PRELIMINARY STUDY OF THE EFFECT OF REVIBRATION ON CONCRETE-STEEL BOND STRENGTH

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A Report on Research Sponsored by
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Abstract

Preliminary Study of
the Effect of Revibration on
Concrete-Steel Bond Strength

The effects of revibration on concrete-steel bond strength are studied. Key variables are concrete slump, bleed, bar position, and the time interval between initial vibration and revibration. #8 deformed reinforcing bars were used with a 2 in. cover and a 10 in. bonded length. Concrete slumps ranged from 2-3/4 in. to 7-1/2 in. Two specimen depths were used. All specimens were modified cantilever beam specimens.

The experimental results show that revibration is not universally beneficial to concrete-steel bond. Revibration appears to improve bond strength for top-cast bars placed in high slump concrete. Revibration may, however, severely damage bond strength for bars cast in well consolidated, low slump concrete. Revibration is almost universally detrimental to the bond strength of bottom-cast bars. Overall, revibration tends to reduce the differences in bond strength caused by differences in slump and bar position.

INTRODUCTION

Vibration of concrete has been the subject of many papers and reports. It is well known that vibration plays a major role in placing high quality concrete. It has been established for a number of years that initial vibration can provide improved concrete-steel bond when compared with hand rodding (3, 9). Much less is known about revibration, the process in which a vibrator is reapplied to concrete at some time period after initial vibration. Few studies have been made on revibration and its effects on concrete compressive strength and bond strength (8, 9, 12).

Vollick (12) found that internal revibration provided increases in the 28-day compressive strength of concrete ranging from 6.9% to 18.7%, depending on the concrete mixes. He did not study the effects of revibration on bond strength. Larnach (8) studied the effects of external initial vibration and revibration on bond and compressive strength using horizontally cast smooth bars. He found that external revibration produced reductions in bond strength ranging from 6% for revibration after 1/2 an hour to 33% at 3 hours. He obtained corresponding reductions in compressive strength of 14% and 16%.

The only study that addressed the effects of internal revibration on the bond strength between concrete and deformed reinforcement was completed by Menzel in 1952 (9). His study indicated that revibration after one hour had no adverse effect on bottom-cast bars, but reduced the bond strength of top-cast bars by over 28%.

Davis, Brown and Kelly (3) studied the effects of delayed vibration on bond strength. They used three types of delayed vibration up to 9 hours after the concrete had been placed by hand. One type of vibration involved clamping the mold to a vibrating table, while the other two involved vibrating the bar itself in two different ways. Increases in ultimate bond strength of up to 62% were recorded, and the effect of delayed vibration up to 9 hours after placement was found to be positive in all cases when compared to non-vibrated concrete. This work on the effects of delayed vibration has been incorrectly referenced in other papers as evidence of the positive effects of revibration (10, 11).

However, since the specimens used by Davis et al. were not initially vibrated, the positive effect can only be attributed to delayed vibration (4).

Recent work by Harsh and Darwin (6, 7) on the effects of simulated traffic induced vibration on bridge deck repairs found that both bond and compressive strengths increased for concretes with slumps below 3-4 in. and decreased for concretes with slumps above 3-4 in.

The previous studies (8, 9, 12) on revibration are in conflict. Many engineers think that once concrete has been vibrated, it should not be disturbed. However, some engineers think that revibration will improve and not diminish concrete quality (10, 11).

This report represents a preliminary study of the effects of revibration. The report considers the effect of revibration on the bond strength between concrete and horizontal deformed bars as a function of concrete slump, bleed, bar position, and the time interval between initial vibration and revibration. The report also considers the effects of revibration on the compressive strength of standard 6x12 in. concrete cylinders. Recommendations are made.

EXPERIMENTAL INVESTIGATION

To examine the effect of revibration on bond strength, test specimens, concrete mix designs, placement procedures, and test procedures were selected to reflect field conditions as closely as possible.

Test Specimens

The forms used in this study were the same as those used in an earlier study at the University of Kansas (2) on the effects of high-range water-reducers on bond strength.

Three specimen types (Fig. 1) were used to study the effect of revibration on bond strength: 9 x 11 x 24 in. shallow, bottom-cast bar specimens, with 2 in. of concrete below the bottom of the bar; 9 x 11 x 24 in. shallow, top-cast bar specimens, with 8 in. of concrete below the bottom of the bar; and 9 x 18 x 24 in. deep, top-cast bar specimens, with 15 in. of concrete below the bottom of the bar.

The specimens were cast in groups of nine, with three specimens of each type. All specimens were initially vibrated. One of each type was revibrated after 45 minutes and one was revibrated after 90 minutes. Four groups of specimens were fabricated, for a total of 36 test specimens.

The test bars were 40 in. #8 deformed bars (Fig. 2). Two 1 in. diameter, 4-1/2 in. long polyvinyl chloride (PVC) pipes were used as bond breakers to limit the bonded length and to provide coupling with a 10 in. long, 1 in. diameter galvanized steel conduit. The conduit allowed access to the test bar for unloaded end slip measurements. Based on previous work at the University of Kansas (2, 4, 5) and on preliminary tests in this study, a 2 in. concrete cover and 10 in. embedment length were used to insure a splitting failure during the pullout tests.

Two #5 deformed bars were placed parallel to the test bar to prevent a flexural failure in the specimens during the pullout tests. Two or three #5 auxiliary bars were used perpendicular to the test bar in the shallow and deep specimens, respectively, for supporting the test bar and handling the specimen.

The test variables, including concrete slump and air content are summarized in Table 1.

Material Properties

Concrete: Air entrained concrete was supplied by a local ready mix plant. Type I portland cement and 3/4 in. nominal maximum size coarse aggregate were used. Concrete slump was adjusted by varying the water and cement contents at a constant water-cement ratio of 0.46. Air content varied from 4.5 to 6%. Mix designs, aggregate properties, and concrete properties are summarized in Table 2.

Steel: ASTM A 615, Grade 60 #8 reinforcing bars were used for all tests. Deformation dimensions, bearing areas, and steel strengths are presented in Table 3.

Placement Procedures

Two placement procedures were used in this study. One procedure was used for Group #1 and then modified for the other three groups.

Groups 2-4: Concrete placement started after the concrete mix was adjusted to the required slump and air content by adding water and an air entraining agent. The specimens were filled in a single lift, with the deep specimens first, followed by the shallow, top-cast bar and shallow, bottom-cast bar specimens. After a 10 minute rest, the specimens were initially vibrated (see Consolidation Procedure). One specimen of each type was hand screeded using a metal-edged screed and floated using a magnesium hand float. The other two specimens of each type were left with a 1 in. concrete surcharge to allow for revibration.

Simultaneously with specimen placement, concrete slump, air content and temperature were measured, and standard 6 x 12 in. cylinders were cast in steel molds. All cylinders were consolidated by rodding; six were finished and six were left with a 1 in. surcharge.

Bleed tests (described below) were started as soon as the concrete surface was finished. The tests were run on the shallow and deep, top-cast bar specimens.

Forty-five minutes after initial vibration, one of the two remaining bond specimens of each type was revibrated, screeded and finished. Bleed testing was initiated. Three of the unfinished cylinders were reconsolidated using a 1-1/8 in. diameter laboratory vibrator.

Ninety minutes after initial vibration, the remaining bond specimen of each type was revibrated, screeded and finished. Bleed testing followed. The remaining cylinders were reconsolidated.

Group 1: The order of filling for the first group of specimens was based on the revibration criteria, i.e., specimens in the set to be revibrated after 90 minutes were filled with concrete first, followed by the set to be revibrated after 45 minutes and the set to undergo initial vibration only. There was no waiting period between concrete placement and initial vibration, as for the later groups.

The cylinders in Group 1 were initially consolidated and reconsolidated using the laboratory vibrator.

Bleed tests: The bleed test was developed in earlier work at the University of Kansas by Donahey and Darwin (4, 5). The test provides data on the amount of bleed water reaching the specimen surface as a function of time.

Five and a half in. square, preweighed paper towels (from the same lot) were placed on the surface of the concrete and covered with a glass plate to prevent evaporation. The towels were replaced when saturated, and the time was recorded for each towel. The tests were continued for two hours. Each wet towel was reweighed; the difference in weight was the amount of bleed water for each towel. The tests were not solely a measure of bleed, since the towels drew water from the specimen surface. The test was performed on the top surface of the specimens, near the edge, away from the bonded length of the test bar.

When the bleed tests were finished, the specimens and the cylinders were covered with polyethlene and kept moist until a strength of about 3300 psi was attained in the companion test cylinders with initial consolidation only. The specimens and cylinders were then stripped and left to dry. Tests were conducted at a compressive strength of about 4000 psi.

Consolidation Procedure

The bond test specimens were consolidated using a 1-1/2 in. hand-held electric internal vibrator. All specimens were initially vibrated.

The time of vibrator insertion varied from one group to another, depending on the concrete workability, slump, and temperature, and the time between initial vibration and revibration.

To be as consistent as possible, the workability of the concrete was used to guide the period of vibration. The vibrator was inserted rapidly at each of six points within a specimen: one near each corner and two near the middle. The vibrator was held in place until the coarse aggregate had settled below the surface, whereupon the vibrator was withdrawn slowly. The same procedure was used to reconsolidate the specimens at 45 or 90 minutes.

Initial vibration required 5-7 seconds for the shallow specimens and 8-12 seconds for the deep specimens, while revibration at 45 minutes required 8-12 seconds and 15-20 seconds for the shallow and deep specimens, respectively. Revibration at 90 minutes required 14-25 seconds and 20-40 seconds for the shallow and deep specimens, respectively.

Test Procedure

The pullout apparatus shown in Fig. 3 was used for the bond tests. It has been used in previous work at the University of Kansas (2, 4-7). The equipment is designed to place the test bars in tension without placing the surrounding concrete in compression.

All specimens from a group were tested within a 6 hour period. The bars were loaded at 5-6 kips per minute. Load, loaded end slip, and unloaded end slip were recorded during the tests (Fig. 4 and 5). Three LVDT's, two load-cells, and a data acquisition system were used to record the data. Cylinders were tested immediately after the pullout tests.

Results and Observations

Pre-test observations: Differences in concrete temperature had a significant effect on the rate of change of concrete workability. Group 1 (2-3/4 in. concrete slump, 80°F concrete temperature), and Group 4 (4-1/2 in. concrete slump, 78°F concrete temperature), required more effort to screed the surface of the specimens and to reconsolidate the cylinders after 90 minutes than was needed for Groups 2 and 3 (cast at 67°F and 61°F). It is likely that these differences in temperature are one reason for some of the scatter obtained in this study.

Bleeding was initially rapid, but slowed substantially after about 45 minutes (Fig. 6). The initially vibrated specimens bled more than the revibrated specimens. The specimens revibrated at 45 minutes bled more than those revibrated at 90 minutes (Fig. 6). The decreased bleed of the revibrated specimens was due, at least in part, to ongoing hydration.

Deep specimens bled more than shallow specimens, with a single exception: in Group 1, the shallow specimen, with initial vibration only, bled more than the deep specimen of the same kind. This difference may be due to the different order of placement used for Group 1, in which the set of specimens with initial vibration only were filled after the specimens in the sets to be revibrated.

Bond strength: Typical load versus loaded and unloaded end slip curves are presented in Fig. 4 and 5. More information about test results, such as bleed, concrete slump, air content, concrete strength, and ultimate load at failure are summarized in Table 1.

All bond specimens failed in a longitudinal splitting mode, with few or no transverse cracks (Fig.7).

Compressive strength: Three or more cylinders for each type of vibration/revibration were tested for each group. The results are summarized in Fig. 8 and Table 1. Without exception, revibration improved the compressive strength of the concrete.

EVALUATION OF EXPERIMENTAL RESULTS

The test results are used to examine the effects of revibration on bond strength with respect to the depth of concrete below the bar, concrete slump, and the time interval between initial vibration and revibration. The effects of revibration on compressive strength are also examined.

The ultimate loads listed in Table 1 represent the maximum bond load recorded. These values are converted to a bond force per unit length and normalized to a strength of 4000 psi, assuming that bond strength is proportional to the square root of the compressive strength. Therefore, the ultimate loads are multiplied by $(4000/f'_c)^{1/2}/10$ to produce values of normalized bond force per unit length, which are also presented in Table 1.

The bond forces are normalized based on the compressive strength of the initially consolidated cylinders, i.e. not the revibrated cylinders. Therefore, the effect on bond strength of the increased concrete strength due to revibration is not included in the normalizing process.

This is in line with current practice, since standard cylinders, upon which concrete strength is judged, undergo an initial consolidation only. Any increase in compressive strength within the structure would be poorly judged based on the strength of revibrated cylinders.

Effect of Revibration

Bond strength: The test results are summarized in Fig. 9-18. Fig. 9-12 show the relationships between normalized bond strengths per unit length and the amount of concrete below the test bars for the bars in Groups 1 through 4 (concrete slumps of 2-3/4, 7-1/2, 4-1/2, and 4-1/2 in., respectively).

A "bond strength ratio", which is equal to the ratio of the bond strength of the revibrated bar to the bond strength of the non-revibrated bar of the same type, is used to measure the effects of revibration.

The bond strength ratio is presented as a function of concrete slump for the shallow, bottom-cast, shallow, top-cast and deep, top-cast bars in Fig. 13, 14 and 15, respectively. The bond strength ratio is presented as a function of the amount of concrete below the bars for slumps of 2-3/4, 4-1/2, and 7-1/2 in. in Fig. 16, 17 and 18, respectively.

The figures demonstrate that revibration helped in some cases and hurt in others. With revibration, bond strengths generally remained constant or decreased for the bottom-cast bars, and remained constant or increased for the top-cast bars (Fig. 13-15). The higher the concrete slump, the less deleterious were the effects on bottom-cast bars and the better were the effects on top-cast bars.

When revibrated at 45 minutes, the average bond strengths for the bottom-cast bars (Fig. 13) dropped by 10 and 11% for the low and medium slump concretes, respectively, and increased by 1% for high slump concrete. When revibrated at 90 minutes, the bond strengths dropped by 21, 27 and 10% for the low, medium, and high slump concretes, respectively.

For the shallow, top-cast bars (Fig. 14), the bond strengths increased for revibration at 45 minutes by 7 and 20% for the low and medium slump concrete and decreased by 1% for the high slump concrete. When revibrated at 90 minutes the bond strengths for the corresponding cases increased by 6, 5, and 6%, respectively.

For the deep, top-cast bars (Fig. 15), the bond strengths increased by 6, 7, and 23% when revibrated at 45 minutes for the low, medium, and high slump concretes. When revibrated at 90 minutes, the bond strengths increased by 10 and 23% for the low and high slump concretes, but decreased by 10% for the medium slump concrete. The deviations from the apparent trends are due in part to the variability inherent in bond tests.

Compressive strength: The effects of revibration on compressive strength are summarized in Fig. 8. The compressive strength ratio, the ratio of the strength of the revibrated concrete to the strength of non-revibrated (normally consolidated) concrete, is used to show the relationship between revibrated and non-revibrated concrete strength as a function of concrete slump.

Overall, the compressive strengths of revibrated concrete increased from 1.5 to 10%. Low slump concrete increased in strength by 4 and 8% when revibrated at 45 and 90 minutes, respectively. The corresponding increases were 2 and 9% for medium slump concrete and 2 and 5% for high slump concrete, respectively. The data do not suggest a clear trend between concrete slump and the effects of revibration on concrete strength. However, it is clear that in every case, revibration at 90 minutes was more beneficial than revibration at 45 minutes.

These results generally agree with the work of Vollick (12). However, it should be noted that, with the exception of Group 1, the cylinders in the current study were initially consolidated by rodding. Also, it is important to keep in mind that the effects within a structure may be quite different than those obtained with reconsolidated cylinders.

Effect of Slump and Bleed on Bond Strength

Earlier work done at the University of Kansas (4, 5) showed a definite correlation between bleed and slump. A similar correlation was found in this study: Bleed increased as the concrete slump increased (Fig. 19 and 20). The earlier also work suggested that the trends of decreased bond with increased slump in top-cast bars may be trends of decreased bond with increased bleed. These trends are not very clear in this study, because of the scatter in the results (Fig. 21 and 22). Fig. 23 and 24, from which the results from Group 4 were dropped, have less scatter than Fig. 21 and 22. They show similar trends to those suggested in the earlier work (4, 5) for initially vibrated bars. However, they also show that aspects other than bleed clearly play an important and perhaps dominant role in controlling bond strength.

Effect of Bar Position on Bond Strength

Initial vibration: The normalized bond strength in the initially vibrated specimens decreased 14 to 40% as the amount of concrete below the test bar increased from 2 to 8 in., and from 12 to 45% as the concrete below the test bar increased from 2 to 15 in. (Fig. 9-12). These results generally agree with those reported in earlier work (2, 4, 5). The effect of an increase in concrete below the bar from 8 to 15 in. is less clear. The normalized bond strength increased in two cases and decreased in two cases as the amount of concrete below the test bar increased from 8 to 15 in.

According to the ACI 318 (1), "top reinforcement" is defined as "horizontal reinforcement so placed that more than 12 in. of concrete is cast in the member below the reinforcement." The current results, along with those of Brettmann et al. (2), indicate that the decrease in bond strength associated with "top reinforcement" does not require 12 in. of concrete below the reinforcement, if the reinforcement is top-cast.

Revibration: The normalized bond strength in the revibrated specimens decreased less or increased in comparison to the initially vibrated bars as the amount of concrete below the test bars increased (Fig. 9-12). For example, the normalized bond strength in low slump revibrated concrete (Fig. 9) increased as the amount of concrete below the bar increased. This trend is due to the decreases in bond strength of bottom-cast bars and the increases in bond strength of top-cast bars that result from revibration.

The bond strength ratios for revibrated bars were generally less than 1.0 for bottom-cast bars and greater than 1.0 for top-cast bars (Fig. 16-18).

For the revibrated low slump concrete (Fig.16), the decrease in bond strength for the bottom-cast bars was greater than the increase in bond strength for the top-cast bars. For the revibrated high slump concrete (Fig. 18), revibration had little effect on bottom and shallow, top-cast bars, but significantly increased the bond strength of the deep, top-cast bars.

RECOMMENDATIONS AND CONCLUSIONS

The limited scope of this study, coupled with the scatter in some of the data, limit the breadth of the conclusions and recommendations that may be offered. However, a number of points are clear.

Revibration is not universally beneficial to the bond strength of reinforcing steel to concrete. The bond strength in initially well consolidated, low slump concrete may be severely damaged by revibration.

Revibration appears to have the greatest benefit for bars most affected by settlement and bleeding, i.e. top-cast bars placed in high slump concrete. The effect of revibration is to reconsolidate the concrete adjacent to the bars, reducing the voids caused by settlement and bleeding. The bond is, therefore, improved. From a practical point of view, the structures in which revibration appears to have its greatest advantage are least likely to receive proper consolidation at any stage, due to the high slump of the concrete.

Revibration appears to be almost universally detrimental to the bond strength of bottom-cast bars. The later the revibration, the lower the bond strength of these bars. This is likely due to the fact that settlement and bleed improve the consolidation around bottom-cast bars, and revibration only serves to disrupt the concrete.

Overall, revibration tends to reduce the differences in bond strength caused by differences in slump and bar position.

Revibration clearly increased the compressive strength of standard 6 x 12 in. concrete cylinders. However, this consolidation is so different from that received in an actual structure, that strength tests of cores from structural concrete are required before this technique can be recommended as a practical method of increasing concrete strength.

Future Study

The effects of revibration require additional study. As implied above, cores from structural concrete would help to establish the practical effects of revibration on compressive strength. The current study of bond strength should be repeated on a larger scale, with careful control on concrete temperature and the added measurement of the change in concrete workability with time. Finally, the effects of revibration on the bond strength of vertical reinforcement is a completely open topic.

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Table 1. Test Specimen Variables and Bond Forces.

Bar Size = #8
Embedment Length = 10 in.
Cover = 2 in.

Group No.	Specimen and Bar Type*	Concrete Strength psi	Slump in.	Air Content %	Ultimate Load kips	Norm.+ Bond Forces k/in.	Bond Strength Ratio	Concrete Strength Ratio	Total Bleed grams 120 min.
1	1A	3910	2-3/4	4.5	44.31	4.48	1.0	1.0	N.A.
	1A45**	4060			40.01	4.05	0.903	1.038	N.A.
	1A90***	4210			34.94	3.53	0.789	1.077	N.A.
	1B	3910			38.02	3.85	1.0	1.0	22.17
	1B45	4060			40.68	4.11	1.07	1.038	12.51
	1B90	4210			40.41	4.09	1.063	1.077	8.36
	1C	3910			39.15	3.96	1.0	1.0	20.67
	1C45	4060			41.42	4.19	1.058	1.038	13.99
	1C90	4210			43.08	4.36	1.100	1.077	9.53
2	2A	3860	7-1/2	5.8	44.42	4.52	1.0	1.0	N.A.
	2A45	3920			45.04	4.59	1.014	1.016	N.A.
	2A90	4050			41.31	4.21	0.938	1.049	N.A.
	2B	3860			31.94	3.25	1.0	1.0	27.75
	2B45	3920			31.60	3.22	0.989	1.016	25.54
	2B90	4050			33.98	3.46	1.064	1.049	20.43
	2C	3860			24.67	2.51	1.0	1.0	28.79
	2C45	3920			30.24	3.08	1.226	1.016	28.59
	2C90	4050			30.30	3.08	1.228	1.049	23.22
3	3A	4060	4-1/2	5.8	41.16	4.09	1.0	1.0	N.A.
	3A45	4120			44.28	4.40	1.076	1.015	N.A.
	3A90	4390			28.32	2.81	0.688	1.081	N.A.
	3B	4060			24.73	2.46	1.0	1.0	27.06
	3B45	4120			29.38	2.92	1.188	1.015	20.57
	3B90	4390			29.06	2.88	1.175	1.081	15.43

					29.38	2.92	1.188	1.015	20.57
	3B90	4390			29.06	2.88	1.175	1.081	15.43

Table 1. Test Specimen Variables and Bond Forces (continued)

Group No.	Specimen and Bar Type*	Concrete Strength psi	Slump in.	Air Content %	Ultimate Load kips	Norm.+ Bond Forces k/in.	Bond Strength Ratio	Concrete Strength Ratio	Total Bleed grams 120 min.
3	3C	4060	4-1/2	5.8	27.14	2.69	1.0	1.0	28.03
	3C45	4120			30.23	3.00	1.114	1.015	23.54
	3C90	4390			25.82	2.56	0.951	1.081	16.51
4	4A	4360	4-1/2	4.5	40.40	3.87	1.0	1.0	N.A.
	4A45	4440			28.22	2.70	0.699	1.018	N.A.
	4A90	4800			30.78	2.95	0.762	1.101	N.A.
	4B	4360			34.46	3.30	1.0	1.0	19.75
	4B45	4440			42.04	4.03	1.220	1.018	11.87
	4B90	4800			31.56	3.02	0.916	1.101	8.07
	4C	4360			32.22	3.09	1.0	1.0	21.71
	4C45	4440			39.32	3.77	1.220	1.018	13.44
	4C90	4800			27.42	2.63	0.851	1.101	9.00

* A = Shallow, Bottom-Cast-Bar Specimens, with 2 in. concrete below bars
B = Shallow, Top-Cast-Bar Specimens, with 8 in. concrete below bars
C = Deep, Top-Cast-Bar Specimens, with 15 in. concrete below bars

** 45 = Revibration after 45 minutes

*** 90 = Revibration after 90 minutes

+ Norm. Bond Forces = $\frac{\text{Ultimate Load}}{10}\left(\frac{4000}{fc'}\right)^{1/2}$

Table 2. Concrete Mix Designs and Properties
(Cubic Yard Batch Weights)

				Aggregate		Concrete			
Group No.	W/C Ratio	Cement #	Water #	Fine+ #	Coarse* #	Temp °F	Slump in.	Air %	Strength** psi
1	0.46	510	235	1511	1544	80	2-3/4	4.5	3910
2	0.46	590	272	1348	1544	67	7-1/2	5.8	3860
3	0.46	550	253	1432	1544	61	4-1/2	5.8	4060
4	0.46	550	253	1432	1544	78	4-1/2	4.5	4360

+ Kansas River Sand - Lawrence Sand Company, Lawrence, KS
Bulk Specific Gravity (SSD) = 2.62, Absorption = 0.5%,
Fineness Modulus = 3.0 to 3.17

* Crushed Limestone - Hamms Quarry, Perry, KS
Bulk Specific Gravity (SSD) = 2.52, Absorption = 3.5%,
Nominal Maximum Size = 3/4 inch

** Concrete Strength based on Non-Revibrated Concrete

Design Air Content = 6%
Air Entraining Agent --- Vinsol resin

Slump and Air Values are as Measured

Table 3. Average Test Bar Data

Bar Size	#8
Deformation Spacing, in.	0.545
Deformation Height, in.	0.057
Deformation Angle, deg.	50
Deformation Gap, in.	0.313
Nominal Weight, lb/ft	2.650
Deformation Bearing Area, sq.in./in. length	0.239
Yield Strength, ksi	63.47
Tensile Strength, ksi	104.6

trength** psi
3910
3860
4060
4360

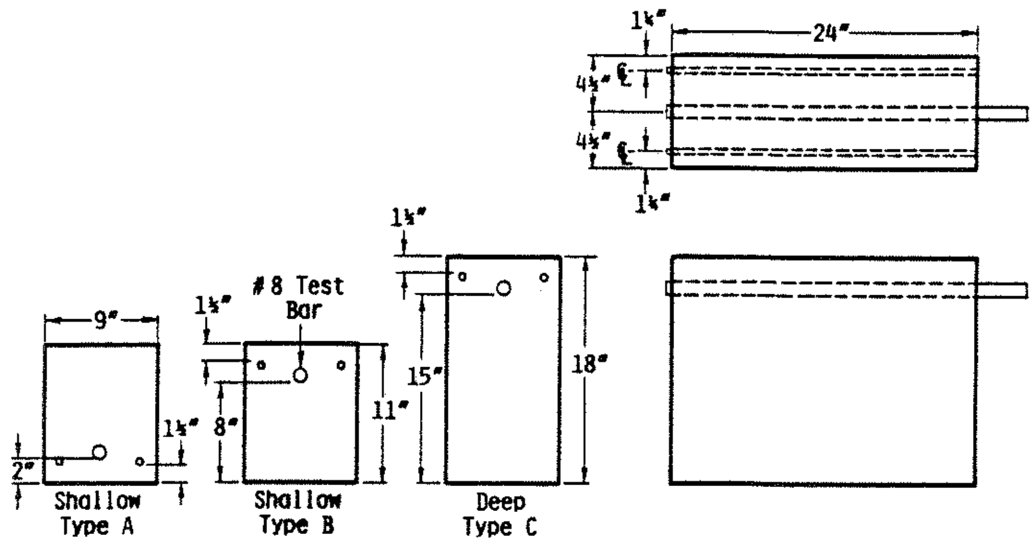

Fig. 1 Test Specimens

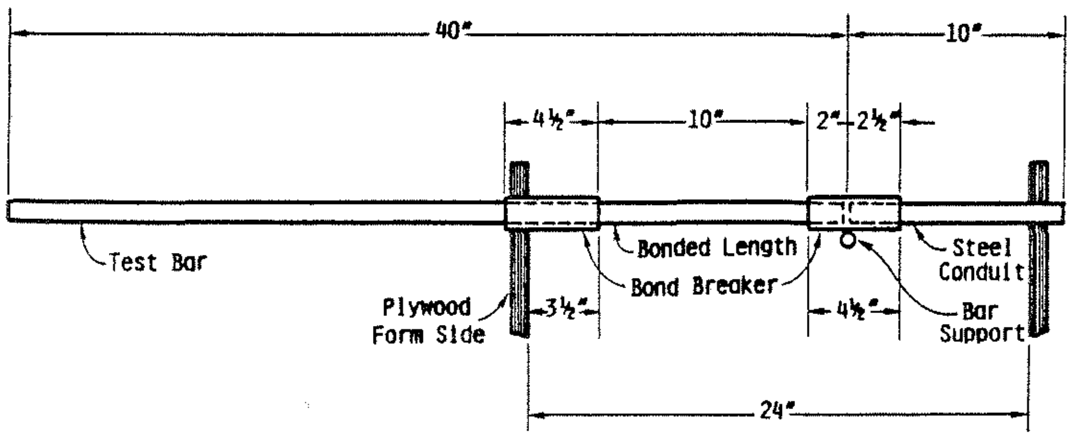

Fig. 2 Test Bar Installation

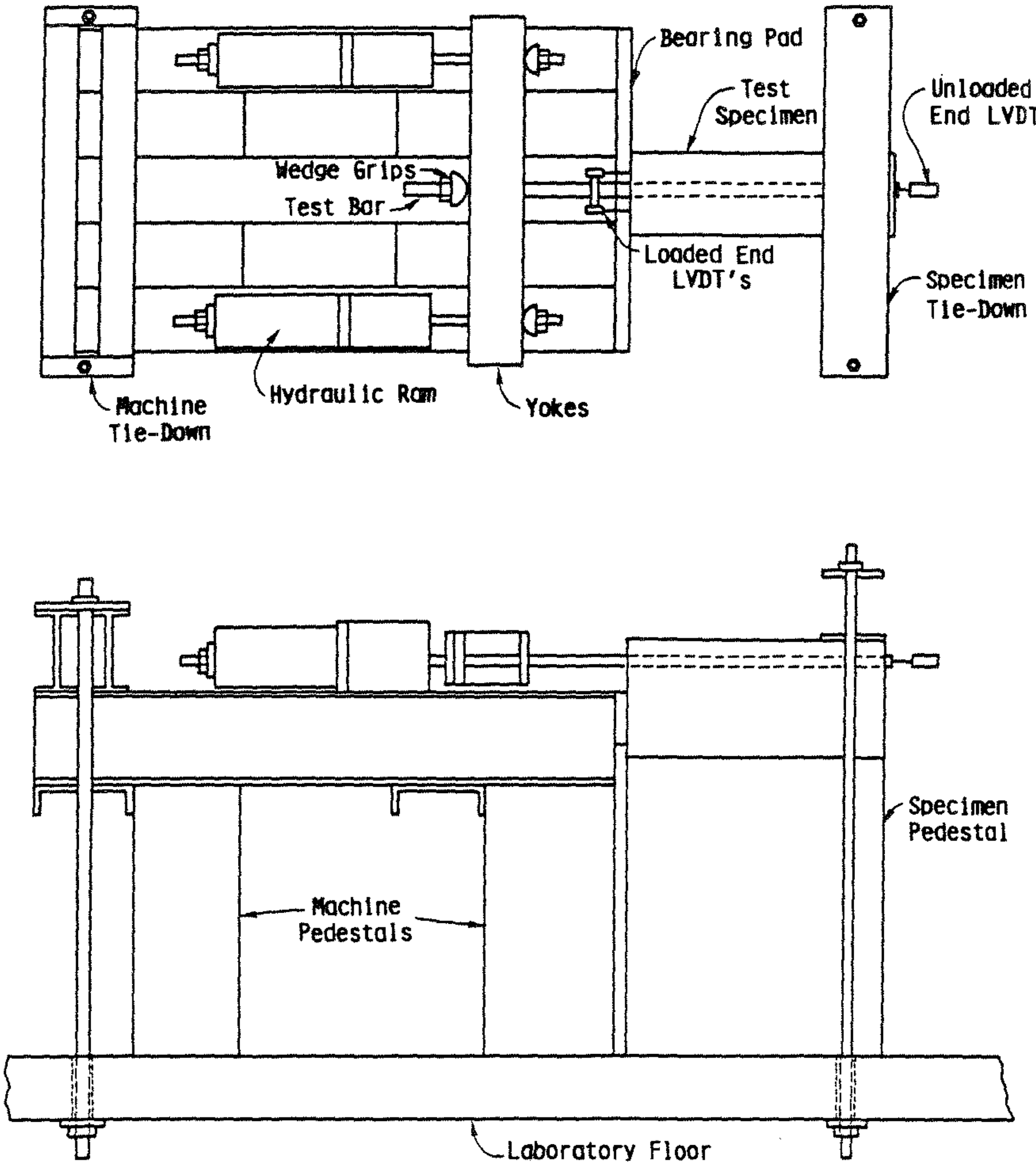

Fig. 3 Schematic of Bond Test

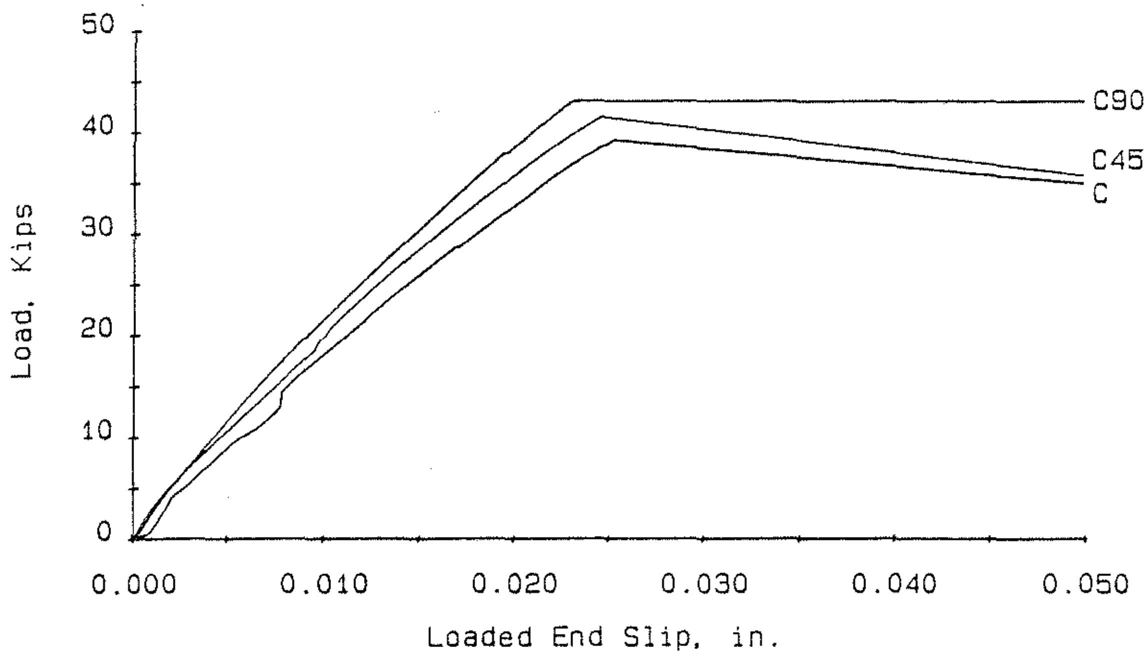

Fig. 4 Typical Load versus Loaded End Slip Curves

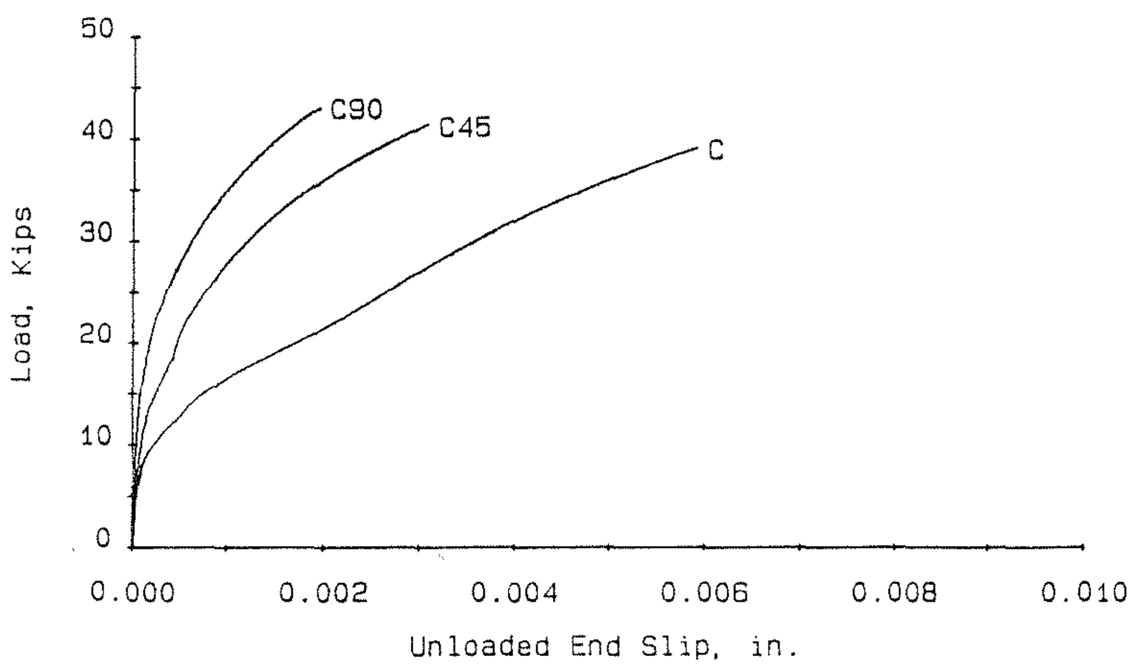

Fig. 5 Typical Load versus Unloaded End Slip Curves

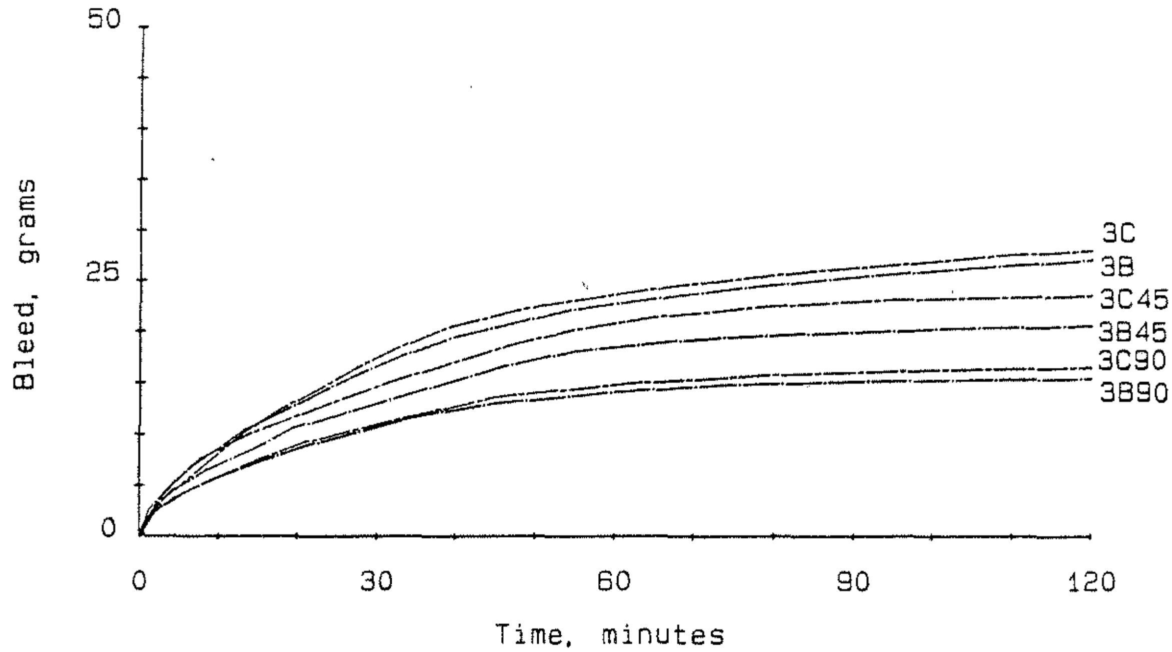

Fig. 6 Typical Bleed versus Time Curves

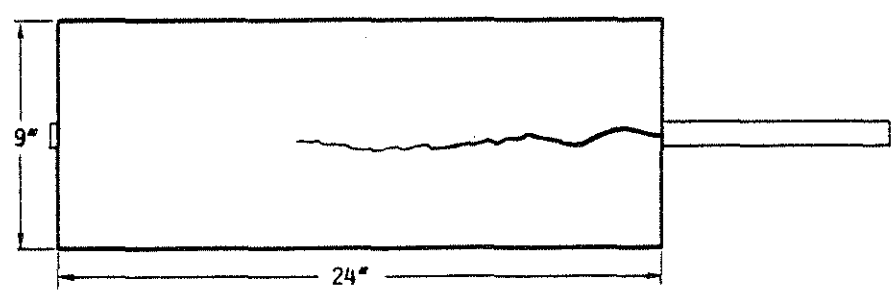

Fig. 7 Test Specimen After Pullout, Top View

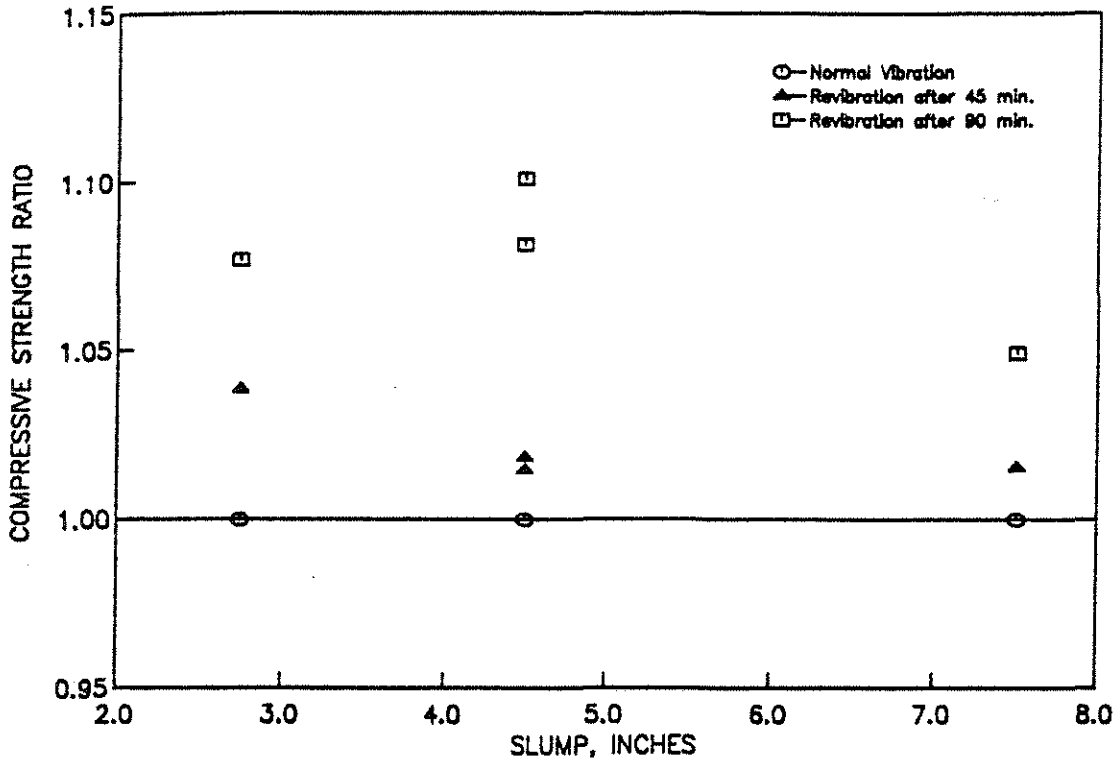

Fig. 8 Concrete Compressive Strength Ratio versus Slump

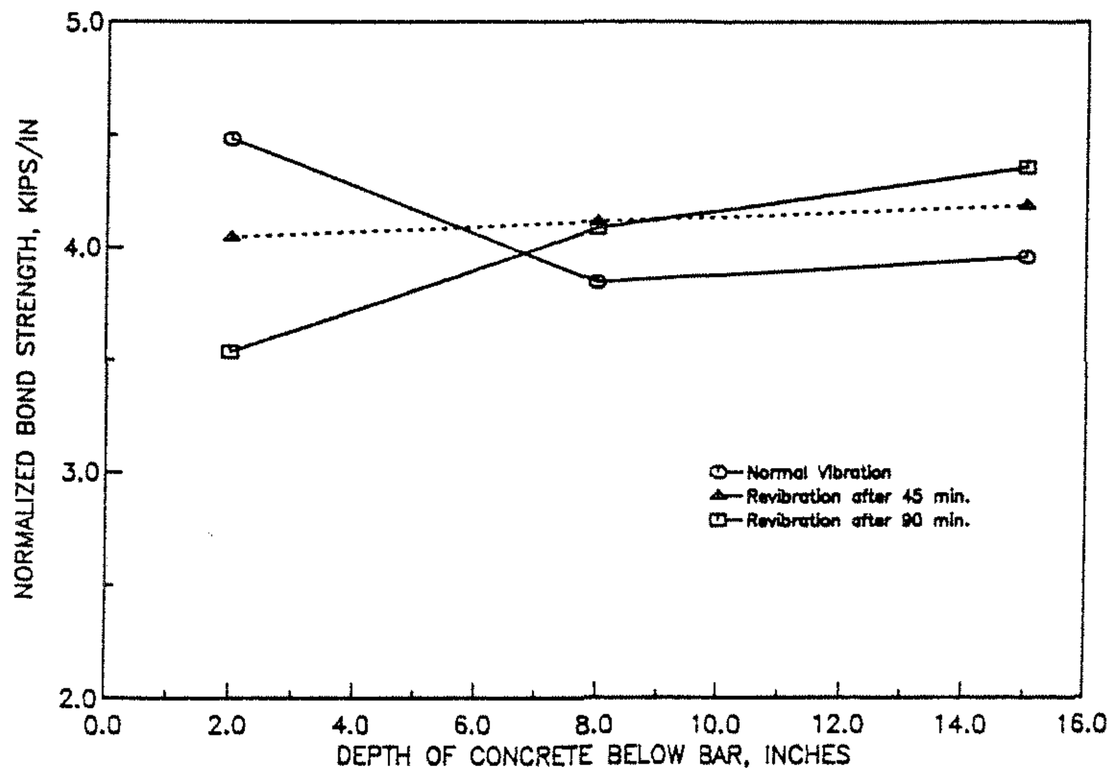

Fig. 9 Normalized Bond Strength versus Depth of Concrete Below Bar for 2-3/4 in. Slump Concrete

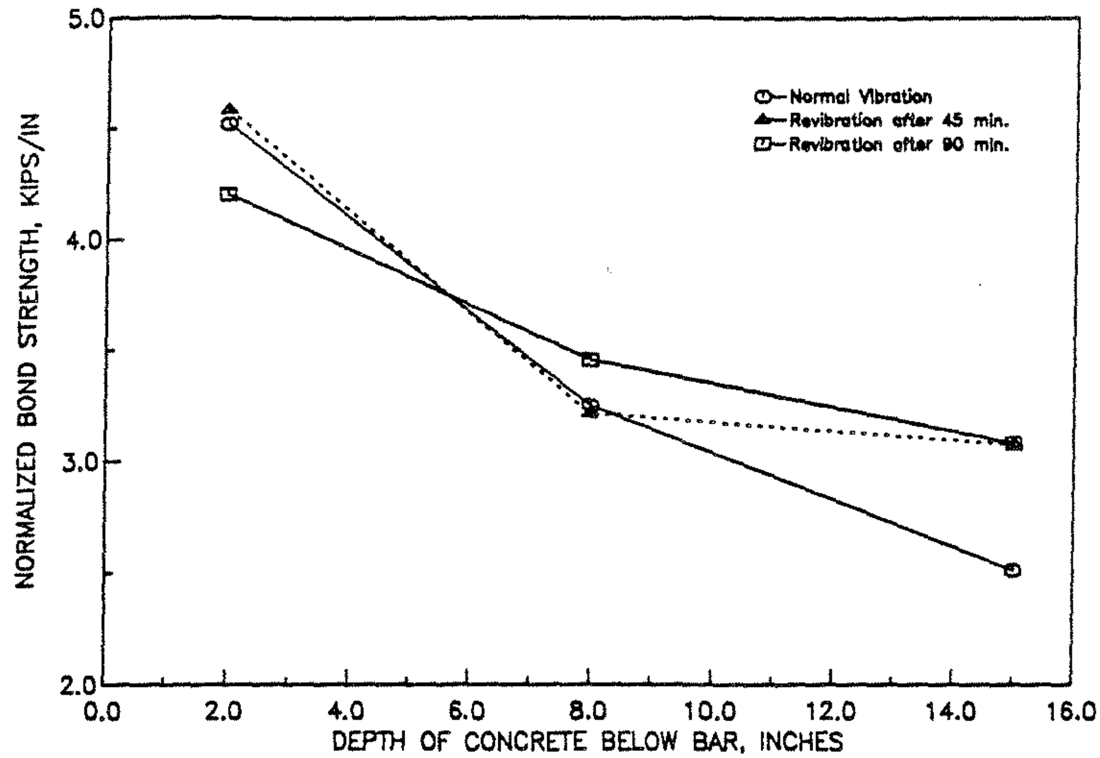

Fig. 10 Normalized Bond Strength versus Depth of Concrete Below Bar for 7-1/2 in. Slump Concrete

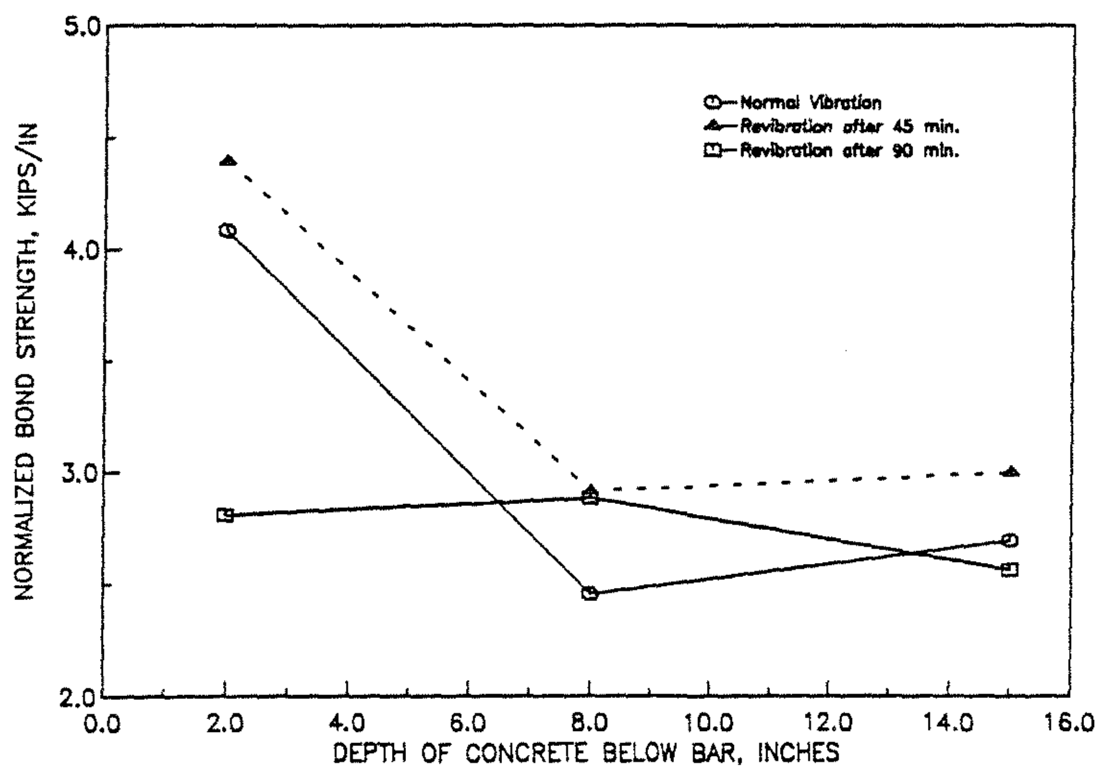

Fig. 11 Normalized Bond Strength versus Depth of Concrete Below Bar for 4-1/2 in. Slump Concrete (Group 3)

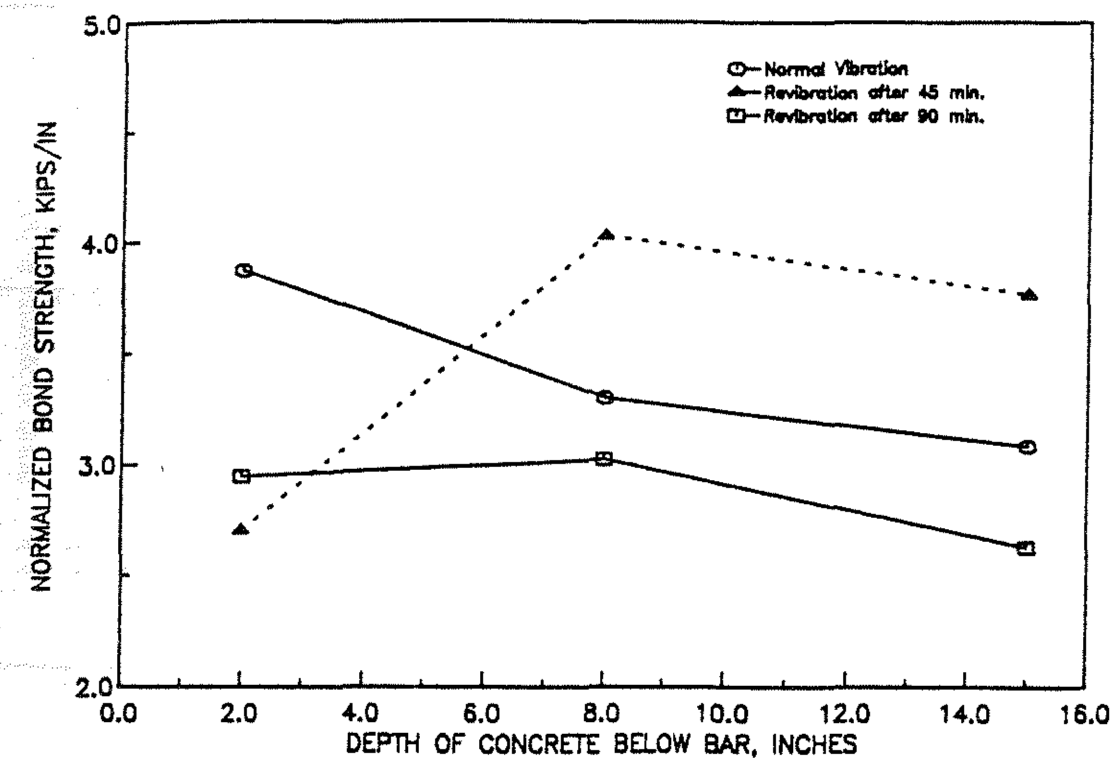

Fig. 12 Normalized Bond Strength versus Depth of Concrete Below Bar for 4-1/2 in. Slump Concrete (Group 4)

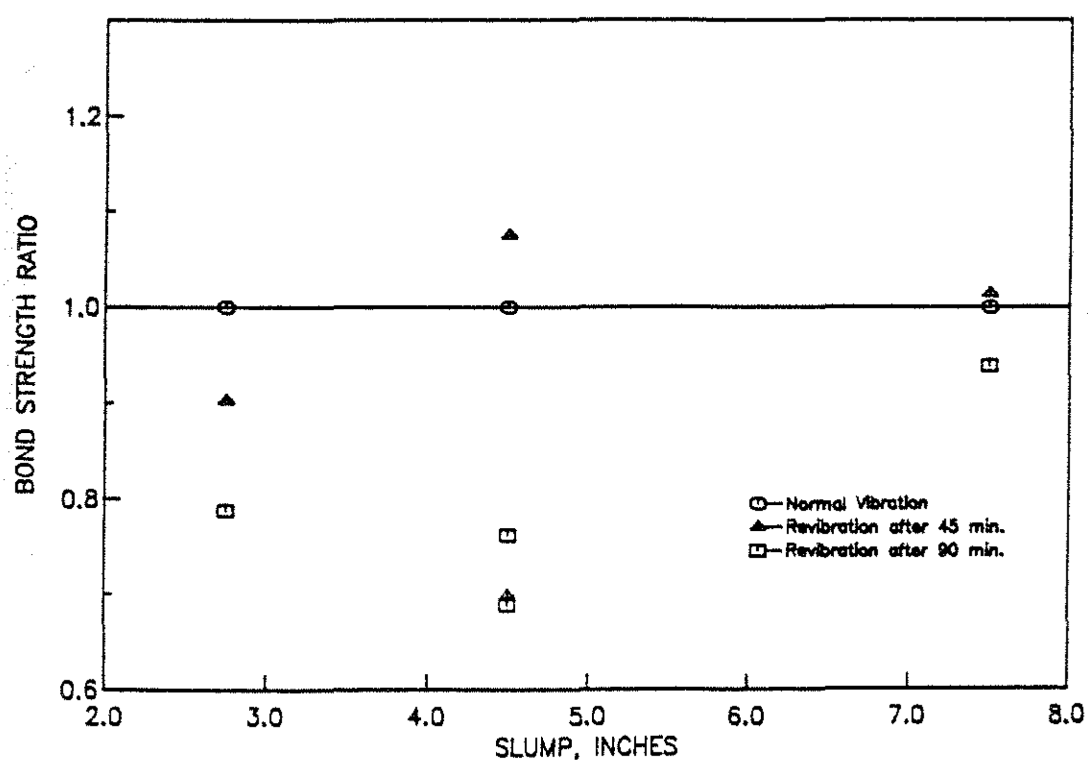

Fig. 13 Bond Strength Ratio versus Slump for Shallow Bottom-Cast Bars

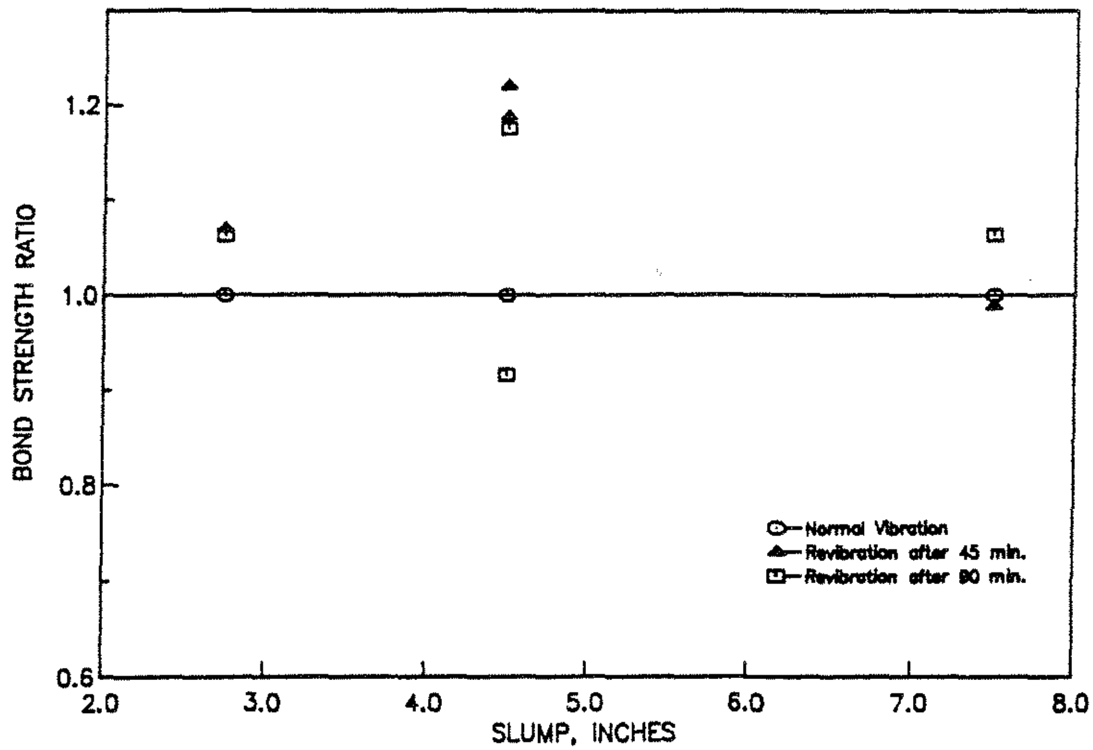

Fig. 14 Bond Strength Ratio versus Slump for Shallow Top-Cast Bars

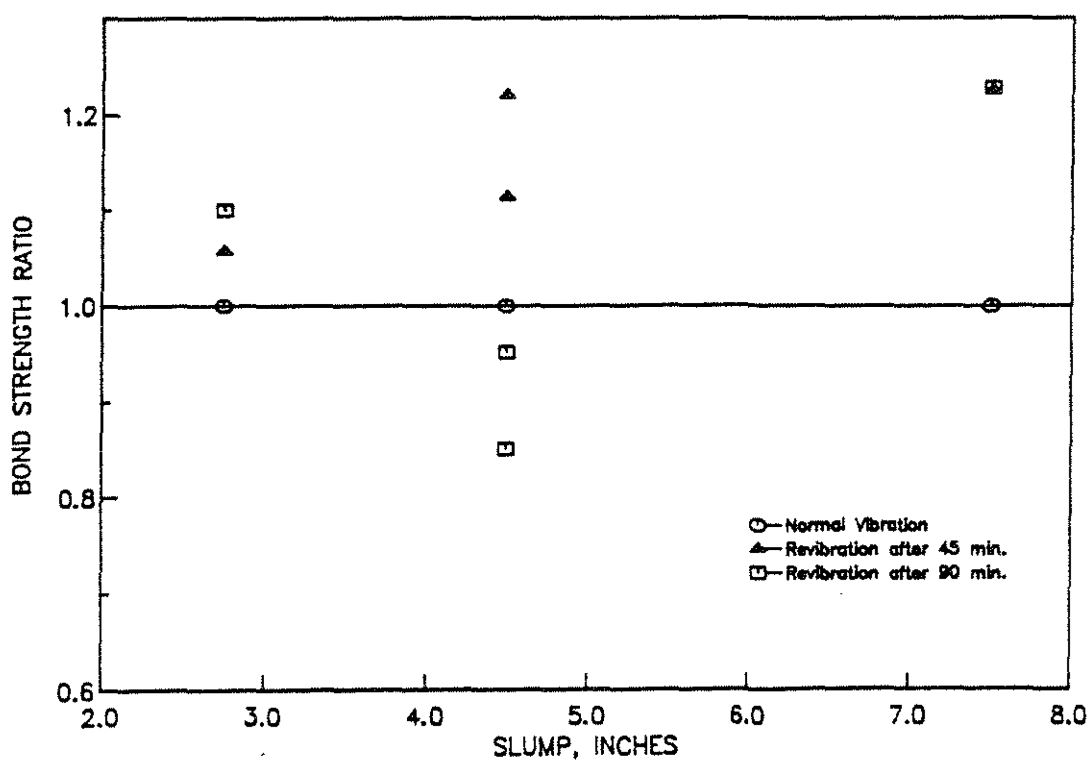

Fig. 15 Bond Strength Ratio versus Slump for Deep Top-Cast Bars

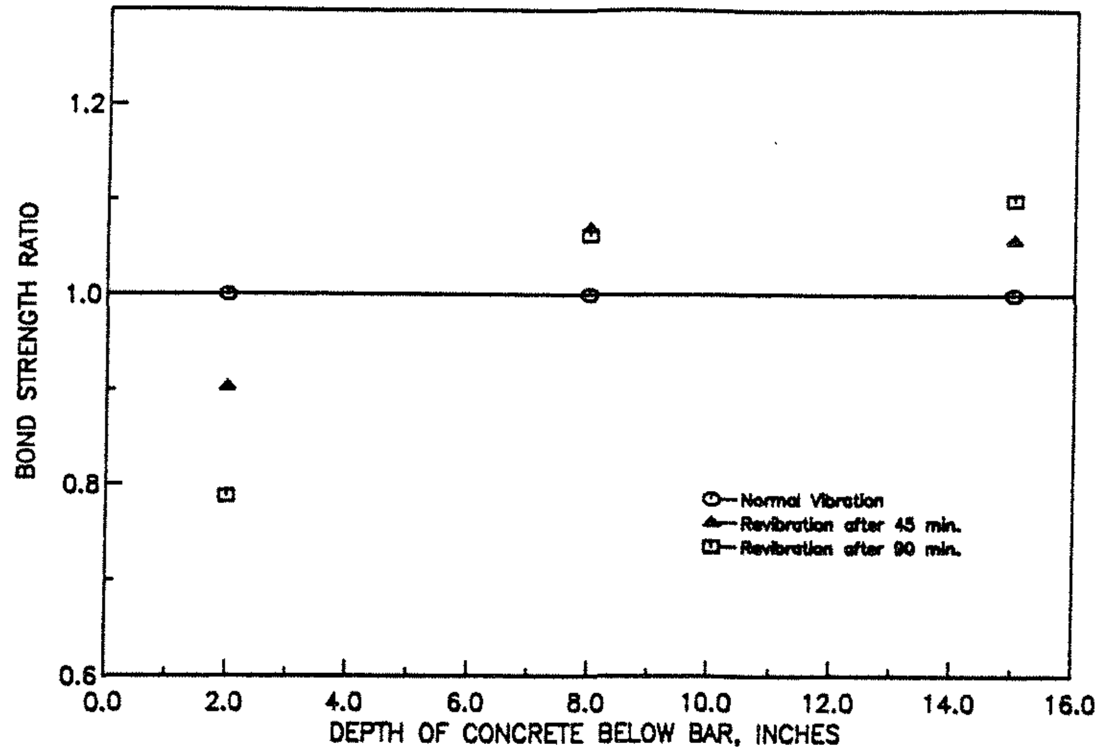

Fig. 16 Bond Strength Ratio versus Depth of Concrete Below Bar for 2-3/4 in. Slump Concrete

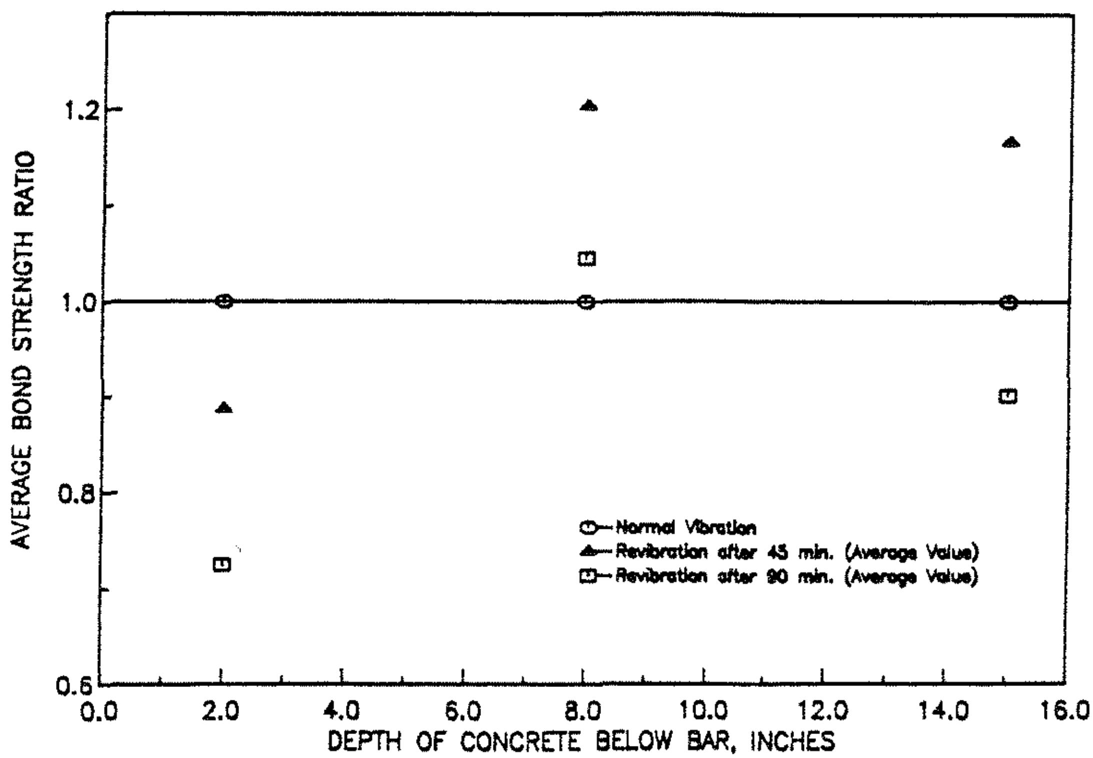

Fig. 17 Average Bond Strength Ratio versus Depth of Concrete Below Bar for 4-1/2 in. Slump Concrete

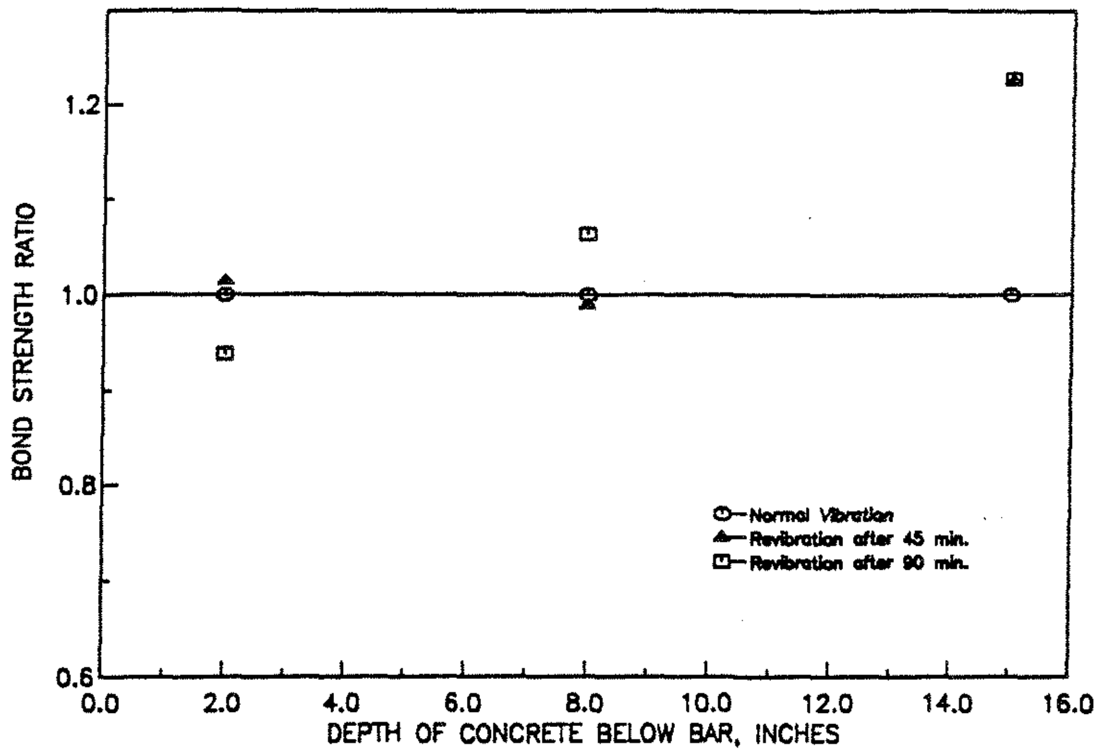

Fig. 18 Bond Strength Ratio versus Depth of Concrete Below Bar for 7-1/2 in. Slump Concrete

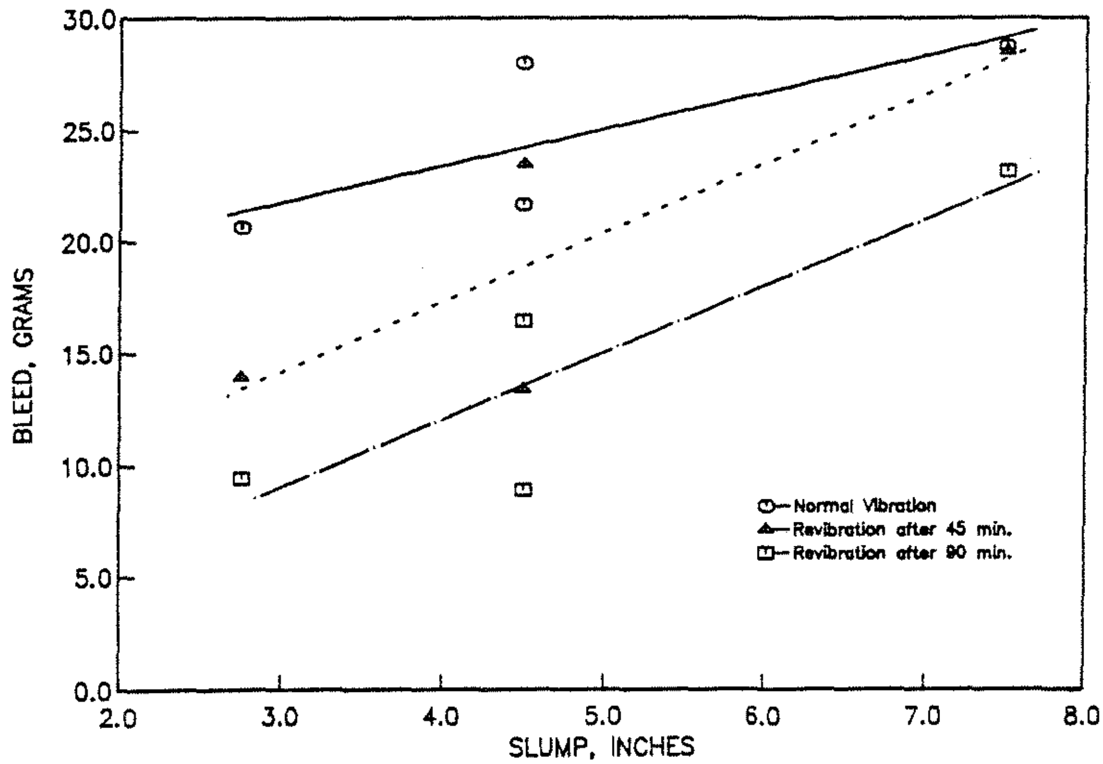

Fig. 19 Bleed versus Slump for Deep Specimens

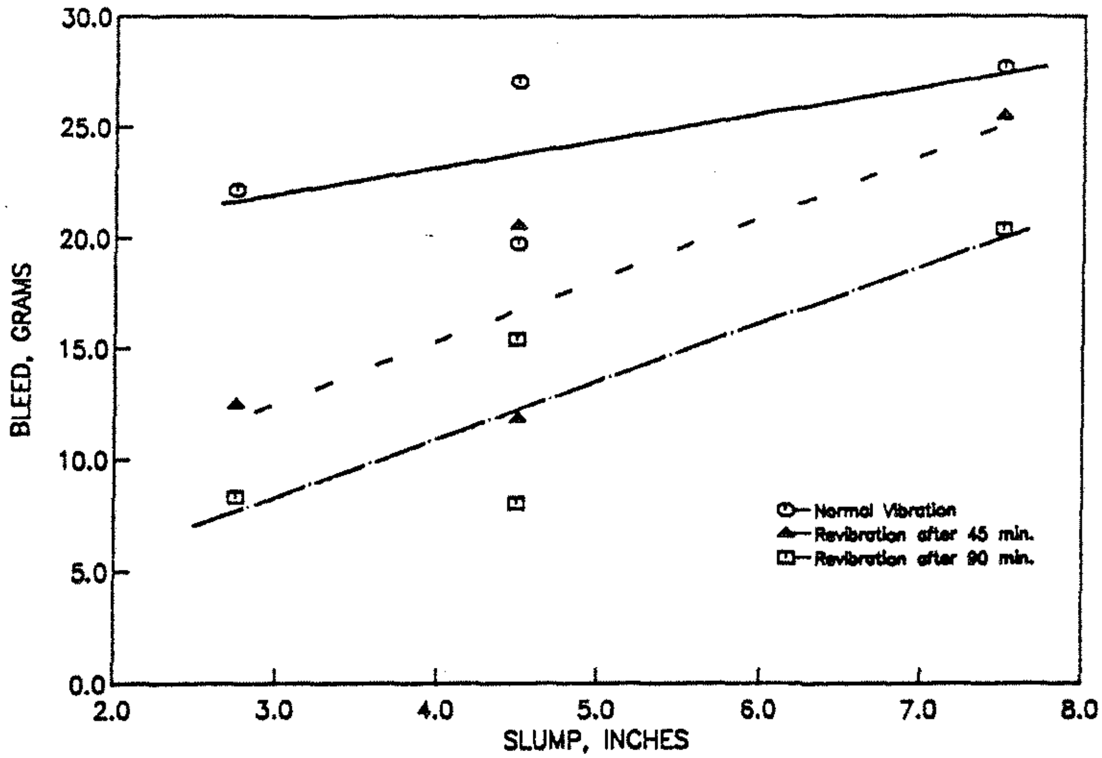

Fig. 20 Bleed versus Slump for Shallow Specimens

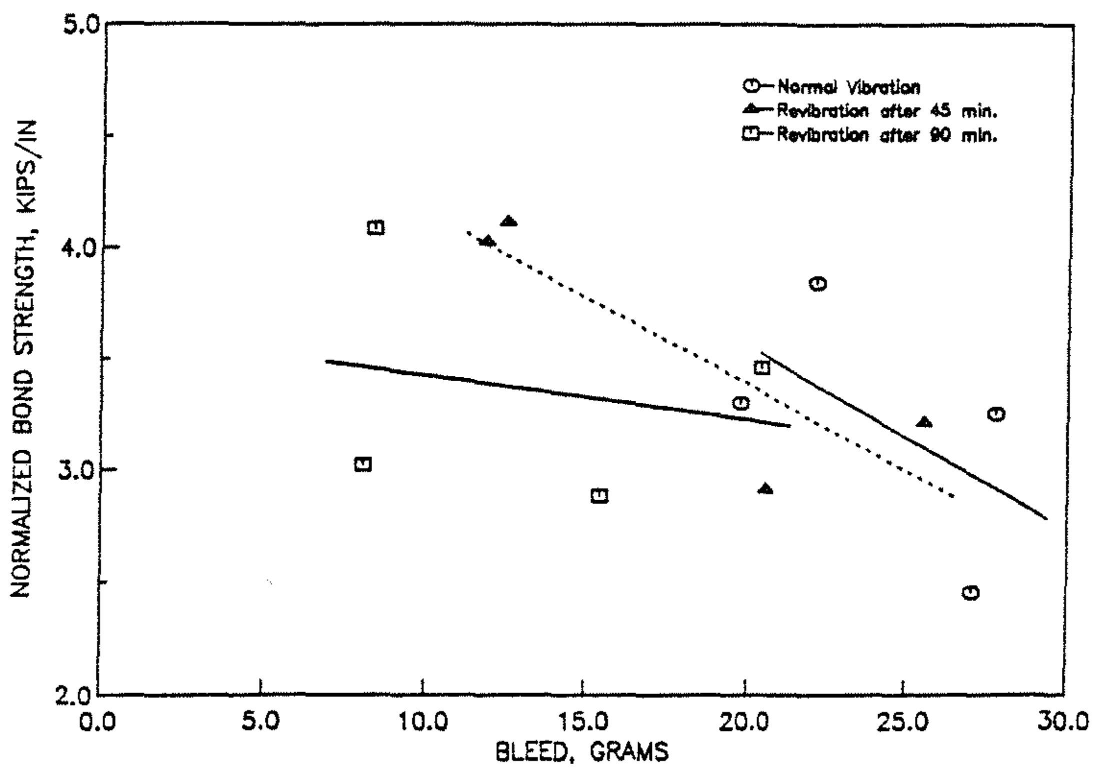

Fig. 21 Normalized Bond Strength versus Bleed for Shallow Top-Cast Bars

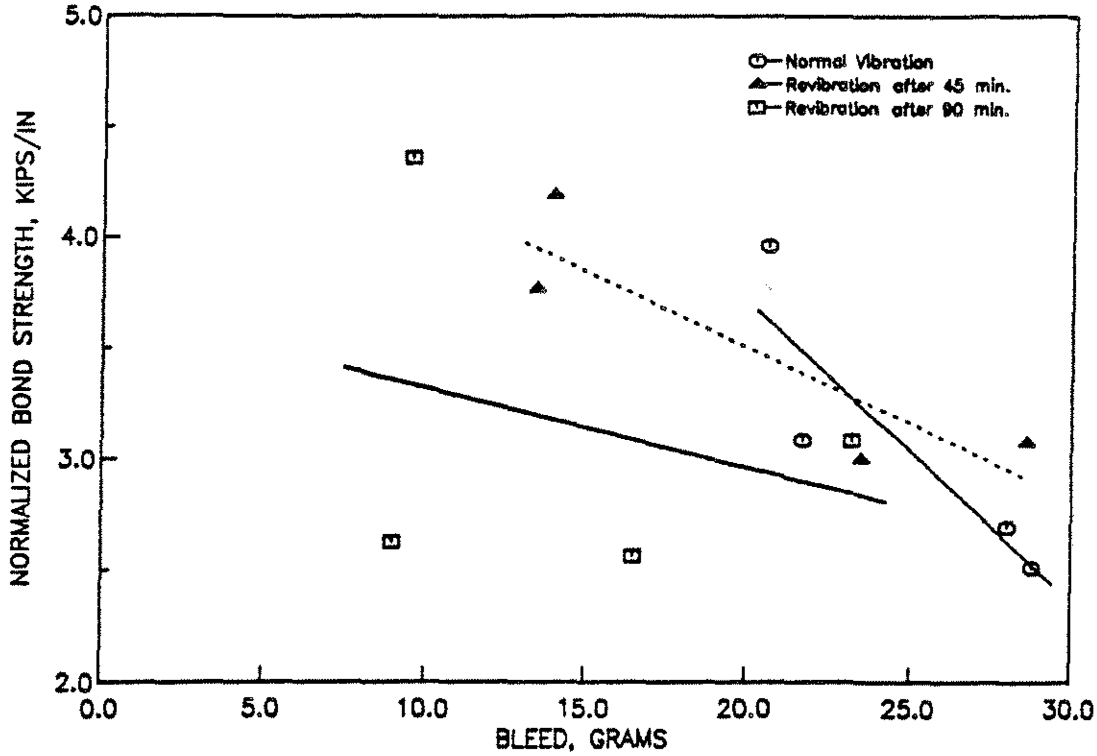

Fig. 22 Normalized Bond Strength versus Bleed for Deep Top-Cast Bars

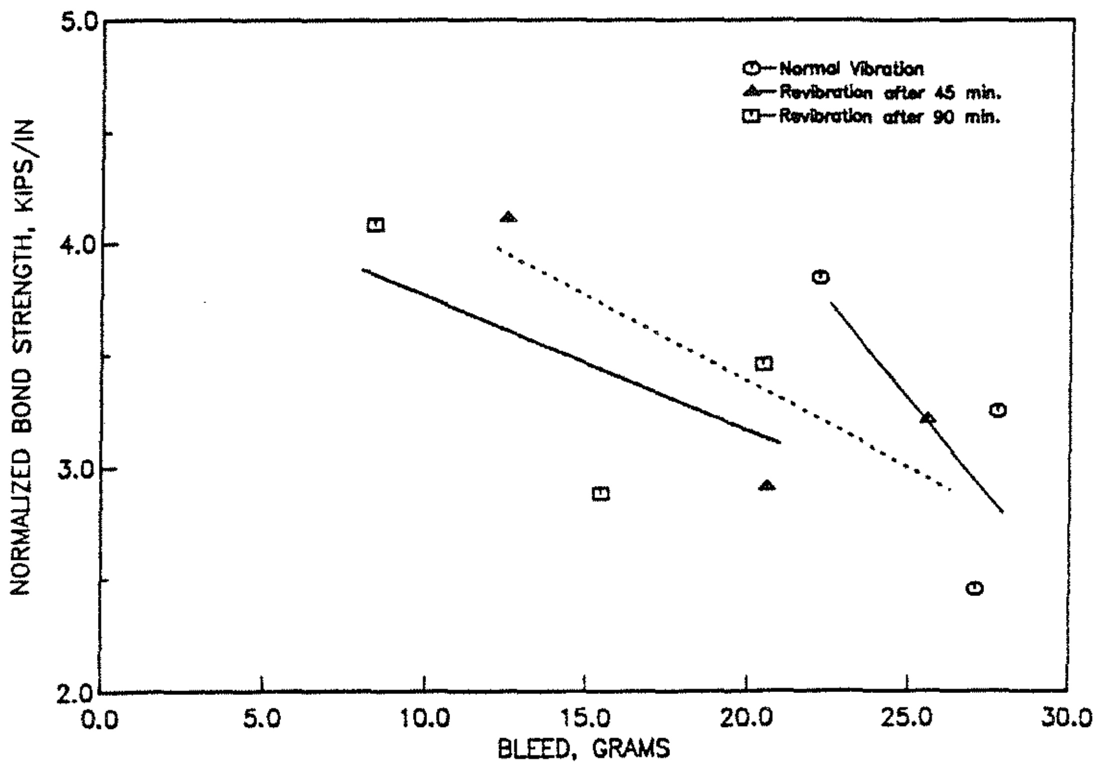

Fig. 23 Normalized Bond Strength versus Bleed for Shallow Top-Cast Bars (Group 4 Data Removed)

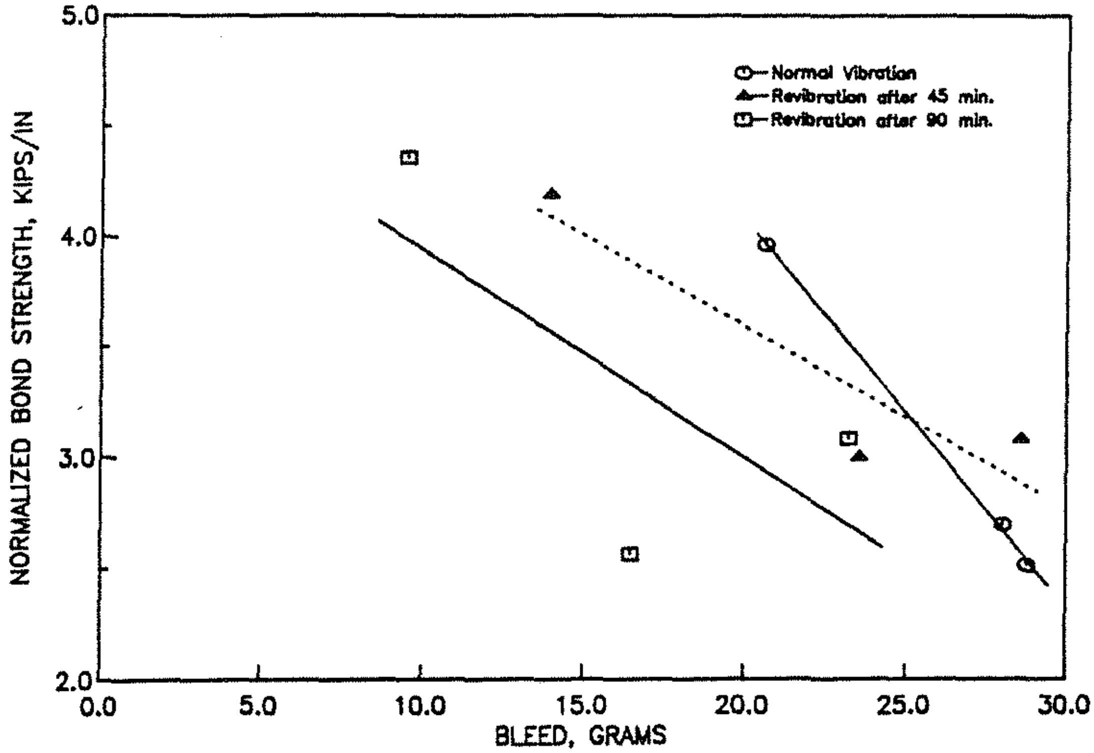

Fig. 24 Normalized Bond Strength versus Bleed for Deep Top-Cast Bars (Group 4 Data Removed)