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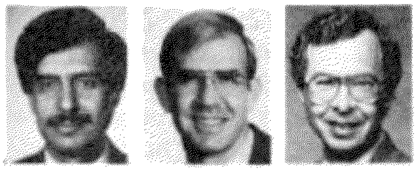
Bond of Reinforcement to Revibrated Concrete



by Wisam A. K. Altowaiji, David Darwin, and Rex C. Donahey

The effects of revibration on concrete-steel bond strength are studied. Key variables are concrete slump, bar position, and the time interval between initial vibration and revibration. No. 8 (25 mm) deformed reinforcing bars were used with a 2 in. (51 mm) cover and a 10 in. (254 mm) bonded length. Concrete slumps ranged from 2¾ to 7½ in. (70 to 190 mm). 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.

Keywords: bond (concrete to reinforcement); concrete construction; consolidation; cover; **reinforced concrete**; reinforcing steels; **revibration**; **vibration**; workability.

It is well known that vibration of concrete 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.[1,2] 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.[2-4]

Vollick[4] found that internal revibration provided increases in the 28-day compressive strength of concrete ranging from 6.9 to 18.7 percent, depending on the concrete mixes. He did not study the effects of revibration on bond strength. Larnach[3] 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 percent for revibration after one half hour to 33 percent at 3 hours. He obtained corresponding reductions in compressive strength of 14 and 16 percent.

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.[2] 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 percent.

Davis, Brown, and Kelly[1] 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 different ways. Increases in ultimate bond strength of up to 62 percent 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 nonvibrated concrete. This work on the effects of delayed vibration has been incorrectly referenced in other papers as evidence of the positive effects of revibration.[5,6] However, since the specimens used by Davis et al. were not initially vibrated, the positive effect can only be attributed to delayed vibration.[7]

Recent work by Harsh and Darwin[8] 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 to 4 in. and decreased for concretes with slumps above 3 to 4 in.

The previous studies[2-4] on revibration are in conflict. Many engineers think that once concrete has been vibrated, it should not be disturbed. However, some engineers argue that revibration will improve, not diminish, concrete quality.[5-6]

This paper presents the results of a study of the effects of revibration.[9] The study considers the effect of revibration on the bond strength between concrete and horizontal deformed bars as a function of concrete slump, bar position, and the time interval between initial vibration and revibration. The paper also considers

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the effects of revibration on the compressive strength of standard 6 by 12 in. concrete cylinders. Recommendations are made.

RESEARCH SIGNIFICANCE

In the field of concrete construction, it is not uncommon to hear that revibration will improve the properties of concrete. Typically one is advised to revibrate as late as possible, as long as the vibrator can penetrate the concrete under its own weight. This study demonstrates that depending on concrete slump and bar placement, revibration can severely damage the bond between concrete and reinforcing steel.

EXPERIMENTAL INVESTIGATION

Test specimens

Three specimen types (Fig. 1) were used to study the effect of revibration on bond strength: 9 by 11 by 24 in. (229 by 279 by 610 mm) shallow, bottom-cast bar specimens, with 2 in. (51 mm) of concrete below the bottom of the bar; 9 by 11 by 24 in. (229 by 279 by 610 mm) shallow, top-cast bar specimens, with 8 in. (203 mm) of concrete below the bottom of the bar; and 9 by 18 by 24 in. (229 by 457 by 610 mm) deep, top-cast bar specimens, with 15 in. (381 mm) 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. (1016-mm) long, #8 (25 mm) deformed bars (Fig. 2). Two 4½-in. (114-mm) long, 1-in. (25-mm) diameter polyvinyl chloride (PVC) pipes were used as bond breakers to limit the bonded length and to provide coupling with a 10-in. (254-mm) long, 1-in. (25-mm) 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[7,10,11] and on preliminary tests in this study, a 2-in. (51-mm) concrete cover and 10-in. (254-mm) embedment length were used to insure a splitting failure during the pullout tests.

Two #5 (16 mm) 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 (16-mm) 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.

Material properties

Concrete: Air-entrained concrete was supplied by a local ready-mix plant. Type I portland cement and ¾-in. (19-mm) 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 percent. Mix designs, aggregate properties, and concrete properties are summarized in Table 1.

Steel: ASTM A 615, Grade 60 #8 (25-mm) reinforcing bars were used for all tests. Deformation dimensions, bearing areas, and steel strengths are presented in Table 2.

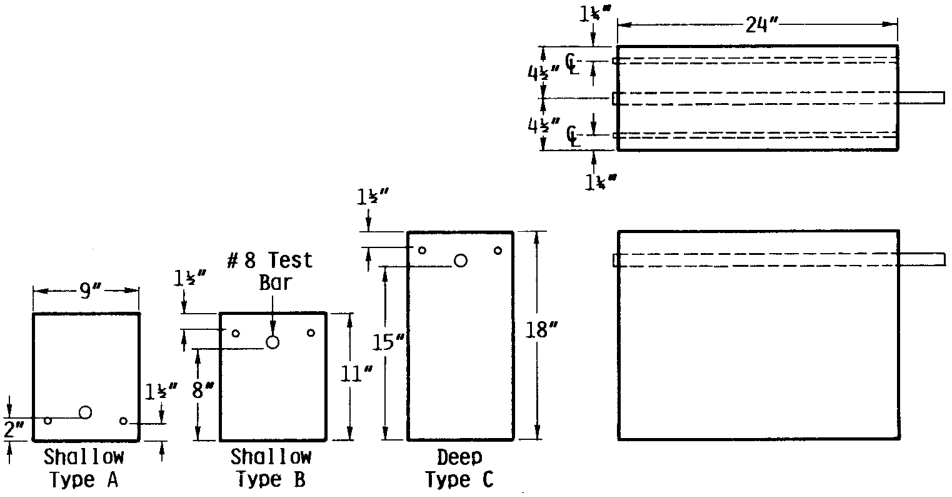

Fig. 1—Test specimens (1 in. = 25.4 mm)

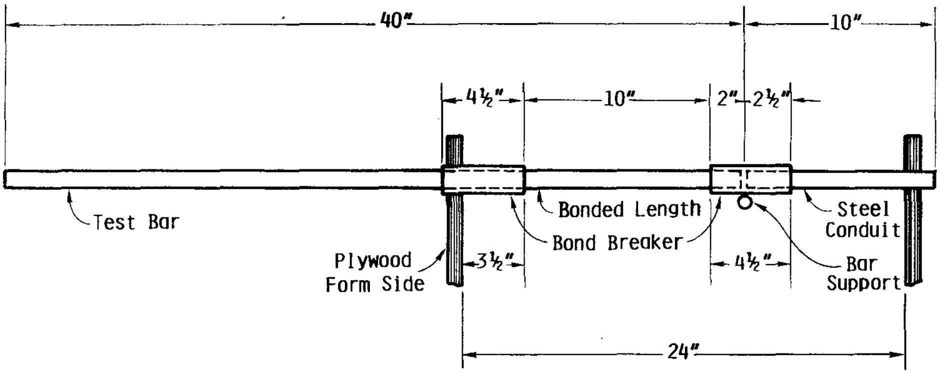

Fig. 2—Test bar installation (1 in. = 25.4 mm)

Table 1 — Concrete mix proportions and properties (cubic yard batch weights)

Group number	Water-cement ratio	Cement, lb	Water, lb	Aggregate		Concrete			
				Fine,* lb	Coarse,† lb	Temperature, F (C)	Slump, in.	Air, percent	Strength,‡ psi
1	0.46	510	235	1511	1544	80(27)	2¾	4.5	3910
2	0.46	590	272	1348	1544	67(19)	7½	5.8	3860
3	0.46	550	253	1432	1544	61(16)	4½	5.8	4060
4	0.46	550	253	1432	1544	78(26)	4½	4.5	4360

*Kansas River sand, bulk specific gravity (SSD) = 2.62; Absorption = 0.5 percent, Fineness Modulus = 3.0 to 3.17.
†Crushed limestone, bulk specific gravity (SSD) = 2.52; Absorption = 3.5 percent; Nominal Maximum Size = ¾ in.
‡Concrete strength based on non-revibrated concrete.
Design air content = 6 percent; air entraining agent, Vinsol resin.
1 lb/yd^3 = 0.5933 kg/m^3; 1 in. = 25.4 mm; 1 psi = 6.895 kPa.

Table 2 — 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, in.^{2}/in. length	0.239
Yield strength, ksi	63.47
Tensile strength, ksi	104.6

1 in. = 25.4 mm; 1 lb/ft = 1.488 kg/m; 1 ksi = 6.895 MPa.

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 to 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 by 12 in. (152 by 305 mm) cylinders were cast in steel molds. All cylinders were consolidated by rodding; six were finished and six were left with a 1-in. (25-mm) surcharge.

Forty-five minutes after initial vibration, one of the two remaining bond specimens of each type was revibrated, screeded, and finished. Three of the unfinished cylinders were reconsolidated using a 1⅛-in. (29-mm) diameter laboratory vibrator.

Ninety minutes after initial vibration, the remaining bond specimen of each type was revibrated, screeded, and finished. 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.

The specimens and the cylinders were covered with polyethylene and kept moist until a strength of about 3300 psi (22.8 MPa) 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 (27.6 MPa).

Consolidation procedure

The bond test specimens were consolidated using a 1½-in. (38-mm), 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 to 7 seconds for the shallow specimens and 8 to 12 seconds for the deep specimens, while revibration at 45 minutes required 8 to 12 seconds and 15 to 20 seconds for the shallow and deep specimens, respectively. Revibration at 90 minutes required 14 to 25 seconds and 20 to 40 seconds for the shallow and deep specimens, respectively.

Test procedure

The specimens were tested as modified cantilever beams using the pullout apparatus developed by Donahey and Darwin.[7,10]

All specimens from a group were tested within a 6-hour period. The bars were loaded at 5 to 6 kips (22 to 27 kN) per minute. Load, loaded-end slip, and unloaded-end slip were recorded during the tests. Three or more cylinders for each type of vibration/revibration

Table 3 — Test specimen variables and bond forces

Group number	Specimen and bar type*	Concrete strength, psi	Slump, in.	Ultimate load, kips	Norm.[§] bond forces, kips/in.	Bond strength, ratio	Concrete strength, ratio
1	1A	3910	2¼	44.31	4.48	1.0	1.0
	1A45[†]	4060		40.01	4.05	0.903	1.038
	1A90[‡]	4210		34.94	3.53	0.789	1.077
	1B	3910		38.02	3.85	1.0	1.0
	1B45	4060		40.68	4.11	1.07	1.038
	1B90	4210		40.41	4.09	1.063	1.077
	1C	3910		39.15	3.96	1.0	1.0
	1C45	4060		41.42	4.19	1.058	1.038
	1C90	4210		43.08	4.36	1.100	1.077
2	2A	3860	7½	44.42	4.52	1.0	1.0
	2A45	3920		45.04	4.59	1.014	1.016
	2A90	4050		41.31	4.21	0.938	1.049
	2B	3860		31.94	3.25	1.0	1.0
	2B45	3920		31.60	3.22	0.989	1.016
	2B90	4050		33.98	3.46	1.064	1.049
	2C	3860		24.67	2.51	1.0	1.0
	2C45	3920		30.24	3.08	1.226	1.016
	2C90	4050		30.30	3.08	1.228	1.049
3	3A	4060	4½	41.16	4.09	1.0	1.0
	3A45	4120		44.28	4.40	1.076	1.015
	3A90	4390		28.32	2.81	0.688	1.081
	3B	4060		24.73	2.46	1.0	1.0
	3B45	4120		29.38	2.92	1.188	1.015
	3B90	4390		29.06	2.88	1.175	1.081
	3C	4060		27.14	2.69	1.0	1.0
	3C45	4120		30.23	3.00	1.114	1.015
	3C90	4390		25.82	2.56	0.951	1.081
4	4A	4360	4½	40.40	3.87	1.0	1.0
	4A45	4440		28.22	2.70	0.699	1.018
	4A90	4800		30.78	2.95	0.762	1.101
	4B	4360		34.46	3.30	1.0	1.0
	4B45	4440		42.04	4.03	1.220	1.018
	4B90	4800		31.56	3.02	0.916	1.101
	4C	4360		32.22	3.09	1.0	1.0
	4C45	4440		39.32	3.77	1.220	1.018
	4C90	4800		27.42	2.63	0.851	1.101

Bar size = #8; embedment length = 10 in.; cover = 2 in.

*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.

[§] Normalized Bond Forces $= \frac{\text{Ultimate Load}}{10}\left(\frac{4000}{f'_c}\right)^{1/2}$

1 in. = 25.4 mm; 1 psi = 6.895 kPa; #8 bar = 25 mm; 1 kip/in. = 175 kN/m.

were tested for each group. The cylinders were tested immediately after the pullout tests.

Results and observations

Pretest observations: Differences in concrete temperature had a significant effect on the rate of change of concrete workability. Group 1 [2¾-in. (70-mm) concrete slump, 80 F (27 C) concrete temperature], and Group 4 [4½-in. (114-mm) concrete slump, 78 F (26 C) 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 (19 C) and 61 F (16 C)].

Test results: The test results, including concrete slump, air content, concrete strength, and ultimate load, are summarized in Table 3.

All bond specimens failed in a longitudinal splitting mode, with few or no transverse cracks (Fig. 3). Without exception, revibration improved the compressive strength of the concrete cylinders.

EVALUATION OF EXPERIMENTAL RESULTS

The ultimate loads listed in Table 3 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 (27.6 MPa), 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 3.

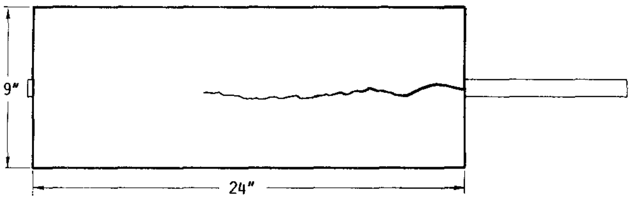

Fig. 3—Test specimen after pullout

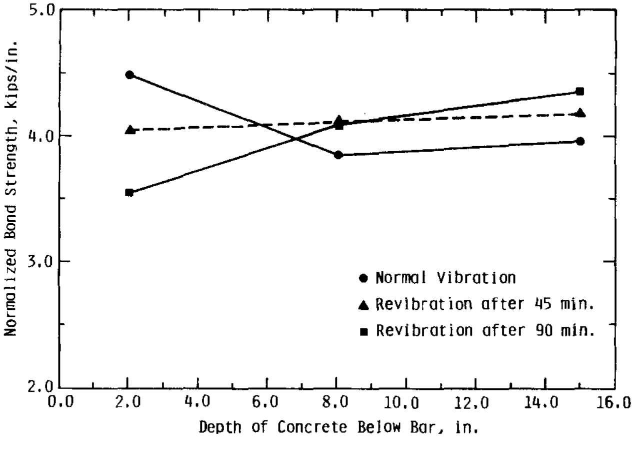

Fig. 5—Normalized bond strength versus concrete below bar for 7½ in. slump concrete, Group 2 (1 in. = 2.54 mm, 1 kip/in. = 175 kN/m)

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: Fig. 4 through 7 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 2¾, 7½, 4½, and 4½-in. (70, 190, 114, 114-mm), respectively].

A bond strength ratio, which is equal to the ratio of the bond strength of the revibrated bar to the bond

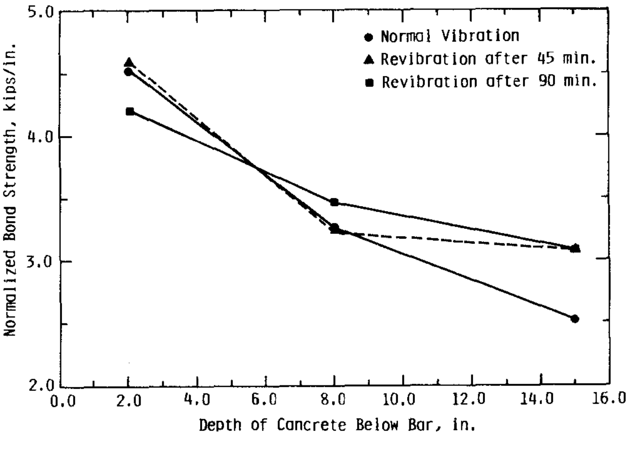

Fig. 4—Normalized bond strength versus concrete below bar for 2¾ in. slump concrete, Group 1 (1 in. = 2.54 mm, 1 kip/in. = 175 kN/m)

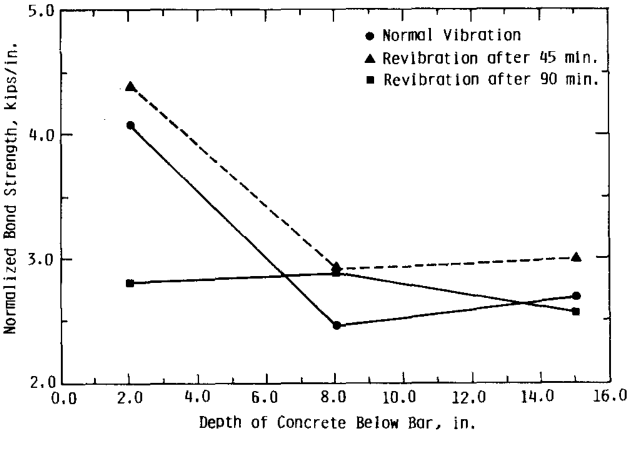

Fig. 6—Normalized bond strength versus concrete below bar for 4½ in. slump concrete, Group 3 (1 in. = 2.54 mm, 1 kip/in. = 175 kN/m)

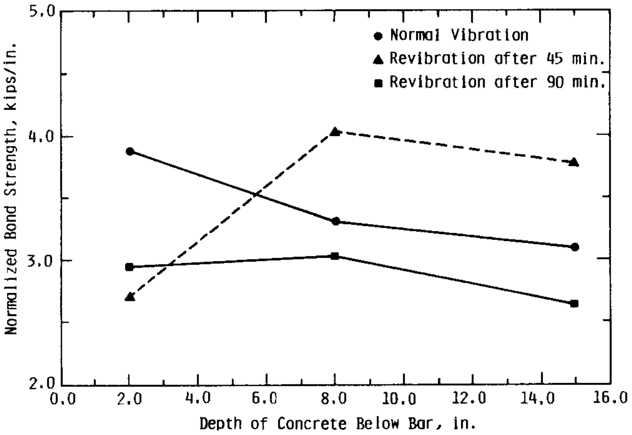

Fig. 7—Normalized bond strength versus concrete below bar for 4½ in. slump concrete, Group 4 (1 in. = 2.54 mm, 1 kip/in. = 175 kN/m)

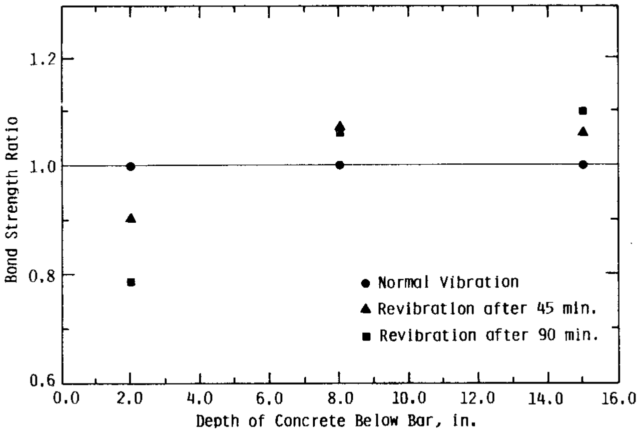

Fig. 8—Bond strength ratio versus concrete below bar for 2¾ in. slump concrete (1 in. = 25.4 mm)

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 the amount of concrete below the bars for slumps of 2¾, 4½, and 7½-in. (70, 114, and 190-mm) in Fig. 8, 9, and 10, repectively.

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. 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 dropped by 10 and 11 percent for the low- and medium-slump concretes, respectively, and increased by 1 percent for high-slump concrete. When revibrated at 90 minutes, the bond strengths dropped by 21, 27, and 10 percent for the low-, medium-, and high-slump concretes, respectively.

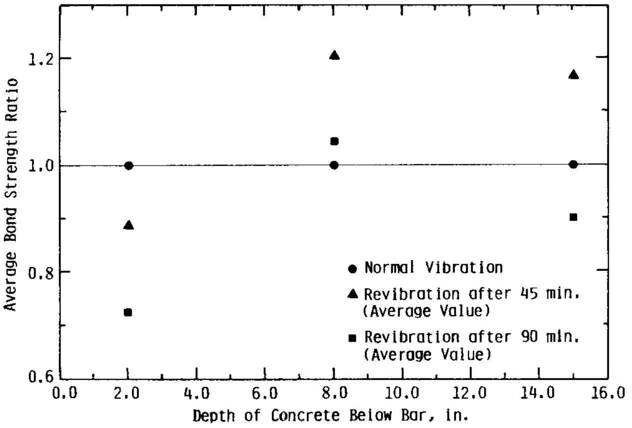

Fig. 9—Bond strength ratio versus concrete below bar for 4½ in. slump concrete (1 in. = 25.4 mm)

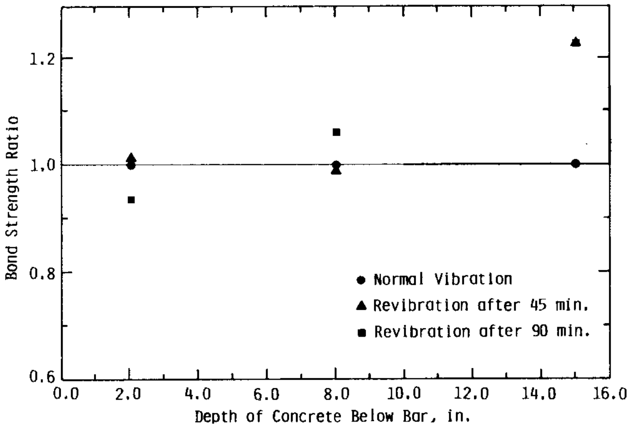

Fig. 10—Bond strength ratio versus concrete below bar for 7½ in. slump concrete (1 in. = 25.4 mm)

For the shallow top-cast bars, the bond strengths increased with revibration at 45 minutes by 7 and 20 percent for the low- and medium-slump concretes and decreased by 1 percent for the high-slump concretes. When reviberated at 90 minutes the bond strengths for the corresponding cases increased by 6, 5, and 6 percent, respectively.

For the deep top-cast bars, the bond strengths increased by 6, 7, and 23 percent 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 percent for the low- and high-slump concretes, but decreased by 10 percent 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. 11. 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 percent. Low-slump concrete increased in strength by 4 and 8 percent when revibrated at 45 and 90 minutes, respectively. The corresponding increases were 2 and 9 percent for medium-slump concrete and 2 and 5 percent 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.[4] 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.

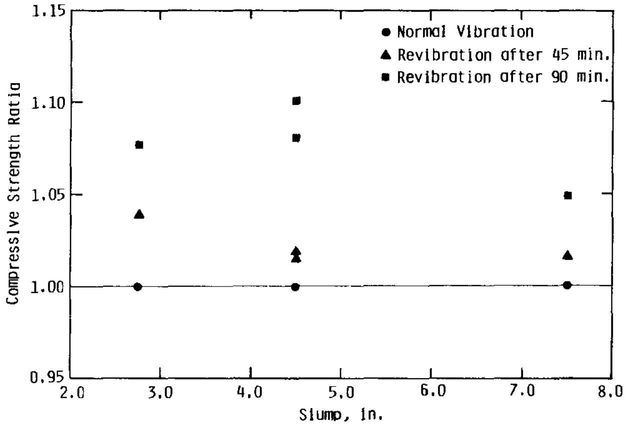

Fig. 11—Concrete compressive strength ratio versus slump (1 in. = 25.4 mm)

Effect of bar position on bond strength

Initial vibration: The normalized bond strength in the initially vibrated specimens decreased 14 to 40 percent as the amount of concrete below the test bar increased from 2 to 8 in. (51 to 203 mm), and from 12 to 45 percent as the concrete below the test bar increased from 2 to 15 in. (51 to 381 mm) (Fig. 4 through 7). These results generally agree with those reported in earlier work.[7,10,11] The effect of an increase in concrete below the bar from 8 to 15 in. (203 to 381 mm) 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. (203 to 381 mm).

According to the ACI Building Code,[12] top reinforcement is defined as "horizontal reinforcement so placed that more than 12 in. (305 mm) of concrete is cast in the member below the reinforcement." The current results, along with those of Brettmann et. al.[11] indicate that the decrease in bond strength associated with top reinforcement does not require 12 in. (305 mm) of concrete below the reinforcement if the reinforcement is top-cast.

Revibration: In contrast to the results obtained by Menzel,[2] revibration was less harmful and/or more helpful to bond strength as the amount of concrete below the bars increased (Fig. 4 through 7). As illustrated in Fig. 8 through 10, 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.

For the revibrated low-slump concrete (Fig. 8), 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. 10), revibration had little effect on bottom-cast bars and shallow top-cast bars, but significantly increased the bond strength of the deep top-cast bars.

RECOMMENDATIONS AND CONCLUSIONS

This study demonstrates that 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 that are 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 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, the effects of revibration on bond strength tend to counter the effects of slump and bar position.

Revibration clearly increased the compressive strength of standard 6 by 12 in. (152 by 305 mm) 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.

Based on the current study, full-depth revibration appears to be a poor construction practice. The damage done to the bond strength of deep bars is not compensated by the increased bond strength of top-cast bars. When used, revibration should be limited to the upper portions of a placement, probably no deeper than the length of the vibrator head. In this way, the effects of settlement and bleeding can be counteracted somewhat around the top-cast reinforcement, without damaging the bond strength of deeper bars. The use of a vibrator to tie together two lifts of concrete is a common application of revibration under these guidelines.

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. It would be useful to repeat the current study on a larger scale, with concrete workability governing the time interval between initial vibration and revibration. Finally, the influence of revibration on the bond strength of vertical reinforcement remains a completely open topic.

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