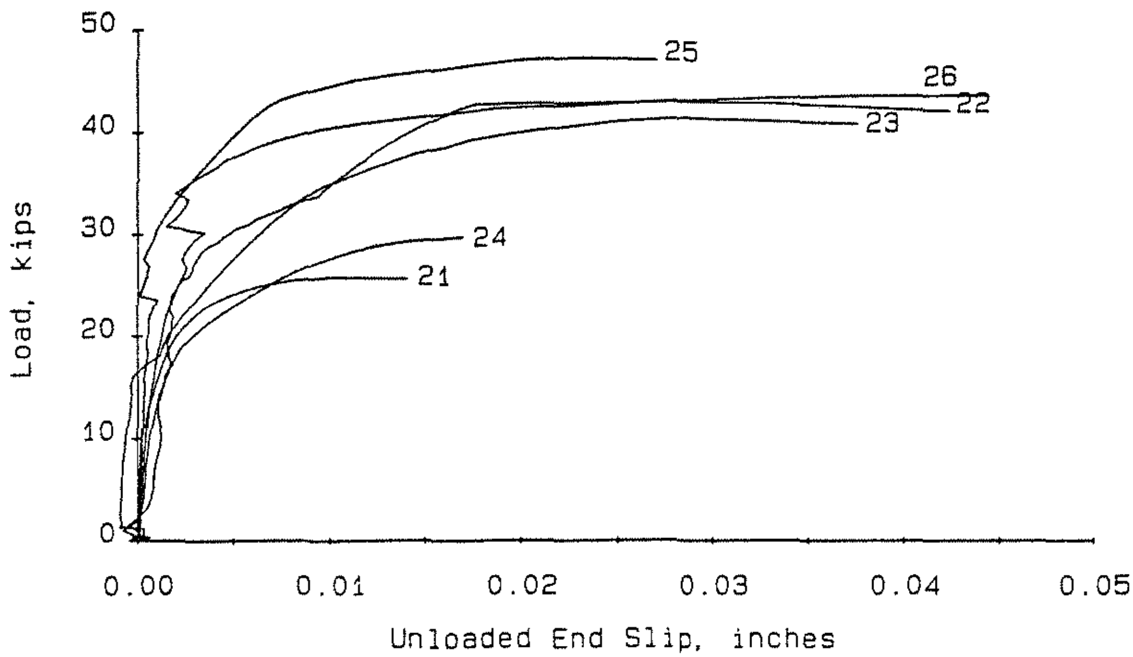


Fig. 4 Load-Slip Curves for Slab 3a.

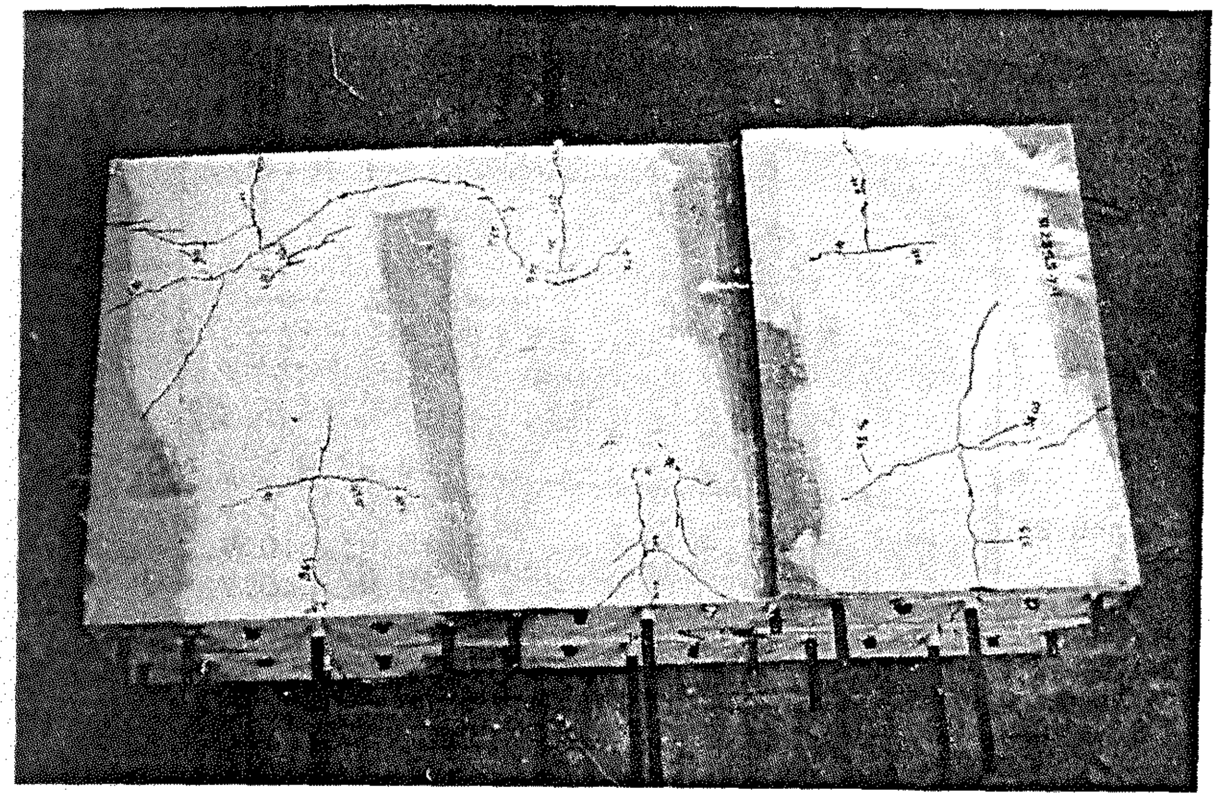
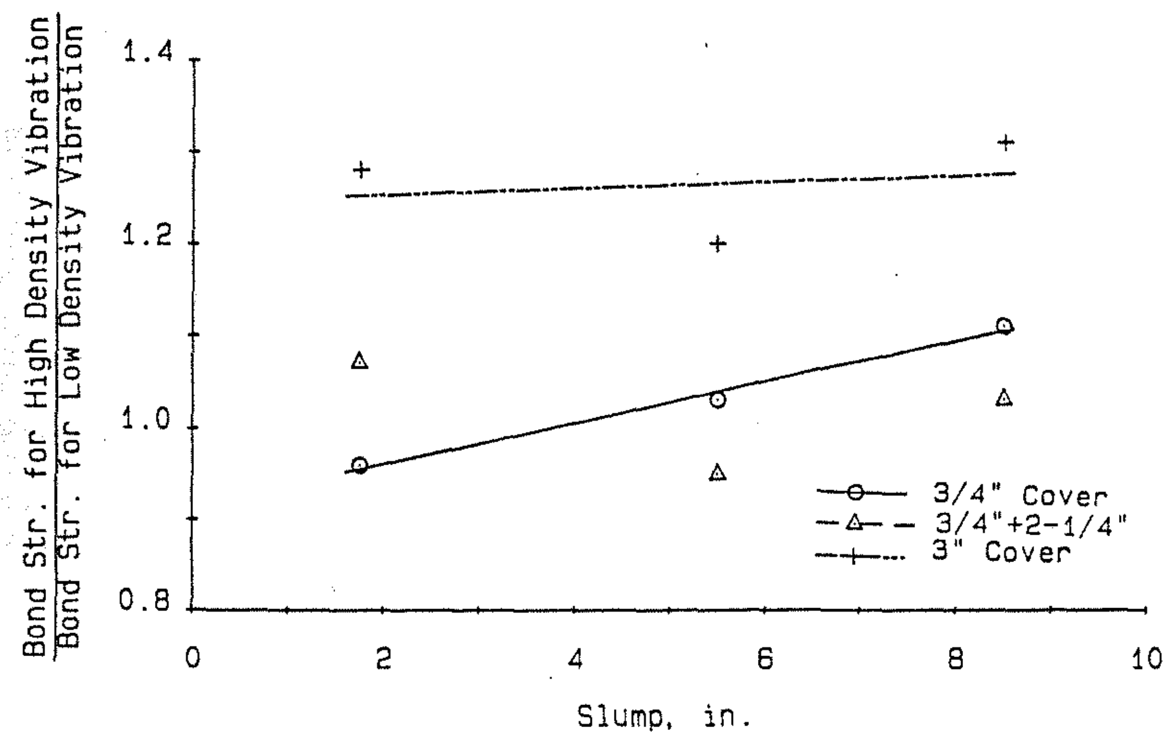


Fig. 5 Shallow Slab with #8 Test Bars After Test.



0.05

Fig. 6 Ratio of Bond Forces for High and Low Density Vibration at 0.005 inch Slip Versus Slump.

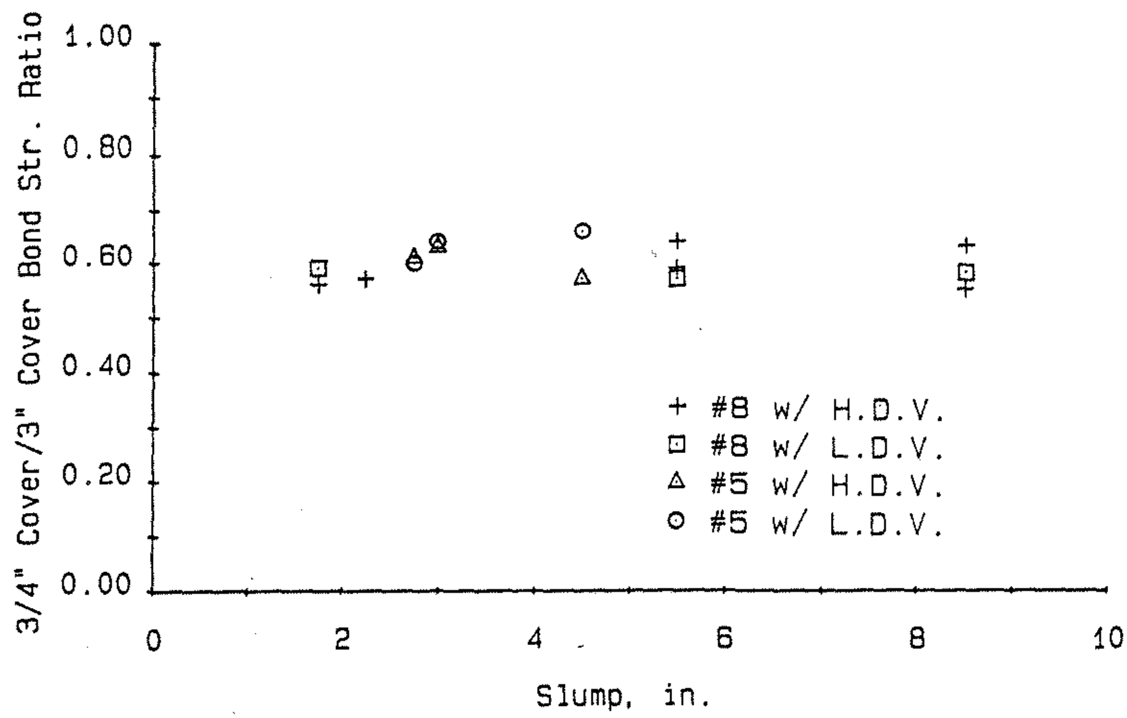


Fig. 7 Ratio of 3/4 inch Cover to 3 inch Cover Bond Strength Versus Slump.

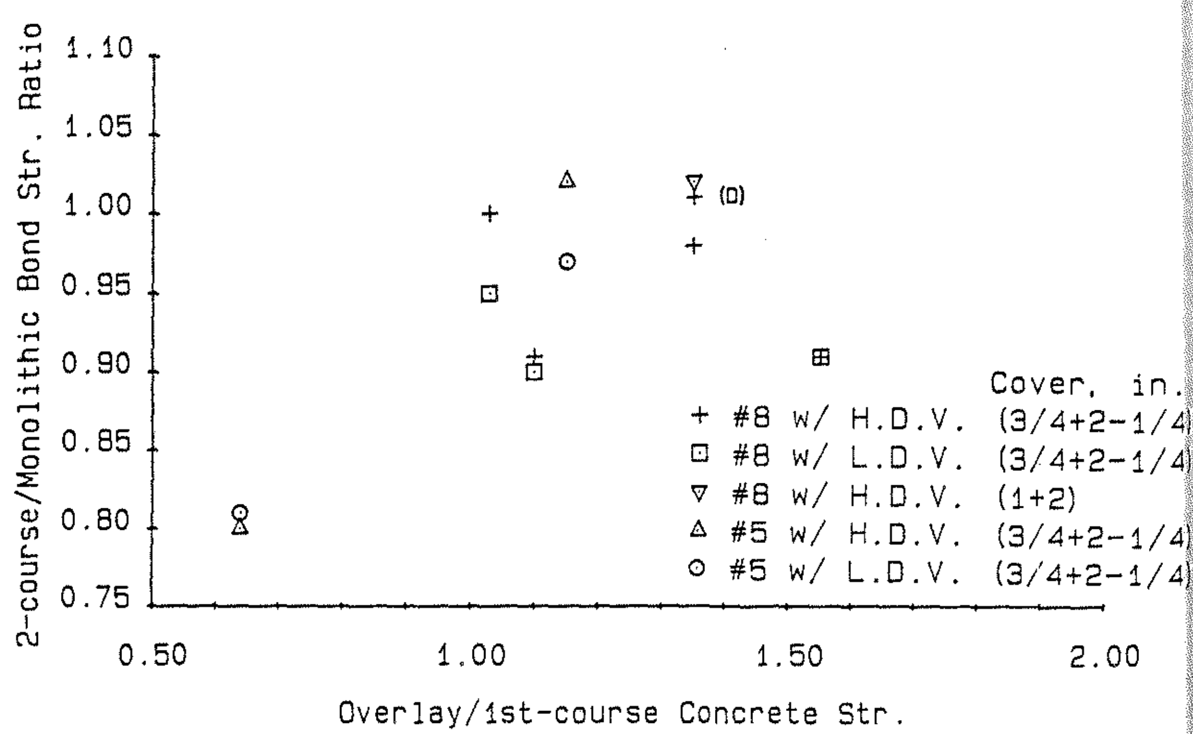


Fig. 8 Ratio of Two-Course to Monolithic Bond Strength Versus Ratio of Overlay to First Course Concrete Strength.

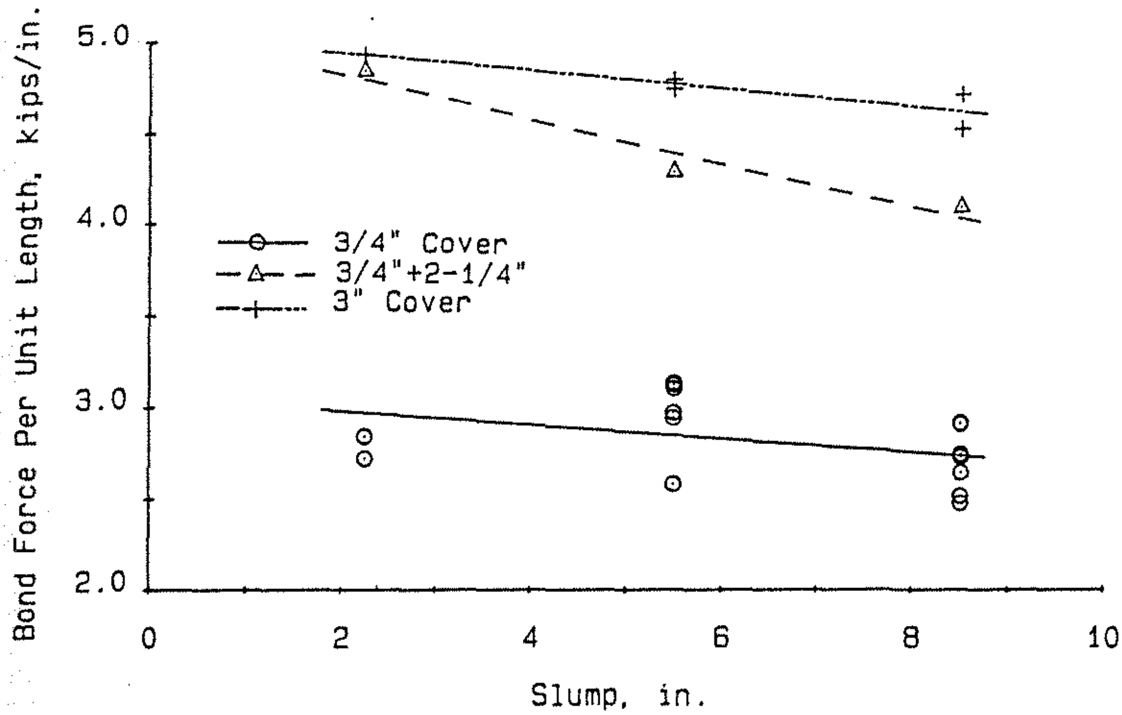


Fig. 9 Bond Forces per Unit Length at Ultimate Load for #8 Bars Versus Slump (High Density Vibration Slabs from Groups 2, 3, and 8).

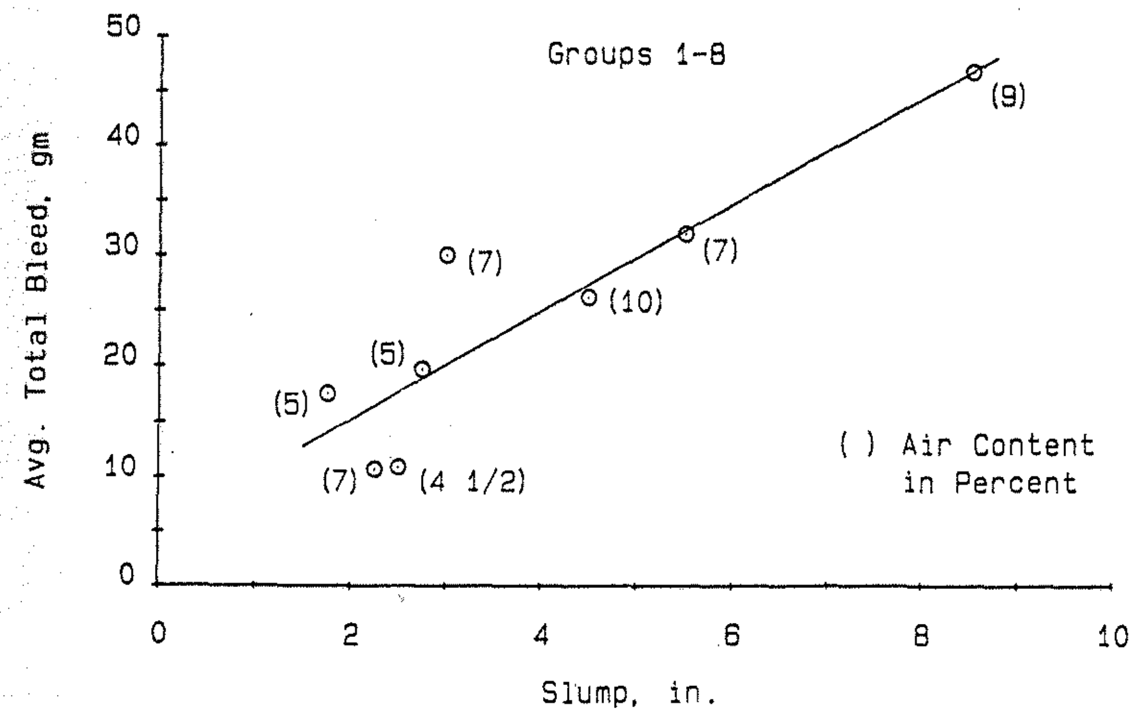


Fig. 10 Average Total Bleed at Two Hours for All Slab Groups Versus Concrete Slump.

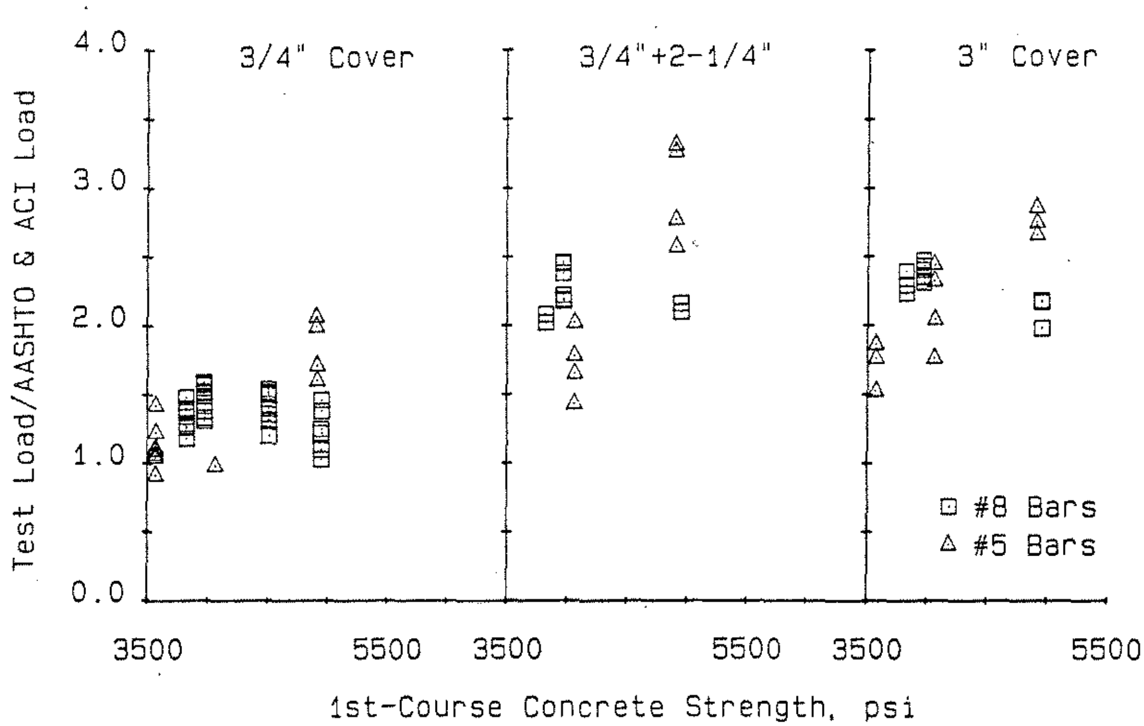


Fig. 11 Comparison of Experimental Bond Strengths to AASHTO (1) and ACI (3) Bond Strengths.