A STUDY OF BOND STRESS BETWEEN CONCRETE AND STEEL

by

Cheng-Yee Wang

B. S., Kansas State University, 1961

A MASTER'S REPORT

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by Cheng-Yee Wang[1]

SYNOPSIS

The bond strength between concrete and steel is an important factor from which to determine a sound design for the reinforced concrete. This problem was introduced as early as 1876 by Mr. Thaddeus. And Mr. Abrams did a magnificent work in this field in 1913.

The purpose of this paper is to introduce the bond formula, the allowable bond stress and some factors influencing the bond strength based on the former valuable reports.

This problem has been studied during the past half century by many research engineers who found that there were a number of factors which would affect the bond strength. Among these elements, they have tested several primary factors for which they have obtained similar results.

To increase the bond stress between concrete and steel a lower than usual water ratio, a large aggregate size, and an increased amount of cement should be used. Also use of vertical bars at casting is considered helpful for bonding. Delayed vibration and additional embedment length, deformed bars and aluminum powder as admixture will offer considerably higher bond resistance. Nevertheless the freezing and thawing, or wetting and drying will greatly reduce it.

Yet, on the remaining unanswered or partially answered questions in this field, further studies should be made.

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INTRODUCTION

Since Mr. Thaddeus in 1876 and Mr. Withey in 1906 presented their reports on the bond strength between concrete and reinforcing steel, this problem has interested many research engineers. Mr. Abrams was outstanding among the early researchers. He carried out remarkable work upon bond strength as applied to the bars and mixtures of that day. While much of his Bulletin 71* (1) is as valid as it was fifty years ago, there are important concepts that need revision in the light of tests on current mixture.

During the last half century, a good many test reports have contributed to the discussion of the characteristics of bond resistance and the factors influencing bond stress. However, those efforts do not cover this field; a lot of question remain which can be answered only partially and wait to be proved by further studies.

Among the items which may influence potential bond resistance are: water ratio to concrete volume, orientation of bars as cast (vertical or horizontal), deformations along the bar, lugs, surface texture of bar, vibration of concrete during or following placement, length of embedment, and possibly the admixture or aggregate used. Environmental conditions of the hardened concrete such as alternate freezing and thawing, alternate wetting and drying, and subjection to a wide temperature variation may well be important because all of these conditions swell and shrink the concrete, producing differential motions tending to break the bond.

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*Numerals in parentheses refer to corresponding items in the References, P. 21

BOND FORMULA

Let Figure 1 represent the general case of simple prismatic beam in which all bars are straight and of full length, and the distance between the center of compression and center of tension, jd, is constant thoughout the entire length.

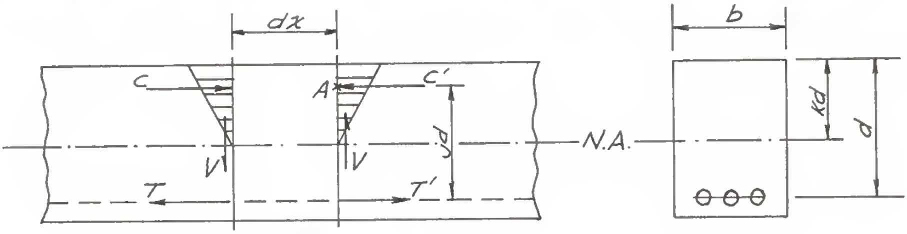

Figure 1

If moment is to be taken about compression center, A,

$\Sigma M_A = 0 \qquad (T-T')jd - Vdx = 0$

then $\qquad T-T' = \frac{Vdx}{jd}$

This unbalanced pull in the steel will cause slipping of the bar unless balanced by the adhesion between the concrete and steel in the length dx. This bond force is equal to the average bond stress u in the length dx times the area of contact between the steel and concrete. The area of contact is equal to the sum of the perimeters of the bars times the length and is written as $(\Sigma o)(dx)$

$$\text{Bond force} = u(\Sigma_o)dx = T-T' = \frac{Vdx}{jd}$$

$$\text{Bond stress} = u = \frac{V}{(\Sigma_o)jd}$$

This expression is known as the "bond formula"

When the total tension in the steel varies directly with the ordinate to the moment curve, T = M/jd, all bars being straight and of full length, the external shear curve will represent, to scale, the distribution of the internal bond unit stress. Since similarly in plate girder work, the shear curve is used to determine the rivets spacing, it will be seen that the same function is served by the bond in a concrete beam and by the shearing resistance of the flange rivets in a plate girder.

WORKING STRESS IN BOND

The bond strength has usually been determined by the tests which pull a bar from a concrete block. In the pull-out tests the block is usually set on the top of the machine and the steel bar is grasped and pulled. The concrete is in compression and the steel is in tension. In the actual beam both are in tension. A few tests have been made with the concrete in tension. They do not indicate a great variation from the usual results. The working bond strength is usually based on the ultimate compressive strength of 28-day concrete, f'_c.

Bond Stress and Compressive Strength: Abrams (3) pointed out in his test in 1925 that the bond on a plain steel bar is about 24 percent of the compressive strength of concrete, and that the ratio decreased slightly for concrete of higher strengths. But in 1937 and 1938, reports presented by Wenisch (7), Davis, Brown and Kelly (8), and Iowa State College modified this idea. They indicated that for concrete above 2,000 psi the increase of bond resistance with added strength was slight. With bond resistance remaining nearly constant and compressive strength increasing, the ratio of bond resistance to compressive strength decreased rapidly as the strength of standard cured concrete increased. The results of bond stress at first slip vs. compressive strength of concrete are plotted in Figure 2.

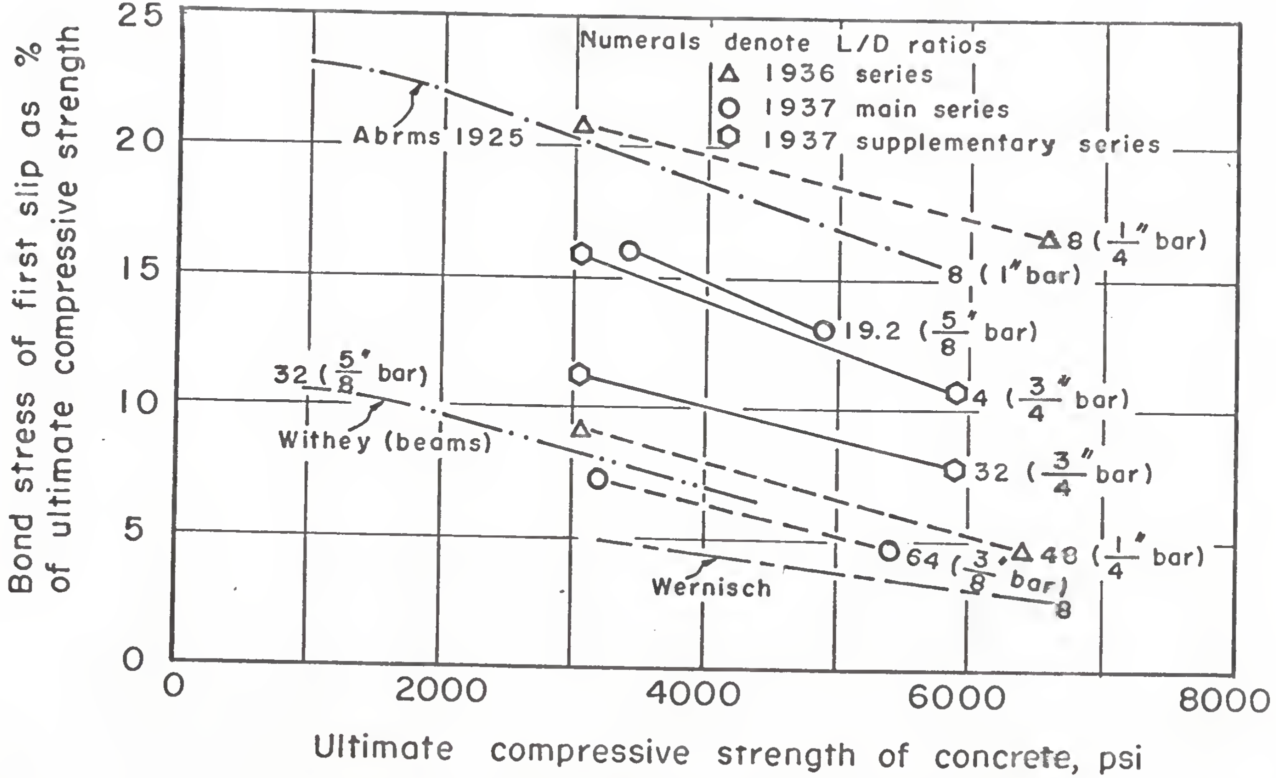

Fig. 2. Bond at first slip vs compressive strength of concrete. (all bars plain, all specimens pullout except Withey beams).

The values of allowable unit bond stress in Table 1 are adopted by the present ACI Building Code.

Table 1. Allowable Unit Stress for Bond

Description	Ultimate compressive strength of concrete			
	$f'_c=2,000$	$f'_c=3,000$	$f'_c=3,750$	$f'_c=5,000$
Deformed Bars				
Top bars ($u=0.07f'_c$)	140	210	245	245
In two-way footings (except top bars)($u=0.08f'_c$)	160	240	280	280
All others ($u=0.10f'_c$)	200	300	350	350
Plain Bars (must be hooked)				
Top bars ($u=0.030f'_c$)	60	90	105	105
In two-way footings (except top bars)($u=0.036$ f'_c)	72	108	126	126
All others ($u=0.045f'_c$)	90	135	158	158

Here, the ACI Code suggests that the bond stress will remain constant for compressive strength of concrete over 3,750 psi.

<u>Factor of Safety in Bond</u>: The safety factor of about 2½ to 3, which was adopted by the ACI Joint Committee, is agreed upon by the experimenters, past and present.

FACTORS AFFECTING BOND STRENGTH

1. <u>Water Ratio</u>: As tested by Abrams, Richart and Scofield both bond and compressive strength decreased in the same manner as the water ratio was increased.

L. N. Edwards and H. L. Greenleaf obtained the same result in 1928.

Figure 3 is plotted to show the relations between water ratio and compressive strength as well as between water ratio and bond strength.

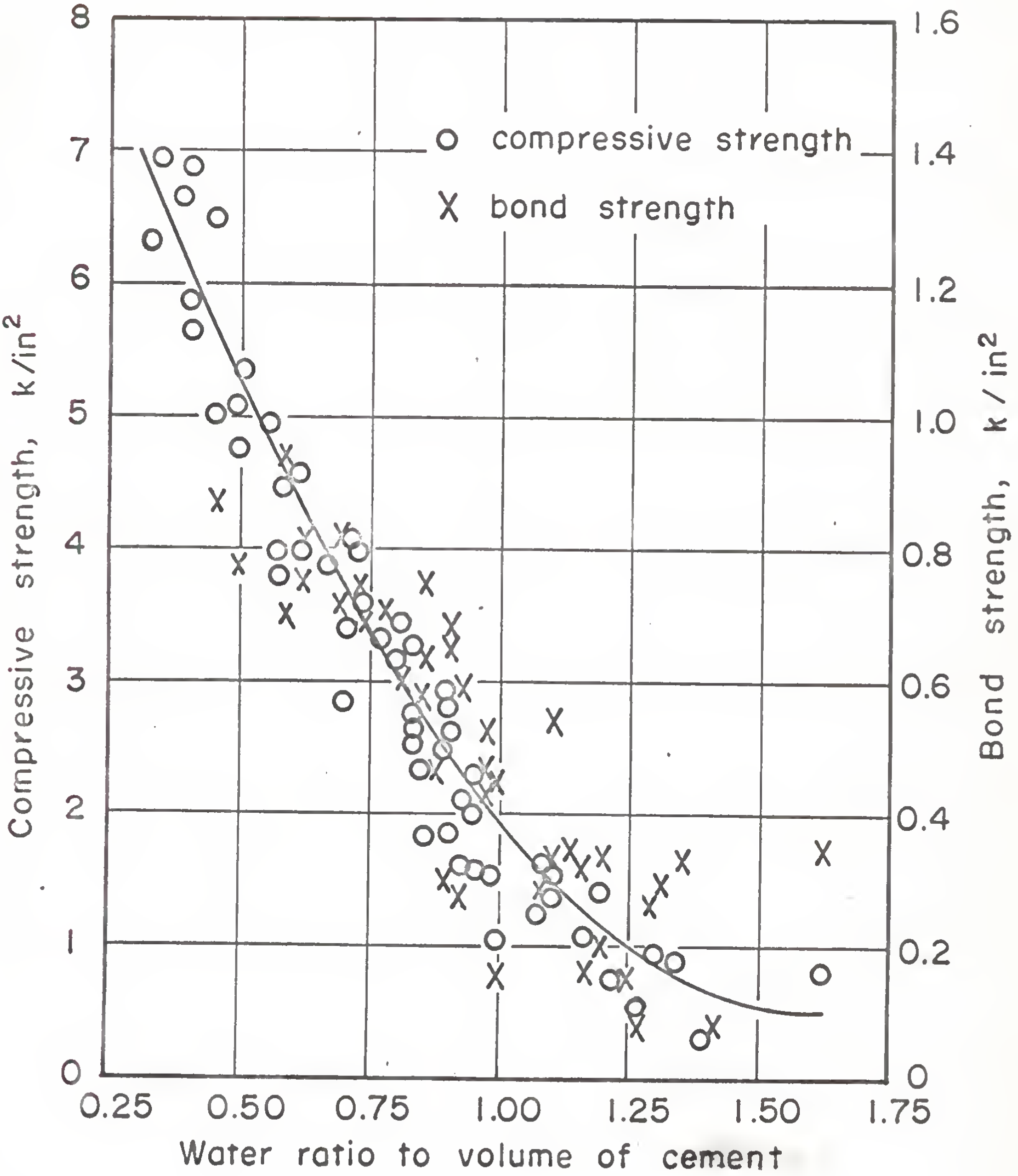

Fig. 3. Water-ratio-strength relation for concrete.

In the year of 1938, Davis, Brown and Kelly (8) reported that at initial slip, bond strength of the rich mix was generally lower than that of the lean one. And with the rich mix, under the condition of moist curing the maximum bond strength was nearly twice as great for the portland-puzzolan cement as for the modified portland cement.

Some other factors associated with water-ratio in affecting bond strength are the fine modulus of aggregate, the quantity of cement, and the age of the test.

The effect of grading of aggregate to the bond strength is shown in Figure 4.

In general, the bond stress will be increased as the fineness modulus of aggregate is increased up to 6.0; as more cement is used; and as more time is allowable for maintenance.

2. <u>Orientation of the Steel at Casting</u>: In Bulletin 71 of the University of Illinois (1913), Abrams (1) pointed out that the specimens molded in a horizontal position gave lower bond resistance than those molded in a vertical position.

The results of bond resistance due to the orientation at casting have been reported in 1938 (8) and are tabulated in Table 2.

Table 2. Bond Stress Due to Orientation at Casting

Bar		Slump in.	Compressive strength lb./sq.in.	Bond strength lb./sq.in.	
Shape	Position			Initial slip	Maximum
Round	Vertical	3½	4,280	190	485
	Horizontal	3½	4,280	105	115
		6½	4,100	90	100
Squre	Horizontal	2½	4,880	120	275
		6	4,330	195	380

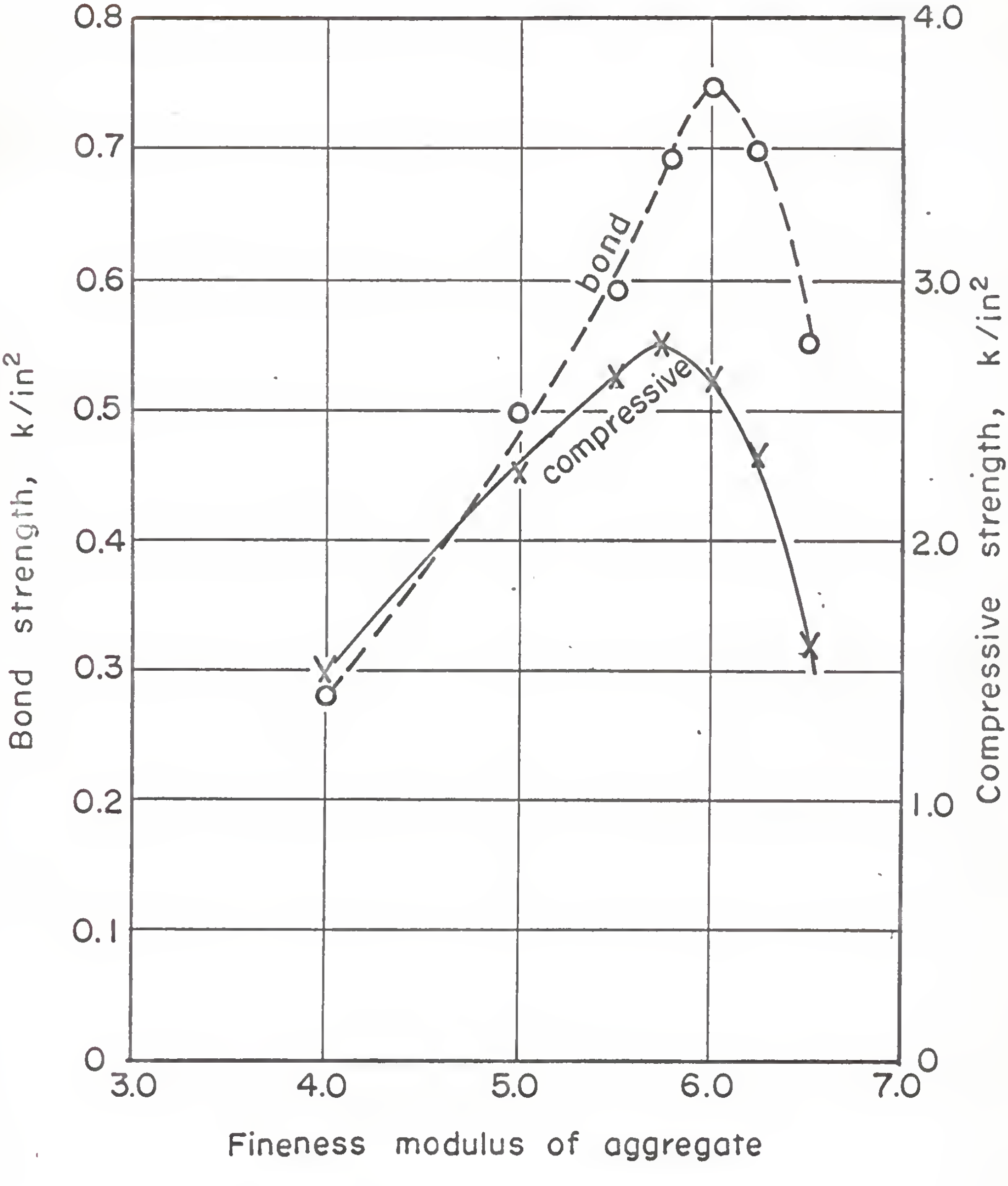

Fig. 4. Effect of grading of aggregate.

From the Table, it is obvious that the bond strength both at first slip and at the maximum are greater for square bars placed horizontally than for round bars placed horizontally.

S. T. Collier's test (16) in 1947 obtained the same result with five different types of deformed bars in testing.

3. <u>Weathering</u> <u>Effect</u>: By testing the specimens which have been subjected to continuously moist-curing condition and those which had been subjected to 56 cycles of (A) freezing and thawing or (B) wetting and drying, Davis, Brown and Kelly (8) concluded that either of these treatments reduced the bond strength at initial slip to a negligible amount and substantially reduced the maximum bond strength. And they also found that the repetition of freezing and thawing or wetting and drying generally resulted in a marked expansion of concrete which perhaps indicated a breaking of the adhesive bond between aggregate and cement paste. This effect would not only destroy the adhesion between bar and paste but also greatly reduce the frictional resistance developed at initial slip.

The effect of treatments simulating the action of weather is shown in Table 3.

Table 3. Bond Strength Due to Weathering

Cyclic treatment	Number of cycles	Temperature at test °F	Compressive strength lb./sq.in.	Bond Strength lb./sq.in.	
				Initial Slip	Maximum
None (continuously in fog at 70° F)	0	70	4,780	125	190
Freezing & thawing (satuated, 16 hr. at 0°F; 8 hr. at 100°F)	56	100	3,960	10	150
Wetting & drying (8 hr. in water at 70° F; 16 hr. in air blast at 160°F)	56	70	4,540	10	120

4. Bar Shapes: Abrams in Bulletin 71 (1), University of Illinois indicated that the square bars gave values of unit stress about 75 percent of those obtained with plain round bars.

Davis's test seemed to get a higher precentage for square bars than for plain round bars.

Since deformed bars developed in a wide application, some experimenters, such as Wernisch (7) and Gilkey (9), reported that the deformed bars slipped initially at bond stresses slightly higher than those for the initial slippage of plain bars. But after initial slippage, the resistance offered by deformed bars continued to increase until failure occurred by splitting from the wedging action of the lugs. They said the deformed bars of current types offered some margin of added bond resistance and a considerable added margin against sudden and complete failure of beams over that offered by plain bars.

In 1942, David Watstein (12) gave his test report as Figure 5. From his six specimens, with steel bars of 3/4 in. in diameter and length of embedment to diameter ratio, L/D, of 24, the bond stresses developed at the loaded ends of deformed bars were considerably greater than those at their free ends for all loads. And the bond stresses of all bars except cold rolled bar "A" varied approximately linearly with the applied load.

S. T. Collier's test (16) in 1947 showed that the specially prepared bars in practically every instance developed higher stresses than the commercial bars especially when the specimens were cast horizontally.

Evidently, the threaded bars will increase greatly the resistance of the bond. Nevertheless, in manufacturing it is hard to produce bars with fine-textured, non-wedging type of surface roughness.

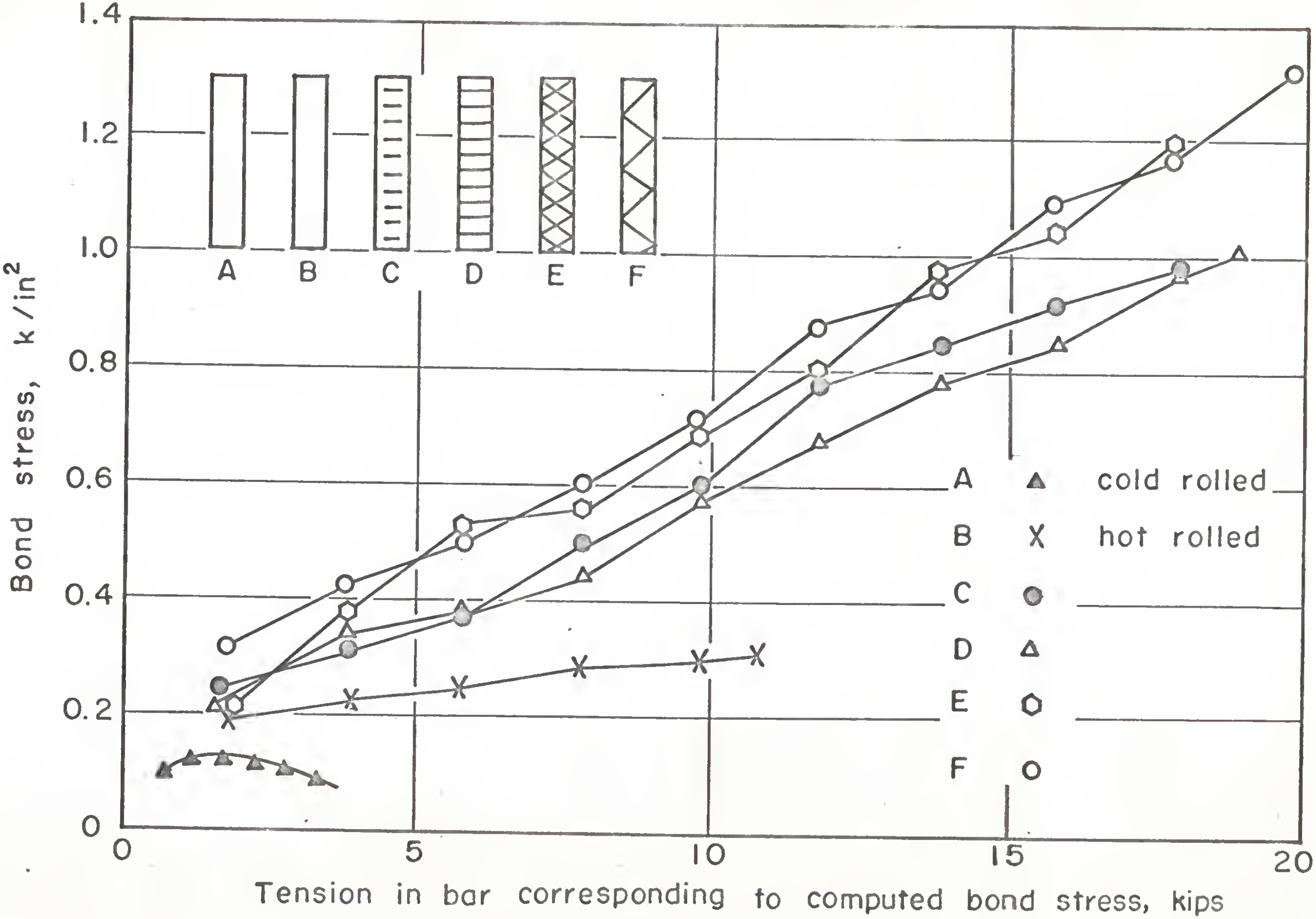

Fig. 5. Computed bond stress at loaded end.

5. Vibration: An exclusive report on the bond of vibrated concrete, by Withey in 1936 (4), indicated that by vibrating a given cement content a higher bond was obtained than by hand placement. The proper use of vibration in placement produced a good bond between old and fresh concrete and also between concrete and steel.

Davis, Brown and Kelly gave their report in 1938 (8) that external vibration applied to molds clamped to a vibrating table increased the bond strengths only slightly over those obtained by hand tamping alone; on the other hand, when vibration through the use of an air hammer was applied axially to the end of the bar, the effect was to increase about 50 percent both the bond strength at initial slip and the maximum bond strength. The increase might have been caused by the vibration of the bar which produced a remixing action of the cement paste in the immediate vicinity of the bar, and through this remixing action a more homogeneous paste structure at the contact surface. The result was tabulated in Table 4.

Table 4. Effect of Vibration for Bond

Method of compacting concrete	Time of vibration sec.	Bond strength lb./sq.in.	
		Initial slip	Maximum
Hand tamping	0	205	740
External vibration (molds clamped to vibrating table)	15	210	845
Axial bar vibration (air hammer operated axially on top end of bar)	30	330	1,075

They also tested three other conditions as well. Results of these tests showed that the bond strength increased more by delayed vibration of the bar than by delayed external vibration of the concrete. Table 5 would show the effect of delayed vibration.

Table 5. Effect of Delayed Vibration

Vibration	Bond Strength at 28 Days						
	Kind	Unvibrated #/in.^{2}	Unvibrated	% of strength of unvibrated specimens			
				0 hr.	3 hr.	6 hr.	9 hr.
External	Initial slip	205	100	103	29	88	142
	Maximum	740	100	114	133	143	126
Bar	Initial slip	205	100	---	200	190	190
	Maximum	740	100	---	147	155	141
Bar (axial)	Initial slip	205	100	161	200	212	83
	Maximum	740	100	145	154	162	128

6. Length of Embedment: Abrams' test (1) with 1¼ in. plain round bars (1913) as well as Gilkey's test (5) with ¼ in. plain and deformed rail steel (1936) were in agreement that the total bond resistance increased in direct proportion to the increase in the length of embedment.

In 1939, Gilkey (9) modified his finding, in that the total bond resistance of plain bars increased with added length of embedment up to the ratio of about 24, beyond which added length of embedment would develop little added resistance for the bond. He plotted the curve as in Figure 6.

Professor T. D. Mylrea (17) presented his report in March of 1948 and stated the required length of embedment to resist withdrawal to be

$$L = \frac{f_s}{4u} D$$

Where L = length of embedment
f_s = tensil stress taken by reinforcement
u = bond strength
D = diameter of reinforcement

It is obvious that the length of embedment is a direct function of the diameter D of a bar. The same length of embedment will also be required for square bars.

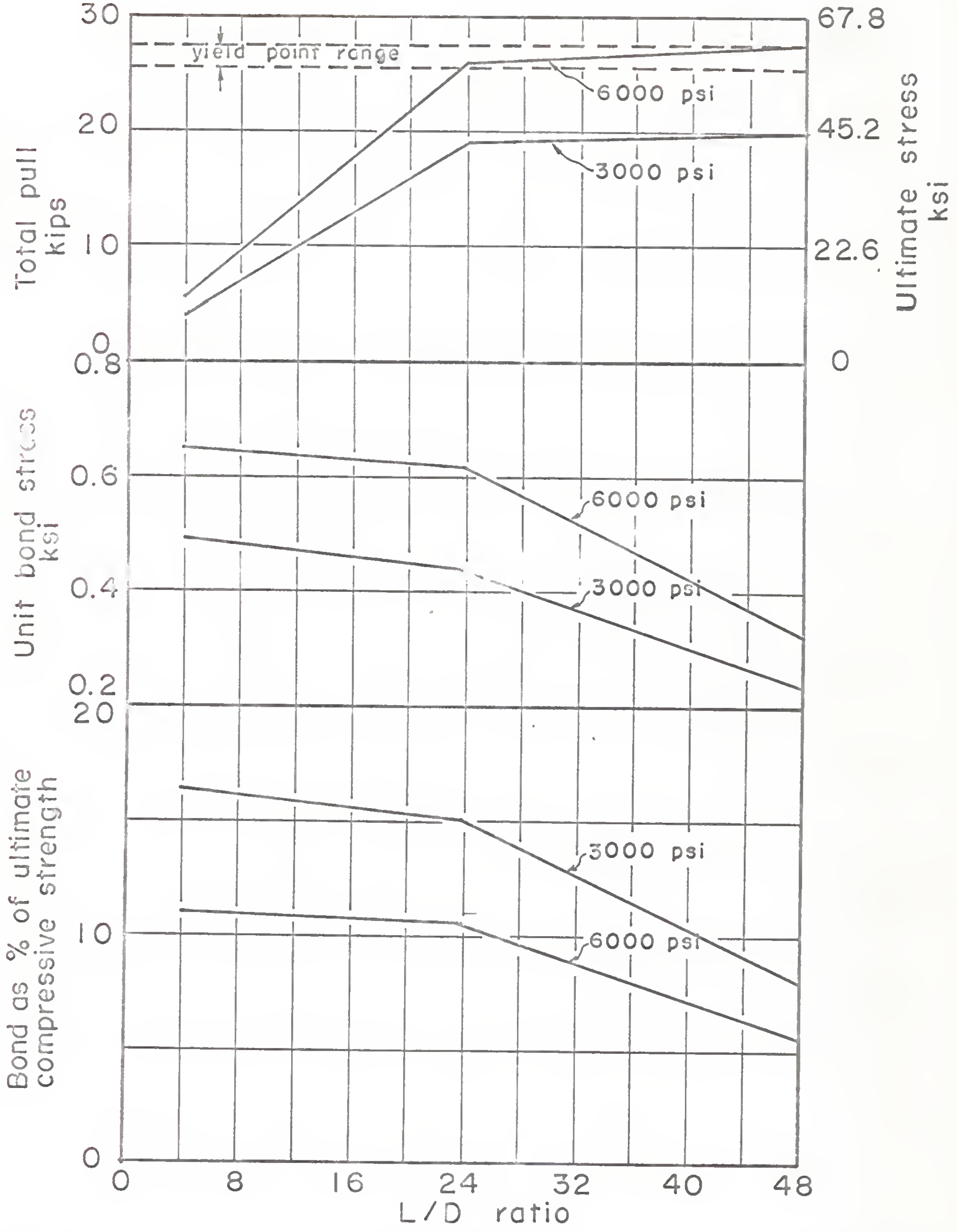

Fig. 6. Effect of length of embedment of plain bars on loads, stresses, and bond ratios at first slip, for two strengths of concrete.

The formula then can be rewritten as:

$$f_s = 4u \frac{L}{D}$$

It is easy to see that the tensile stress that can be developed by bond is directly proportional to L/D as well to the average bond unit stress.

7. Surface Coating: For the purpose of protecting steel embedded in concrete from corrosion due to the action of sea water and air, Slater, Richart and Scofield (2) in 1919 tested several series of specimens with many different types of preservative coatings including asphaltic and metallic coatings, coal tar, ferric oxide, metal spray, red lead and phosphate on both plain and deformed bars. Bond tests were also made to determine the effect of the various anti-corrosion treatments on bond resistance of a bar. The results of these pull-out tests indicated that in general all protective treatments used, except the phosphate treatment, reduced the bond resistance materially.

8. Rusted Steel: In 1913, Abrams in Bulletin 71 (1) reported that the rusted bars gave bond resistance about 15 percent higher than similar bars with the ordinary mill surface.

In 1940, Bruce Johnston and Kenneth C. Cox (11) with 420 bond pull-out tests on deformed rusted bar for three different series found that the rusted deformed bars gave higher strength at low value of slip than the unrusted bars. And the rusted bars did not affect the ultimate pull-out strength. Some of their tests showed that brushing the rusted bars had no well defined effect upon the bond strength but some of the tests had only a little effect. Also, they indicated the total amount of slip before reaching maximum load was usually greater for bars in the unrusted or slightly rusted condition than for those which were heavily rusted. His result has been plotted in Figure 7 and Figure 8.

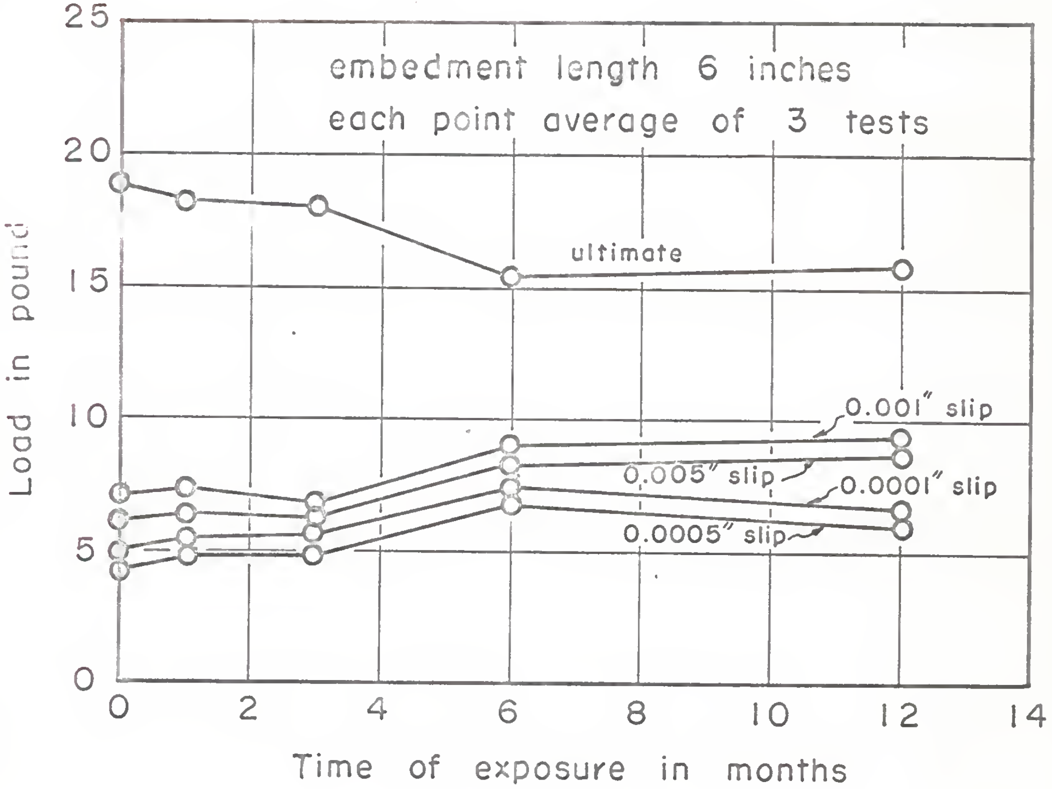

Fig. 7. Effect of rusted $\frac{3}{4}$-in deformed round bars on bond strength.

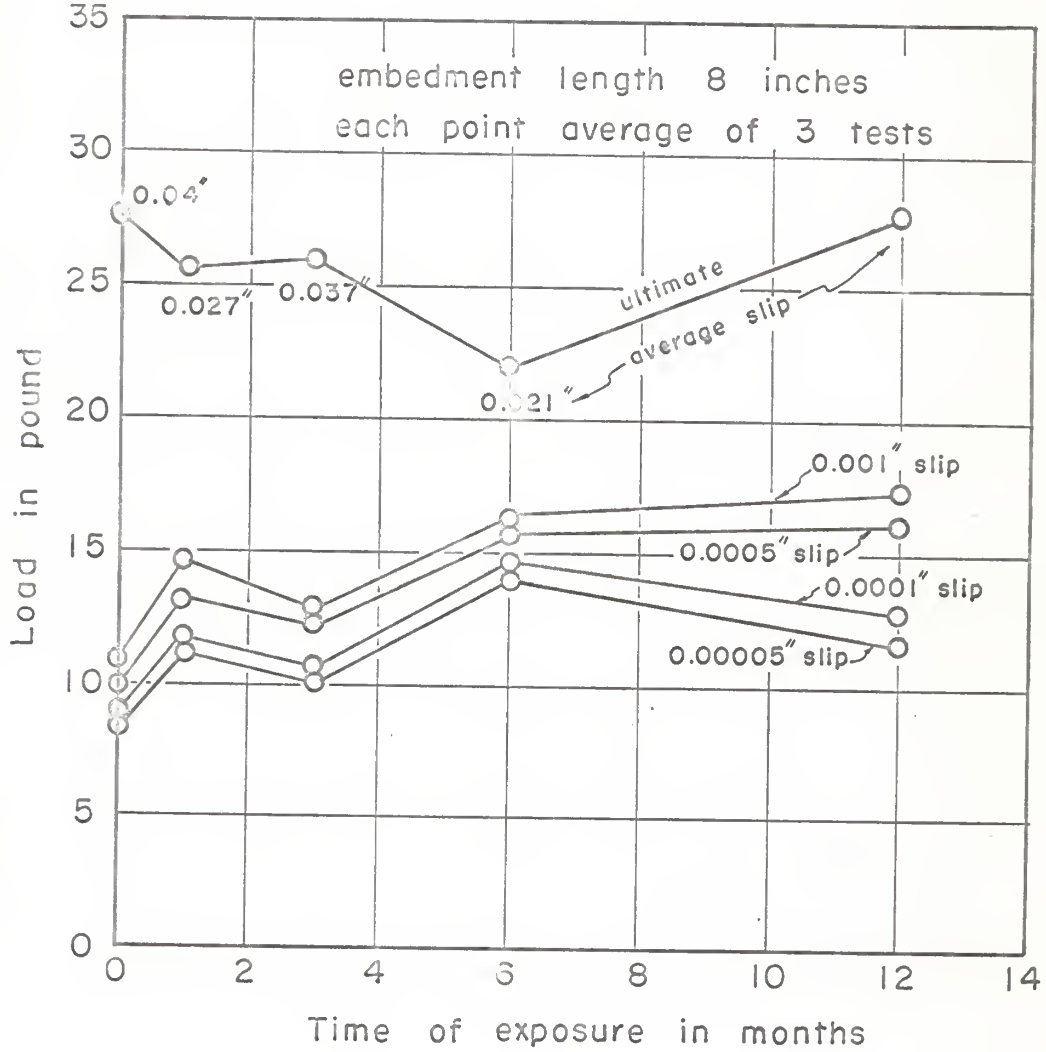

Fig. 8. Effect of rusted 1-in deformed square bars on bond strength.

It is known that the loose rust on the surface of the rusted bars has to be brushed off if increasing the bond strength is desired. Thus, the further tests should made to prove how the brushing of rusted bars increases the bond resistance.

9. Small Addition of Aluminum Powder to Concrete: In deep beams the bond resistance developed by horizontal reinforcing bars held rigidly in pull-out specimens decreases rapidly as the depth of the concrete under the bar increases. This decrease in bond has been shown to be mainly due to differences in the amount of settlement of the concrete under the bars.

Adding a very small amount (seven thousands of one percent) of aluminum powder to the concrete will release the gas which produces a slight swelling in volume sufficient to overcome the normal settlement of the concrete under the fixed bars.

The use of aluminum powder will decease the compressive strength about 15 to 18 percent for quantities of powder normally required to offset settlement; on the other hand, the improvement in bond resistance will be attained. This result was proved by F. R. McMillan (13) in 1942.

Meanwhile, the addition of aluminum powder to concrete will also result in great improvement in the ability of concrete to resist freezing and thawing, especially where thawing is brought about with calcium chloride. Thus, to add aluminum powder to concrete is a good idea to increase not only bond resistance but also concrete durability as well.

CONCLUSIONS

The foundation of the subject of bond resistance was first laid down by Withey and Abrams. Since then, even though great contributions have been made by many research engineers in modifying some of the old concepts, further studies should be made on the remaining unanswered, or partially answered, questions on bond strength.

The report may be summarized as follows:

(1) The bond resistance varies proportionally to the compressive strength of concrete up to 3,000 psi and remains constant for the compressive strength over 3,750 psi.

(2) Bond strength will be increased with a lower than usual water ratio, a large aggregate size, an increased amount of cement and more time allowable for maintenance.

(3) Vertical bars will increase the bond resistance more than horizontal bars.

(4) Bond strength is reduced more by freezing and thawing, or wetting and drying than by moist curing.

(5) Deformed bars offer higher bond strength than plain bars.

(6) Vibration will increase bond resistance, especially the delayed vibration (6 hours after casting).

(7) Adding the length of embedment of steel up to a ratio of L/D about 24 will increase the bond stress.

(8) Most surface coatings, except phosphate, will decrease the resistance of the bond.

(9) Use of rusted steel is one of the convenient ways to increase the bond strength but the loose rust on the bar surface must be brushed off.

(10) Adding a small amount of aluminum powder in concrete will attain the increase both in bond resistance as well as the concrete durability.

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