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

EFFECTS OF TRAFFIC INDUCED VIBRATIONS ON BRIDGE DECK REPAIRS

By
Shraddhakar Harsh
David Darwin

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

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Abstract

Effects of Traffic Induced Vibrations on Bridge Deck Repairs

The effects of simulated traffic induced vibrations on concrete-steel bond strength and concrete compressive strength in full-depth bridge deck repairs are studied. The effects of concrete slump, bar size, and cover are also considered. The vibrations match values obtained from field measurements; vibration amplitude (including that obtained for heavy vehicles) and frequency are duplicated in the laboratory. 1-1/2 in. and 3 in. top covers, #5 and #8 deformed reinforcing bars, and concrete slump ranging from 1-1/2 in. to 7-3/4 in. are used.

Based on the experimental work, traffic induced vibrations appear to have no detrimental effect on either bond strength or compressive strength in bridge deck repairs, if low slump concrete is used. As slump is increased above about 4 in., however, both bond strength and compressive strength drop in comparison with nonvibrated concrete.

INTRODUCTION

Over the years there has been considerable concern about the advisability of maintaining traffic on concrete bridges during repair operations. While it is generally agreed that vibration assists in the consolidation of plastic concrete (2,4,14,16), special concern has centered on the effects of traffic induced vibrations on the repair, if the vibrations continue as the concrete undergoes its initial set.

In spite of the importance of this question, only a limited number of studies have been carried out (7,12). To date, the bulk of the evidence seems to indicate that maintaining traffic during concrete placement does not lower the quality of the repairs (11). However, a number of questions remain.

This report presents the results of a study of the effects of simulated traffic induced vibrations on concrete-steel bond strength and concrete compressive strength in full-depth bridge deck repairs. The effects of concrete slump, bar size, and cover are also considered. The results are analyzed and compared with predictions of the AASHTO Bridge Specifications (1) and the ACI Building Code (3).* Recommendations are made. Additional details of this study are presented in Reference 8.

EXPERIMENTAL INVESTIGATION

To study the effects of traffic induced vibrations on bridge deck repairs, a simply supported steel bridge frame was constructed in the laboratory (Fig. 1). Reinforced concrete deck specimens were bolted to the frame to obtain full composite action. The deck slabs contained block-outs in which "repairs" were made. In addition, cylinder molds were bolted to the slabs to determine the effect of the vibrations on compressive strength. Following the placement of plastic concrete, the bridge frame was subjected to vibrations of an amplitude and frequency typical of those occurring on highway bridges. Nonvibrated, control specimens were used for comparison.

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

Test Specimens

Fifteen 4 ft x 8 ft shallow deck specimens (Fig. 2) were used to study the effects of the vibrations on bond strength. The specimens had a total depth of 12 in. The slab specimens were fabricated in groups of three: Two were subjected to simulated traffic induced vibrations, while the third served as a nonvibrated, control slab. Two top covers were studied, 1-1/2 in. and 3 in.

The slab specimens were cast with 23 in. x 18 in. blockouts, as shown in Fig. 2. The "vibrated" slabs had two block-outs, while the control slabs had four block-outs. With each of the slab groups, one vibrated slab contained #5 bars, while the other contained #8 bars. The reference slab had both #5 and #8 bars. Dummy bars (not tested) were placed 6 in. on either side of the test bars.

Full information on the test variables, including embedment length, cover, bar size, and concrete slump are presented in Table 1.

Standard 6 in. x 12 in. cylinders were used to obtain compressive strength.

Material Properties

Concrete: Air entrained concrete was supplied by a local ready mix plant for both the initial placement and the repair of the test specimens. Type I cement and 3/4 in. nominal maximum size coarse aggregate was used.

Laboratory mixed concrete was used to obtain additional information about the effects of the vibration on compressive strength.

Mix designs, aggregate and concrete properties are summarized in Table 2.

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

Preparation of Test Specimens

When the blocked-out slabs had gained a strength of 3000 psi, as determined from companion test cylinders, the forms were stripped and the areas to be "repaired" were cleaned with a water blaster (rated at 2000 psi) until all of the laitence and carbonation had been removed. Two slabs were then moved to the bridge frame and bolted in place. The nonvibrated slabs remained on the floor.

The test bars were firmly secured, as shown in Fig. 3.

Repair concrete was placed within 24 hours of water blasting. The concrete was allowed to rest for 10 minutes and then was consolidated using a hand held 1-1/2 in. electric vibrator. The slabs were screeded and floated by hand.

Coincident with the placement of the repair concrete, four 6 in. x 12 in. cylinder molds were filled and then attached to the slabs on the bridge frame. Four control cylinders were also made. These cylinders were consolidated using a 1 in. laboratory vibrator for slumps less than 3 in. and rodded for higher slumps. Ten minutes after the concrete had been floated, the simulated traffic induced vibrations were started. The vibrations continued for a period of 30 hours.

The two vibrated test slabs were spaced equally on either side of the center line of the bridge frame (Fig. 1). Linear variable differential transformers (LVDT's) were placed at the slab center lines and used to monitor the amplitude of the vibrations. One LVDT provided feedback for the system, insuring that the desired movement was obtained at the center of the slab. A closed-loop servo-hydraulic actuator was used to drive the system.

Vibrations imposed on the test specimens were selected to match those measured in the field (5,10,11). Throughout the 30 hour period, the slab center lines were subjected to a sinusoidal vibration of ± 0.02 in. in amplitude, at a frequency of 4.0 Hz. To simulate intermittent truck traffic, a single excursion of a 0.5 in. static amplitude, at a frequency of 0.5 Hz., was superimposed upon the small amplitude vibrations once every four minutes (Fig. 4). The vibrations correspond to a peak particle acceleration of 15.6 in./sec.^{2} and a peak particle velocity of 1.44 in./sec.

Vibrations were terminated after 30 hours. The slabs were left in place until the repair concrete had attained a strength of approximately 3000 psi and were then removed for testing.

Test Procedure

The pullout apparatus shown in Fig. 5 was used for the bond tests. The equipment was designed (6) so that both the test bars and the surrounding concrete in the "modified cantilever" slab specimens would be placed in tension, as would occur in a bridge deck.

Prior to testing, pre-existing settlement and shrinkage cracks were marked on the surface of the repairs and photographed.

Each group of three slabs was tested within a 10-hour period, at ages ranging from 4 to 10 days. The test cylinders from the repair concrete, along with cylinders from the surrounding slab concrete, were tested immediately following the pullout tests.

Results and Observations

Pre-test observations: No settlement cracks were observed over bars with a 3 in. cover (Groups 1, 2 and 3).

Settlement cracks were observed in both groups of specimens with a 1-1/2 in. cover (Groups 4 and 5). The settlement cracks followed both test and dummy bars within the repaired area.

In addition to settlement cracks, Group 5 (1-1/2 in. cover, 7-1/2 in. slump) also exhibited shrinkage cracks. Crack intensity was approximately the same on both the vibrated and nonvibrated slabs.

Bond Strength: Typical load versus unloaded end slip curves are presented in Fig. 6. The test results are summarized in Table 1.

The failure mode was dependent upon cover and bar size. The #5 bars with 1-1/2 in. cover and all of the #8 bars failed by longitudinal splitting. Pullout of the #8 bars was accompanied by significant transverse cracking, in addition to the longitudinal cracking. The #5 bars with 1-1/2 in. cover exhibited very little transverse cracking. The #5 bars with the 3 in. cover exhibited no surface cracking upon pullout.

Compressive Strength: A set of four traffic vibrated and four control cylinders were cast with each of the last three groups of repair specimens. Three additional sets, of three vibrated and three control cylinders each, were also tested. The results of these tests are presented in Table 2. Upon crushing, the vibrated and nonvibrated cylinders exhibited a typical conical failure, with the exception of one high slump (7-1/2 in.) vibrated cylinder, which crushed locally at the top end.

Low slump concrete developed a higher strength in the vibrated cylinders, while high slump concrete gave a higher strength in the control cylinders.

EVALUATION OF EXPERIMENTAL RESULTS

The test results are used to examine the effects of traffic induced vibrations on both bond strength and compressive strength. The effects of slump, bar size, and cover on bond strength and of slump on compressive strength are considered in conjunction with the effects of the vibrations. The bond strengths obtained are also compared with those predicted by the AASHTO Bridge Specifications (1) and the ACI Building Code (3).

The ultimate loads listed in Table 1 represent the maximum recorded load for each test. In addition, bond forces for unloaded end slips of 0.010 in. and 0.005 in. are shown for #5 and #8 bars, respectively.

Bond Strength

The bond strength results are summarized in Fig. 7 and 8. Fig. 7 shows the relationship of traffic vibrated to control bond strength as a function of concrete slump, bar size and cover. Fig. 8 compares the individual bond strengths to the values predicted by AASHTO (1) and ACI (3) as a function of concrete strength, bar size, and cover.

The results indicate the *relative* effects of simulated traffic induced vibration; the strengths represent carefully fabricated laboratory specimens. It is the *relative* changes in strength (both increases and decreases) that should be superimposed upon bond strengths as they exist in the field.

Effect of Slump: Fig. 7 illustrates the importance of slump in determining whether traffic induced vibrations are detrimental to concrete-steel bond in bridge deck repairs. The points plotted in Fig. 7 represent the ratio of the bond strengths of the individual vibrated bars to the average value for the control bars for a particular slab group.

For low to medium slump concrete with a 3 in. cover over the bars, the traffic induced vibrations increased the average bond strength by values ranging from 0.1% for #5 bars with 4-1/2 in. slump concrete up to 14.1% for #8 bars with 1-1/2 in. slump concrete. The large scatter exhibited by the results is typical of bond tests with individual values ranging from a decrease in bond strength of 9% to an increase of 18%.

The two control #5 bars from Group 1 yielded. Had these bars been higher in strength, they would have provided a somewhat higher bond strength. In that case, the slope of the line for the #5 bars with 3 in. cover would have been flatter than shown in Fig. 7b.

The bars with 1-1/2 in. cover and high slump concrete (Groups 4 and 5) also exhibit the effect of slump on bond strength. For the #8 bars, the average bond strength of the traffic vibrated bars shows a 7.1% increase at 4 in. slump and a 3.7% decrease with 7-1/2 in. slump concrete, as compared to the control bars.

The same trend is not observed for the #5 bars, because one of the two vibrated bars for the 4 in. slump concrete (Group 4) had an especially low strength (only 88% of the control bar bond strength). The vibrated #5 bars had average bond strengths 7.5% and 6.2% below the control bars for 4 in. and 7-1/2 in. slump concrete, respectively.

Overall, traffic induced vibrations do not appear to be detrimental to bond strength in bridge deck repairs, if the concrete slump is low enough.

Bar size: As seen in Fig. 7, the effects of vibration seem to be more detrimental to the bond strength of #5 bars than #8 bars. This difference might be due to the fact that the slabs in this test were of constant depth. Therefore, for a given cover, the #5 bars had slightly more concrete beneath them. However, it seems unlikely that this small difference (3/8 in.) could explain the relatively large differences observed in these tests.

It is more likely that the difference in the results is due to a difference in failure mode, since at pullout the #8 bars tended to crack more concrete through the depth of the slabs. In that way, the #8 bars were able to utilize the strength of the higher density concrete in the lower portions of the vibrated slabs.

Pullout of the #5 bars was dependent only upon the concrete in the local vicinity of the bar. Since the bars were all near the upper portion of the slab, the higher degree of bleeding and local settlement cracking caused by the vibrations would have had a greater effect.

Effect of Cover: A study of the results (Fig. 8 and Table 1) indicates that lower cover results in decreased bond strength. This is true for slabs subjected to traffic induced vibrations as well as nonvibrated slabs and has been observed in previous investigations (6,9,13,15). The #5 and #8 bars with a 1-1/2 in. cover had average bond strengths equal to 73% and 63% respectively of bars with a 3 in. cover.

A study of Fig. 7 might also lead to the conclusion that bars with a low cover are affected more by the vibrations than bars with a high cover.

However, based on the limited number of tests, this statement should be made with caution.

Design Equations: The test results are compared to the predicted values of bond strength obtained from the expressions for development length in the AASHTO Bridge Specifications (1) and the ACI Building Code (3) in Fig. 8. The following equations express the bond strength, T, for #11 bars and smaller:

$$T = 1.25 \cdot 25L\sqrt{f'_c} \qquad [1]$$

$$T = 1.25 \cdot 625\pi L d_b \qquad [2]$$

in which f'_c = concrete compressive strength (psi); L = the embedded length (in.); and d_b = nominal bar diameter (in.). The 1.25 factors take into account the 20% reduction in development length (equivalent to a 25% increase in bond strength) allowed for bars with a lateral spacing of at least 6 in.

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

As observed in Fig. 8, the AASHTO and ACI requirements are conservative for all of the bars tested, with no individual test result below 1.45 times the predicted value. The results for the #8 bars are more closely grouped than for the #5 bars, because Eq. 1, which is used for the #8 bars, takes into account concrete strength, while Eq. 2, which is used for the #5 bars, does not.

It should be emphasized that all of the bars in these tests were tightly secured to the deck slabs and supporting forms prior to subjecting the decks to vibration, and that these results do not pertain to cases in which the bars may be subjected to some movement relative to the supporting structure while the concrete is setting.

Compressive Strength

Fig. 9 illustrates the effect of the simulated traffic induced vibrations on the compressive strength of standard 6 in. x 12 in. cylinders. The ratio of vibrated to control cylinder strength is plotted as a function of concrete slump. Three data points represent ready mixed concrete, while the other three represent concrete produced in the laboratory. The trend of the results is the same for both sources of concrete. The vibrations result in a small increase in strength for low slump concrete and a decrease in strength for high slump concrete.

The 1-1/2 in. slump concrete was strengthened 4.1% and 0.5% by the traffic induced vibrations for the ready mixed and laboratory concrete, respectively; concrete with a slump of 4 in. (ready mix) and 5 in. (lab) was, respectively, strengthened 2.5% and weakened 1.3% by the vibrations; and concrete with a slump of 7-1/2 (ready mix) and 7-3/4 in. (lab) underwent reductions in strength of 4.8% and 7.7%, respectively.

It is likely that the effects of traffic induced vibration, as a function of slump, depend largely on the amount of segregation that occurs in the concrete. The higher slump concrete will have significantly more bleed water, which will rise in the test cylinders. The greater the agitation, the greater the bleed water that will rise to the top. Therefore, high slump concrete will have a layer of high water-cement ratio, low strength concrete at the upper end of the cylinder. During the compression test, this weaker concrete should dominate the cylinder strength.

On the other hand, the vibrations will help to consolidate the lower slump concrete, resulting in a denser material and a small increase in strength.

Like the bond results, these tests seem to suggest that traffic induced vibrations are not detrimental to concrete strength, if the slump is below about 4 in.

RECOMMENDATIONS AND CONCLUSIONS

Traffic induced vibrations appear to have no detrimental effect on either bond strength or compressive strength in bridge deck repairs, if high quality, low slump concrete is used. In fact, both bond strength and compressive strength appear to increase slightly for low slump concretes.

As slump is increased, however, traffic induced vibrations result in lower bond and compressive strengths. The results indicate that slumps in the range of 4 to 5 in. can be detrimental. Slumps in the range of 7 to 8 in. have a measureable effect when coupled with traffic induced vibrations; for higher slump concretes, decreases of from 5% to 10% can be expected in both bond strength and compressive strength.

Trends in bond strength are similar for both #5 and #8 bars, but the #5 bars appear to be somewhat more adversely affected than the #8 bars. This may be due to differences in failure mode upon pullout.

Increased cover increases bond strength. The data are not extensive enough to provide firm conclusions as to the effect of cover on the change in bond strength due to traffic induced vibrations.

Based on the tests and analyses described in this report, it is recommended that traffic can be maintained on bridge decks undergoing repair, with the stipulations that (1) low slump concrete (3 in. or less) is used for the repair and (2) reinforcement is securely fastened to the structure prior to concrete placement.

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Table 1 Test Specimen Variables and Bond Strength

Slab	Bar No.	Bar Size	Concrete Strength		Slump in.	Embed. Length in.	Cover in.	Specimen Type V-Vib C-Con	End-Slip Load kips	Ultimate Load kips
			Vib. psi	Con. psi						
1b	1	#5	na	3480	1 1/2	5	3	V	8.92	17.8
1b	2								9.35	18.3
1a	3							C	18.9Y	18.9Y
1a	4								12.5	18.4Y
1a	5	#8				9			36.7	41.8
1a	6								23.5	44.2
1c	7							V	33.6	42.4
1c	8								32.7	43.6
2a	9	#5	na	3410	4 1/2	4	3	C	5.76	15.6
2a	10								8.76	19.3
2b	11							V	5.21	16.1
2b	12								8.74	18.7
2a	13	#8				9		C	28.4	42.8
2a	14								20.4	43.1
2c	15							V	14.1	43.5
2c	16								28.8	47.3
3a	17	#5	3080	2960	1 1/2	4	3	C	5.03	11.7
3a	18								5.45	13.3
3b	19							V	5.11	13.1
3b	20								6.71	14.1
3a	21	#8				9		C	20.0	35.2
3a	22								17.3	36.8
3c	23							V	25.3	39.4
3c	24								31.9	42.5
4a	25	#5	3310	3230	4	4	1 1/2	C	4.12	9.92
4a	26								4.52	10.6
4b	27							V	4.62	8.99
4b	28								6.33	10.0
4a	29	#8				9		C	15.5	25.2
4a	30								13.8	25.2
4c	31							V	21.9	26.4
4c	32								21.8	27.5
5a	33	#5	2770	3000	7 1/2	4	1 1/2	C	9.08	12.4
5a	34								8.19	12.8
5b	35							V	8.12	11.5
5b	36								8.35	12.2
5a	37	#8				9		C	11.3	24.0
5a	38								25.6	30.5
5c	39							V	19.2	25.8
5c	40								18.3	27.1

Y after load indicates pullout force
exeeded yield strength

Table 2(a) Concrete Mix Design and Properties

	Slab Concrete								Repair Concrete							
				Aggregate								Aggregate				
Test Group	W/C Ratio	Cement #	Water #	Fine # *	Coarse # +	Slump in.	Air %	Strength psi	W/C ratio	Cement #	Water #	Fine # *	Coarse # +	Slump in.	Air %	Strength psi
1	0.44	591	235	1470	1482	4	na	5160	0.46	579	267	1448	1449	1 1/2	5	3480
2	0.46	579	265	1453	1441	1 1/4	4 1/2	na	0.49	614	300	1413	1425	4 1/2	2	3410
3	0.44	555	244	1455	1545	4 1/4	10 1/2	2960	0.44	555	244	1455	1536	1 1/2	7	2960
4	0.44	555	244	1455	1536	3 1/4	5 1/2	5160	0.44	564	248	1491	1455	4	7	3230
5	0.44	555	244	1455	1536	5 1/2	7 1/2	3760	0.44	680	300	1300	1440	7 1/2	7 1/2	3000

+Crushed Limestone - Hamm's quarry, Perry, KS
Bulk specific gravity = 2.52, absorption = 3.5%
Maximum size = 3/4 inch
*Kansas river sand - Lawrence Sand Co., Lawrence KS
Bulk specific gravity = 2.62, absorption = 0.5%
Fineness modulus = 3.0
Air entraining agent - Vinsol resin
Design air entrainment = 6%
Slump and air values are as measured

Table 2(b) Concrete Mix Design and Properties
(Cylinder Test)

				Aggregate				
Cylinder Group	W/C ratio	Cement #	Water #	Fine #	Coarse #	Slump in.	Air %	Strength psi
1	0.44	680	300	1300	1440	7 3/4	5 1/2	3770
2	0.44	645	284	1375	1438	5	4 1/2	3870
3	0.44	555	244	1536	1435	1 1/2	5	3930

Materials used are same as test slabs
Design air entrainment = 6%
Slump and air values are as measured

Table 3 Average Test Bar Data

Bar Size	#5	#8
Deformation Spacing in.	0.336	0.545
Deformation Height in.	0.041	0.057
Deformatio Angle Deg.	54	50
Deformation Gap in.	0.118	0.313
Nominal Weight #/ft.	1.012	2.650
Deformation Bearing Area sq. in./in. length	0.196	0.239
Yield Strength ksi	59.50	63.47
Tensile Strength ksi	102.9	104.6

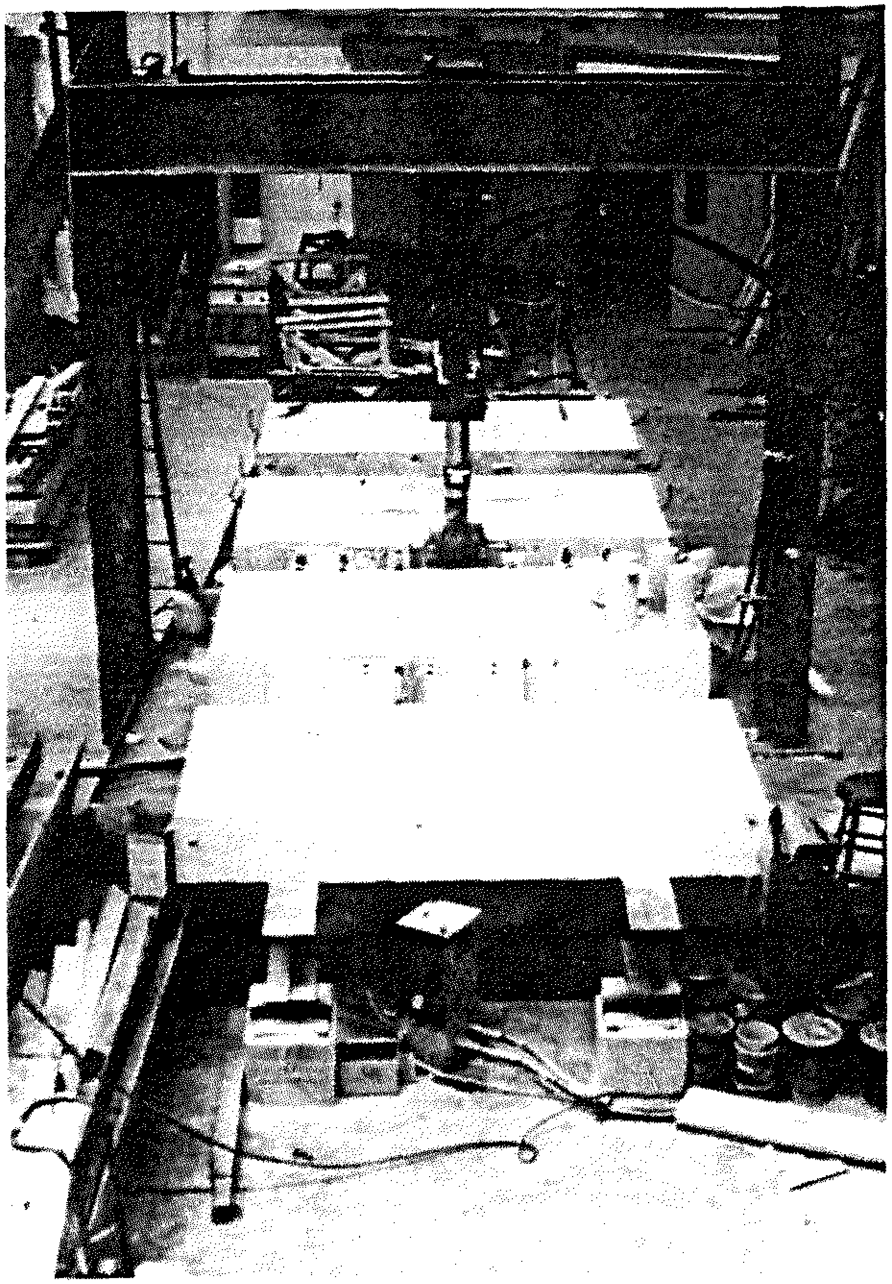
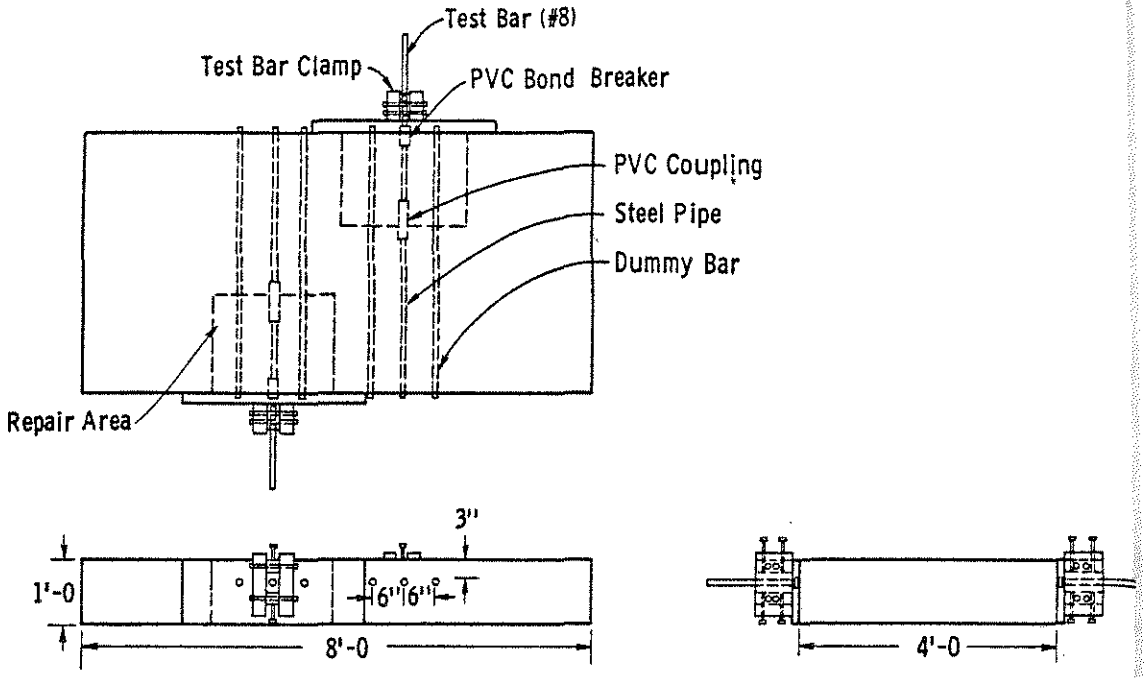
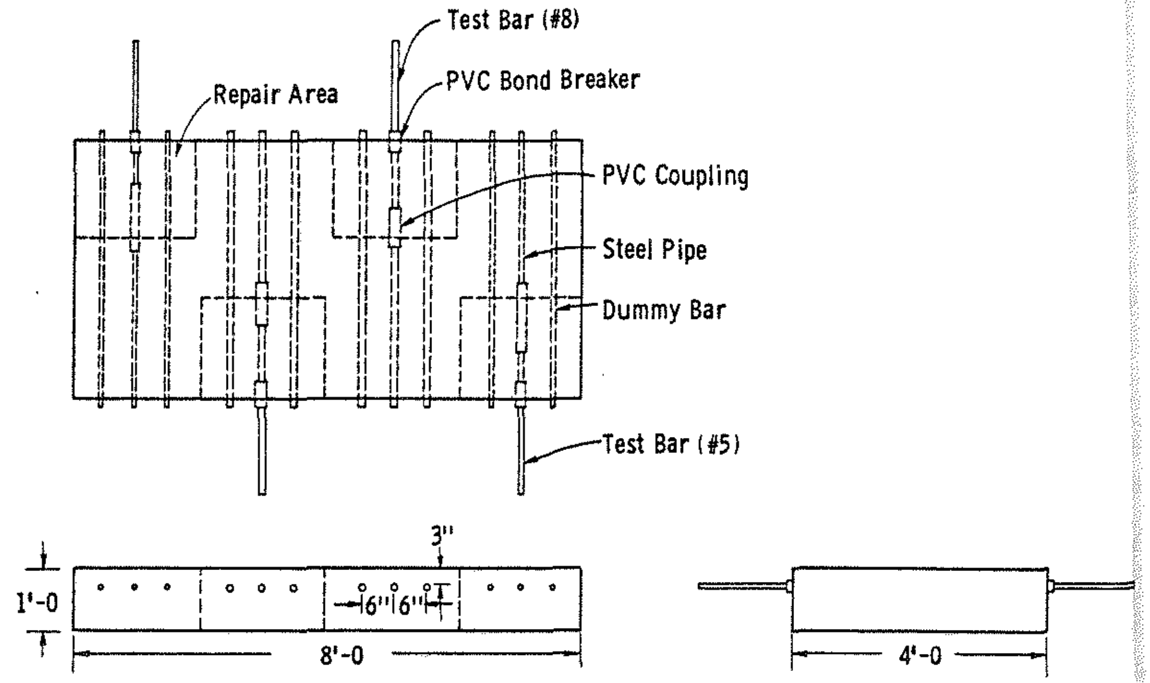


Fig. 1 Bridge Frame, Actuator and Test Slabs.

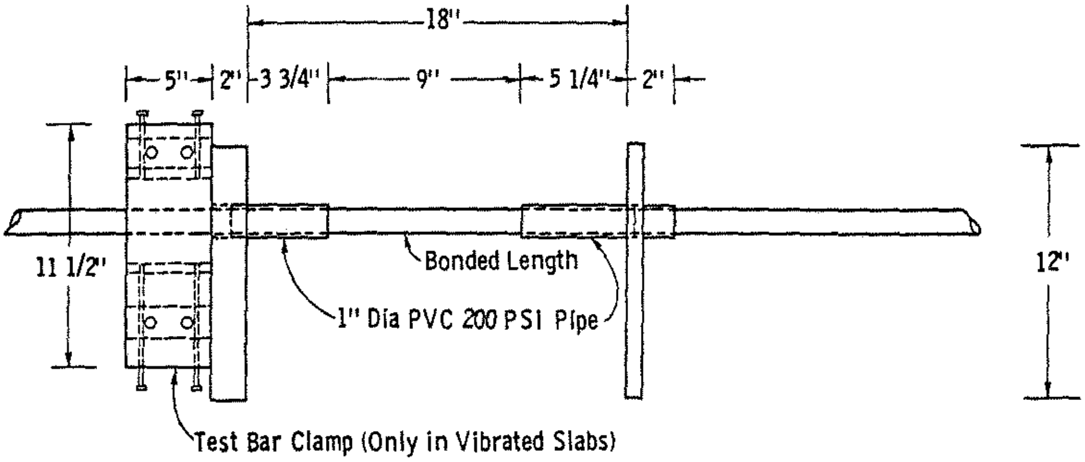


Traffic Vibrated Slab

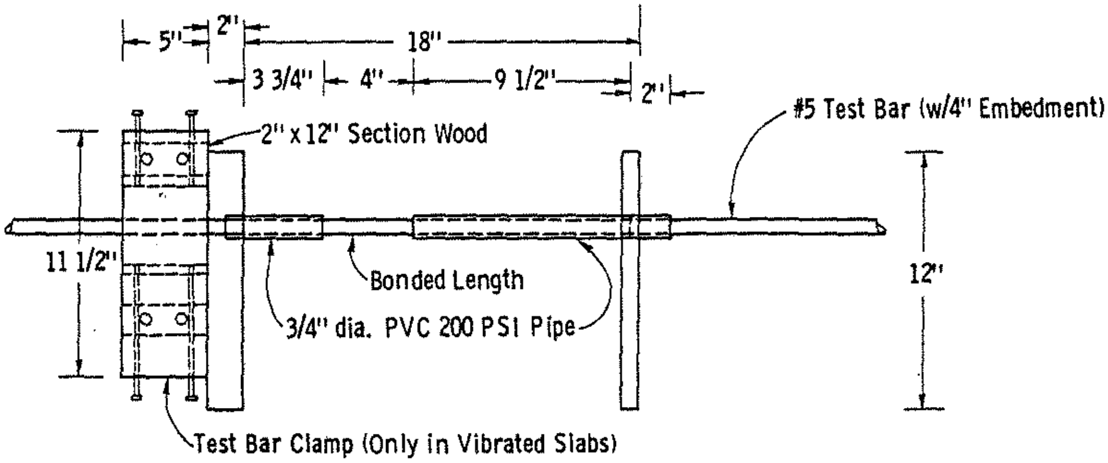


Control Slab

Fig. 2 Test Slabs.



#8 Test Bar Installation



#5 Test Bar Installation

Fig. 3 Test Bar Installation.

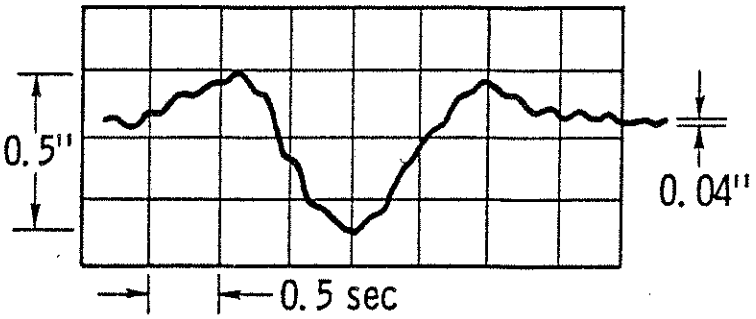


Fig. 4 Typical Time Trace of Intermittent Large Vibration.

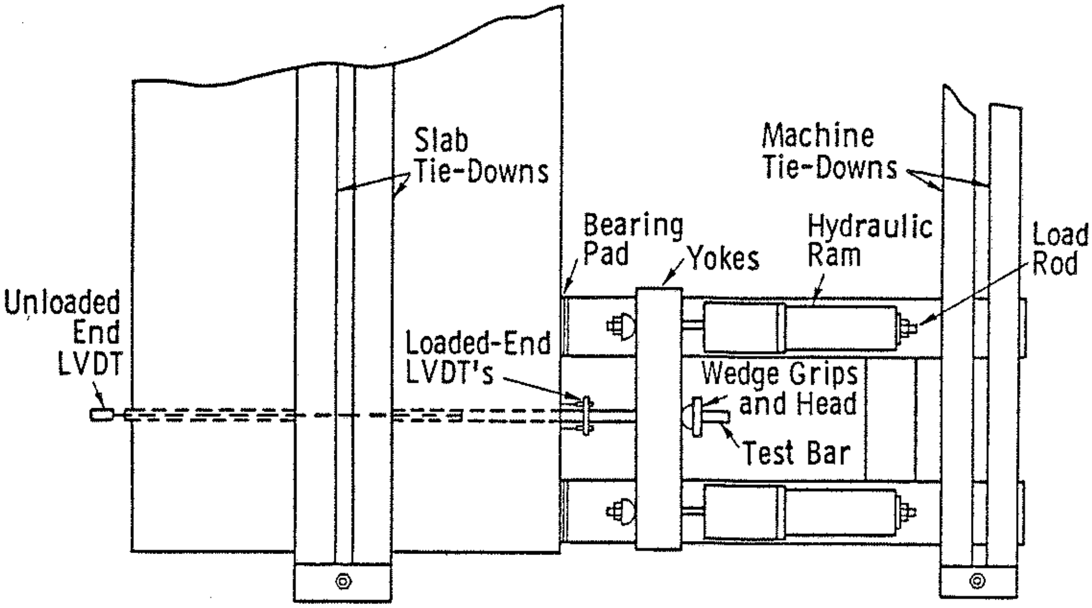


Fig. 5 Schematic of Bond Test.

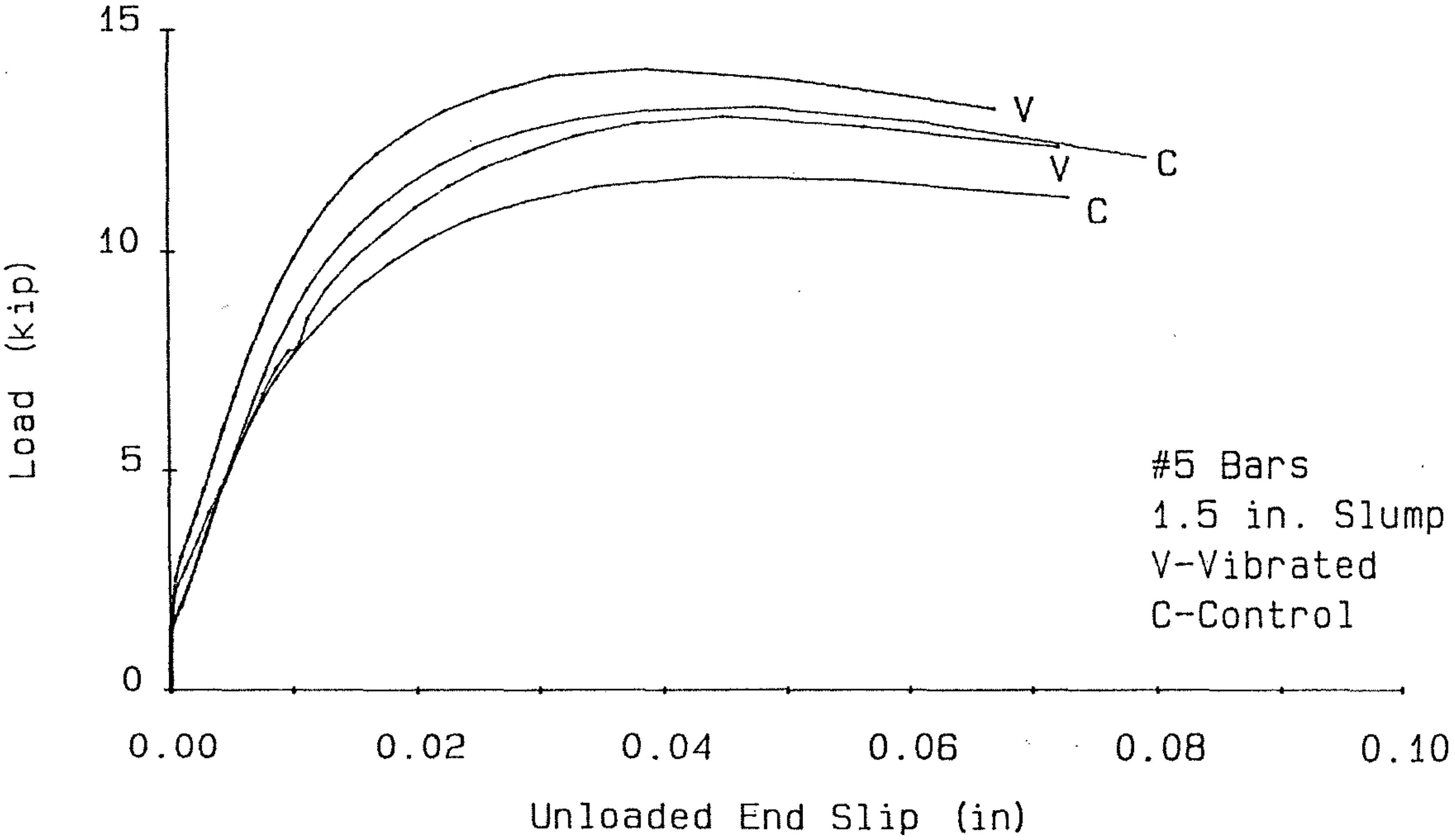
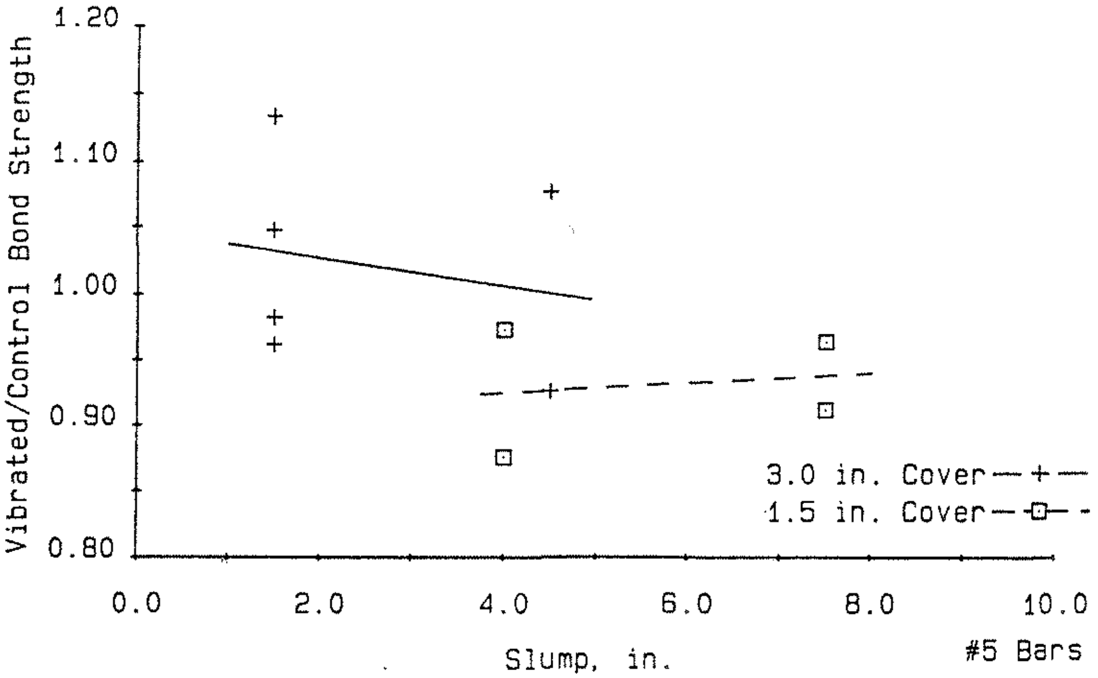
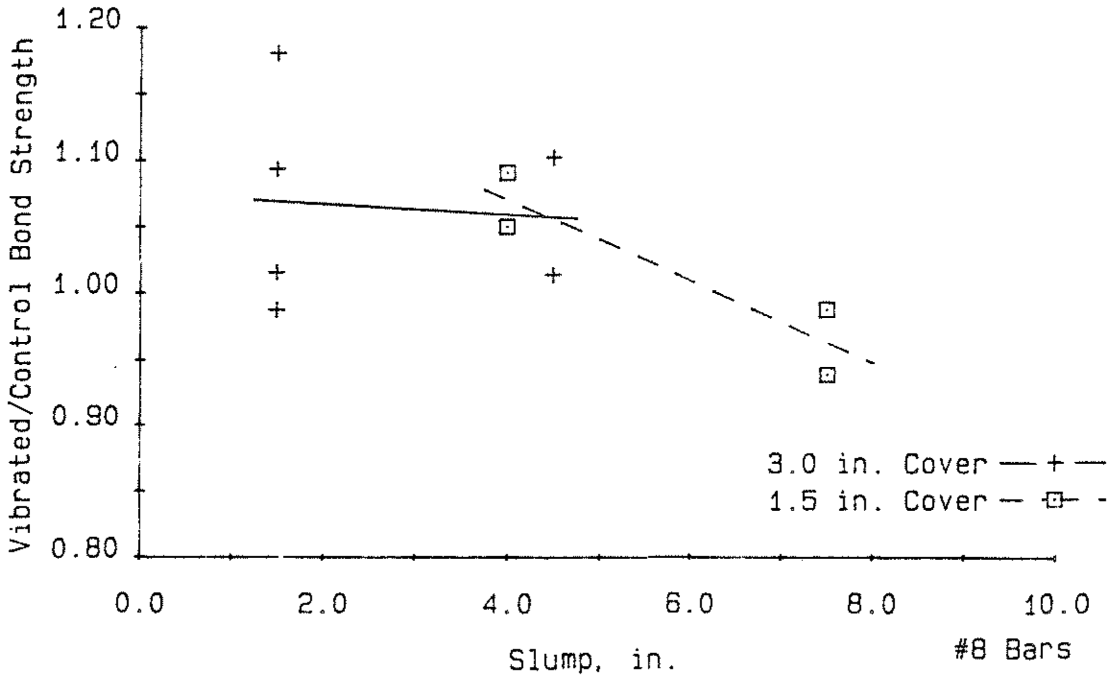


Fig. 6 Typical Load-Slip Curves.



a)



b)

Fig. 7 Ratio of Traffic Vibrated to Control Bond Strength versus Slump.

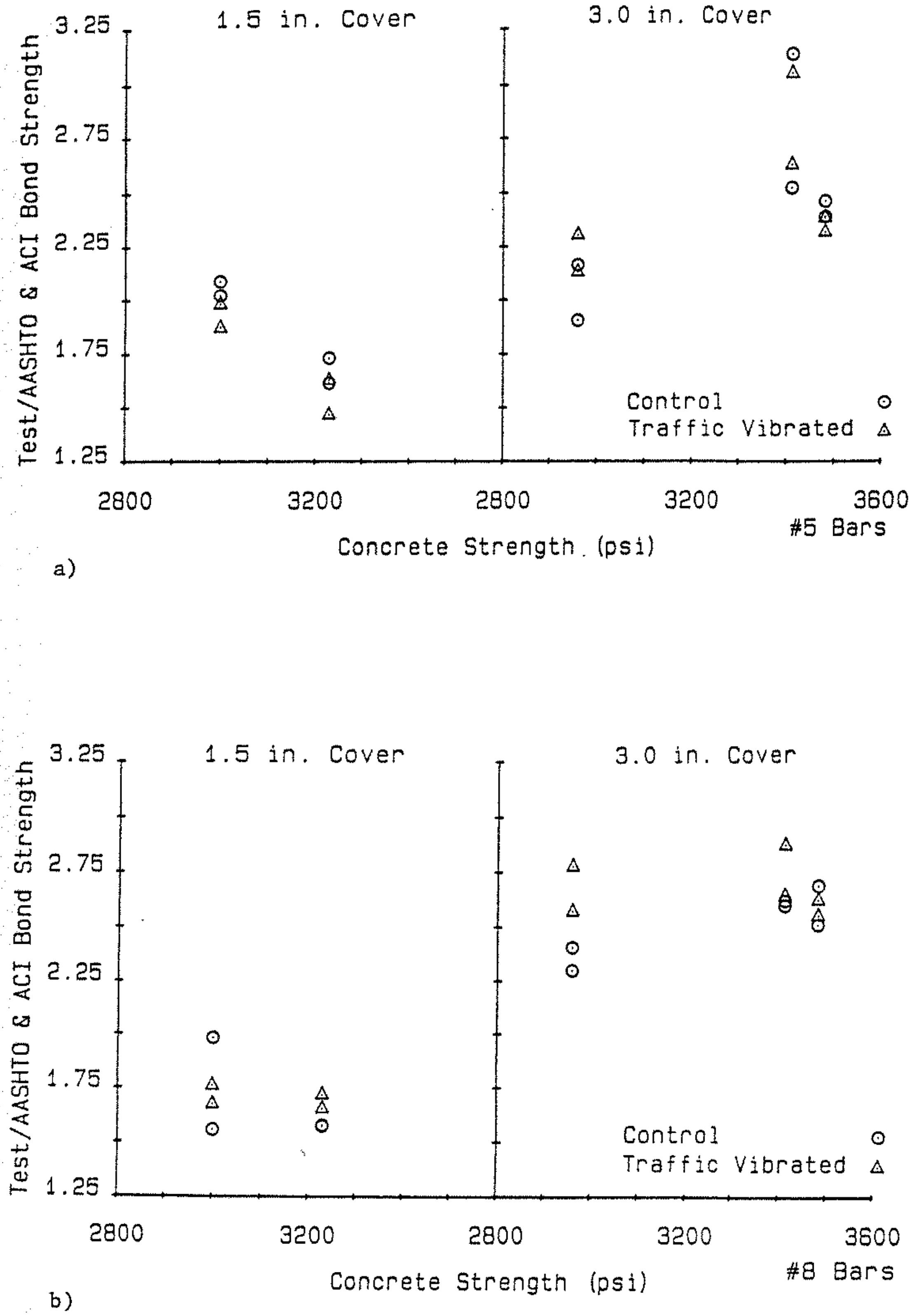


Fig. 8 Comparison of Experimental Bond Strengths to AASHTO(1) and ACI(3) Bond Strengths.

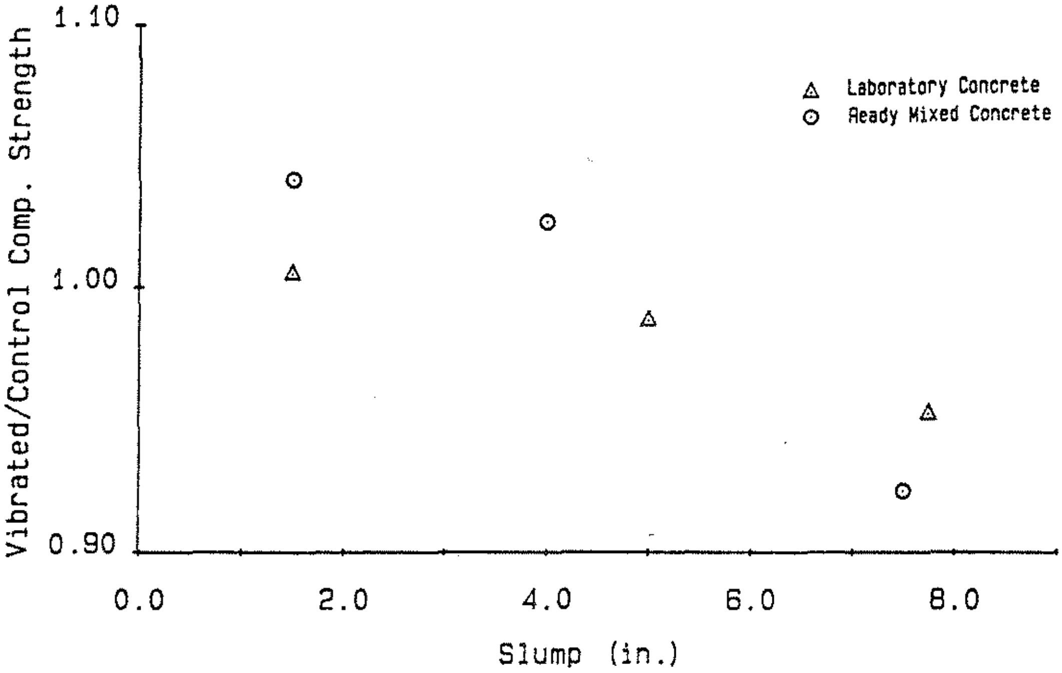


Fig. 9 Ratio of Traffic Vibrated to Control Compressive Strength versus Concrete Slump.