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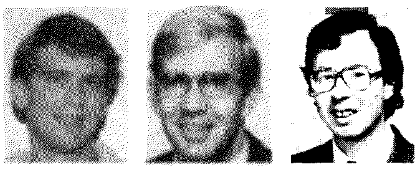
Bond of Reinforcement to Superplasticized Concrete



by Barie B. Brettmann, David Darwin, and Rex C. Donahey

The effects of superplasticizers on concrete-steel bond strength were studied. Key variables were degree of consolidation; concrete slump, both with and without a superplasticizer; concrete temperature; and bar position. No. 8 deformed reinforcing bars were used with a 2-in. (51-mm) cover and a 10 in. (254 mm) bonded length. Concrete slumps ranged from 1¾ in. to 9 in. (44 to 229 mm). Three specimens depths were used. All specimens were modified cantilever beam specimens.

The experimental results show that high-slump superplasticized concrete provides a lower bond strength than low-slump concrete of the same strength. Vibration of high-slump concrete increases the bond strength compared to high-slump concrete without vibration. The current ACI top-bar requirements appear to be unconservative for top-cast bars with less than 12 in. (305 mm) of concrete below the bar and are possibly overconservative for nontop-cast bars with more than 12 in. (305 mm) of concrete below the bar when low-slump concrete is used.

Keywords: **bond (concrete to reinforcement)**; concrete construction; consolidation; cover, **plasticizers;** pullout tests; **reinforced concrete;** reinforcing steels; vibration; **water-reducing agents.**

One of the major advances in concrete technology in the last 20 years has been the development of high-range water-reducers. These admixtures, also known as superplasticizers, are used to make high-slump, very workable normal-strength concrete as well as low-slump, low water-cement ratio, high-strength concrete. While superplasticizers have a number of important advantages, there is some concern with the high-slump mixtures, since previous work has shown that bond strength tends to decrease with increasing slump for concrete without superplasticizers, especially for top-cast bars.[1-6]

This report presents the results of a study of the effects of high-range water-reducers on the bond strength between horizontal deformed reinforcing bars and concrete. The key variables are the degree of consolidation; concrete slump, both with and without a superplasticizer; concrete temperature; and bar position. Additional details of this study are presented in Reference 7.

RESEARCH SIGNIFICANCE

This research has special significance for constructing and designing reinforced concrete.

In construction, according to conventional wisdom, little if any vibration is required if high-slump superplasticized concrete is used. The use of a superplasticizer to obtain flowable concrete is generally considered to have only positive effects on concrete quality. The findings reported in this paper indicate that the conventional wisdom is not correct in two respects. High-slump superplasticized concretes will give a lower bond strength than low- and medium-slump concretes of the same compressive strength, and high-slump concretes will undergo a significant drop in bond strength if not vibrated.

In design, the top-bar effect on bond strength is thought to be caused by bleeding and the settlement of concrete below the reinforcement. The top-bar effect is currently considered in design for all reinforcement with more than 12 in. (305 mm) of concrete cast below the reinforcement.[8] This research shows that a significant reduction in bond strength can also occur for bars with less than 12 in. (305 mm) of concrete below the bar if the bars are top-cast (upper-surface) bars. This observation has an important implication for design.

EXPERIMENTAL INVESTIGATION

Test specimens

Four specimen types and five different test-bar positions were used for each set of specimens (Fig. 1): two shallow specimens, 9 x 11 x 24 in. (229 x 279 x 610 mm), one with a bottom-cast bar (2 in. [51 mm] of concrete below the bar) and the other with a top-cast bar (8 in. [203 mm] of concrete below the bar); one medium specimen, 9 x 18 x 24 in. (229 x 457 x 610 mm), with a top-cast bar (15 in. [381 mm] of concrete below the bar); and one deep specimen, 9 x 39 x 24 in. (229 x 991 x 610 mm), with both a bottom-cast bar (2 in. [51 mm] of concrete below the bar) and a top-cast bar (36

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in. [914 mm] of concrete below the bar). Eight sets of specimens were tested, each with different concrete properties, for a total of 32 test specimens and 40 bars.

The test bars were 40 in. (1016 mm) long with a 10 in. (254 mm) bonded length. 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 of the test bar and to prevent a cone-type pull-out failure on the front surface of the specimen (Fig. 2). A 1 in. (25 mm) diameter steel conduit was used to provide access to the test bar for unloaded end-slip measurements.

Material properties

Concrete—Non-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. A water-cement ratio of 0.55 was used for all placements. Concrete slump was varied using both water content and high-range water-reducer. Superplasticizer was added directly into the ready-mix truck immediately before placing until the desired slump was reached. Table 1 summarizes mix proportions, aggregate properties, and concrete properties.

Steel—ASTM A 615,[9] Grade 60 No. 8 reinforcing bars from the same heat were used for all tests. Table 2 presents deformation dimensions, bearing areas, and steel strengths.

High-range water-reducer—The high-range water-reducer was an anionic naphthalene base material that met the requirements of ASTM C 494[10] for Type F and G admixtures.[11] Table 1 gives high-range water-reducer dosages.

Placement procedure

The test specimens were placed in three groups. Each group consisted of two or three sets of specimens.

The first set of specimens in Group 1 was fabricated using low-slump concrete as it arrived from the ready-mix plant. After placing and vibrating the first set, high-range water-reducer was added to the concrete to increase the slump. One set of vibrated and one set of nonvibrated specimens were made with the superplasticized concrete. These specimens were placed at a concrete temperature of 84 F (29 C), which caused the superplasticizer to rapidly lose effectiveness and the concrete in the upper layers of the deep specimens to have a reduced slump.

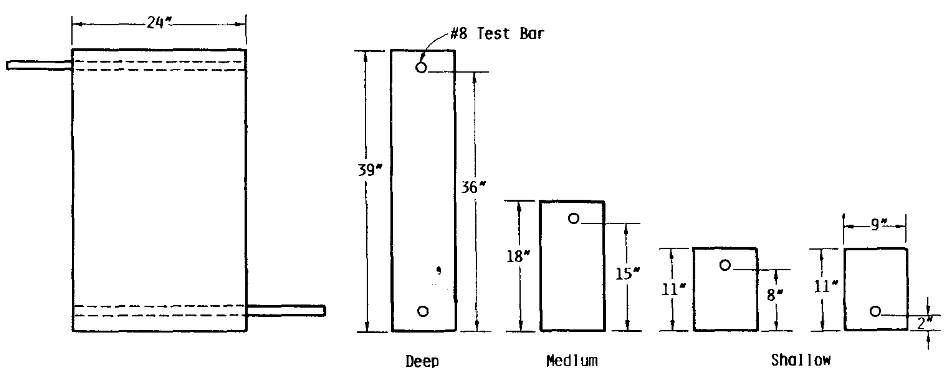


Fig. 1 — Test specimens (1 in. = 25.4 mm)

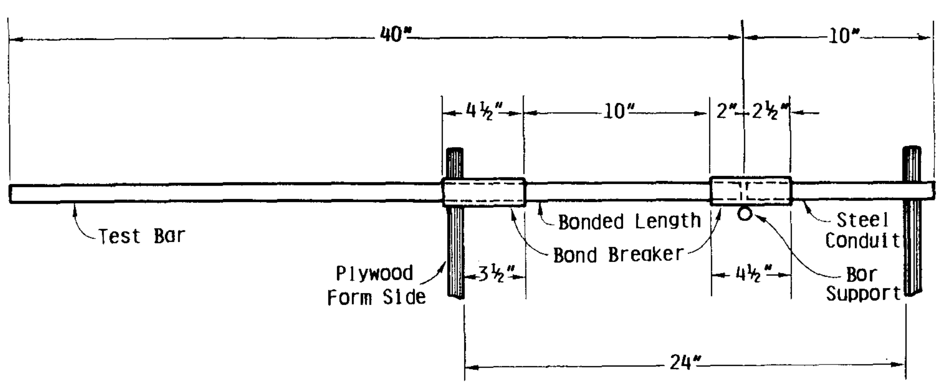
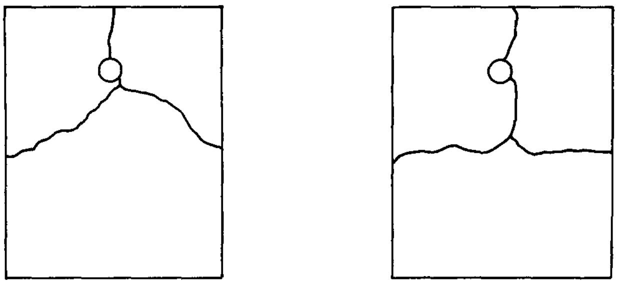


Fig. 2 — Test bar installation (1 in. = 25.4 mm)

Table 1 — Concrete mix proportions and properties*

				Aggregate				Base or regular concrete			Superplasticized concrete			
Mix design	w/c	Cement	Water	Fine†	Coarse‡	Temperature, F	Age at test, Days	Slump, in.	Air, percent	Strength, psi	SP-HRWR, oz	Slump, in.	Air, percent	Strength, psi
1	0.55	500	275	1555	1579	84	5	1¾	2¾	4280	96	6-9	§	4760
2	0.55	545	300	1453	1579	78	22	9	1	4000	—	—	—	—
3	0.55	510	280	1534	1579	53	11	3¾	1½	4470	72	9	1½	4830

*yd^3 batch weights.
†Kansas river sand: bulk specific gravity = 2.62; absorption = 0.5 percent; fineness modulus = 3.0 to 3.17.
‡Crushed limestone: bulk specific gravity = 2.52; absorption = 3.5 percent; maximum size = ¾ in.; design air content = 2 percent. Slump and air values are as measured.
§Not measured.
Note: 1 lb/yd^3 = 0.5933 kg/m^3.



(a) (b)

Fig. 3 — Test specimens after pullout: (a) low strength, and (b) high strength

Group 2 was made using a high-slump regular (i.e., nonsuperplasticized) concrete, with a concrete temperature of 78 F (26 C). One set of vibrated and one set of nonvibrated specimens were made.

Group 3 was placed at a concrete temperature of 53 F (12 C). The first set in Group 3 used a medium-slump concrete as it arrived from the ready-mix plant. After placing and vibrating the medium-slump specimens, high-range water-reducer was added, and one set each of vibrated and nonvibrated specimens were placed.

For the vibrated specimens, the shallow, medium, and deep specimens were placed in one, two, and three lifts, respectively. The nonvibrated specimens were placed in a single lift.

The vibrated specimens were consolidated using a 1½ in. (38 mm) electric internal vibrator. The specimens were vibrated at six points, with the vibrator inserted rapidly and withdrawn slowly. The concrete was vibrated until paste was seen coming to the surface. There was no attempt to consolidate the nonvibrated specimens.

After all of the specimens of a concrete type were consolidated, the specimens were screeded using a metal-edged screed. Immediately after screeding, the surface was finished using a magnesium hand float. Tests for surface bleed were then run.[7]

The specimens were covered with polyethylene and kept moist. The forms were stripped when the concrete strength reached about 3500 psi.

Standard 6 x 12 in. (152 x 305 mm) compression cylinders were made for each type of concrete, four for measuring the strength gain and four for determining the concrete strength at the time of testing.

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.	0.239
Yield strength, ksi	63.47
Tensile strength, ksi	104.6
Deformation pattern	Sheffield

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

Test procedure

The bond tests were made at concrete strengths between 4000 and 4800 psi (28 and 34 MPa). The specimens were tested as modified cantilever beams using the pullout apparatus developed by Donahey and Darwin.[4-6]

The specimens from a group were tested within a 10-hr period, at ages ranging from 5 to 22 days. The bars were loaded at approximately 6 kips (27 kN) per min. Load, loaded end slip, and unloaded end slip were recorded during the tests.

Results and observations

During pullout, a splitting-type bond failure occurred in all cases. The top surface crack ran parallel to and above the test bar over the bonded section of the bar and fanned out over the rear PVC bond breaker. Two different cracking patterns were observed on the front surface of the specimens (Fig. 3). A triple crack, with one crack running straight down from the top to the test bar and then two others at approximately 120 deg to the first, generally occurred in the specimens with lower bond strengths. A double crack, with one crack passing down from the top surface to the test bar, continuing under the test bar to the top of the bearing pad of the testing machine and accompanied by a crack perpendicular to the first running across the face of the specimen at the top of the bearing pad, occurred in the higher bond strength specimens. The ultimate bond forces are listed along with the test variables in Table 3.

The compressive strength of the superplasticized concrete was 8 to 12 percent (360 psi [2.5 MPa] to 460 psi [3.2 MPa]) higher than the strength of the companion regular concrete (Table 3).

EVALUATION OF EXPERIMENTAL RESULTS

The test results are used to examine the effects of high-range water-reducers on bond strength. The results are also used to examine the influence of the de-

Table 3 — Test specimen variables and bond strength*

Specimen, No.	Specimen, size†	Bar position‡	Concrete below bar, in.	Concrete strength, psi	Slump, in.	Consolidation§	Bond strength, kips/in.	Normal. bond strength, kips/in.	Concrete mix design, No.**	Specimen, No.	Specimen, size	Bar position	Concrete below bar, in.	Concrete strength, psi	Slump, in.	Consolidation	Bond strength, kips/in.	Normal. bond strength, kips/in.	Concrete mix design, No.**
1A	S	B	2	4280	1¾	V	4.46	4.31	1-R	2E	S	B	2	4000	9	V	4.57	4.57	2-R
1B	S	T	8				4.26	4.12		2F	S	T	8				3.33	3.33	
1C	M	T	15				3.52	3.40		2G	M	T	15				3.24	3.24	
1D	D	B	2				4.74	4.58		2H	D	B	2				4.71	4.71	
1D	D	T	36				3.76	3.64		2H	D	T	36				2.76	2.76	
1E	S	B	2	4760	9	V	4.44	4.07	1-SP	3A	S	B	2	4470	3¾	V	4.09	3.87	3-R
1F	S	T	8		9		4.65	4.26		3B	S	T	8				2.81	2.66	
1G	M	T	15		9		4.03	3.70		3C	M	T	15				3.98	3.77	
1H	D	B	2		8		4.41	4.04		3D	D	B	2				4.60	4.35	
1H	D	T	36		6		2.97	2.72		3D	D	T	36				2.35	2.22	
1I	S	B	2	4760	9	N	3.12	2.86	1-SP	3E	S	B	2	4830	9	V	3.81	3.47	3-SP
1J	S	T	8		9		3.78	3.47		3F	S	T	8				3.22	2.93	
1K	M	T	15		8		4.44	4.07		3G	M	T	15				2.57	2.34	
1L	D	B	2		8		3.48	3.19		3H	D	B	2				3.76	3.42	
1L	D	T	36		6		2.98	2.73		3H	D	T	36				2.33	2.12	
2A	S	B	2	4000	9	N	4.31	4.31	2-R	3I	S	B	2	4830	9	N	3.51	3.19	3-SP
2B	S	T	8				2.99	2.99		3J	S	T	8				2.82	2.57	
2C	M	T	15				2.68	2.68		3K	M	T	15				1.84	1.67	
2D	D	B	2				4.45	4.45		3L	D	B	2				3.47	3.16	
2D	D	T	36				1.56	1.56		3L	D	T	36				1.38	1.26	

*Bar size: #8; embedment length: 10 in.; cover: 2 in.
†S = shallow specimen; M = medium specimen; D = deep specimen.
‡B = bottom-cast; T = top-cast.
§V = vibrated, N = nonvibrated.
**R = regular; SP = superplasticized.
Note: 1 in. = 25.4 mm; 1 psi = 6.895 kPa; #8 bar = 25 mm; 1 kip/in. = 175 kN/m.

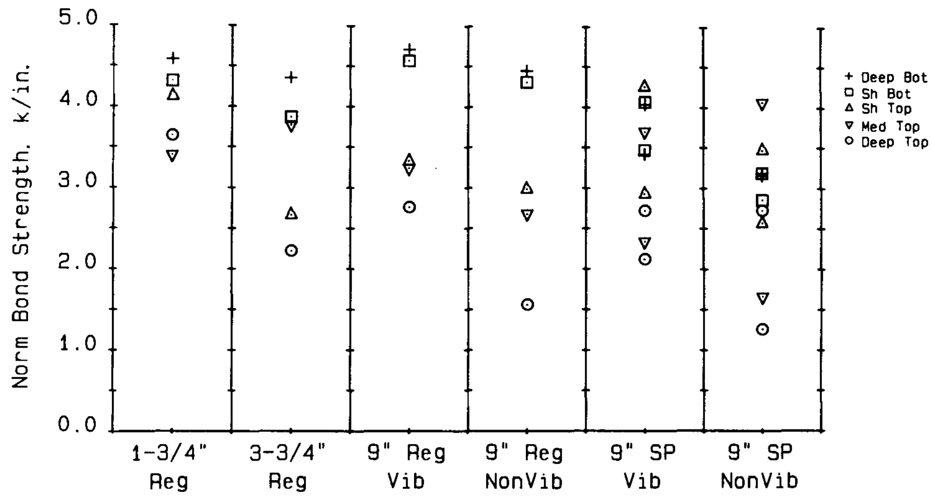


Fig. 4 — Comparison of normalized bond strengths for different types of concrete (1 in. = 25.4 mm, 1 kip/in. = 175 kN/m)

gree of consolidation; concrete slump, both with and without a superplasticizer; concrete tempature; and bar position.

The bond forces are converted to a bond force per unit length (kip/in.). These values are normalized to a concrete strength of 4000 psi (28 MPa) using the assumption that, within the tested concrete range (4000 psi [28 MPa] to 4800 psi [34 MPa]), bond strength is proportional to the square root of the compressive strength. Therefore, the values are multiplied by $(4000/f_c')^{1/2}$. The normalized values are summarized in Table 3 and Fig. 4.

Comparing bond strengths on a normalized basis is necessary because, in practice, job concrete strength is based on the concrete used, not on the nonsuperplasticized base concrete. Therefore, there would be no increase in bond strength due to the higher strength obtained with a high-range water-reducer.

Effect of high-range water-reducer

For the higher temperature (84 F [29°C]) concrete (Group 1), the actual bond strengths are nearly the same for the low-slump base concrete, all of which was vibrated, and the vibrated superplasticized concrete (Table 3). The bond strengths are comparable at least in part because of the increased compressive strength of the superplasticized concrete. However, the bond strength of the nonvibrated superplasticized concrete is an average of 14 percent lower when compared to the base concrete, in spite of the higher concrete strength.

For the same mixes (Group 1), the normalized bond strength of the vibrated superplasticized specimens decreases an average of 6 percent when compared to the low-slump base concrete (Fig. 5). The normalized bond strength of the nonvibrated superplasticized concrete decreases an average of 19 percent compared to the base concrete. The top-cast bar bond strengths for the

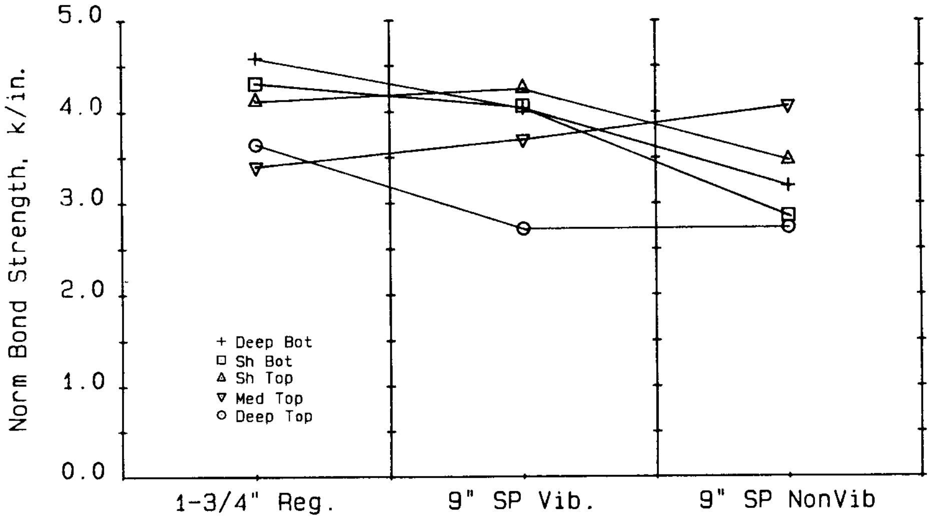


Fig. 5 — Comparison of normalized bond strengths for 84 F (29 C) base and superplasticized concretes (Group 1)(1 in. = 25.4 mm, 1 kip/in. = 175 kN/m)

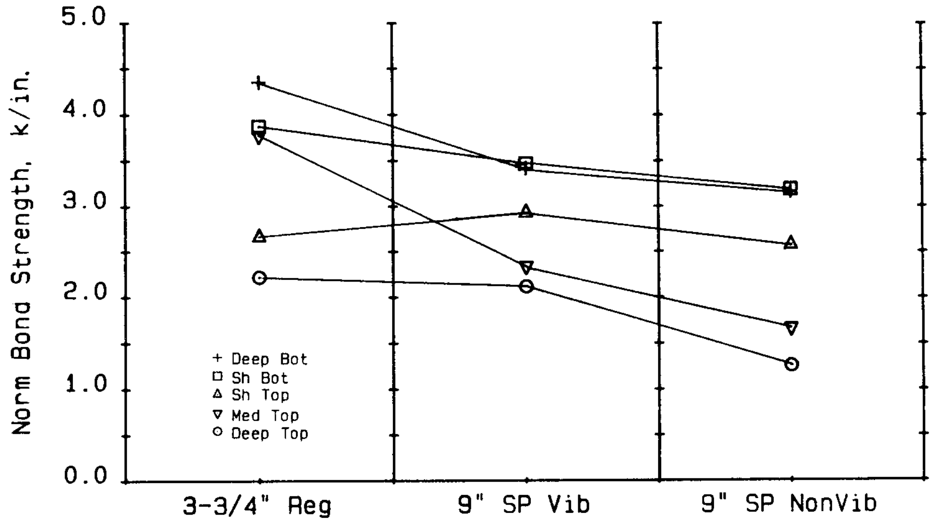


Fig. 6 — Comparison of normalized bond strengths for 53 F (12 C) base and superplasticized concretes (Group 3)(1 in. = 25.4 mm, 1 kip/in. = 175 kN/m)

nonvibrated superplasticized concrete may not be fully representative of nonconsolidated concrete. The concrete in these specimens was at a much lower slump when finished than when placed because of the loss in effectiveness of the high-range water-reducer, and required more effort to finish the top surface. Therefore, the concrete around the top-cast bars was probably well consolidated. The bottom-cast bars, which were not influenced by the extra finishing, should be more representative of nonvibrated concrete.

In the lower temperature (53 F [12 C]) specimens (Group 3), both the actual and normalized bond strengths decrease from the medium-slump base concrete, all of which was vibrated, to the higher slump superplasticized concrete, whether vibrated or not (Table 3 and Fig. 6). For the vibrated superplasticized specimens, the actual and normalized bond strengths drop an average of 12 and 15 percent, respectively. For the nonvibrated superplasticized specimens, the actual and normalized bond strengths respectively decrease an average 27 and 30 percent. These values may be a better gage of the general trends than the higher temperature specimens because there was no extra consolidation around the top bars (the concrete remained at a high slump during finishing).

Effect of slump

Concrete slump does not affect the normalized bond strengths of bottom-cast bars in regular concrete (Fig. 4). This observation agrees with earlier work.[1-3]

However, the bond strengths of bottom-cast bars in the superplasticized concrete are significantly lower than those of bottom-cast bars in the corresponding base concrete (Fig. 5 and 6), with an average decrease of 9 percent in Group 1 and 16 percent in Group 3 for the vibrated specimens.

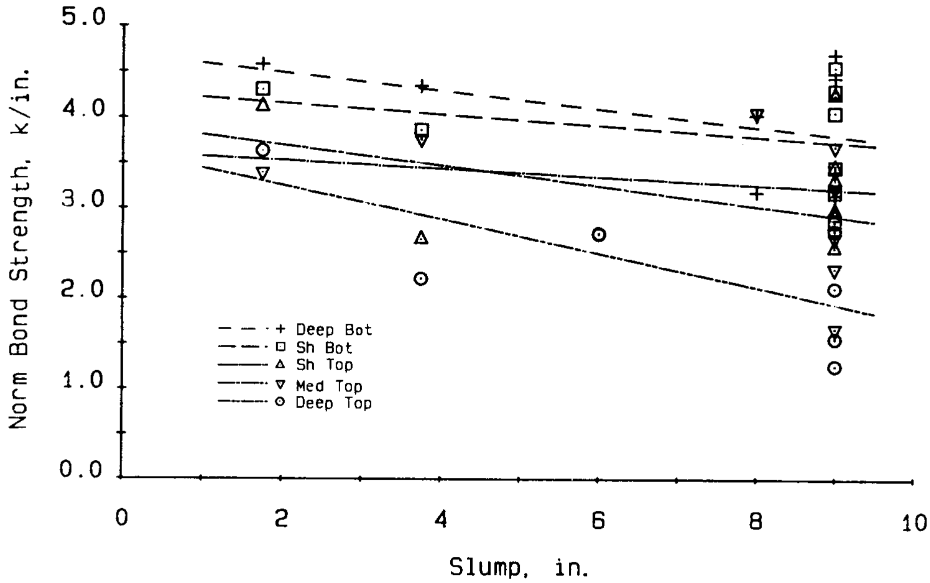


Fig. 7 — Normalized bond strength versus slump (1 in. = 25.4 mm, 1 kip/in. = 175 kN/M)

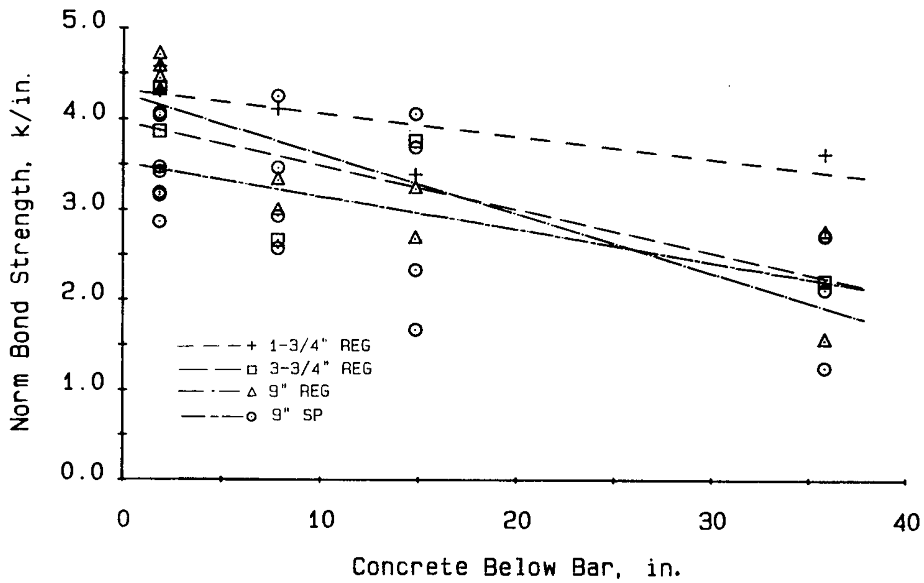


Fig. 8 — Normalized bond strength versus concrete below bar (1 in. = 25.4 mm, 1 kip/in. = 175 kN/m)

In most cases, an increase in slump decreases the bond strength of top-cast bars (Fig. 4 and 7).

Effect of bar position

Concrete below bar — As the amount of concrete below the test bar increases, the normalized bond strength decreases (Fig. 8). The decrease appears to be the least for the low-slump regular concrete (Group 1), approximately 16 percent as the depth below the test bar increases from 2 to 36 in. (51 to 914 mm). The greatest decrease, 40 percent, occurs for the high-slump regular concrete (Group 2).

Casting position — The effect of casting position is seen when comparing top-cast to bottom-cast bars. The ratio of normalized top-cast strength to the average normalized bond strength of the two bottom-cast bars, or bond efficiency ratio,[2] is plotted as a function of the concrete below the bar (Fig. 9 and 10).

For the higher-temperature regular concrete specimens (low slump in Group 1 and high slump in Group 2), there is a 10 to 40 percent decrease in the normalized bond strength between a bottom-cast bar and the top-cast bar with the least amount (8 in. [203 mm]) of concrete below the bar. The main portion of the de-

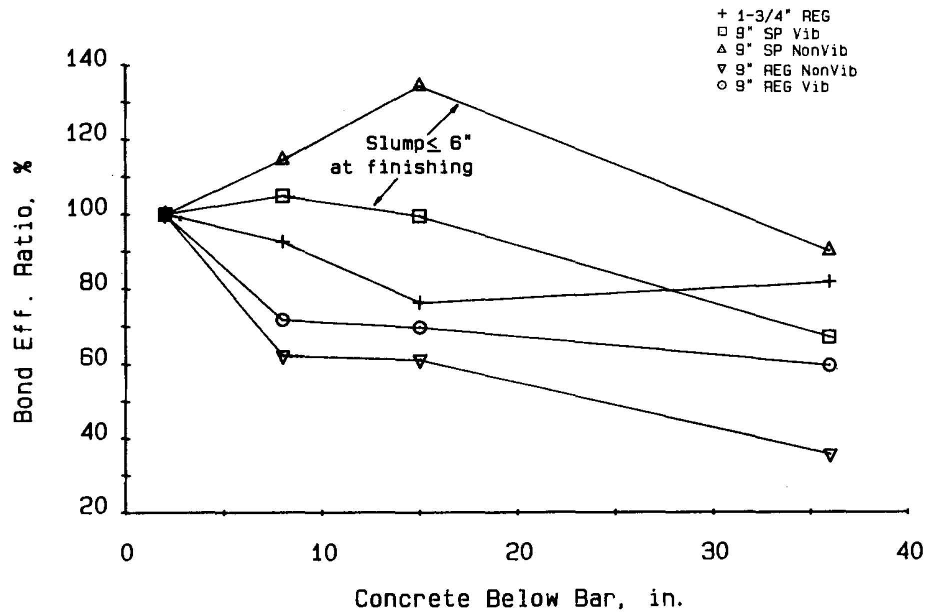


Fig. 9 — Bond efficiency ratio versus concrete below bar for higher temperature concretes (78 F [26 C] to 84 F [29 C])(1 in. = 25.4 mm)

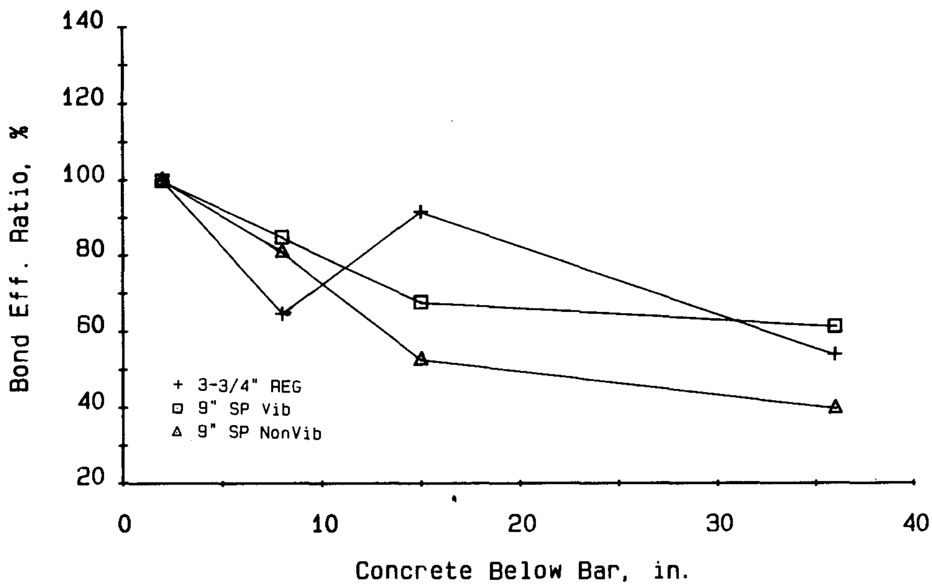


Fig. 10 — Bond efficiency ratio versus concrete below bar for lower temperature concrete (53 F [12 C])(1 in. = 25.4 mm)

crease appears to be due to an upper surface effect. A smaller additional decrease in bond strength is obtained as the concrete depth below the top-cast bars increases to 15 and 36 in. (381 to 914 mm).

In the higher-temperature superplasticized specimens (Group 1), another factor strongly effects the casting position results. Although the concrete initially had a 9 in. (229 mm) slump, the slump had dropped to under 6 in. (152 mm) by the end of placement (all other 9 in. [229 mm] slump specimens remained at a 9 in. [229 mm] slump through finishing). This decrease in slump required more effort for finishing, which improved the relative consolidation around the top bars, especially the nonvibrated specimens (Fig. 9). This extra consolidation may account for the strength increases between bottom-cast and top-cast bars of 5 percent in some vibrated specimens to 35 percent in some nonvibrated specimens.

The effect of casting position is seen more clearly for the lower temperature specimens (Group 3), with decreases of 15 to 60 percent (Fig. 10). There is some scatter in the 3¾ in. (95 mm) slump specimens. Again, the effect of casting position appears to be dominated by the upper surface effect, and the superplasticized

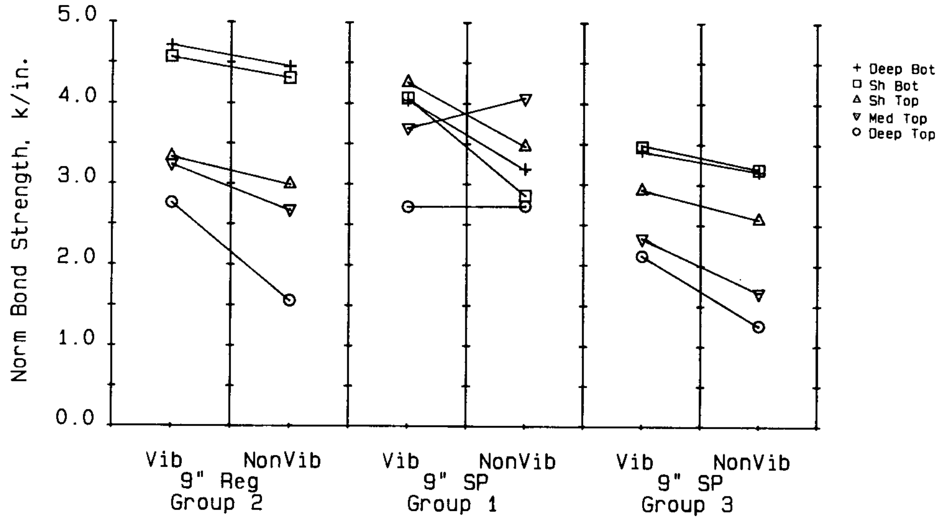


Fig. 11 — Comparison of average normalized bond strengths for vibrated and nonvibrated high-slump concrete mixes (1 in. = 25.4 mm, 1 kip/in. = 175 kN/m)

specimens show only a slight decrease in normalized bond strength as concrete below the bar increases from 15 to 36 in. (381 to 914 mm).

ACI top bars versus other top-cast bars — ACI 318[8] defines a top bar, or, more accurately, top reinforcement, as "horizontal reinforcement so placed that more than 12 in. (305 mm) of concrete is cast in the member below the reinforcement." In practice, a great deal of reinforcement falls under this definition without being top-cast reinforcement.

In the current research, the differences in bond strength between the bars with 8 in. (203 mm) of concrete below the bar, nontop bars, and bars with 15 in. (381 mm) of concrete below the bar (ACI "top bars"), are relatively small, with the exception of the nonvibrated superplasticized mix placed at 53 F (12 C) (Group 3) (Fig. 9 and 10). There is a greater reduction in bond strength for the bars with 36 in. (914 mm) of concrete below them. But even here, sizeable drops are obtained only for the high-slump, nonvibrated specimens. This shows that the choice of 12 in. (305 mm) of concrete below the bar for the 30 percent reduction in bond strength (equivalent to the 40 percent increase in development length in ACI 318) for a top bar is arbitrary. There seems to be a gradual decrease in bond strength with no sharp drop-off point.

Comparing these results (Fig. 9 and 10) to research by Luke et al.[2] indicates that much of the drop-off in bond strength is an upper surface effect. In Luke's tests, nontop-cast bars generally showed a gradual and relatively low decrease in bond strength with an increase in concrete below the bars from 2 to 39 in. (51 to 991 mm). In the current study, top-cast bars with only 8 in. (203 mm) of concrete below the bar show a sharp decrease in bond strength compared to bottom-cast bars with 2 in. (51 mm) of concrete below the bar. In this light, it makes more sense to apply the top-bar factor to top-cast bars, regardless of the amount of concrete below the bar. It is questionable if such a large penalty is necessary for nontop-cast bars with more than 12 in. (305 mm) of concrete below the bar. It may still be necessary to impose a large penalty for nontop-cast bars with more than 36 in. (914 mm) of concrete below the bar, particularly if high slump concrete is used.[2]

A precise definition of "top-cast" may be difficult based on the current limited research, but a practical definition might include reinforcement with less than 3 in. (76 mm) of top cover.[4]

Effect of vibration on high-slump specimens

The results clearly show the importance of vibration on bond strength in specimens made with high-slump concrete. As shown in Fig. 11, the bond strengths in the vibrated specimens exceed the bond strengths in the nonvibrated specimens in all but two cases. The observations agree with the results obtained by Donahey and Darwin.[4-6]

For the high-slump regular concrete, the bond strengths are an average of 14 percent lower for the nonvibrated specimens than for the vibrated specimens. For the bottom-cast bars, there is an average decrease of only 6 percent for the nonvibrated specimens, largely due to the consolidating effect of the concrete above the bar. The top-cast bars average a 23 percent decrease when not vibrated.

The superplasticized concrete, with just two exceptions, has a lower bond strength with nonvibrated specimens (Fig. 11). The trend is not apparent in two sets of the higher-temperature top-cast specimens (Group 1). As mentioned earlier, this is probably the result of the greater relative consolidation applied to some of the top-cast bars, especially the nonvibrated specimens.

The bottom-cast bars, which are away from the top surface, provide a good indication of the importance of

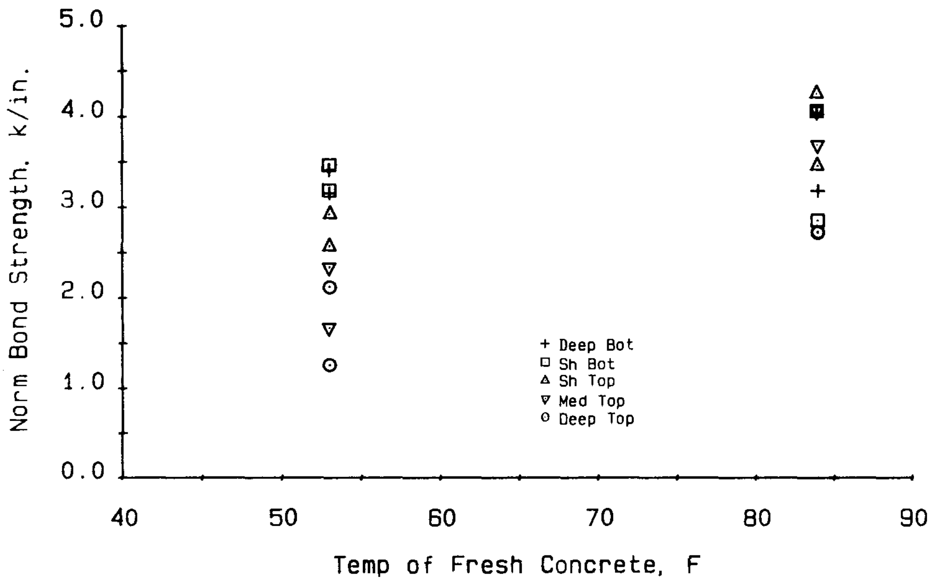


Fig. 12 — Normalized bond strength versus temperature of superplasticized concrete at placement (vibrated and nonvibrated) [$t_c = (t_f - 32)/1.8$, *1 kip/in. = 175 kN/m*]

vibration, with the nonvibrated specimens exhibiting a 25 percent decrease in bond strength compared to the vibrated specimens.

The nonvibrated lower temperature superplasticized specimens (Group 3) exhibit a uniform decrease in bond strength compared to the vibrated specimens, with the values dropping from 8 percent for the bottom-cast bars to 41 percent to the top-cast bars in the deep specimens.

Effect of temperature

Generally, the more rapidly the concrete sets up, the less deletereous are the effects of high slump and depth of concrete below the bar. The bond strengths of the lower-temperature superplasticized specimens (Group 3) are noticeably less than the bond strengths of the higher-temperature superplasticized specimens (Group 1)(Fig. 12). This is true regardless of whether the specimen was vibrated or not. The lower temperature causes the high-range water-reducer to keep the specimen at a higher slump for a longer time and to delay set. This allows the lower-temperature specimens to both bleed[7] more and settle more, causing more settlement cracking. The increased bleed and settlement decreases bond strength.

CONCLUSIONS

The following conclusions are drawn from the evaluation of the test results described in this paper.

1. Vibrated high-slump concrete made with a high-range water-reducer provides a lower bond strength than low- or medium-slump concrete of equal strength.
2. A decrease in bond strength occurs when high-slump concrete (superplasticized or not) is not vibrated.
3. Increased concrete slump has a negative effect on the bond strength of top-cast bars.
4. When using high-range water-reducers, the longer the concrete remains plastic (obtained with lower concrete temperatures in this study), the lower the bond strength.
5. A sharp drop-off in bond strength between bottom-cast bars and top-cast bars strongly suggests an upper surface effect, even for relatively low amounts of concrete below the bar. The current ACI[8] top-bar requirements appear to be unconservative for top-bars with less than 12 in. (305 mm) of concrete below the bar and are possibly overconservative for nontop-cast bars with more than 12 in. (305 mm) of concrete below the bar when low-slump concrete is used.
6. The bond strength of top-cast bars decreases as the amount of concrete below a bar increases.

RECOMMENDATIONS

The results of the current research emphasize the importance of concrete slump, consolidation, and bar position on bond strength. The following recommendations reflect these findings.

1. The lowest-slump concrete that can be properly consolidated should be used to obtain the best concrete-steel bond strength.
2. High-slump concrete, with or without a superplasticizer, should be vibrated in members with horizontal reinforcement.
3. The current ACI top-bar requirements[8] should be applied to top-cast bars.

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REFERENCES

1. Menzel, Carl A., "Effect of Settlement of Concrete on Results of Pullout Tests," *Research Department Bulletin* No. 41, Portland Cement Association, Skokie, Nov. 1952, 49 pp.

2. Luke, J. J.; Hamad, B. S.; Jirsa, J. O.; and Breen, J. E., "The Influence of Casting Position on Development and Splice Length on Reinforcing Bars," *Research Report* No. 242-1, Center for Transportation Research, Bureau of Engineering Research, University of Texas, Austin, June 1981, 153 pp.

3. Zekany, A. J.; Neumann, S.; Jirsa, J. O.; and Breen, J. E., "The Influence of Shear on Lapped Splices in Reinforced Concrete," *Research Report* No. 242-2, Center for Transportation Research, Bureau of Engineering Research, University of Texas, Austin, July 1981, 88 pp.

4. Donahey, Rex C., and Darwin, David, "Effects of Construction Procedures on Bond in Bridge Decks," *SM Report* No. 7, University of Kansas Center for Research, Lawrence, Jan. 1983, 125 pp.

5. Donahey, Rex C., and Darwin, David, "Effects of Innovative Construction Procedures on Bridge Decks: Part 1, Effects of Construction Procedures on Bond in Bridge Decks," *SL Report* No. 83-1, University of Kansas Center for Research, Lawrence, June 1983, 28 pp.

6. Donahey, Rex C., and Darwin, David, "Bond of Top-Cast Bars in Bridge Decks," ACI Journal, *Proceedings* V. 82, No. 1, Jan.-Feb. 1982, pp. 57-66.

7. Brettman, Barie B.; Darwin, David; and Donahey, Rex C., "Effect of Superplasticizers on Concrete-Steel Bond Strength," *SL Report* No. 84-1, University of Kansas Center for Research, Lawrence, Apr. 1984, 32 pp.

8. ACI Committee 318, "Building Code Requirements for Reinforced Concrete (ACI 318-83)," American Concrete Institute, Detroit, 1983, 111 pp.

9. "Standard Specification for Deformed and Plain Billet-Steel Bars for Concrete Reinforcement," (ASTM A 615-82), *1984 Annual Book of ASTM Standards,* V. 01.04, ASTM, Philadelphia, pp. 502-507.

10. "Standard Specification for Chemical Admixtures for Concrete," (ASTM C 494-82), *1983 Annual Book of ASTM Standards,* V. 04.02, ASTM, Philadelphia, pp. 317-327.

11. "PSI Super, Superplasticizing High-Range Water-Reducer," Gifford-Hill and Co., Chemical Division, Charlotte, 1983, 2 pp.