LABORATORY INVESTIGATION OF DELAMINATION AND DEBONDING OF THIN-BONDED OVERLAYS DUE TO VEHICULAR VIBRATION

by

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EFFECT OF VEHICULAR VIBRATION ON DEBONDING AND DELAMINATION OF CONCRETE OVERLAYS

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APPENDIX A

A Summary of an Investigation of the Delamination of Thin-Bonded Overlays

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A Summary of an Investigation of the Delamination of Thin-Bonded Concrete Overlays

Introduction

An investigation of the delamination of thin-bonded concrete overlays was conducted on 6 overpasses on IH-10 in El Paso, Texas. These 200-ft overpasses consist of 3 spans of Precast Concrete Box Beams with a wood float finish. The 30 inch diameter columns rest on 36-in. diameter drilled shafts. The overpasses were constructed in two phases with the thin-bonded overlays (average 3 1/2 inch depth) being poured in the summer of '87 (phase I; outside lanes) and in the spring of '88 (phase II; inside lanes).

The placement, consolidation and curing methods were the same for all areas and phases. The 7-sack, Type II cement concrete mix was placed directly from the chutes of the ready mix trucks used for concrete mixing and delivery. Hand-held vibrators, in conjunction with an Allen Razorback vibratory air screed, were used for consolidation. The overlays were cured with wet burlap for 24 hours followed by 7 days of water cure (wet mat). Phase I overlay pours were placed during a construction sequence when that portion of the structure was not subjected to the direct vibrations caused by IH-10 traffic (new structure not connected to old structure). However, Phase II overlay pours were placed after traffic had been diverted to the newly completed section (Phase I) and were consequently, subjected to the vibrations from IH-10 traffic during the placement, consolidation and curing of the concrete.

Eight months after the thin-bonded concrete overlays had been placed they began to show signs of distress. All interior bent line transverse joints were severely cracked and loss of material was not uncommon. Alligator cracks also appeared throughout the overlays with no specific pattern from one overpass to the next. Some overpasses exhibited much more distress than others.

Investigation

In January 1989, soundings of the overpasses were conducted to determine the extent of the delamination. Standard size hammers were used to sound the decks and the areas of delamination were recorded on Deck Layout Plan Sheets. Some areas were difficult to distinguish between delamination or merely the reverberations of the prestressed box beams hollow voids. Core samples of the overlays were then obtained to try to confirm the results of the soundings. A total of 110 cores were obtained and analyzed visually for delamination. Several possibilities for the overlay failure were investigated including mix design variations. The air-content, fly-ash content and even the cement sources were reviewed. The weather conditions at the time of placement for each overlay pour were also checked. However, any changes in these conditions could not be correlated to the overlay failure areas. The construction method was also reviewed and found to be in complete accordance with the specifications of the item.

Since this type of thin-bonded concrete overlay had been used on other projects in El Paso, a comparison of this project, with its unique construction phasing requiring overlays to be placed adjacent to active IH-10 traffic and its accompanying vibrations, was made against two other overlay projects, Darbyshire Overpass and Raynolds Street Overpass. During the construction of these structures, however, no through traffic was permitted and consequently experienced no vibrations. The cores obtained from both the Darbyshire and Raynolds Street projects exhibited tight bonding at the interface and the decks were virtually crack free.

In April 1989, the overpasses were resounded to determine the progression of the delamination. The delaminated areas and severe cracks were plotted on the Deck Layout Plan Sheets for permanent reference and for comparison to the original sounding. Some overpasses were found to have more delaminated areas than 3 months earlier. Others remained virtually the same except for new or more severe cracking.

It was then clear that the delaminated concrete overlay would have to be removed and replaced or some how sealed against moisture to prevent further damage from occurring. After determining that an epoxy coating to seal the overlay was prohibitive because of cost and the inability to thoroughly clean all cracks, a method for removing and replacing the existing

lines for additional strength at the maximum moment location.

The Type III concrete was placed on the west half of the test section (dry surface; 1/2 grout - 1/2 without grout) followed by the placement of the Pyrament concrete (SSD surface; no grout). Both concretes were consolidated by the use of immersion vibrators (spud type) and a vibrating screed. The finishing and texturing was in accordance with the contract specification (Item 439). The entire test area was cured with a clear membrane curing compound. All IH-10 traffic was routed to the frontage road during and for 12 hours after the pour. Several different types of tests were performed on the test section specimens at specified time intervals for 24 hours. Core samples were drilled for the direct tension bond test. The Center for Transportation Research - UT Austin performed the tests. Results in tensile, shear, compression, and flexure tests lead to the decision of the material to be used and the construction methods to be followed in the repair of the delaminated thin-bonded concrete overlay.

Experimental Test Section Results

A 12 hour result was selected for comparison in the tensile, shear, compressive, and flexural tests because of field conditions. During the repair of the concrete overlay, IH-10 traffic was routed onto the frontage roads during and for 12 hours after the completion of the concrete placement as in the case of the test section. The "pull-out" tests (tension) performed in the test section indicate that the Type III concrete mix without bonding grout attained a higher psi value. However, this value of 119 psi was not much greater than the Type III with grout. The Pyrament results on a saturated surface dry condition was quite low, 80 psi. This was the reason the Pyrament representative requested an additional test section be prepared with a dry surface, with and without bonding grout, and additional tests be performed. The results on a dry surface were much better than on the SSD section but still with no significant advantage over either of the Type III results.

Pyrament concrete obtained an average flexural strength of only 53 psi greater than the Type III at 12 hours. In compression, however, the Type III cylinders surpassed the Pyrament specimens by 680 psi. A comparison between Type III and Pyrament could not be made in the direct shear test because a test for Pyrament was not obtained. The difference between Type III with grout and without grout was insignificant, only 16 psi.

A direct shear test was also performed on 12 original concrete overlay core specimens and signified and important correlation. The average of the outside lane (construction Phase I) exceeds the average of the inside lane (construction Phase II) by 301 psi, indicating a difference in the bond strength at the interface of the overlay and box beam. Phase I overlays were placed during a construction sequence when that portion of the structure (new) was completely separate

from the old overpass and therefore, not subjected to the vibrations caused by IH-10 traffic. Construction Phase II overlays were placed after traffic had been diverted to the newly completed section and were consequently, subjected to the direct vibration of ÍH-10 traffic on the adjacent lanes during placement, consolidation and curing. Although the core specimen areas were poured at different times (approx. 8 months apart), after more than one year, the difference in strength cannot be attributed to the age of the concrete. The difference in direct shear test results substantiates the delamination detected by the bridge soundings. These soundings found considerably more delamination on the inside than on the outside lanes.

In 12 hours, the Type III direct shear results average 520 psi. This value is approximately 78% of the 669 psi obtained in direct shear on the original overlay cores (outside lanes; Phase I). These two values were compared because both concrete overlays were placed under similar conditions, i.e. no direct vibrations caused by adjacent travel lane
traffic.

Concrete Overlay Repair Procedure

Upon review of the test section results, field conditions, construction procedures and numerous other factors, it was determined that the Type III Cement/Concrete would be used in the repair of the delaminated concrete overlay areas. Only those areas where delamination was detected during the second sounding, either for the first time or as confirmation of the first test, was repaired. The second sounding was believed to be more accurate because the "sounders" had gained experience from the initial tests. Approximately 31% of the original total overlay was replaced (about 2900 S.Y.).

The delaminated overlay areas were saw-cut and removed by jackhammers. This method proved to be much faster and more economical than using a roto-mill machine. The edges of the removed areas were also a good indication if all the delaminated overlay had been removed. A good, tight bond between the overlay and the box beam was quit evident. A void or a loose bond indicated delamination in which case the limits of removal were extended until all delaminated overlay was removed. The box beam surface was then roughened with a scabbler or at times with a bushing hammer in small areas. Sand patch tests were randomly taken to ensure the desired texture was obtained (0.05 in. minimum).
The interior bent line transverse joints were reinforced with #4 epoxy coated rebar with alternate rebars allowed to protrude into the longitudinal repair areas for additional tie. A bond breaker consisting of mastic plus two layers of 15-lb. felt, graphite, and grease was placed at the joint in order to prevent any cracking in the shear key caused by beam deflections from reflecting into the overlay. The surface was sandblasted by a compressed, filtered, air blast. The filter was used, unlike in the original overlay placement, to prevent any oil contaminants from being

applied to the surface - acting as a bond breaker. A dry surface with no bonding grout was required based on the test section results.

An eight sack concrete mix design with Type III cement was used. In addition to the results of the test section, Type III cement is a common, well-known and readily available material. Concrete with Type III cement and a good slump is workable and not easily affected by local weather conditions and it does not require special mixing instructions or expertise. Test section results showed Pyrament to be comparable to the Type III mix in strengths. However, Pyrament was not selected primarily because its test results did not justify the extra cost (twice that of Type III or about $155.00/C.Y.). Results of 2 to 3 times the Type III design were initially established as an acceptance criteria. The preparation (batching) of the Pyrament concrete is a slow process which requires a Pyrament representative to obtain a proper, workable mix because of its special procedure for mixing and adding water. The daily occurrence of low humidity and high temperatures in the El Paso area hinders the workability of Pyrament. Construction workers are expected to work at a fast pace with little room for error because of Pyrament's 90 minute set time. On pours which might continue for several hours, it is unreasonable to expect such a working pace to be maintained. The placement, consolidation, finishing, tinning and curing sequence appeared so critical that even a minor equipment breakdown would result in the loss of the pour. Overall, Pyrament was much too sensitive in its preparation and placement requirements for this application.

The placement of the concrete overlay was accomplished during the weekend when IH-10 traffic was routed to the frontage road. The interstate remained closed to traffic for such time that a minimum of 12 hours was allowed for bonding after the last concrete placed had taken initial set. As stated previously, 78% of the bonding strength (direct shear) was achieved in 12 hours when no direct vibrations occurred. The compressive, flexural and tensile strengths obtained in 12 hours were also considered acceptable (sufficient for good bonding to occur).

The consolidation, finishing, texturing and curing were similar to the original concrete overlay placement. Wet burlap was placed on the overlay as soon as no damage to the overlay would occur. Soon after, mats were placed on top of the burlap and a wet mat cure was maintained for 5 days instead of the original 7 day cure because of the high early strength (Type III) cement used. Also, the linseed oil originally placed after the wet mat cure was omitted in the repair work. Experience has shown that it is impossible to maintain the linseed oil surface treatment due to high traffic volumes. Because of the required construction phasing, numerous longitudinal joints were created. It was decided that a Two-Course Hot Asphalt-Rubber Seal Coat would be applied to the entire concrete overlay acting as a moisture barrier. The seal coat was believed to be imperative for the life expectancy of the overlay.

Summary

The total cost of the replacement of the delaminated concrete overlay was approximately $434,000 or $150/S.Y.. This cost included the removal, replacement, materials, traffic control, etc. Also an additional 71 days (3 1/2 months) was granted to the contractor. The repair work was completed on September 3, 1989 and with an Average Daily Traffic (ADT) of 133,000 vehicles, the system has been working well.

A roughened, dry surface without bonding grout, an 8 sack Type III mix design, and the elimination of traffic vibrations combined to create an ideal situation for a strong bond to develop at the interface between the overlay and the box beam. A strong bond prevents future delamination from developing and gives a thin-bonded concrete overlay a satisfactory life expectancy.

APPENDIX B

Bridge Vibration Field Measurements

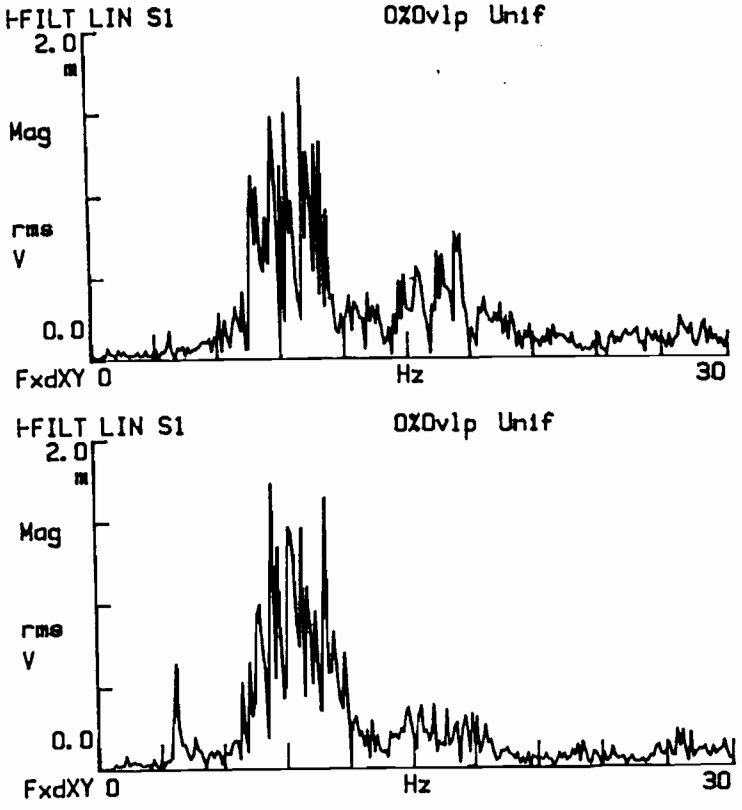

Figure B.1 Displacement Spectra of Short Span of Hawkins Bridge at 8:35 A.M.
Top : Peak-Hold Average
Bottom : Arithmetic Average

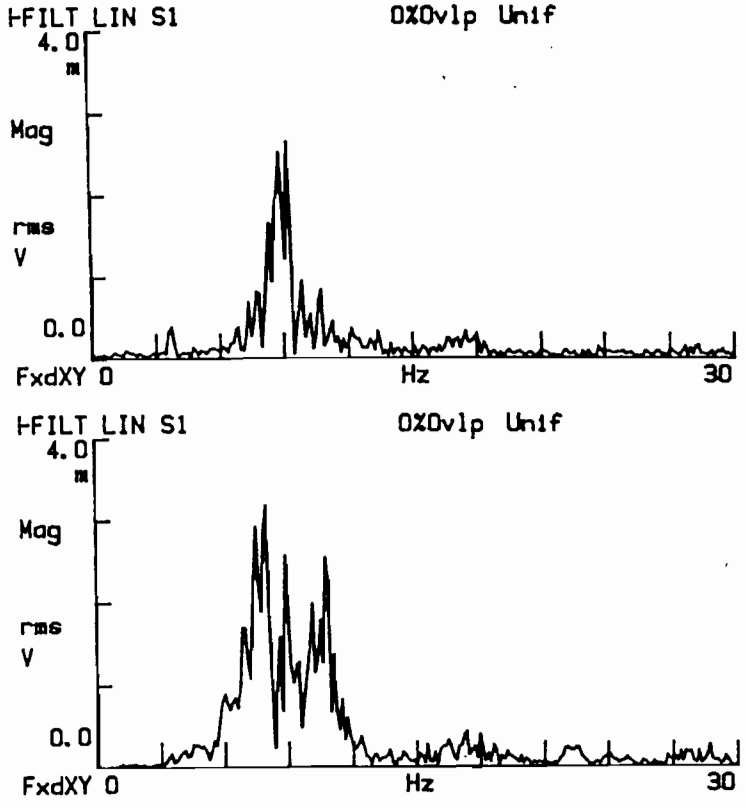

Figure B.2 Displacement Spectra of Short Span of Hawkins Bridge at 8:54 A.M.
Top : Peak-Hold Average
Bottom : Arithmetic Average

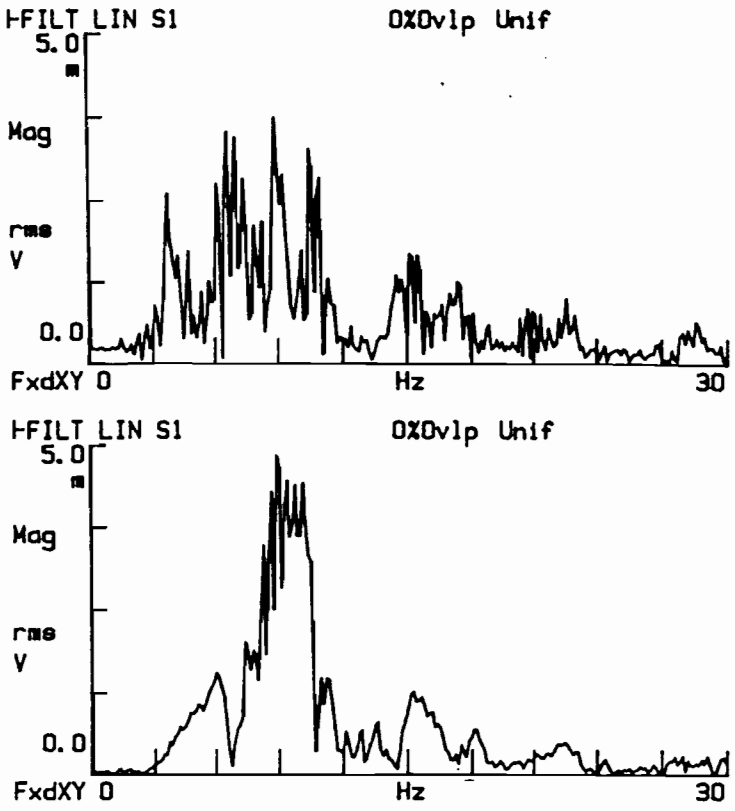

Figure B.3 Displacement Spectra of Short Span of Hawkins Bridge at 9:14 A.M.
Top : Peak-Hold Average
Bottom : Arithmetic Average

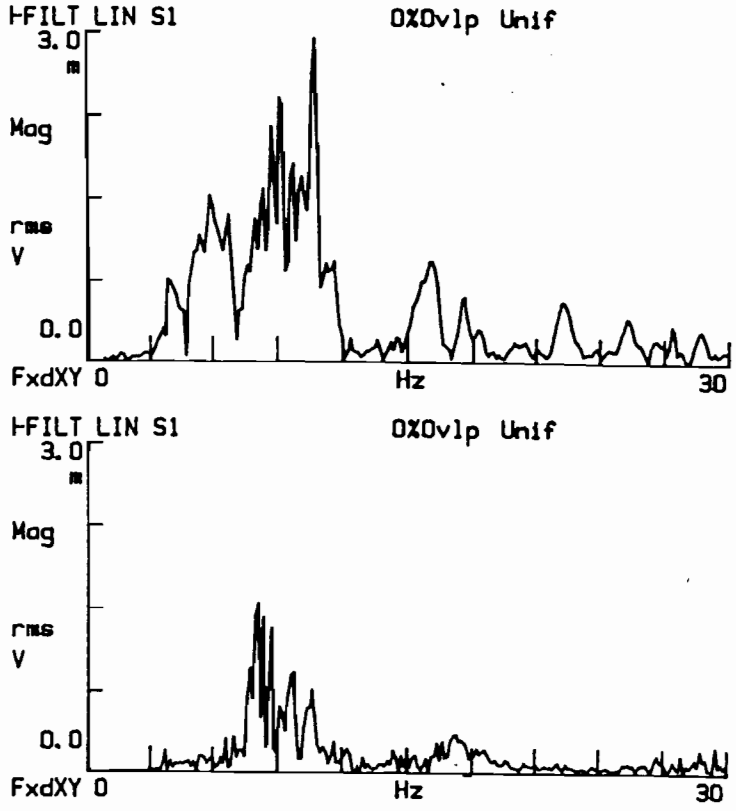

Figure B.4 Displacement Spectra of Short Span of Hawkins Bridge at 9:36 A.M.
Top : Peak-Hold Average
Bottom : Arithmetic Average

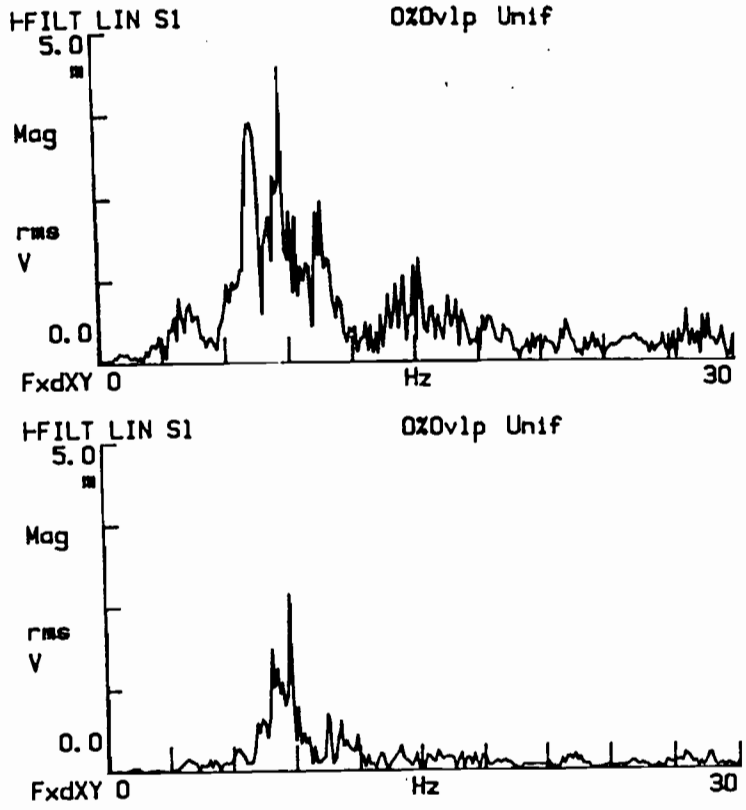

Figure B.5 Displacement Spectra of Short Span of Hawkins Bridge at 9:56 A.M.
Top : Peak-Hold Average
Bottom : Arithmetic Average

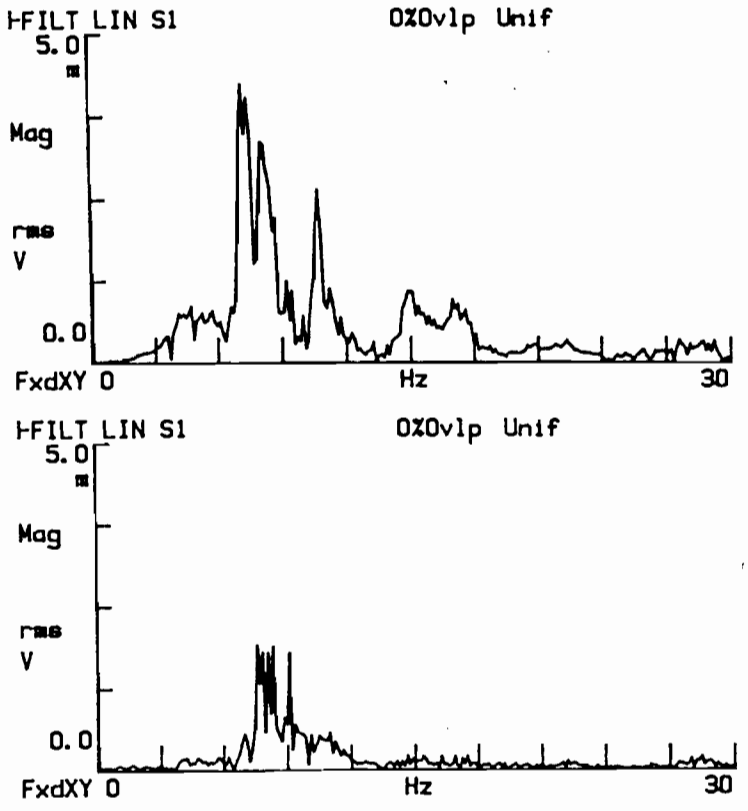

Figure B.6 Displacement Spectra of Short Span of Hawkins Bridge at 10:17 A.M.
Top : Peak-Hold Average
Bottom : Arithmetic Average

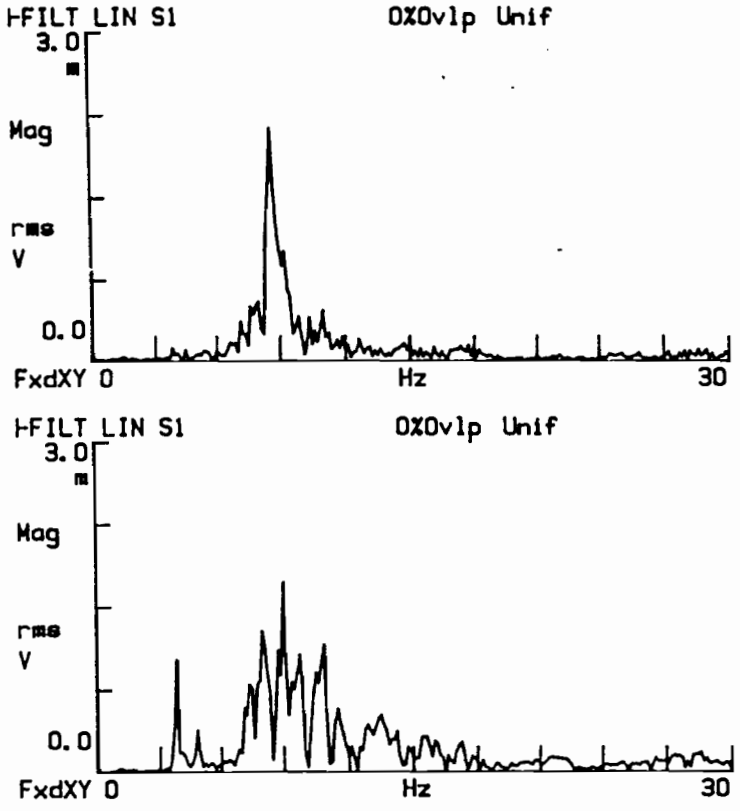

Figure B.7 Displacement Spectra of Short Span of Hawkins Bridge at 10:38 A.M.
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Bottom : Arithmetic Average

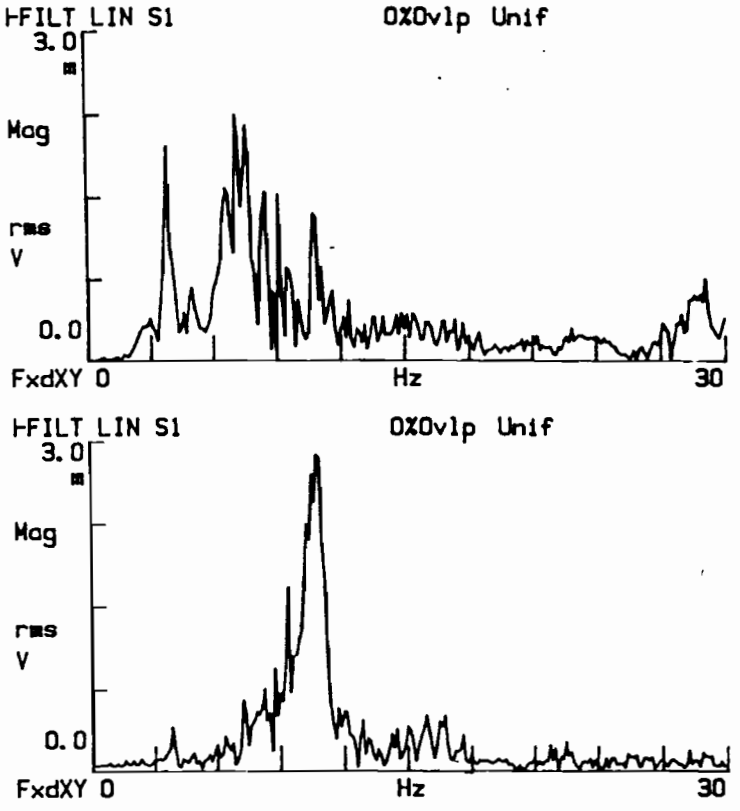


Figure B.8 Displacement Spectra of Short Span of Hawkins Bridge at 10:58 A.M.
Top : Peak-Hold Average
Bottom : Arithmetic Average

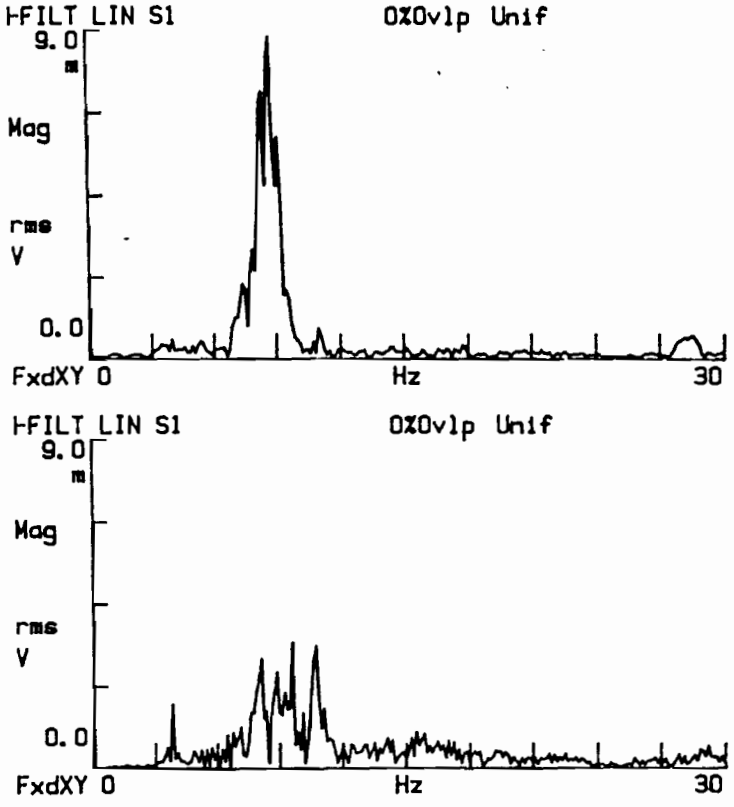


Figure B.9 Displacement Spectra of Short Span of Hawkins Bridge at 11:18 A.M.
Top : Peak-Hold Average
Bottom : Arithmetic Average

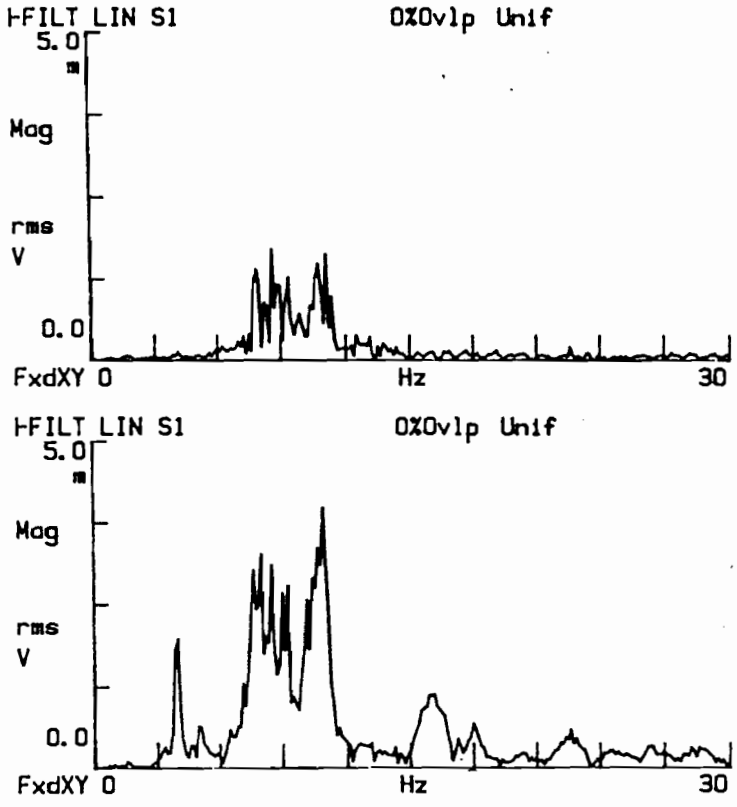


Figure B.10 Displacement Spectra of Short Span of Hawkins Bridge at 11:36 A.M.
Top : Peak-Hold Average
Bottom : Arithmetic Average

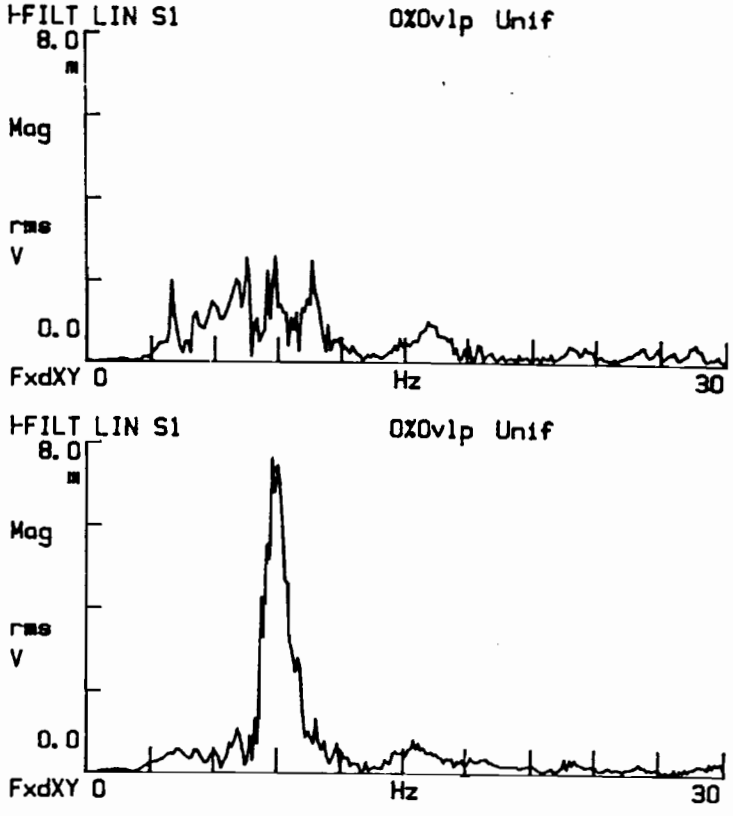


Figure B.11 Displacement Spectra of Short Span of Hawkins Bridge at 11:51 A.M.
Top : Peak-Hold Average
Bottom : Arithmetic Average

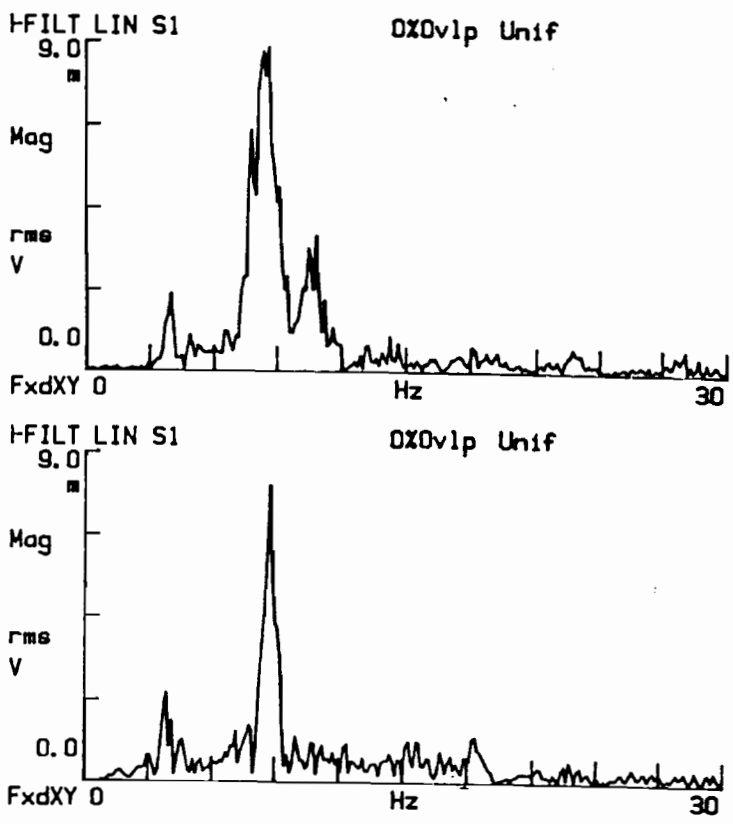
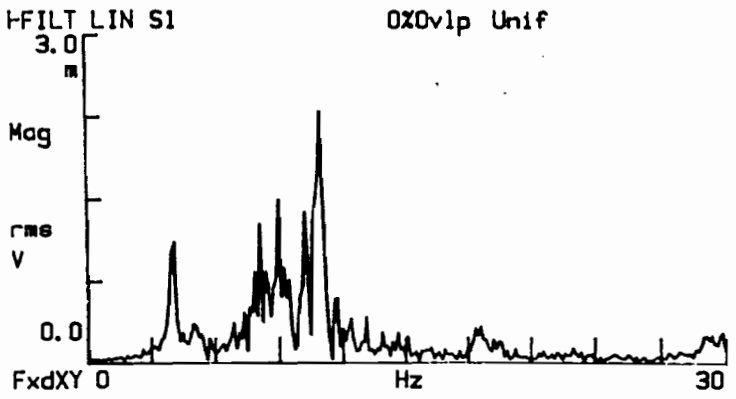


Figure B.12 Displacement Spectra of Short Span of Hawkins Bridge at 12:07 P.M.
Top : Peak-Hold Average
Bottom : Arithmetic Average



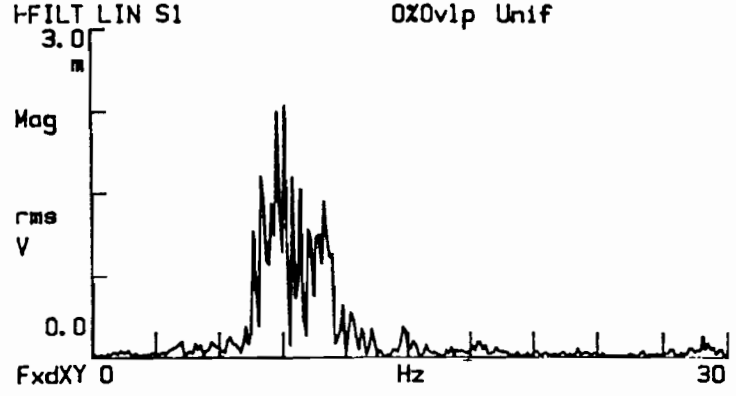
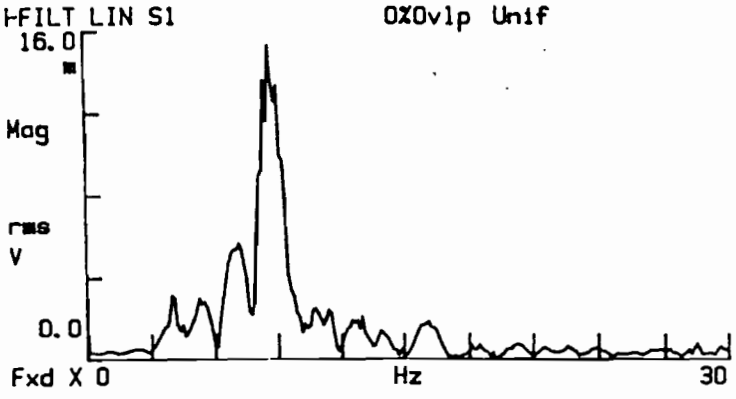


Figure B.13 Displacement Spectra of Short Span of Hawkins Bridge at 12:26 P.M.
Top : Peak-Hold Average
Bottom : Arithmetic Average



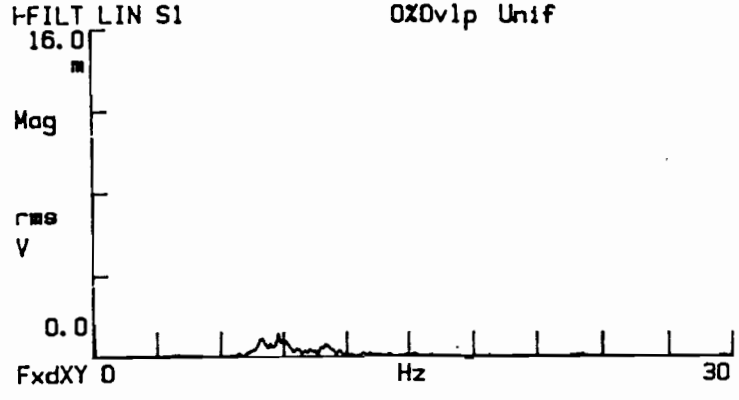


Figure B.14 Displacement Spectra of Short Span of Hawkins Bridge at 12:43 P.M.
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Bottom : Arithmetic Average

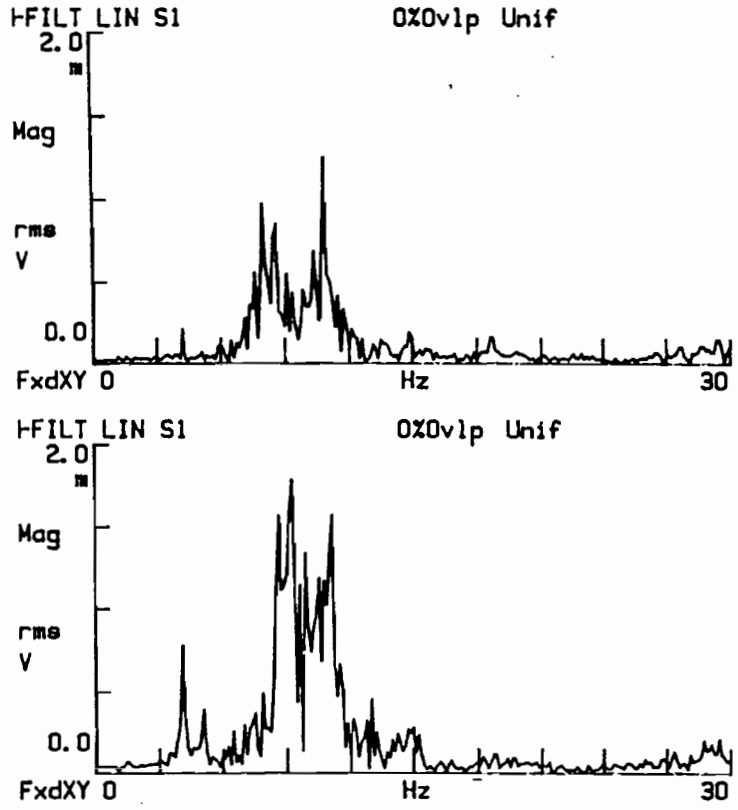

Figure B.15 Displacement Spectra of Short Span of Hawkins Bridge at 12:59 P.M.
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Bottom : Arithmetic Average

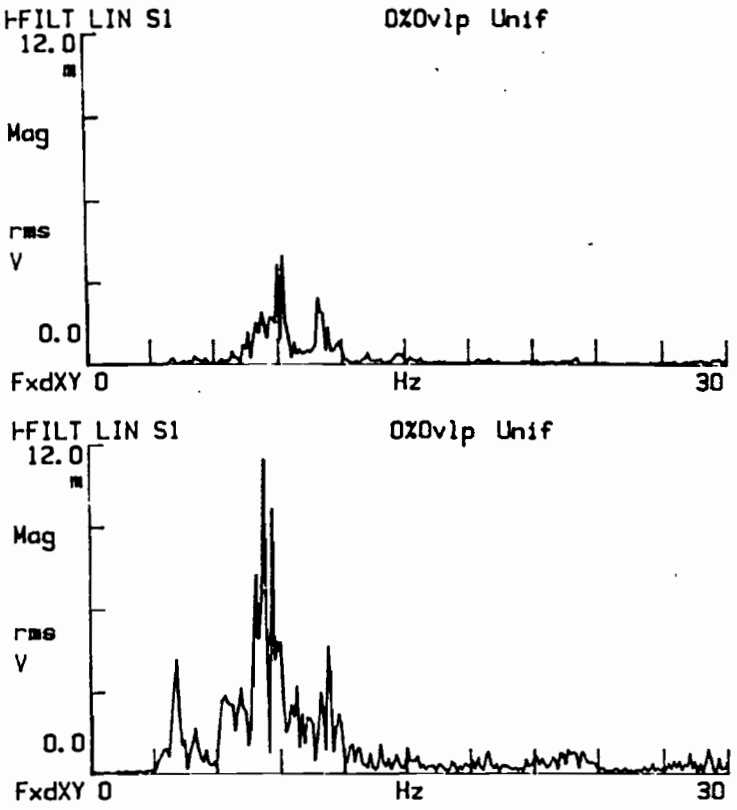


Figure B.16 Displacement Spectra of Short Span of Hawkins Bridge at 13:18 P.M.
Top : Peak-Hold Average
Bottom : Arithmetic Average

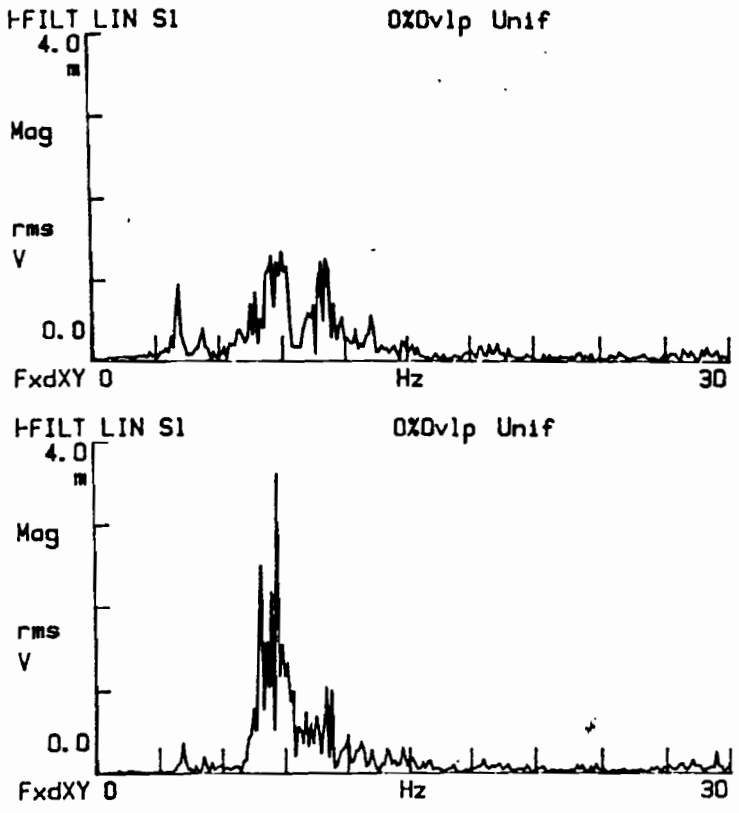


Figure B.17 Displacement Spectra of Short Span of Hawkins Bridge at 13:27 P.M.
Top : Peak-Hold Average
Bottom : Arithmetic Average

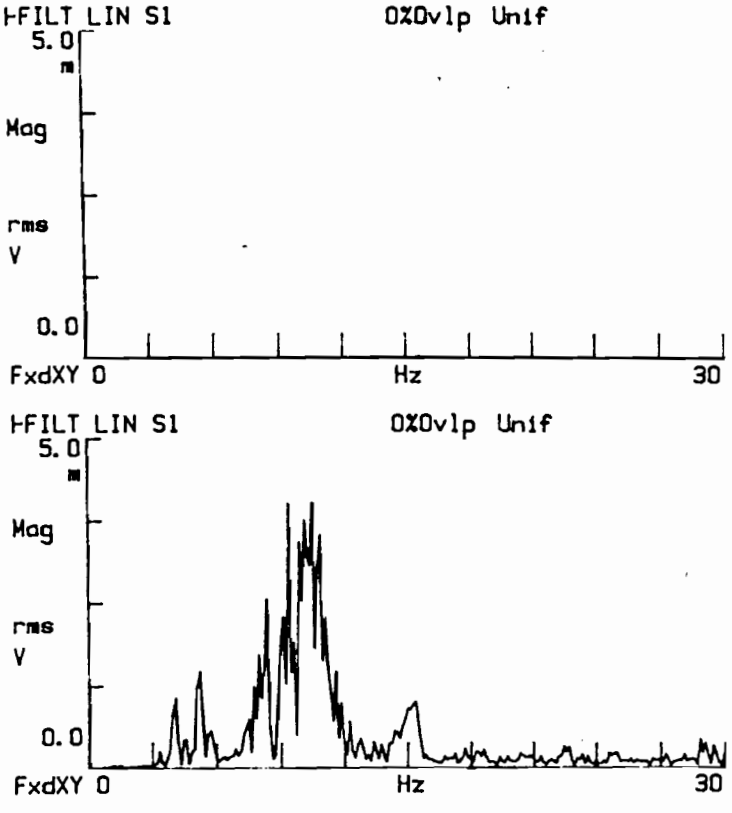


Figure B.18 Displacement Spectra of Short Span of Hawkins Bridge at 13:44 P.M.
Top : Peak-Hold Average
Bottom : Arithmetic Average

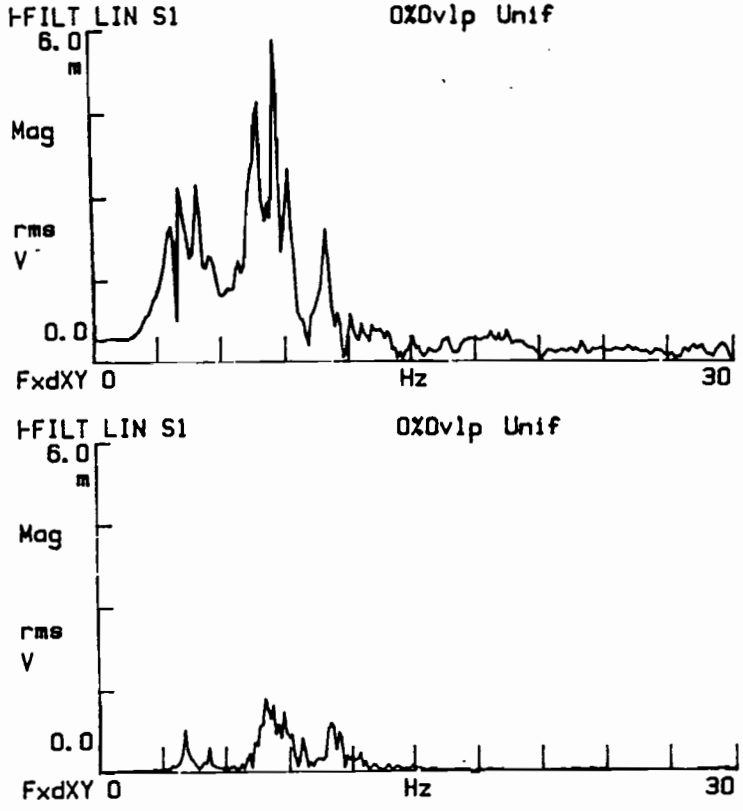


Figure B.19 Displacement Spectra of Short Span of Hawkins Bridge at 14:00 P.M.
Top : Peak-Hold Average
Bottom : Arithmetic Average

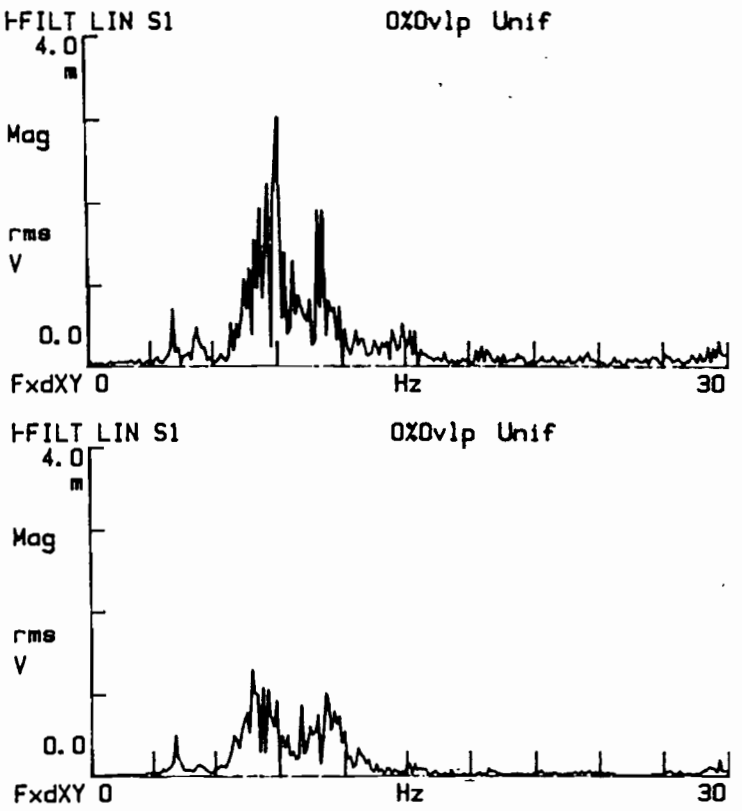
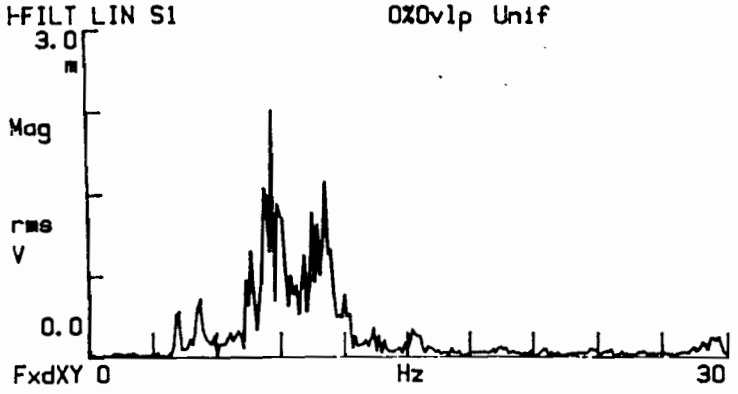


Figure B.20 Displacement Spectra of Short Span of Hawkins Bridge at 14:13 P.M.
Top : Peak-Hold Average
Bottom : Arithmetic Average



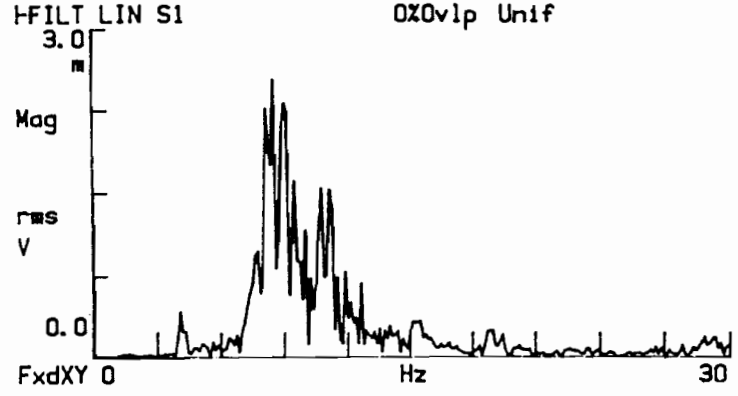
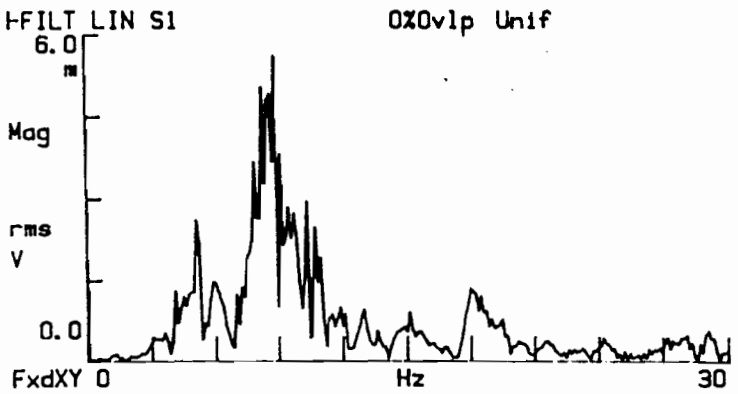


Figure B.21 Displacement Spectra of Short Span of Hawkins Bridge at 14:28 P.M.
Top : Peak-Hold Average
Bottom : Arithmetic Average



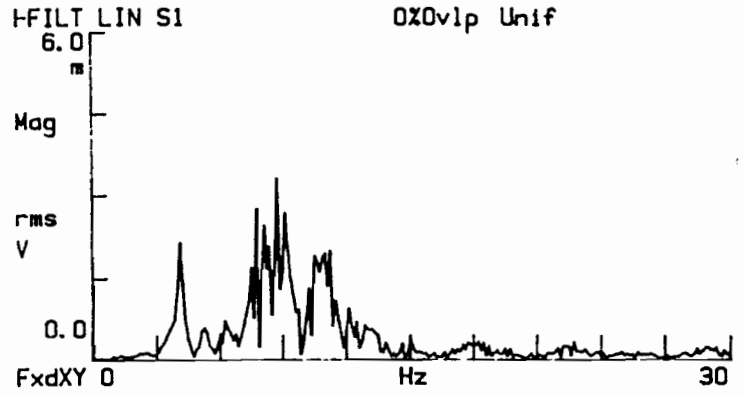


Figure B.22 Displacement Spectra of Short Span of Hawkins Bridge at 14:49 P.M.
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Bottom : Arithmetic Average

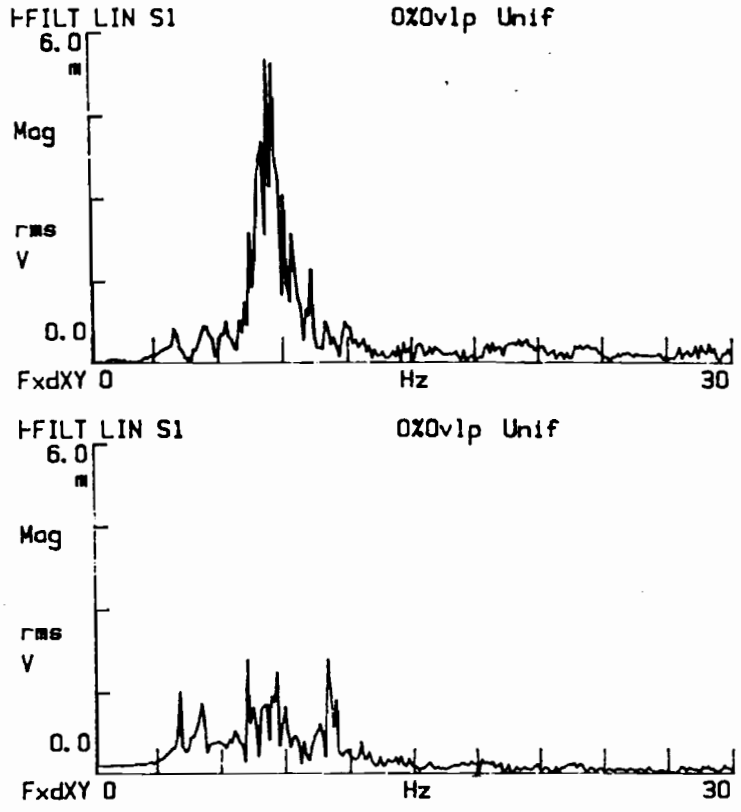


Figure B.23 Displacement Spectra of Short Span of Hawkins Bridge at 15:10 P.M.
Top : Peak-Hold Average
Bottom : Arithmetic Average

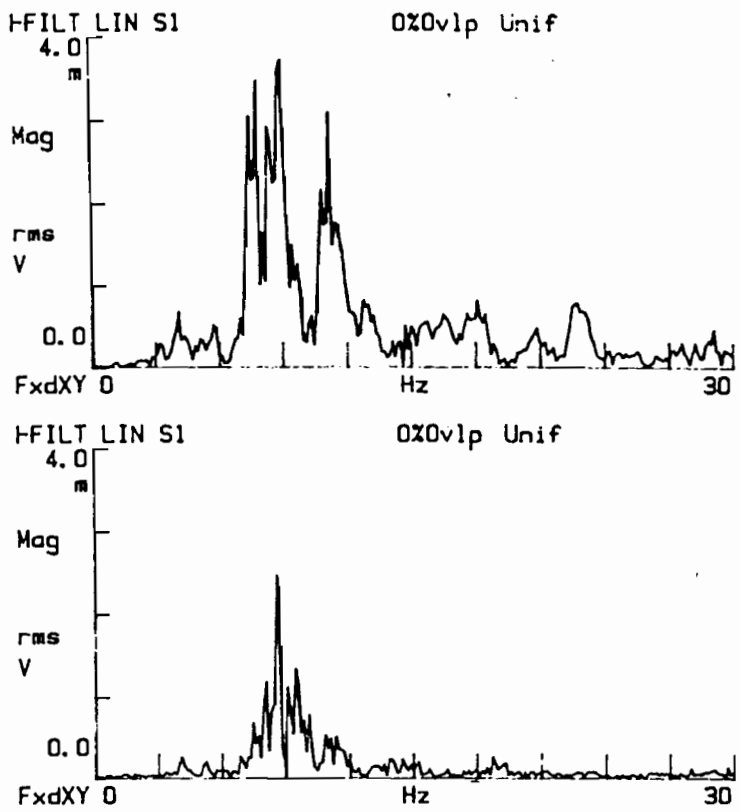


Figure B.24 Displacement Spectra of Short Span of Hawkins Bridge at 15:31 P.M.
Top : Peak-Hold Average
Bottom : Arithmetic Average

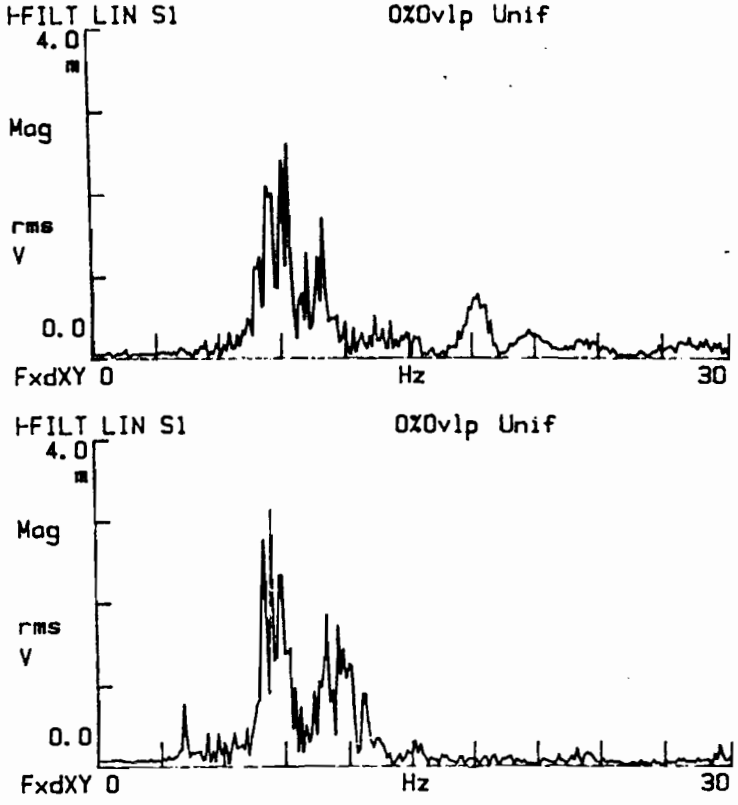


Figure B.25 Displacement Spectra of Short Span of Hawkins Bridge at 15:47 P.M.
Top : Peak-Hold Average
Bottom : Arithmetic Average

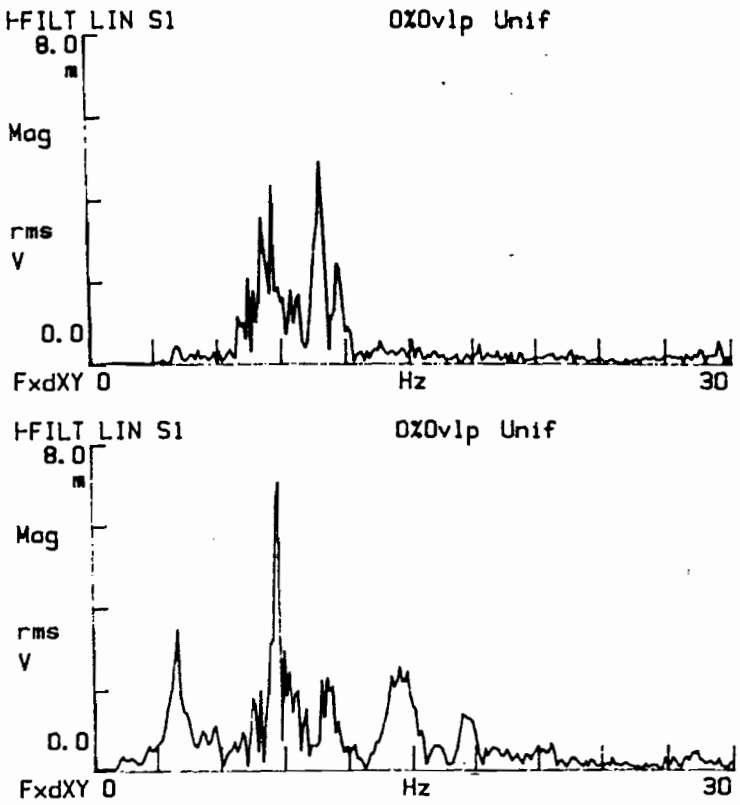


Figure B.26 Displacement Spectra of Short Span of Hawkins Bridge at 16:06 P.M.
Top : Peak-Hold Average
Bottom : Arithmetic Average

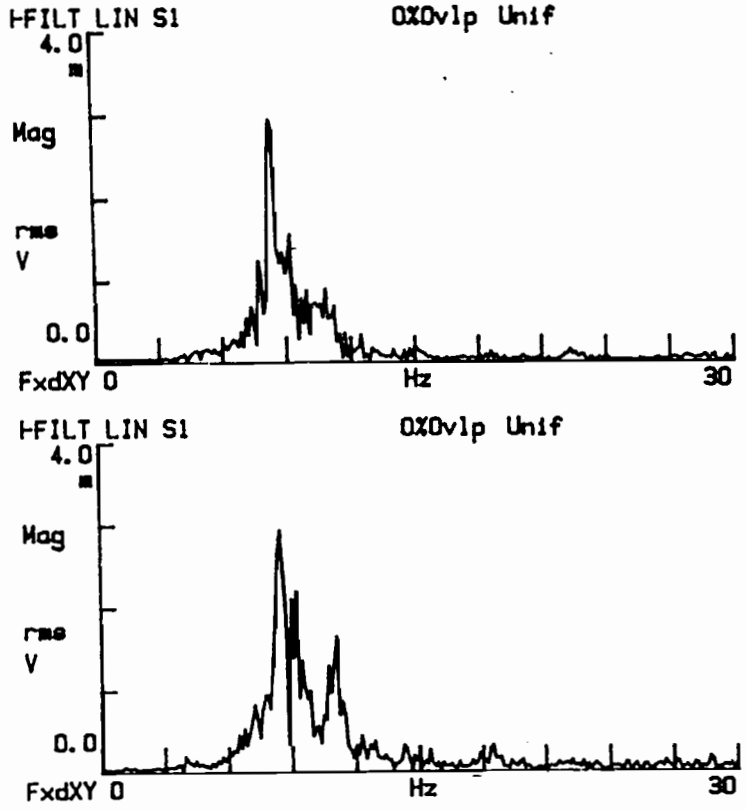


Figure B.27 Displacement Spectra of Short Span of Hawkins Bridge at 17:00 P.M.
Top : Peak-Hold Average
Bottom : Arithmetic Average

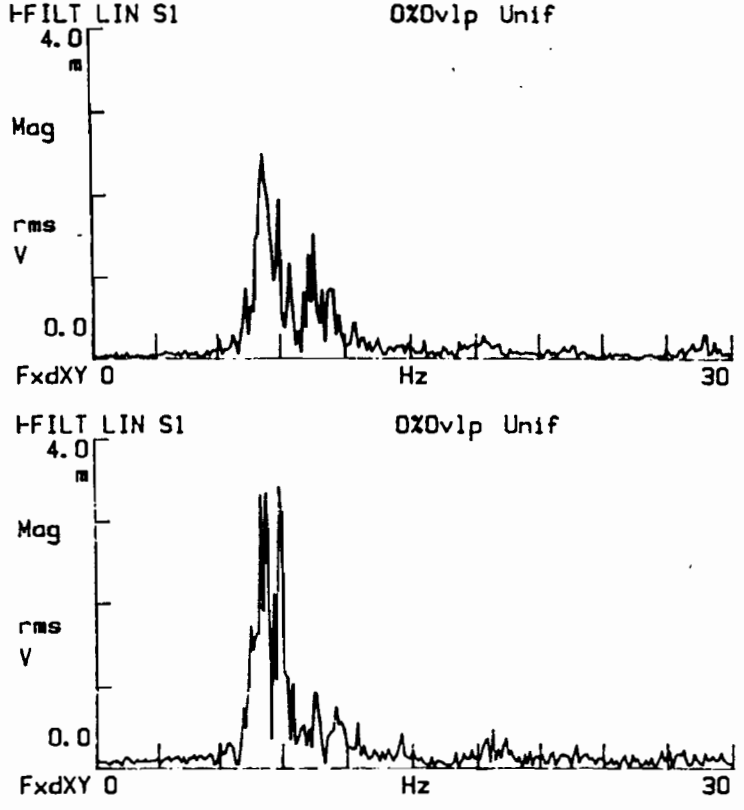


Figure B.28 Displacement Spectra of Short Span of Hawkins Bridge at 17:17 P.M.
Top : Peak-Hold Average
Bottom : Arithmetic Average

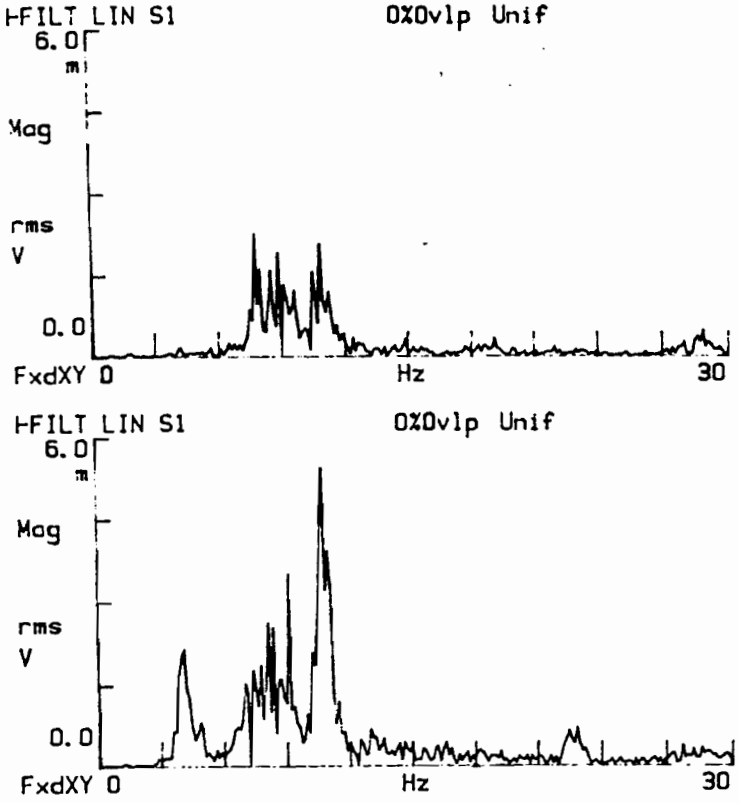


Figure B.29 Displacement Spectra of Short Span of Hawkins Bridge at 17:30 P.M.
Top : Peak-Hold Average
Bottom : Arithmetic Average

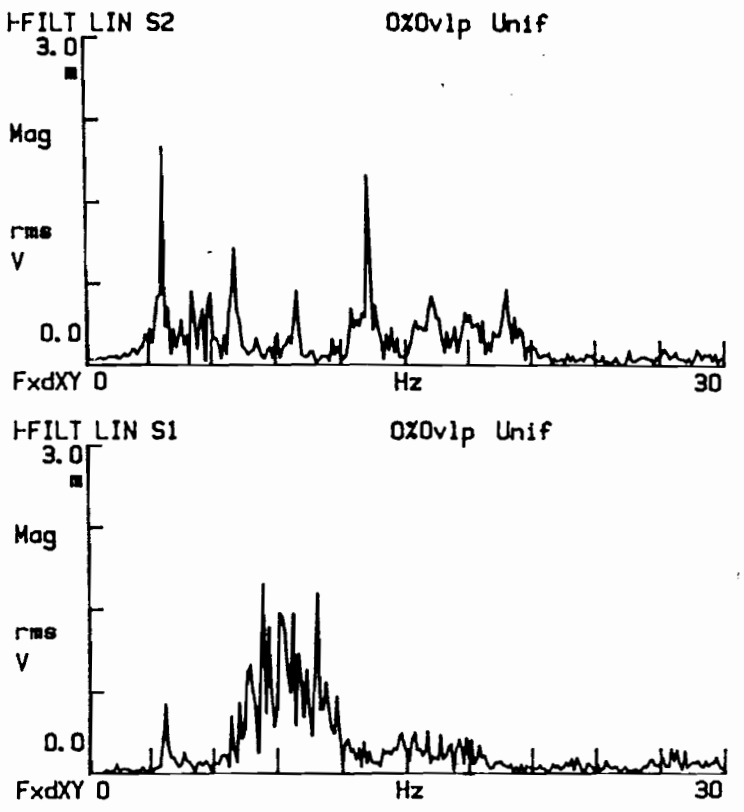


Figure B.30 Displacement Spectra of Long Span of Hawkins Bridge at 8:35 A.M.
Top : Peak-Hold Average
Bottom : Arithmetic Average

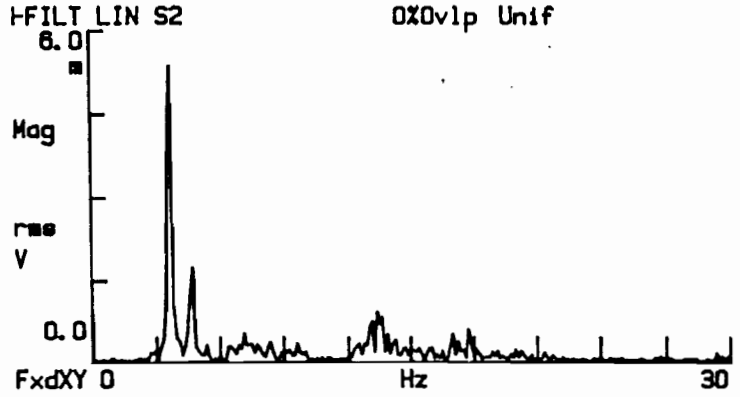


Figure B.31 Displacement Spectra of Long Span of Hawkins Bridge at 8:55 A.M.
Top : Peak-Hold Average
Bottom : Arithmetic Average

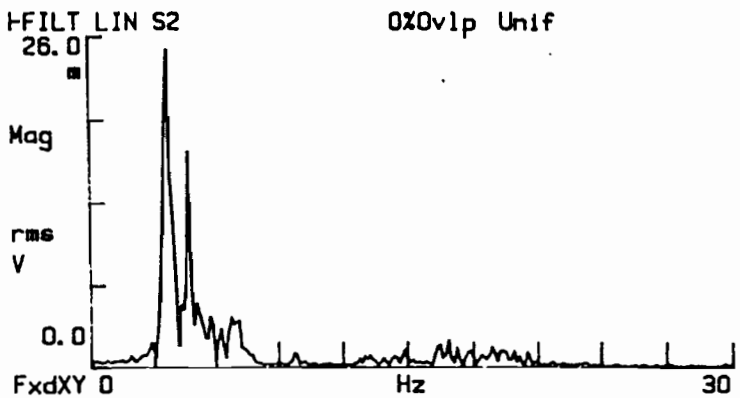


Figure B.32 Displacement Spectra of Long Span of Hawkins Bridge at 9:15 A.M.
Top : Peak-Hold Average
Bottom : Arithmetic Average

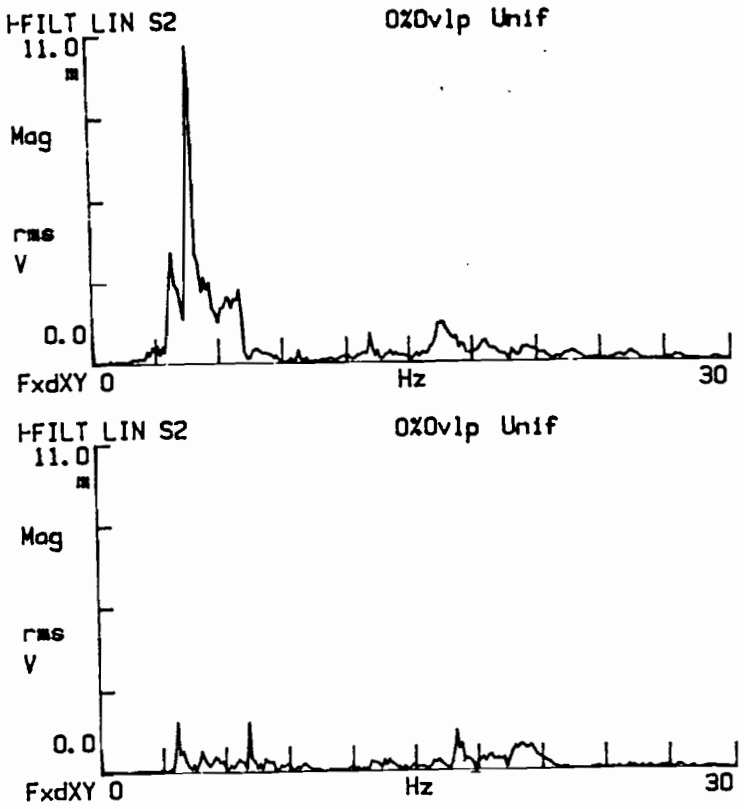


Figure B.33 Displacement Spectra of Long Span of Hawkins Bridge at 9:36 A.M.
Top : Peak-Hold Average
Bottom : Arithmetic Average

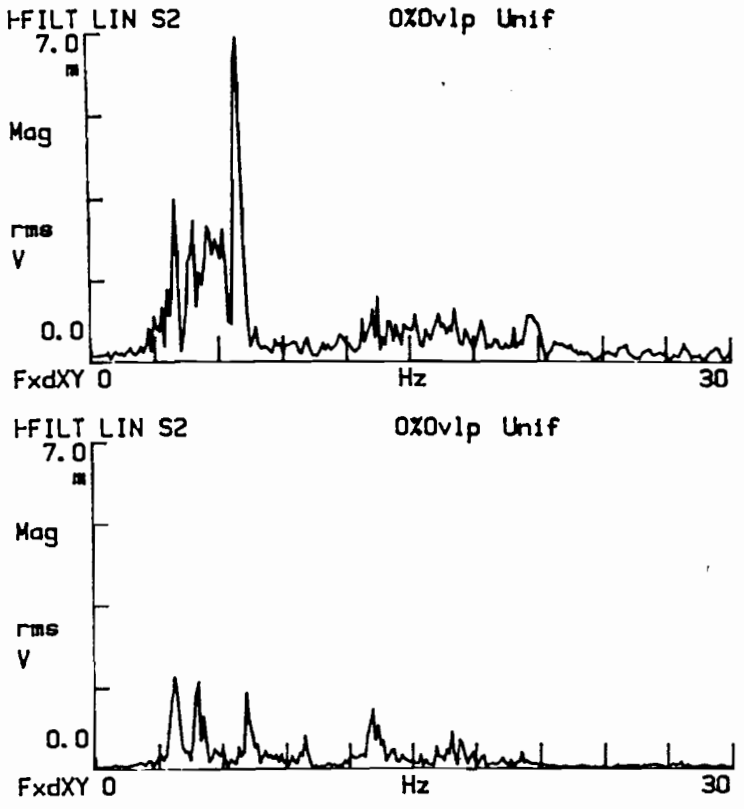


Figure B.34 Displacement Spectra of Long Span of Hawkins Bridge at 9:56 A.M.
Top : Peak-Hold Average
Bottom : Arithmetic Average

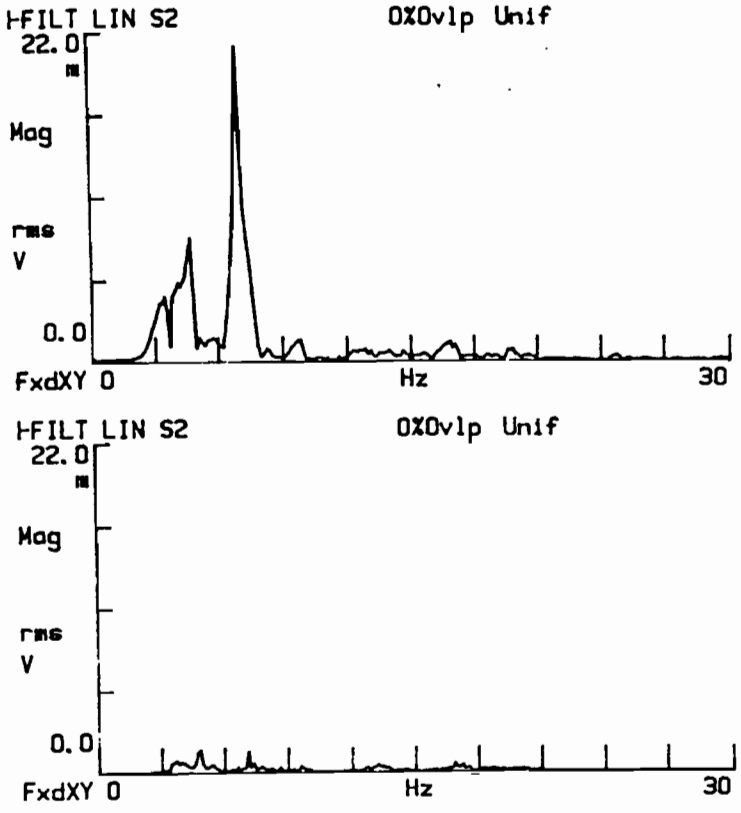


Figure B.35 Displacement Spectra of Long Span of Hawkins Bridge at 10:16 A.M.
Top : Peak-Hold Average
Bottom : Arithmetic Average

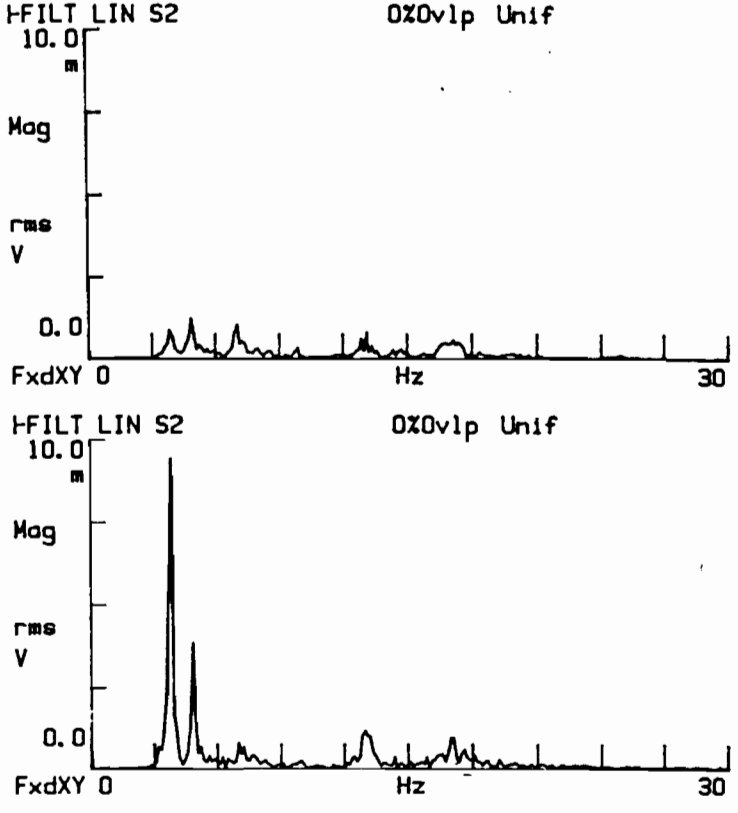


Figure B.36 Displacement Spectra of Long Span of Hawkins Bridge at 10:37 A.M.
Top : Peak-Hold Average
Bottom : Arithmetic Average

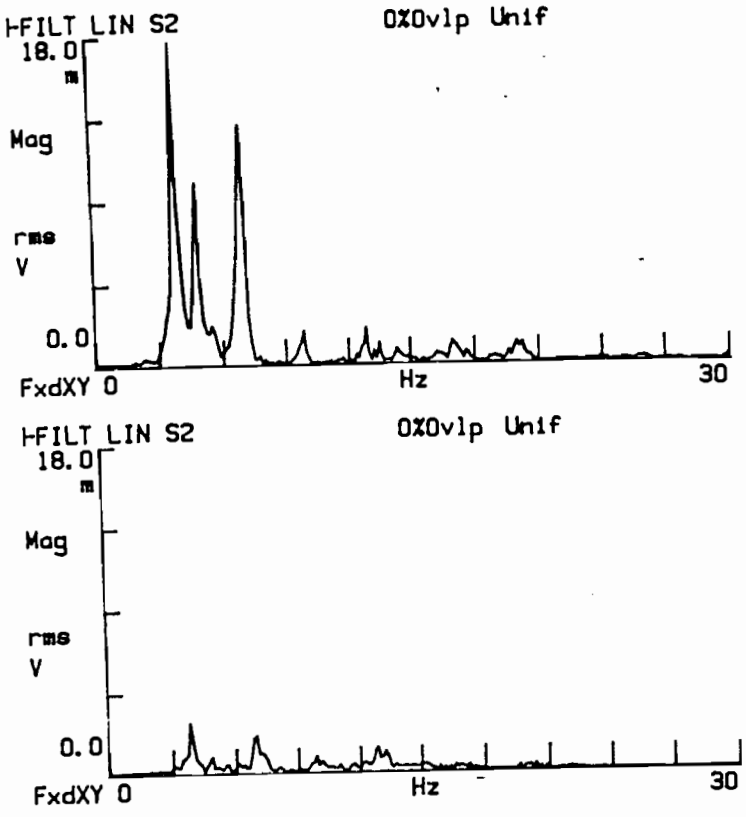


Figure B.37 Displacement Spectra of Long Span of Hawkins Bridge at 10:57 A.M.
Top : Peak-Hold Average
Bottom : Arithmetic Average

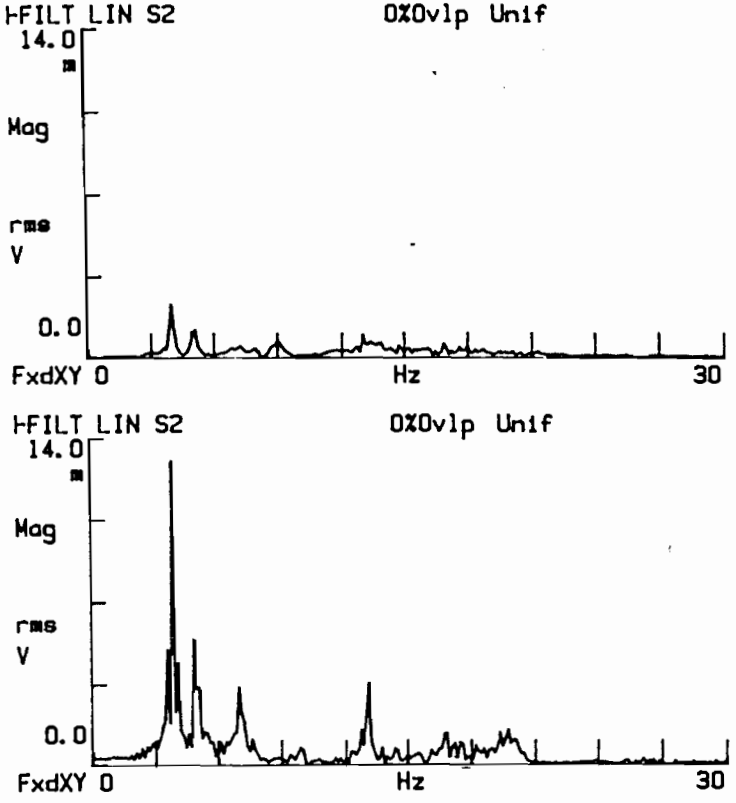
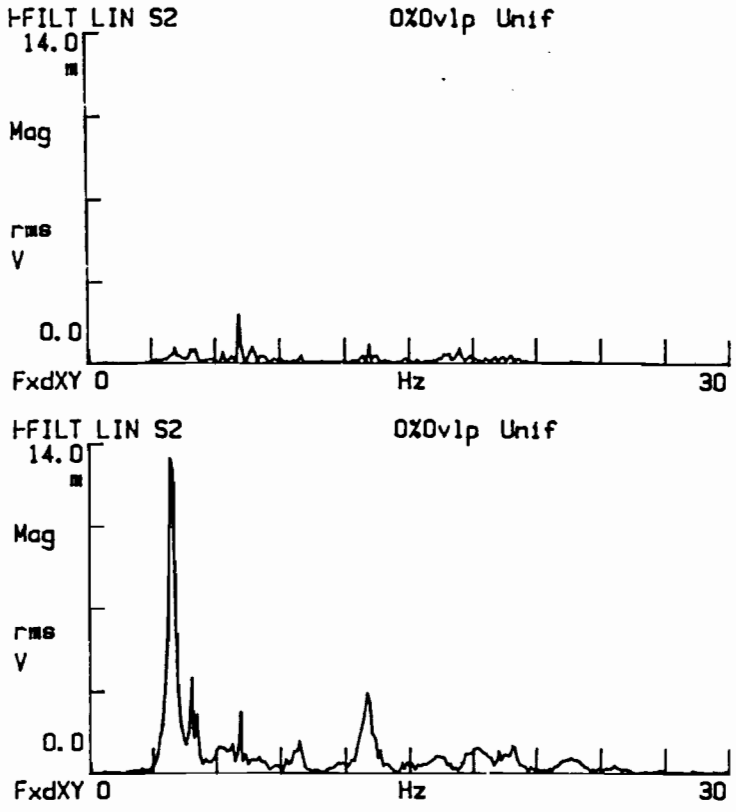


Figure B.38 Displacement Spectra of Long Span of Hawkins Bridge at 11:17 A.M.
Top : Peak-Hold Average
Bottom : Arithmetic Average



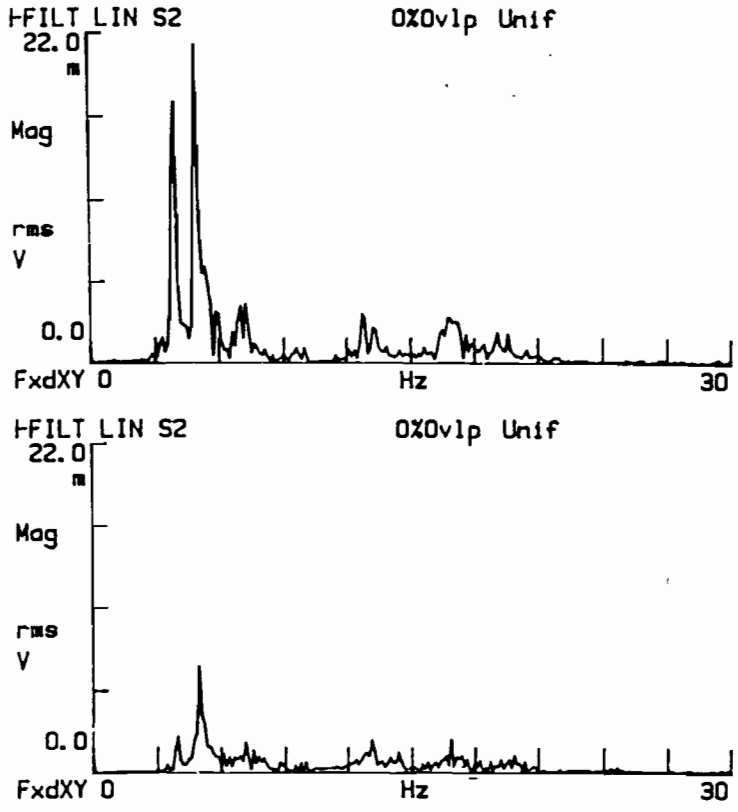


Figure B.39 Displacement Spectra of Long Span of Hawkins Bridge at 11:36 A.M.
Top : Peak-Hold Average
Bottom : Arithmetic Average

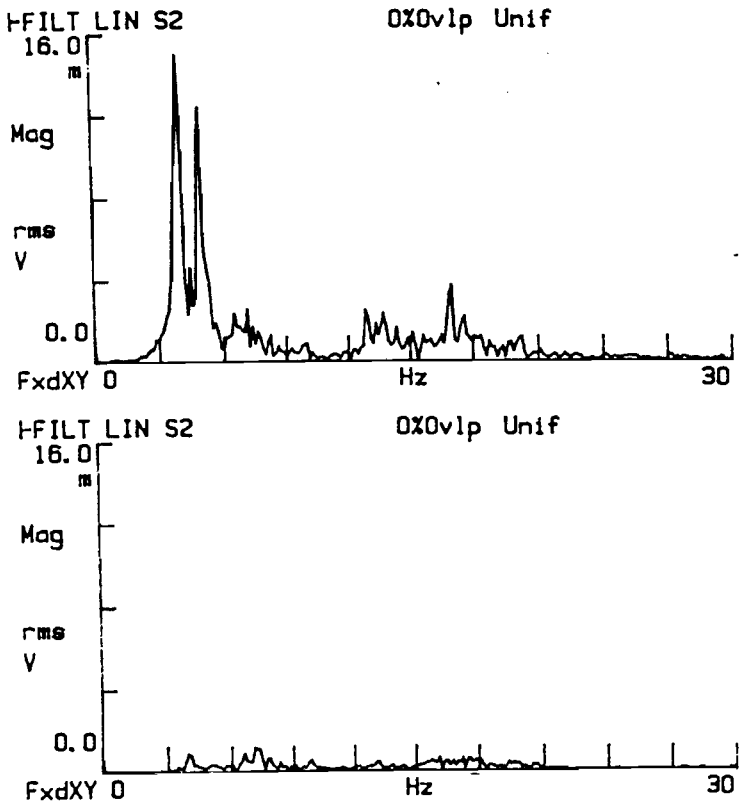


Figure B.41 Displacement Spectra of Long Span of Hawkins Bridge at 12:07 P.M.
Top : Peak-Hold Average
Bottom : Arithmetic Average

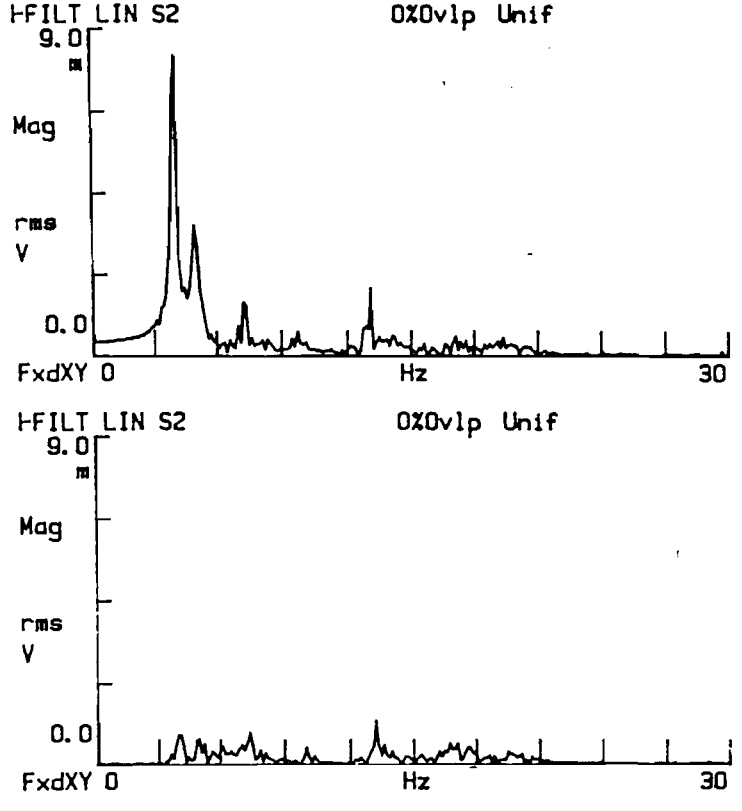


Figure B.42 Displacement Spectra of Long Span of Hawkins Bridge at 12:25 P.M.
Top : Peak-Hold Average
Bottom : Arithmetic Average

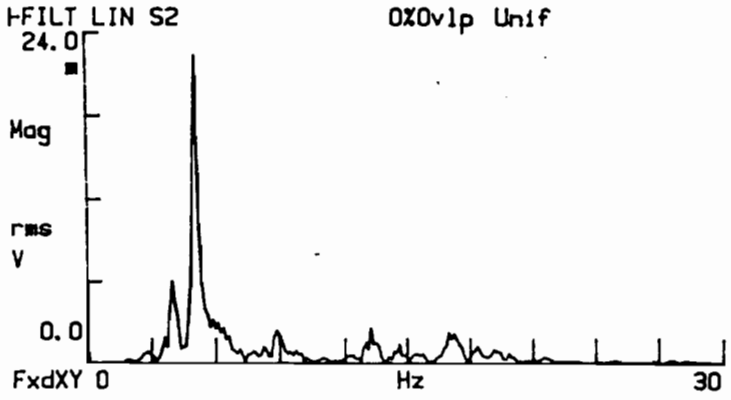


Figure B.43 Displacement Spectra of Long Span of Hawkins Bridge at 12:43 P.M.
Top : Peak-Hold Average
Bottom : Arithmetic Average

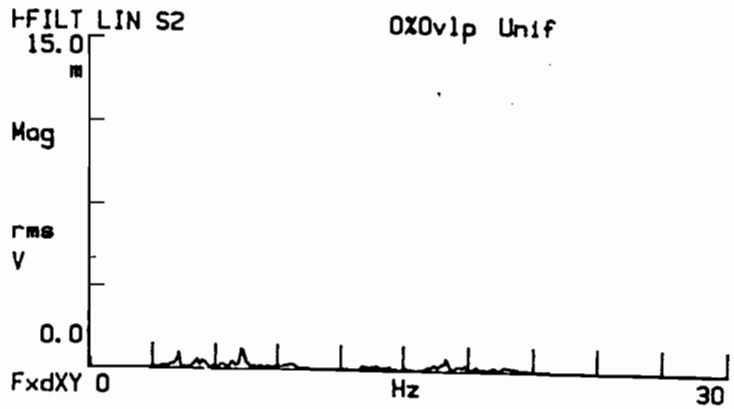


Figure B.44 Displacement Spectra of Long Span of Hawkins Bridge at 12:59 P.M.
Top : Peak-Hold Average
Bottom : Arithmetic Average

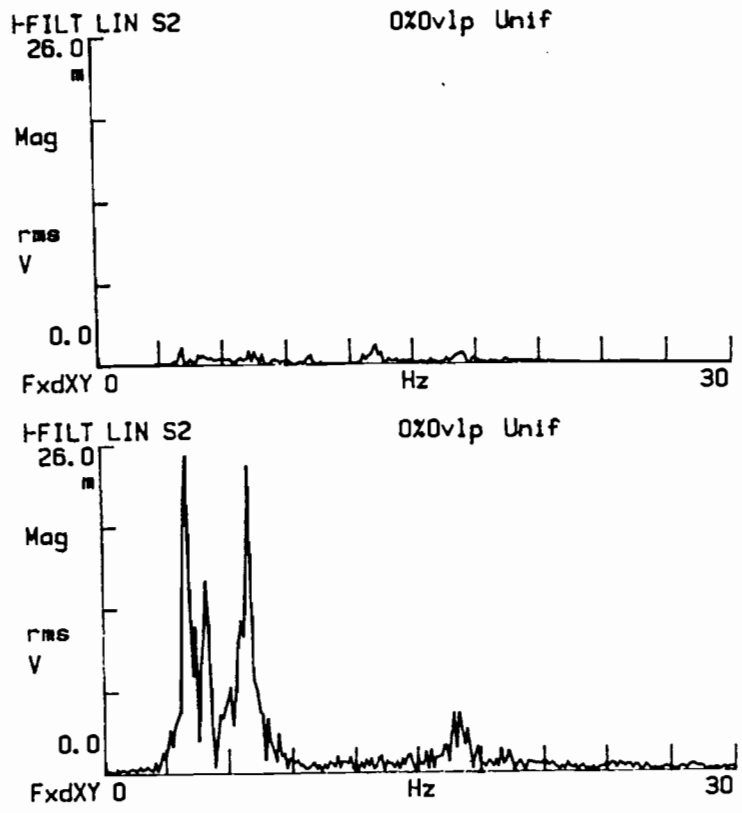


Figure B.45 Displacement Spectra of Long Span of Hawkins Bridge at 13:17 P.M.
Top : Peak-Hold Average
Bottom : Arithmetic Average

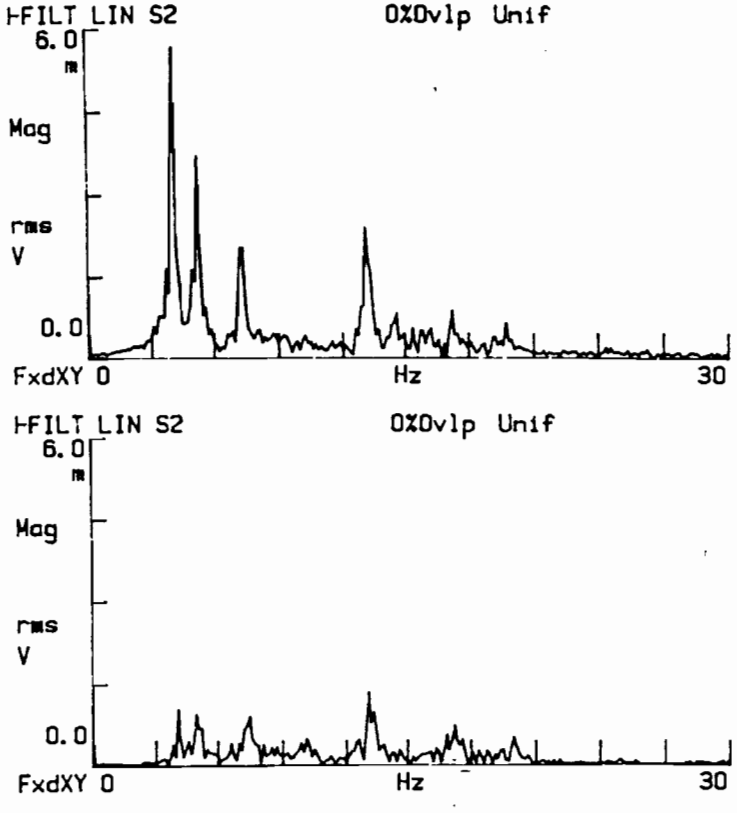


Figure B.46 Displacement Spectra of Long Span of Hawkins Bridge at 13:27 P.M.
Top : Peak-Hold Average
Bottom : Arithmetic Average

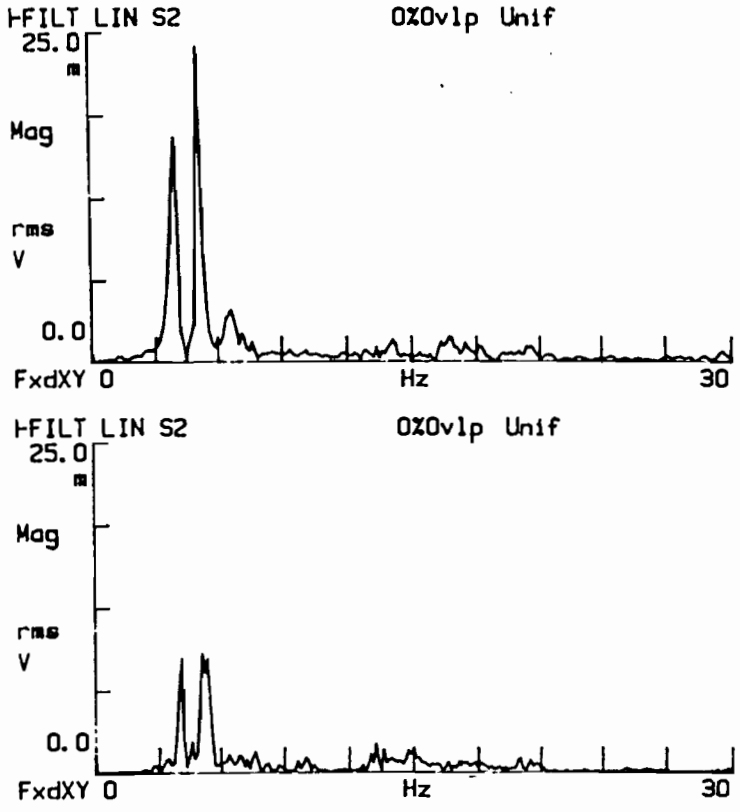


Figure B.47 Displacement Spectra of Long Span of Hawkins Bridge at 13:45 P.M.
Top : Peak-Hold Average
Bottom : Arithmetic Average

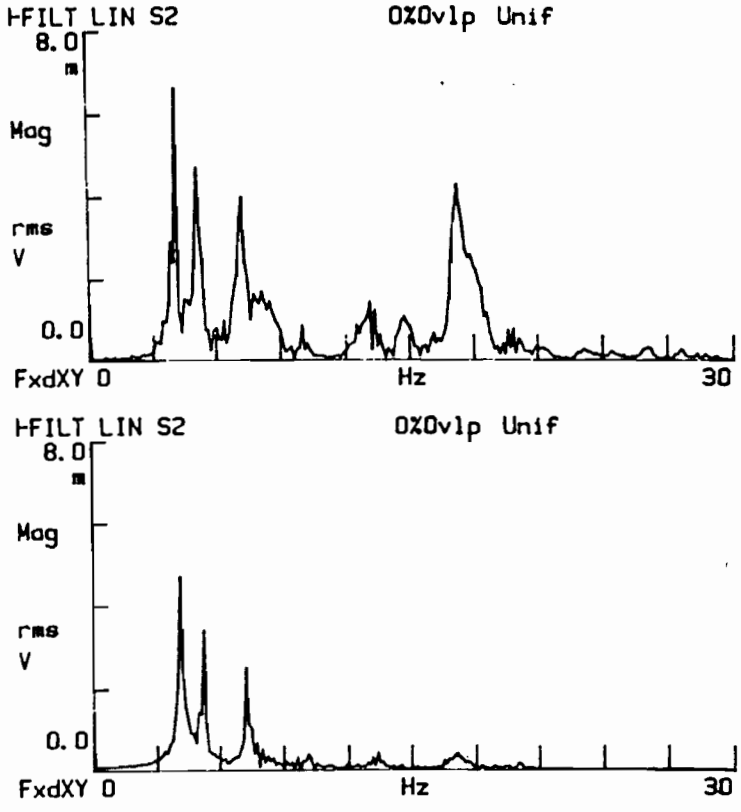
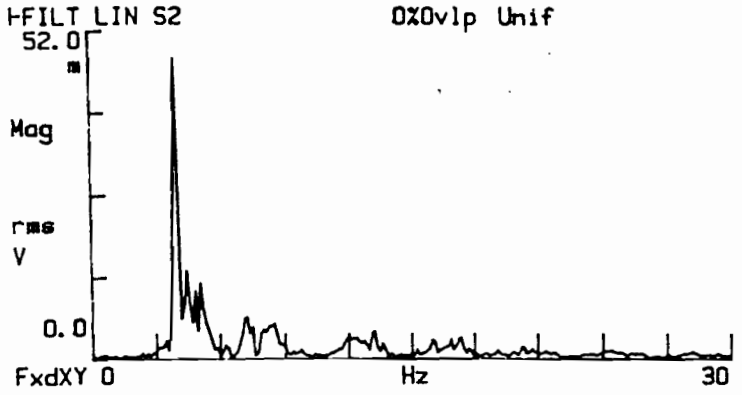


Figure B.48 Displacement Spectra of Long Span of Hawkins Bridge at 14:00 P.M.
Top : Peak-Hold Average
Bottom : Arithmetic Average



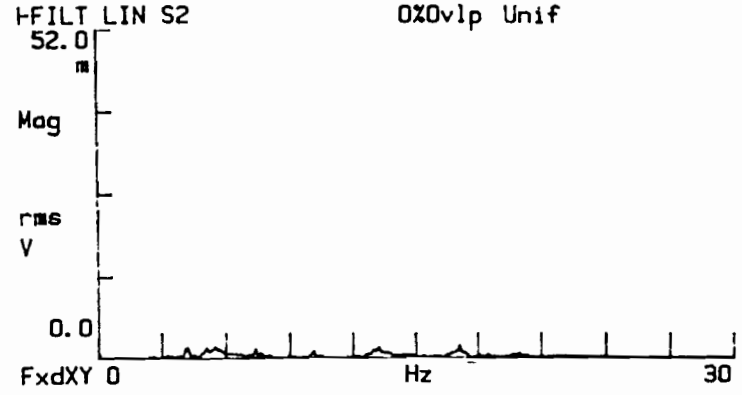
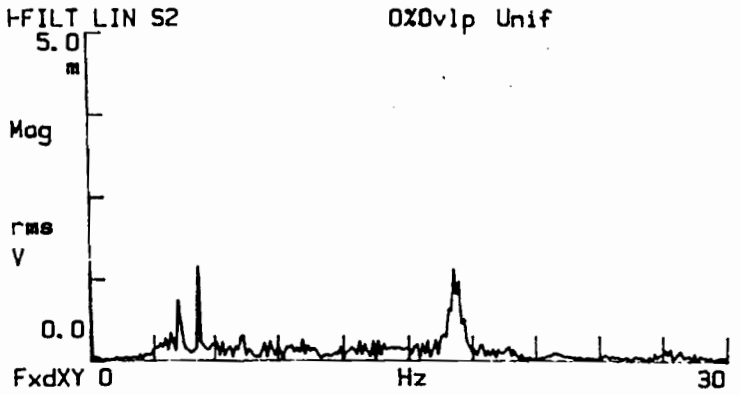


Figure B.49 Displacement Spectra of Long Span of Hawkins Bridge at 14:14 P.M.
Top : Peak-Hold Average
Bottom : Arithmetic Average



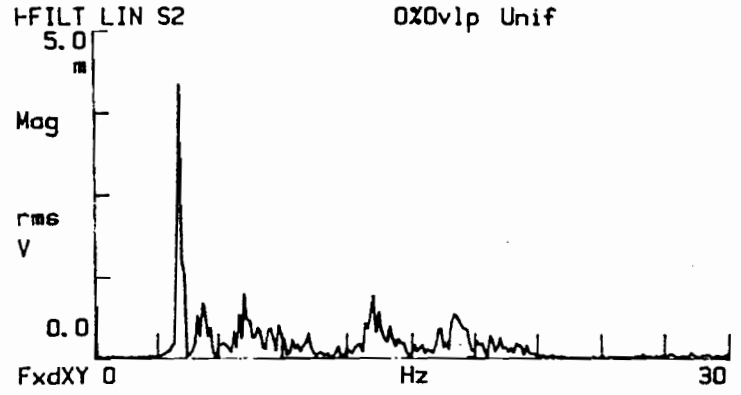


Figure B.50 Displacement Spectra of Long Span of Hawkins Bridge at 14:38 P.M.
Top : Peak-Hold Average
Bottom : Arithmetic Average

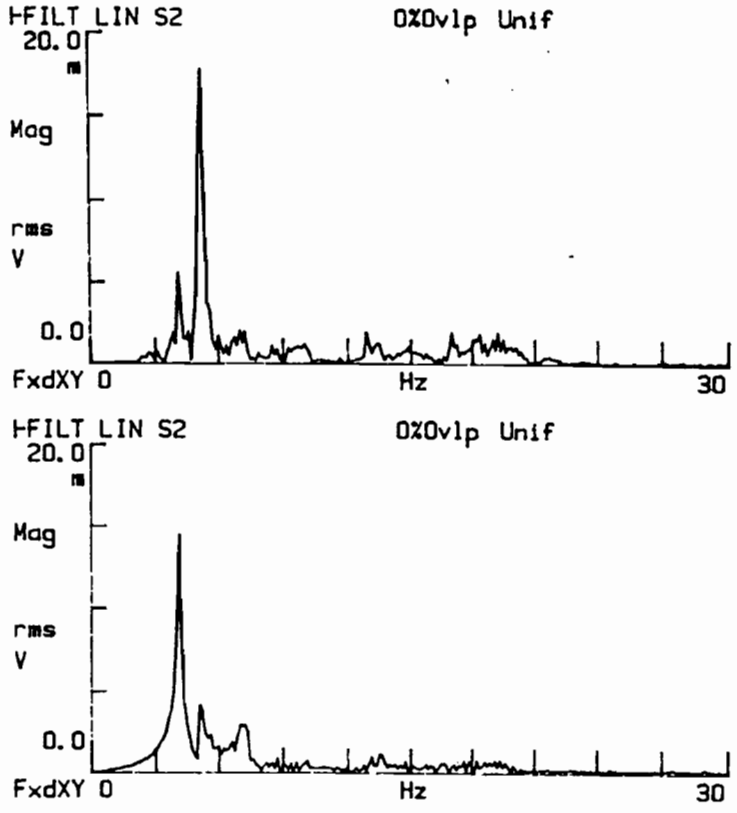


Figure B.51 Displacement Spectra of Long Span of Hawkins Bridge at 14:49 P.M.
Top : Peak-Hold Average
Bottom : Arithmetic Average

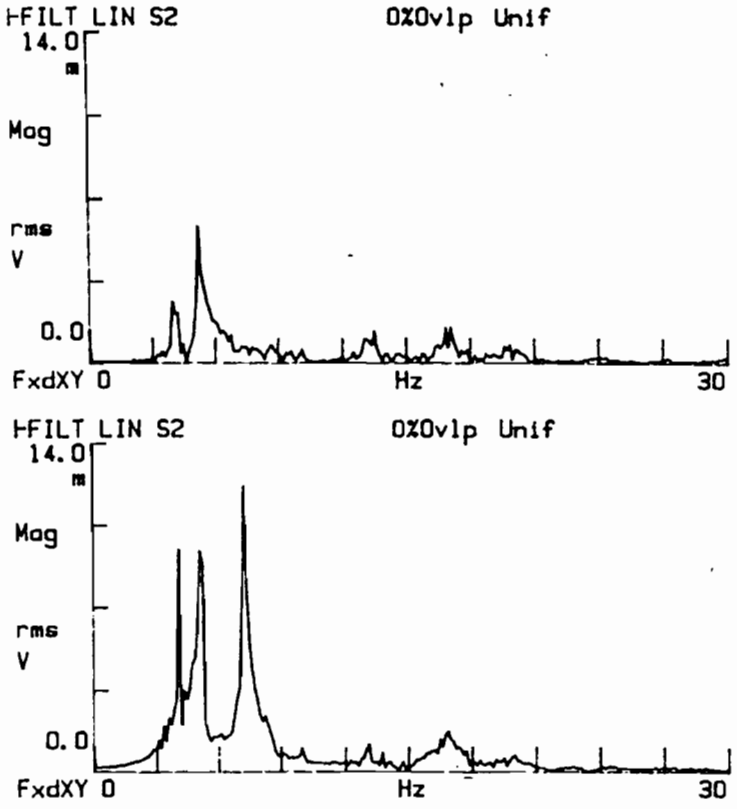


Figure B.52 Displacement Spectra of Long Span of Hawkins Bridge at 15:10 P.M.
Top : Peak-Hold Average
Bottom : Arithmetic Average

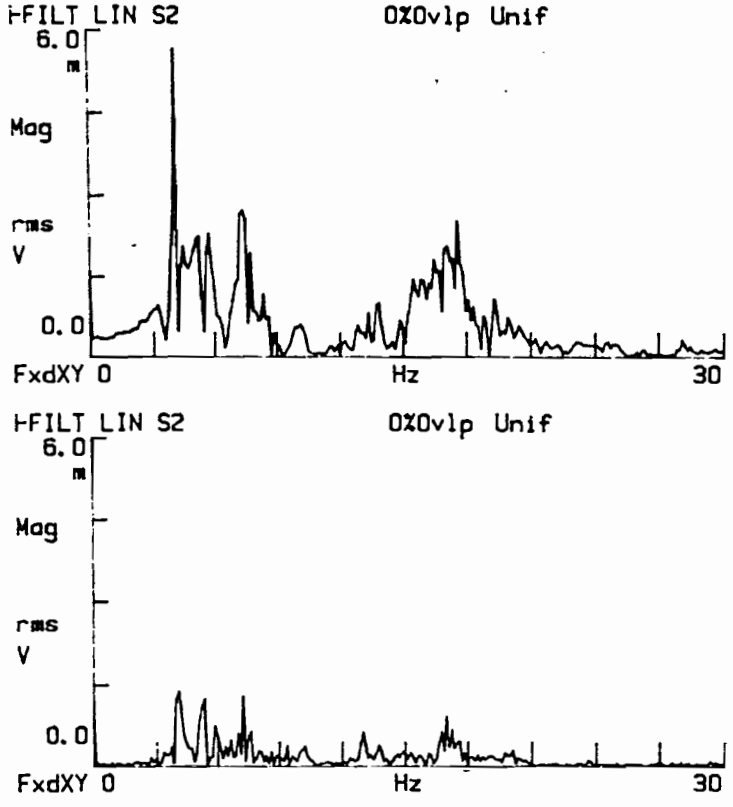


Figure B.53 Displacement Spectra of Long Span of Hawkins Bridge at 15:30 P.M.
Top : Peak-Hold Average
Bottom : Arithmetic Average

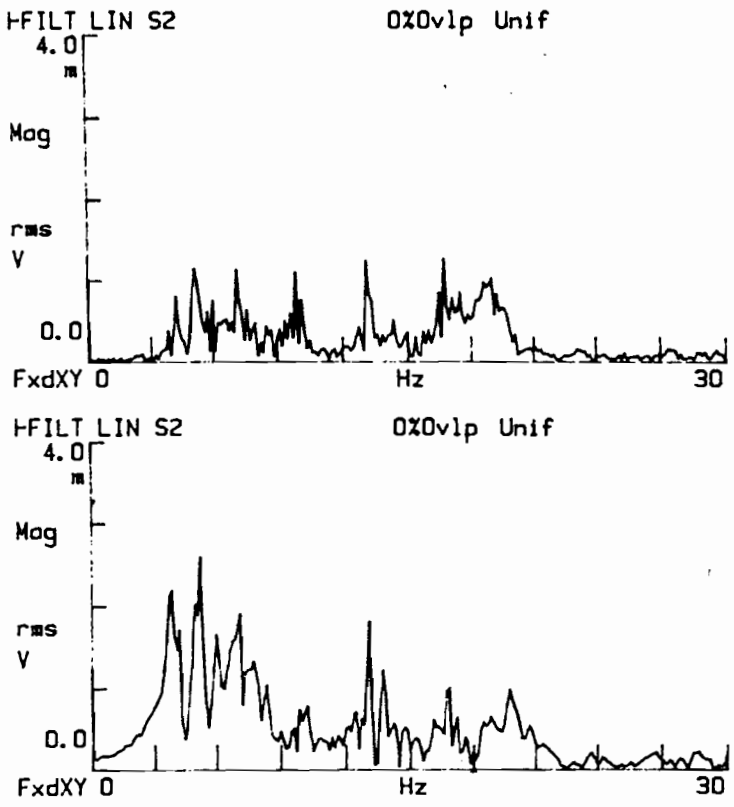


Figure B.54 Displacement Spectra of Long Span of Hawkins Bridge at 15:48 P.M.
Top : Peak-Hold Average
Bottom : Arithmetic Average

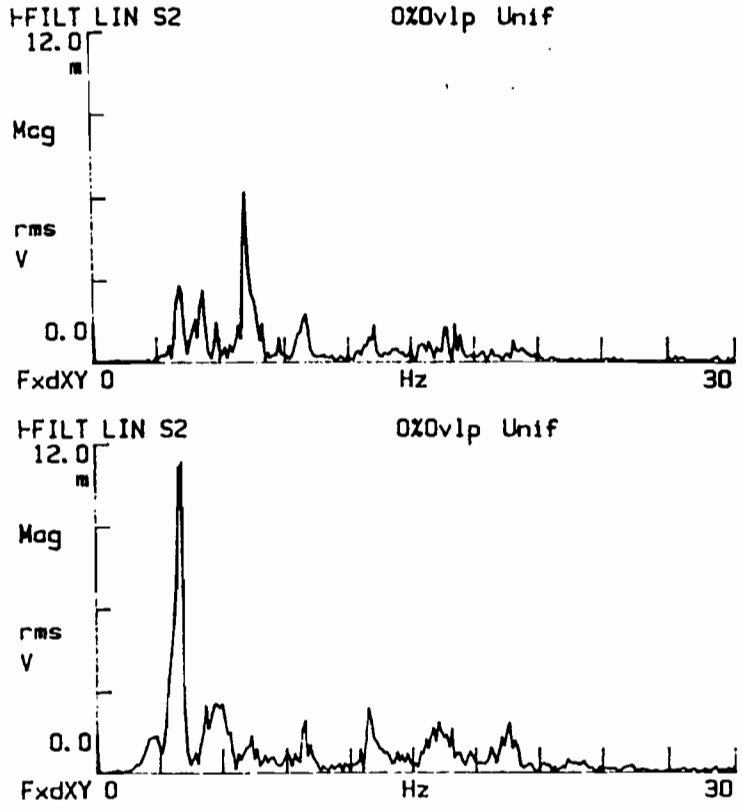


Figure B.55 Displacement Spectra of Long Span of Hawkins Bridge at 16:06 P.M.
Top : Peak-Hold Average
Bottom : Arithmetic Average

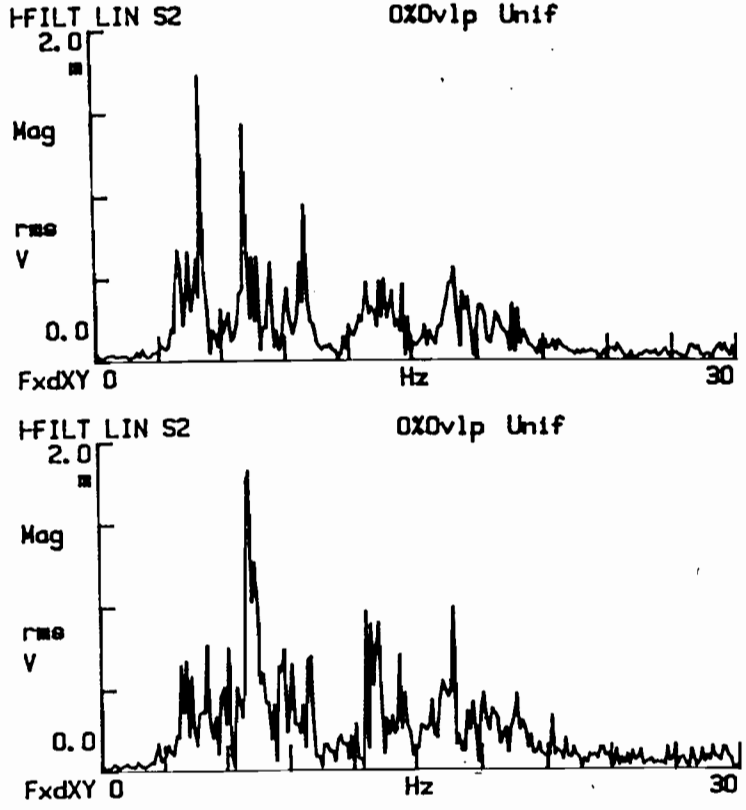


Figure B.56 Displacement Spectra of Long Span of Hawkins Bridge at 17:00 P.M.
Top : Peak-Hold Average
Bottom : Arithmetic Average

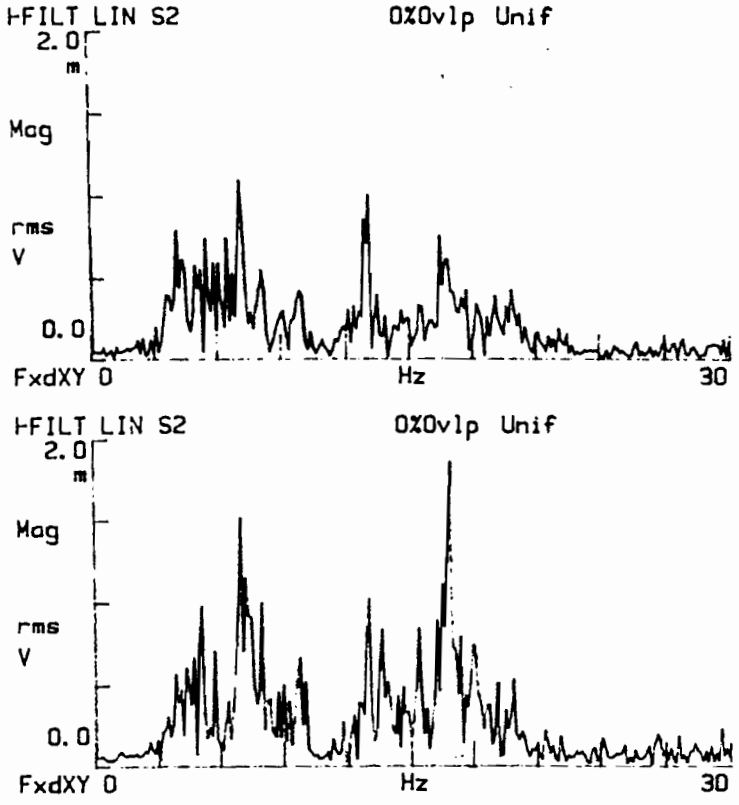


Figure B.57 Displacement Spectra of Long Span of Hawkins Bridge at 17:17 P.M.
Top : Peak-Hold Average
Bottom : Arithmetic Average

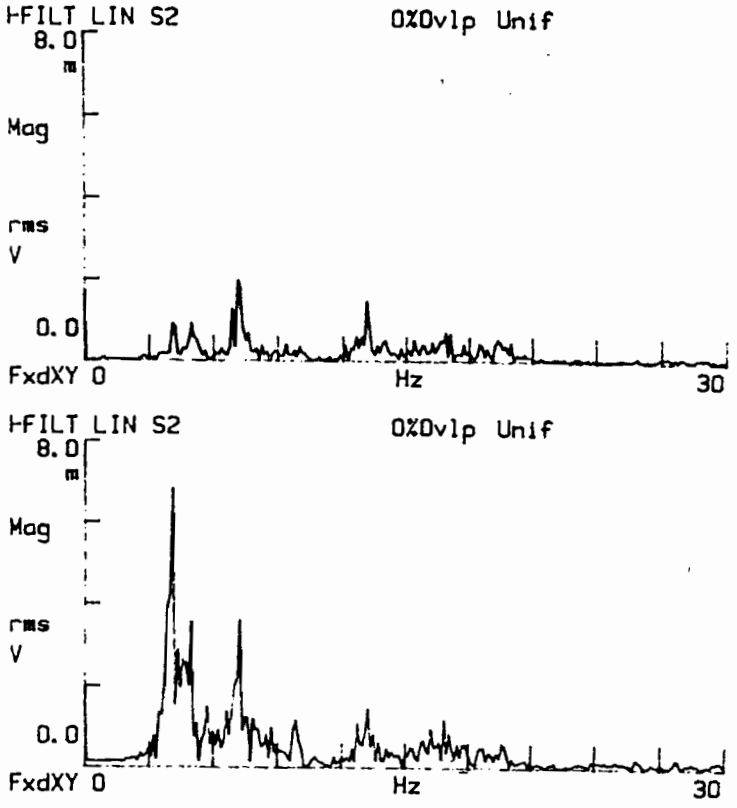


Figure B.58 Displacement Spectra of Long Span of Hawkins Bridge at 17:30 P.M.
Top : Peak-Hold Average
Bottom : Arithmetic Average

APPENDIX C

Guillotine Direct Shear Test Apparatus

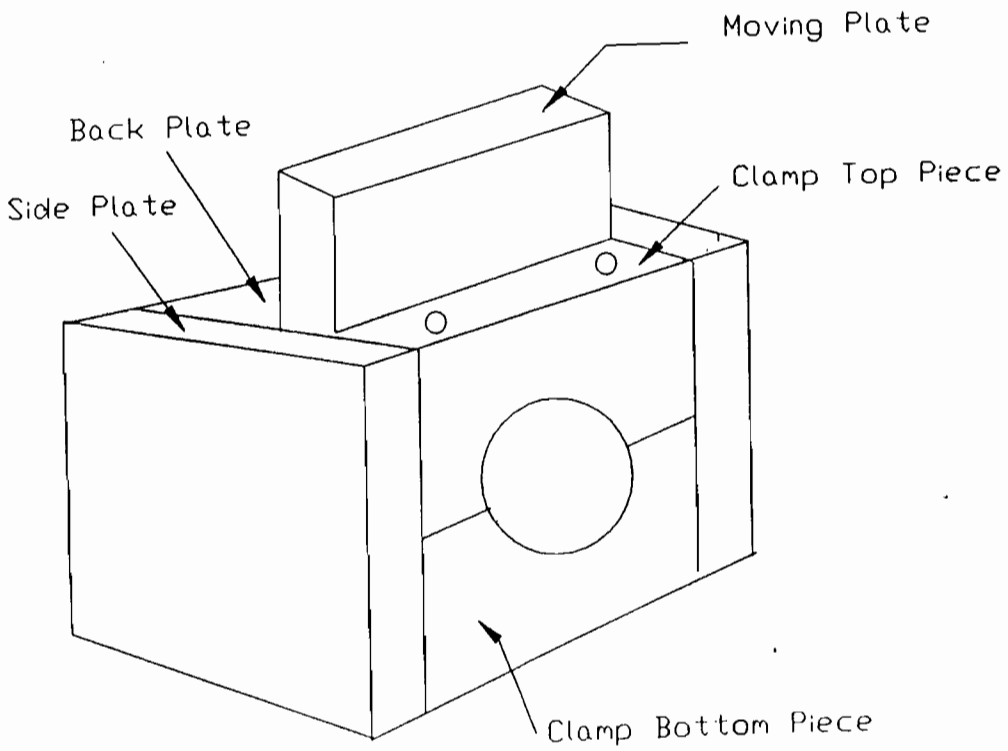


Figure C.1 Guillotine Direct Shear Test Apparatus

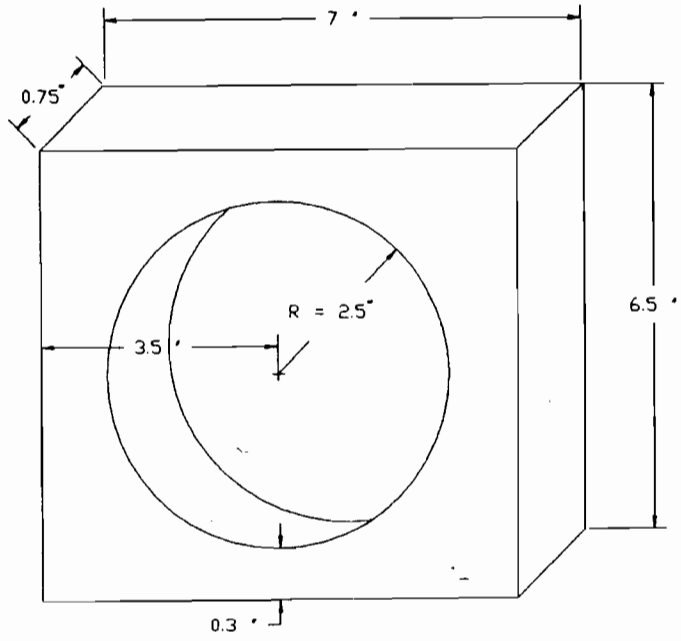


Figure C.2 Back Plate of Guillotine Direct Shear Test Apparatus

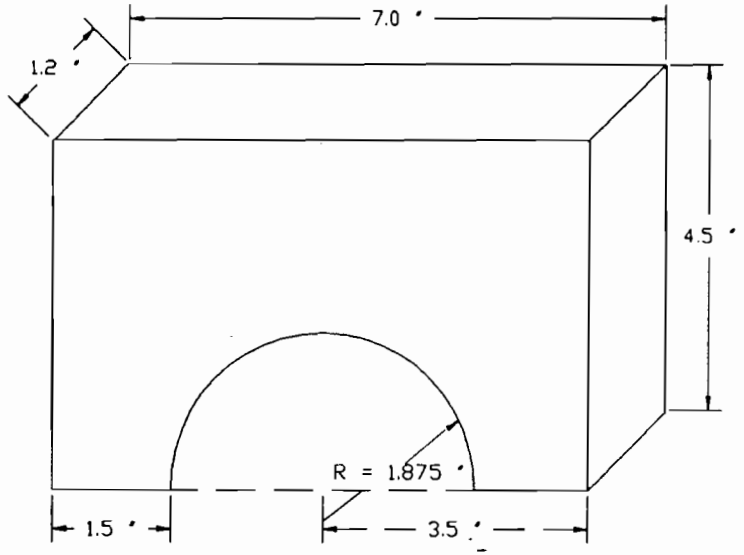


Figure C.3 Moving Plate of Guillotine Direct Shear Test Apparatus

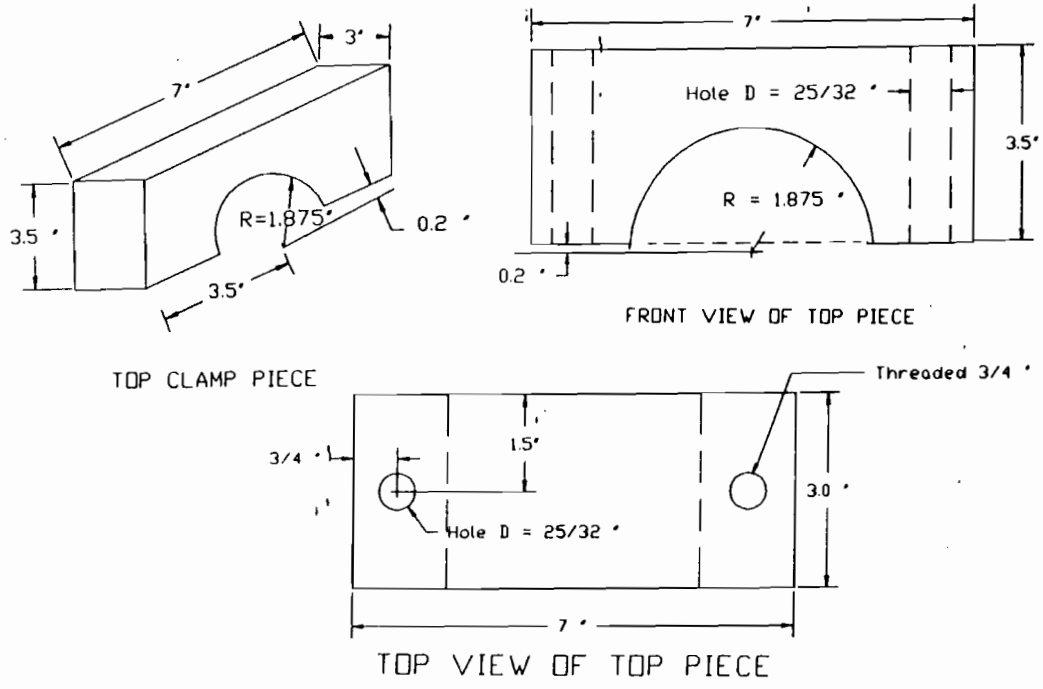


Figure C.4 Top Clamp Piece of Guillotine Direct Shear Test Apparatus

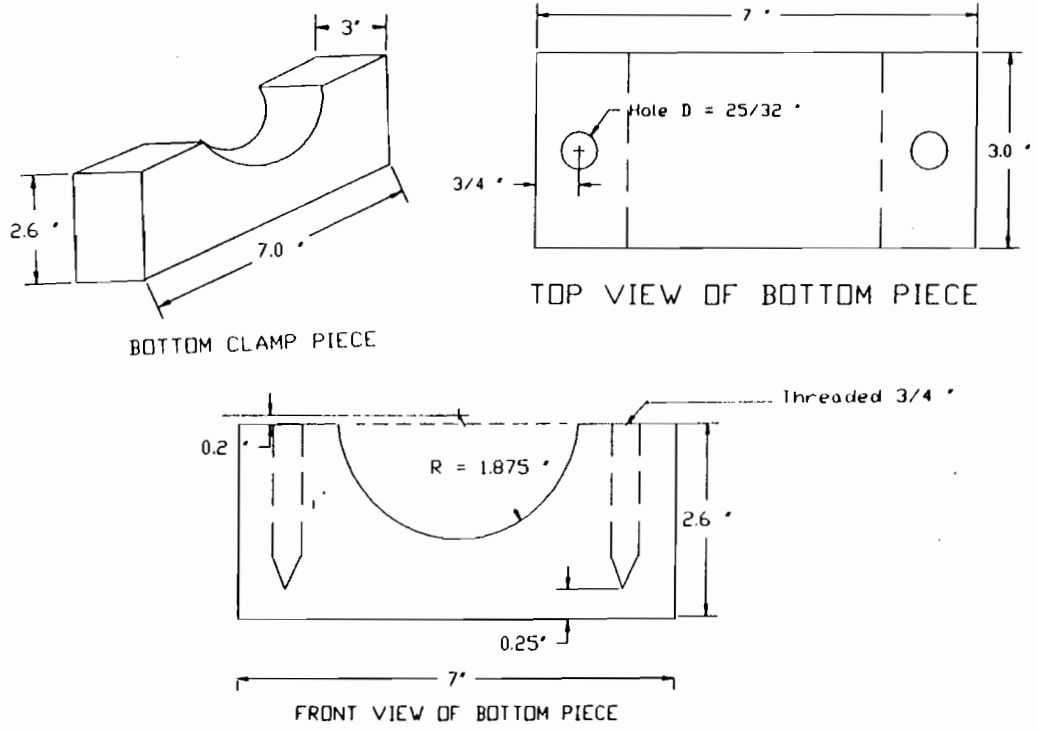


Figure C.5 Bottom Clamp Piece of Guillotine Direct Shear Test Apparatus

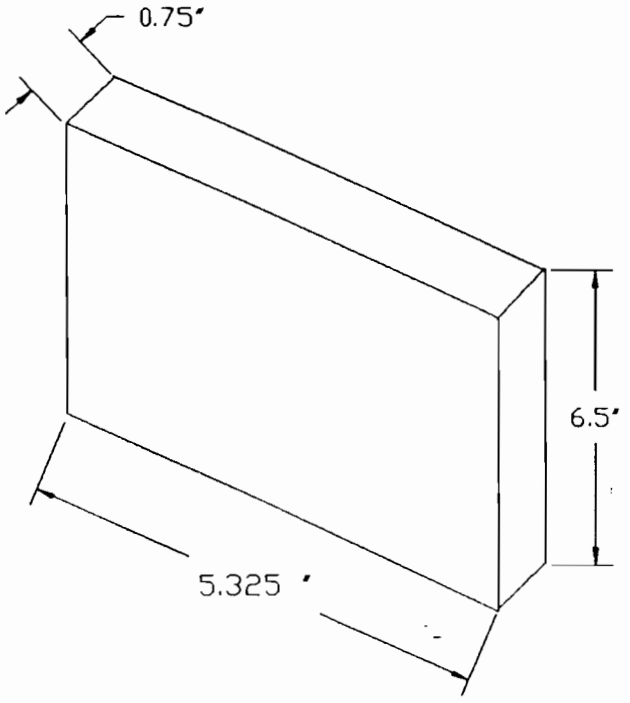


Figure C.6 Side Plate of Guillotine Direct Shear Test Apparatus

APPENDIX D

Beam Platform

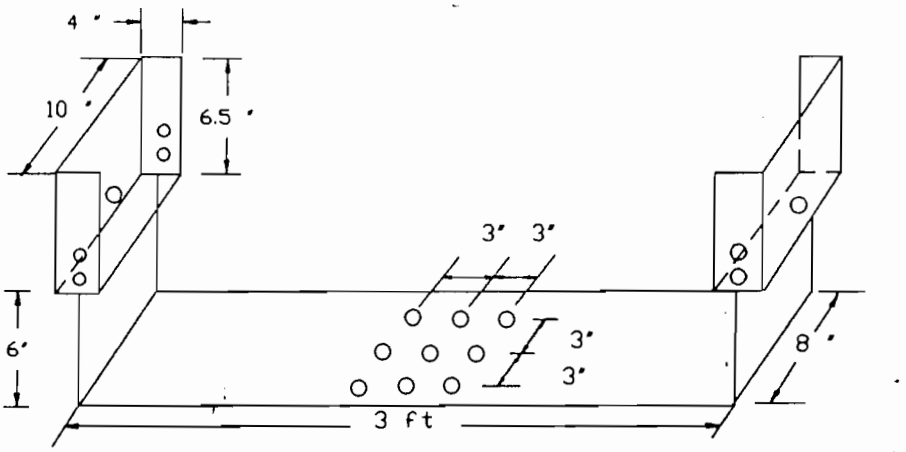


Figure D.1 Perspective View of Beam Platform

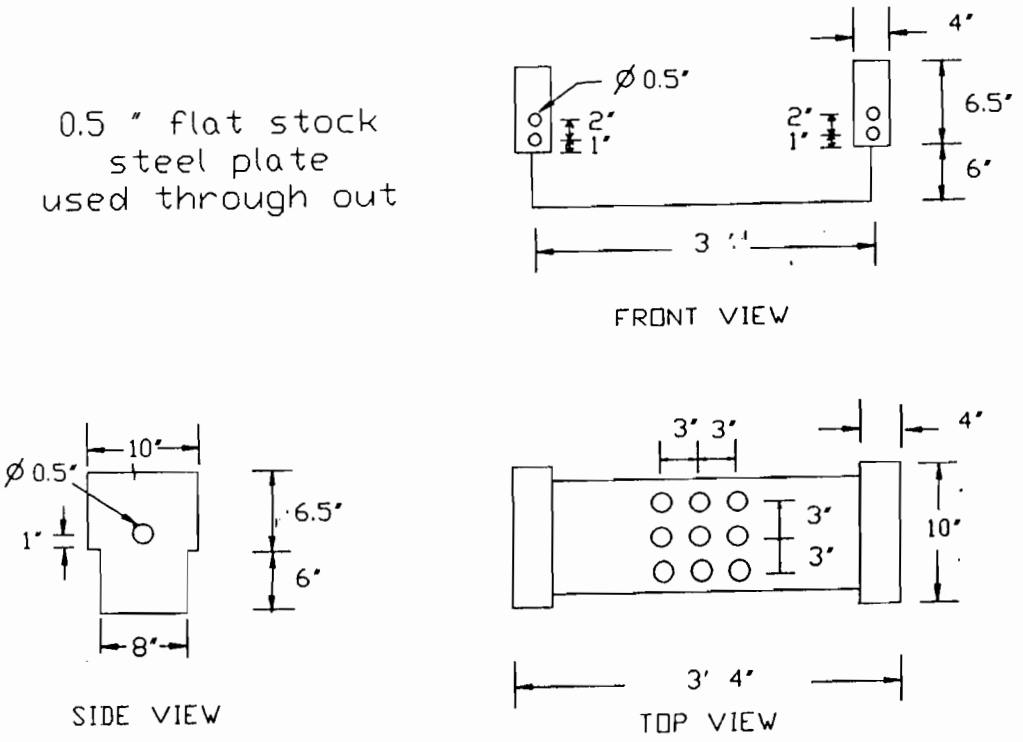


Figure D.2 Front, Top and Side Views of Beam Platform

APPENDIX E

Shear Strength Plots

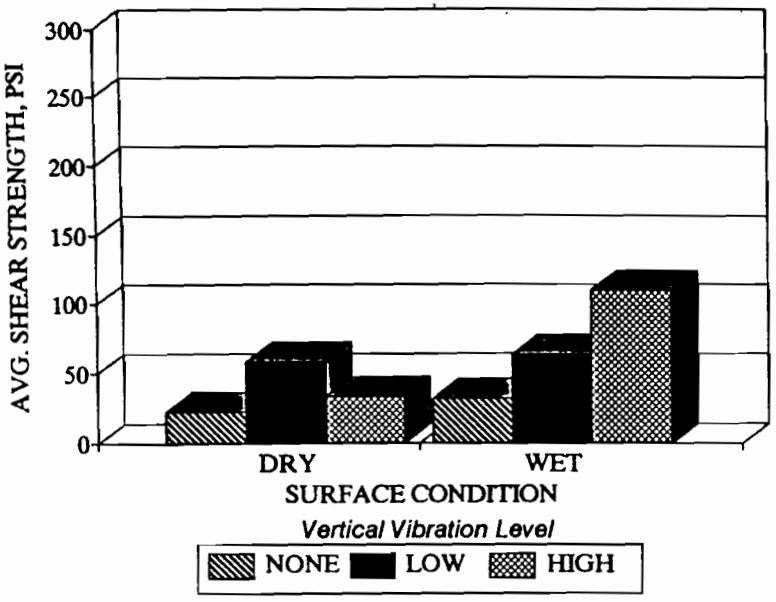


Figure E.1 Comparison of Average Shear Strengths for a 2-in. Overlay After 0 Hrs. of Pre-Vibration Cure (Smooth Interface) Under Vertical Vibration Mode

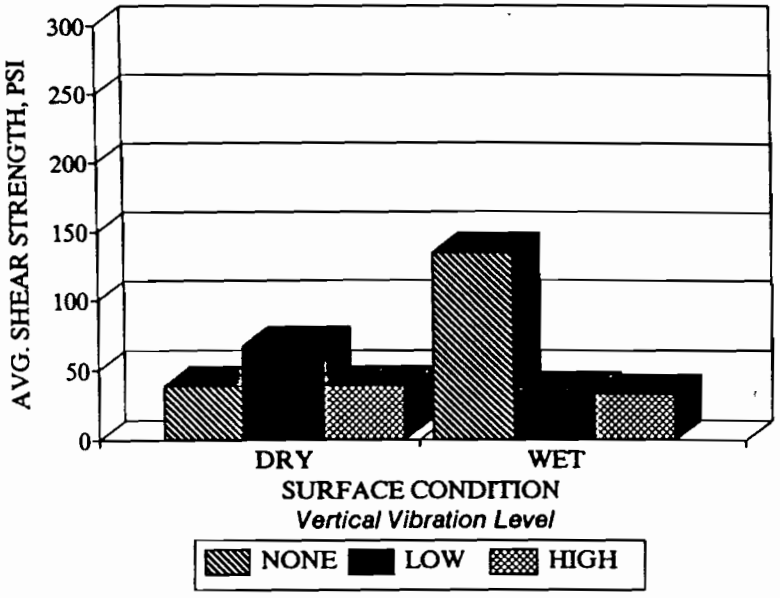


Figure E.2 Comparison of Average Shear Strengths for a 2-in. Overlay After 0 Hrs. of Pre-Vibration Cure (Rough Interface) Under Vertical Vibration Mode

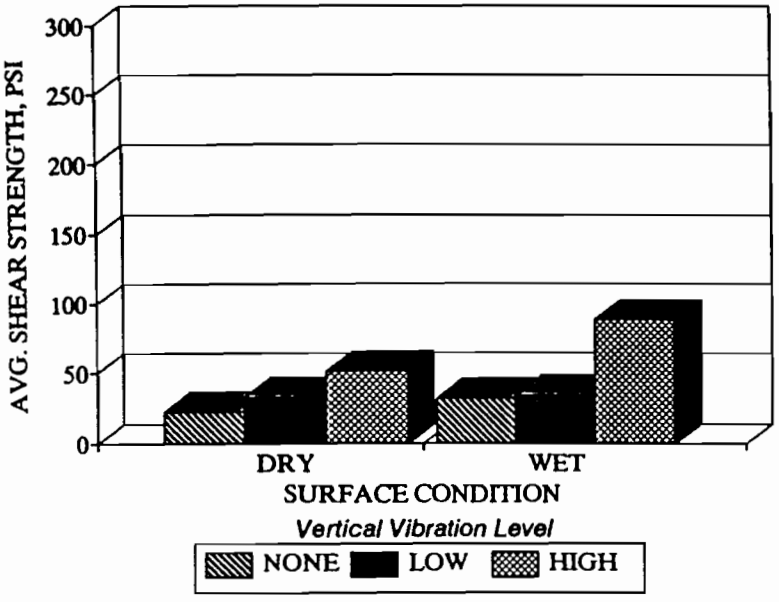


Figure E.3 Comparison of Average Shear Strengths for a 2-in. Overlay After 4 Hrs. of Pre-Vibration Cure (Smooth Interface) Under Vertical Vibration Mode

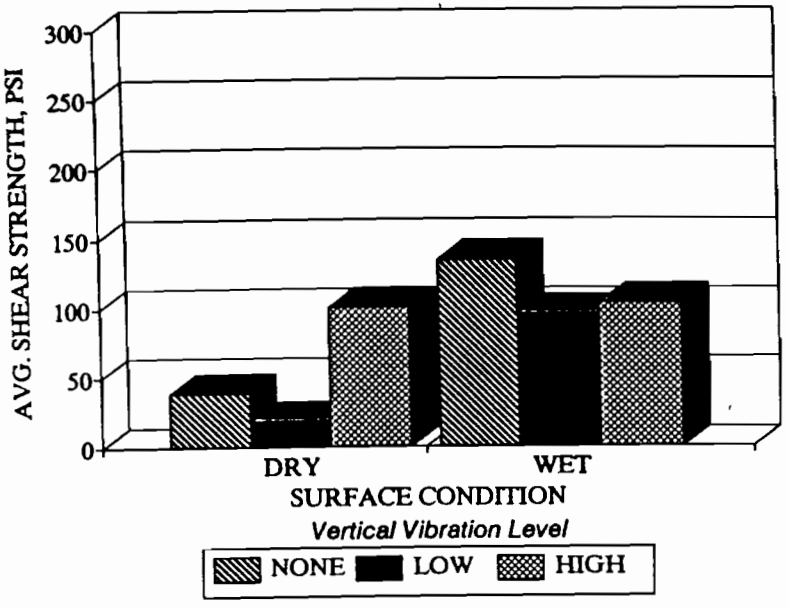


Figure E.4 Comparison of Average Shear Strengths for a 2-in. Overlay After 4 Hrs. of Pre-Vibration Cure (Rough Interface) Under Vertical Vibration Mode

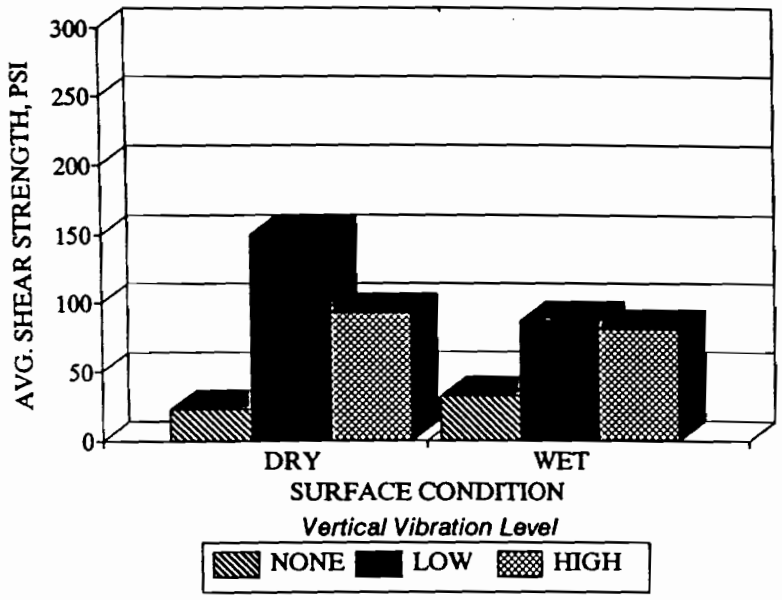


Figure E.5 Comparison of Average Shear Strengths for a 2-in. Overlay After 12 Hrs. of Pre-Vibration Cure (Smooth Interface) Under Vertical Vibration Mode

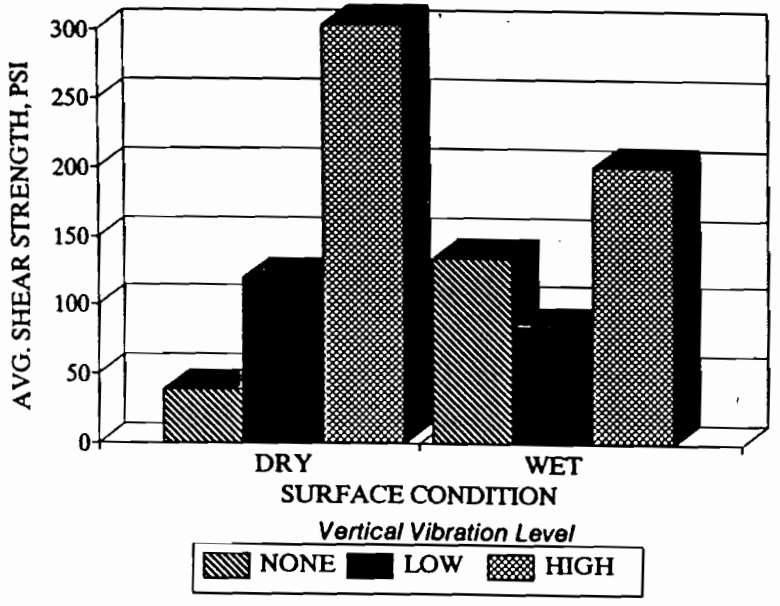


Figure E.6 Comparison of Average Shear Strengths for a 2-in. Overlay After 12 Hrs. of Pre-Vibration Cure (Rough Interface) Under Vertical Vibration Mode

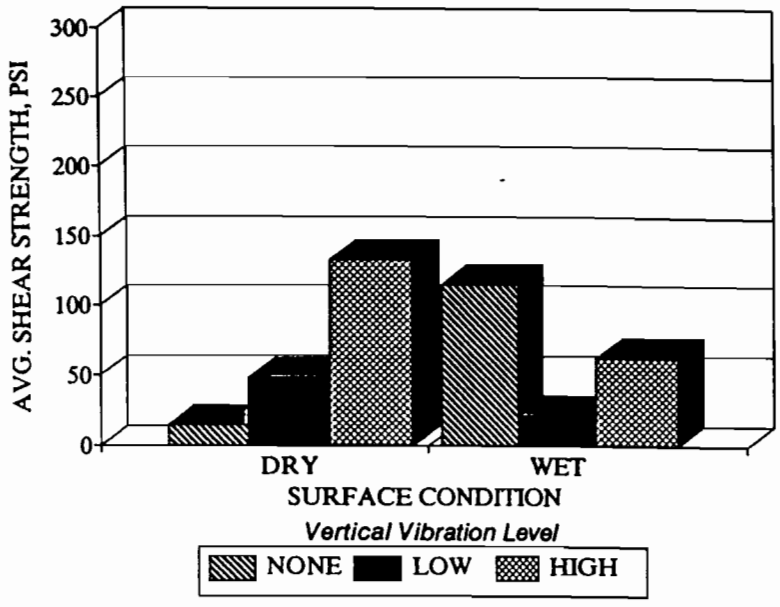


Figure E.7 Comparison of Average Shear Strengths for a 4-in. Overlay After 0 Hrs. of Pre-Vibration Cure (Smooth Interface) Under Vertical Vibration Mode

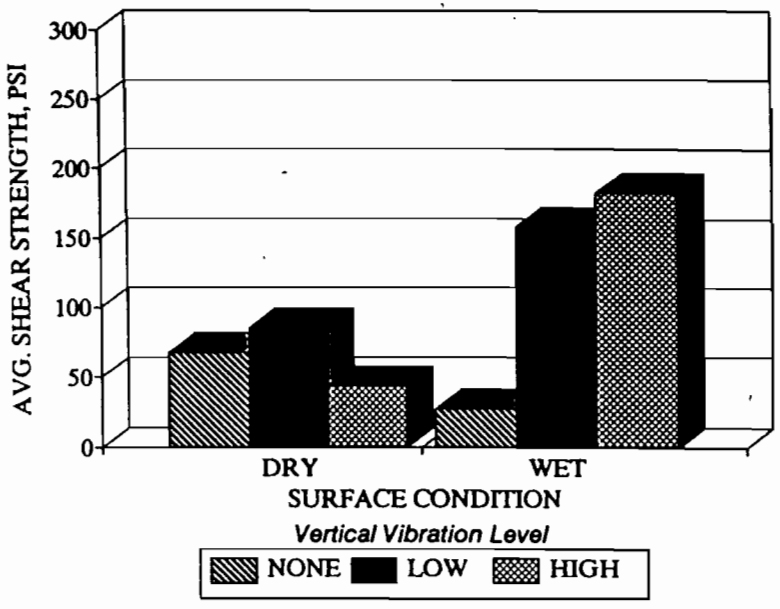


Figure E.8 Comparison of Average Shear Strengths for a 4-in. Overlay After 0 Hrs. of Pre-Vibration Cure (Rough Interface) Under Vertical Vibration Mode

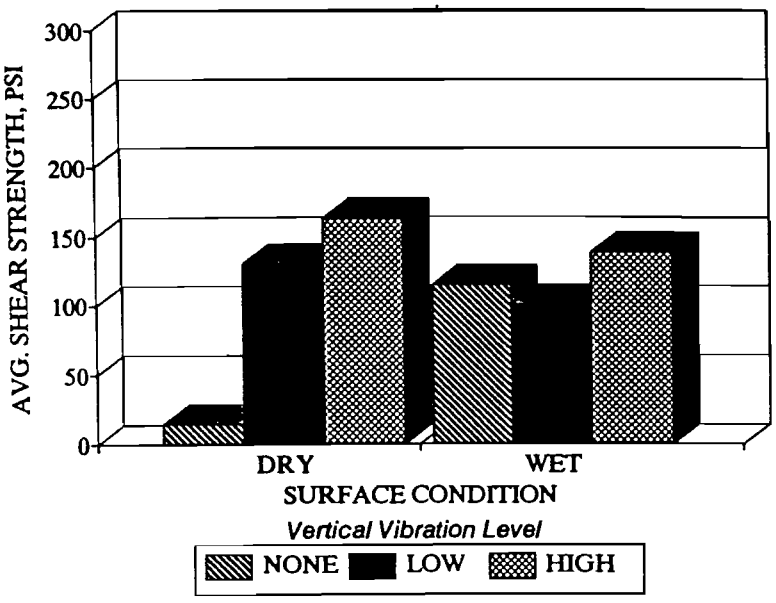


Figure E.9 Comparison of Average Shear Strengths for a 4-in. Overlay After 4 Hrs. of Pre-Vibration Cure (Smooth Interface) Under Vertical Vibration Mode

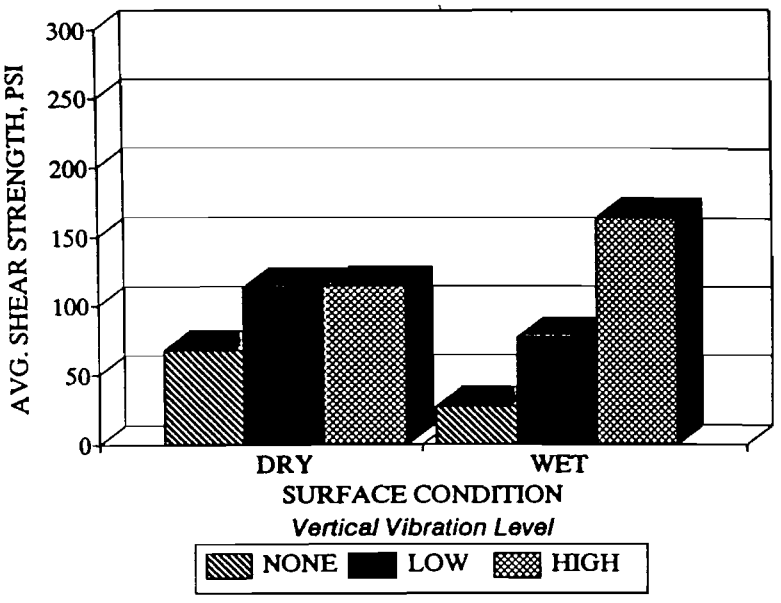


Figure E.10 Comparison of Average Shear Strengths for a 4-in. Overlay After 4 Hrs. of Pre-Vibration Cure (Rough Interface) Under Vertical Vibration Mode

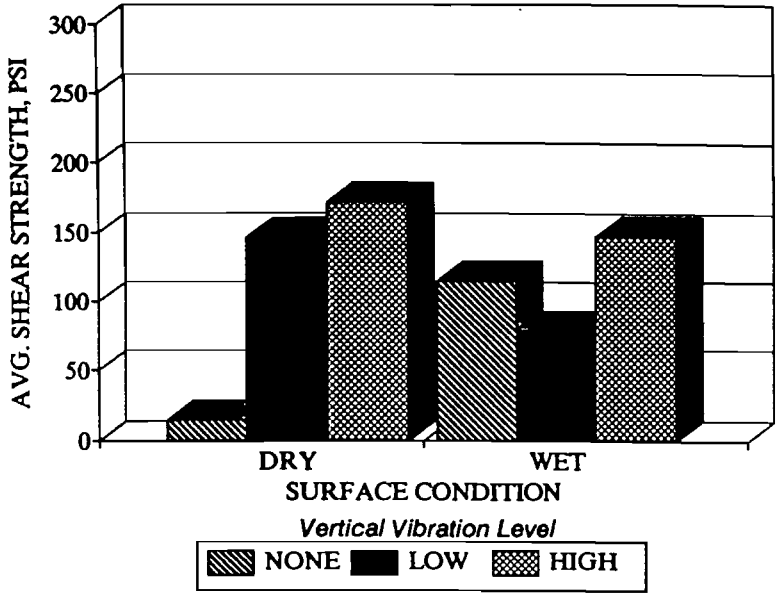


Figure E.11 Comparison of Average Shear Strengths for a 4-in. Overlay After 12 Hrs. of Pre-Vibration Cure (Smooth Interface) Under Vertical Vibration Mode

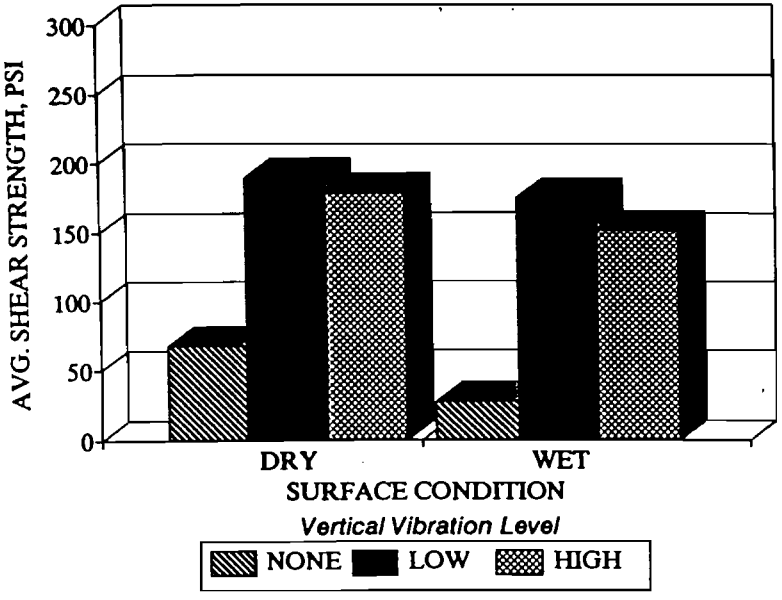


Figure E.12 Comparison of Average Shear Strengths for a 4-in. Overlay After 12 Hrs. of Pre-Vibration Cure (Rough Interface) Under Vertical Vibration Mode

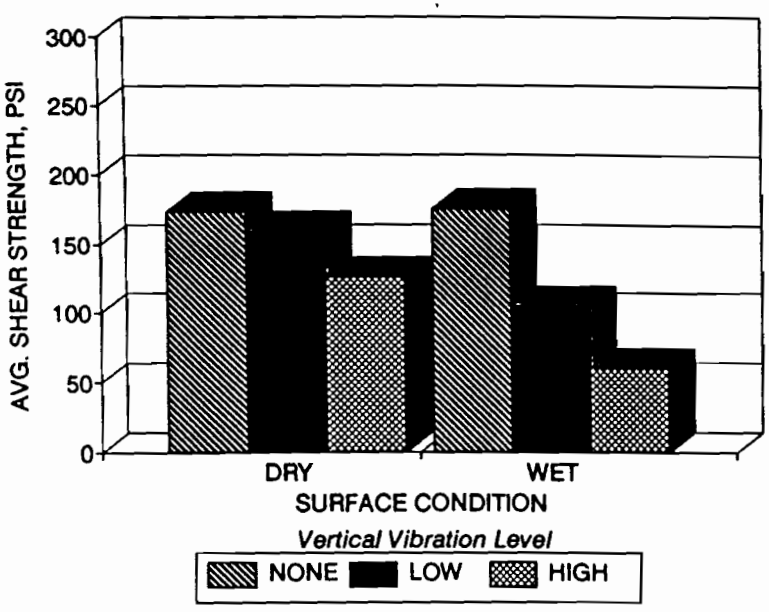


Figure E.13 Comparison of Average Shear Strengths for a 6-in. Overlay After 0 Hrs. of Pre-Vibration Cure (Smooth Interface) Under Vertical Vibration Mode

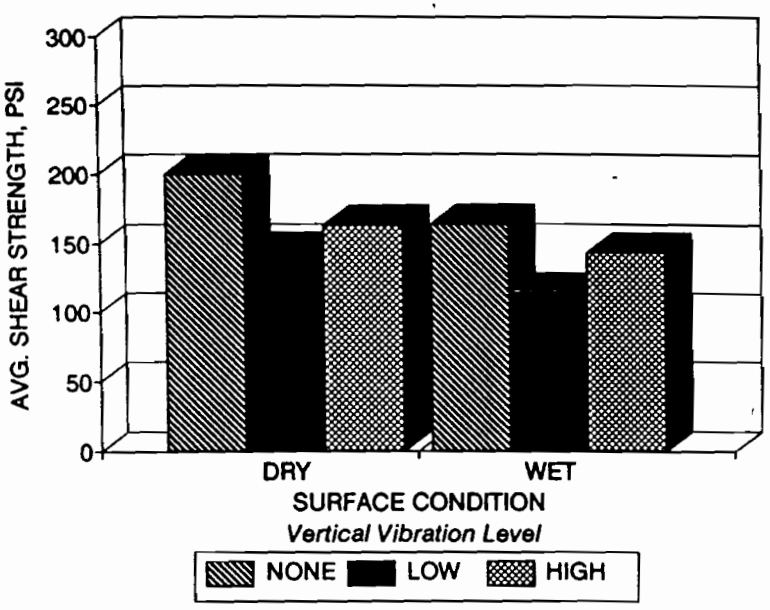


Figure E.14 Comparison of Average Shear Strengths for a 6-in. Overlay After 0 Hrs. of Pre-Vibration Cure (Rough Interface) Under Vertical Vibration Mode

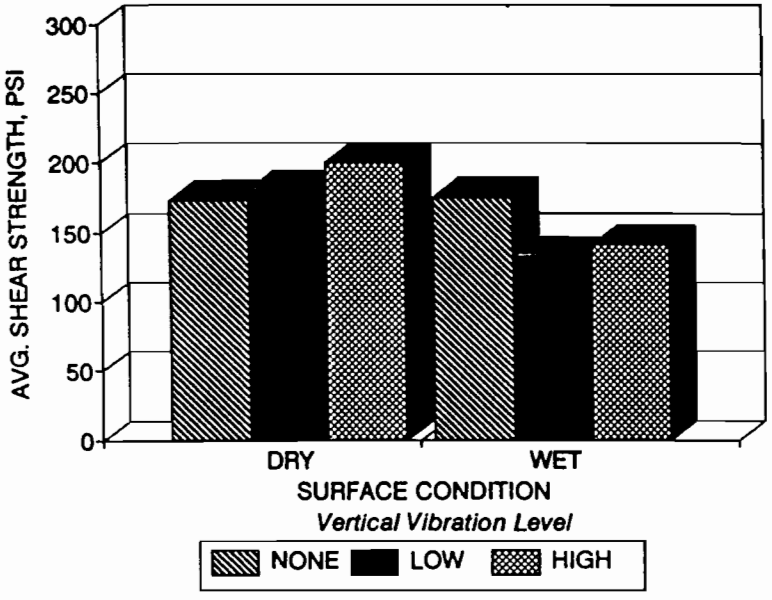


Figure E.15 Comparison of Average Shear Strengths for a 6-in. Overlay After 4 Hrs. of Pre-Vibration Cure (Smooth Interface) Under Vertical Vibration Mode

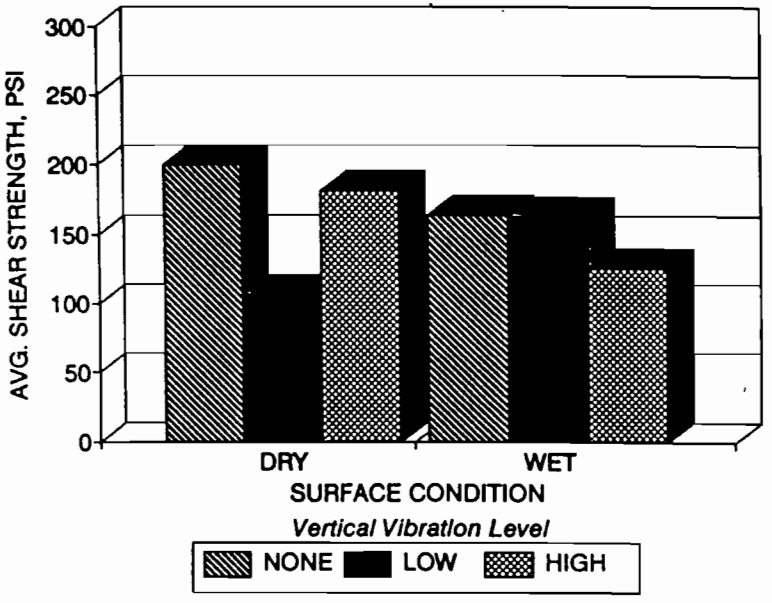


Figure E.16 Comparison of Average Shear Strengths for a 6-in. Overlay After 4 Hrs. of Pre-Vibration Cure (Rough Interface) Under Vertical Vibration Mode

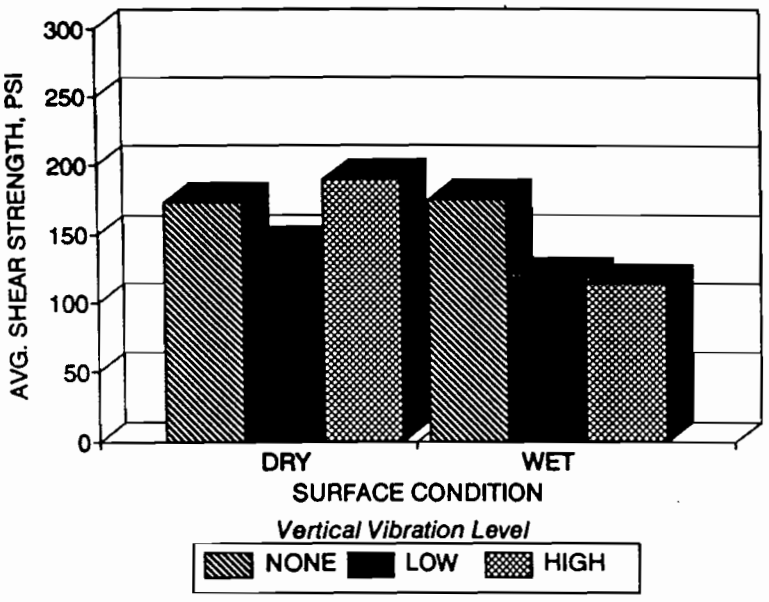


Figure E.17 Comparison of Average Shear Strengths for a 6-in. Overlay After 12 Hrs. of Pre-Vibration Cure (Smooth Interface) Under Vertical Vibration Mode

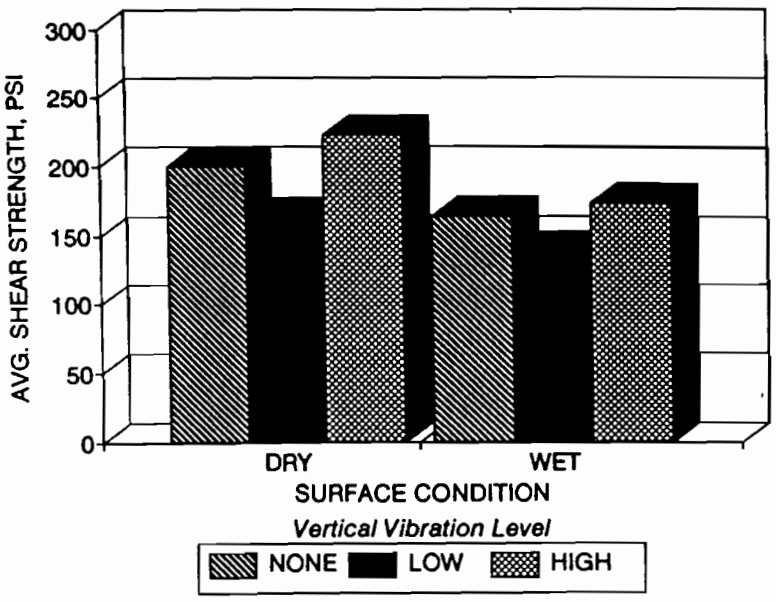


Figure E.18 Comparison of Average Shear Strengths for a 6-in. Overlay After 12 Hrs. of Pre-Vibration Cure (Rough Interface) Under Vertical Vibration Mode

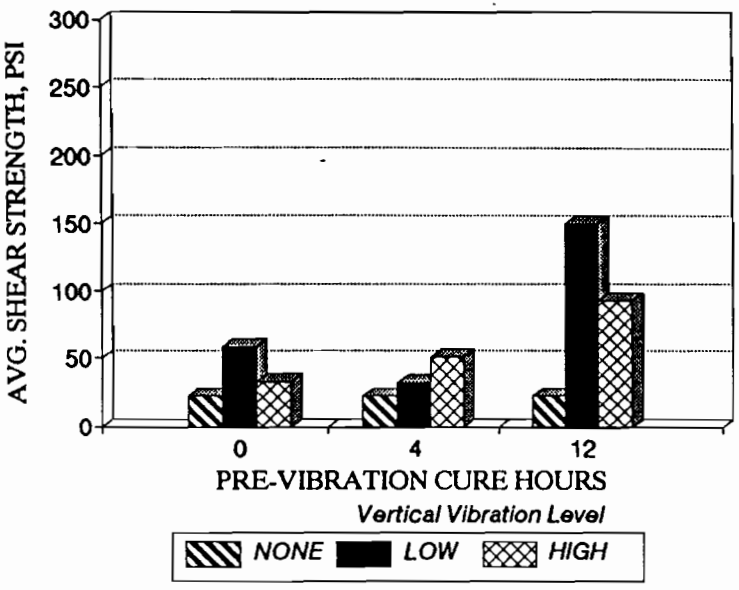


Figure E.19 Comparison of Average Shear Strengths for a 2-in. Overlay (Smooth-Dry Interface) Under Vertical Vibration Mode

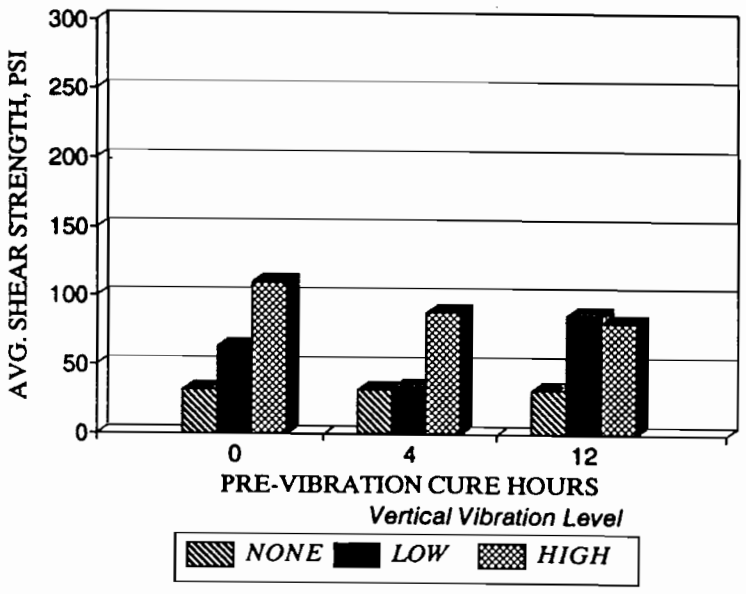


Figure E.20 Comparison of Average Shear Strengths for a 2-in. Overlay (Smooth-Wet Interface) Under Vertical Vibration Mode

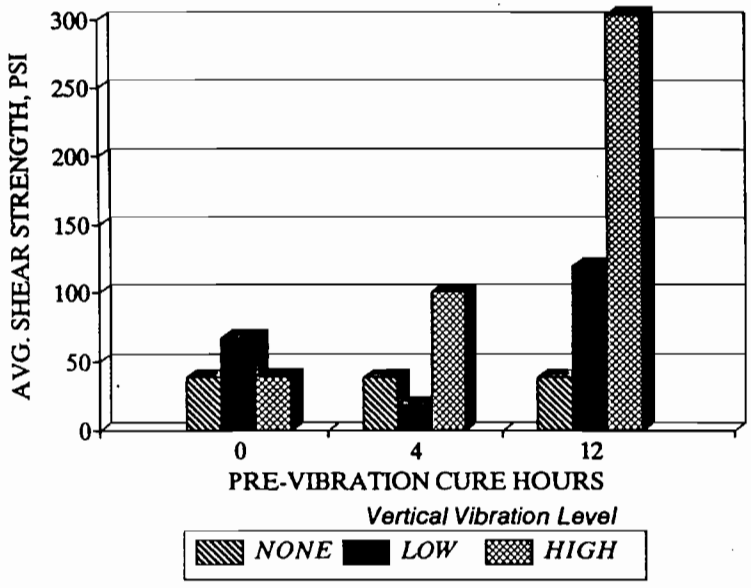


Figure E.21 Comparison of Average Shear Strengths for a 2-in. Overlay (Rough-Dry Interface) Under Vertical Vibration Mode

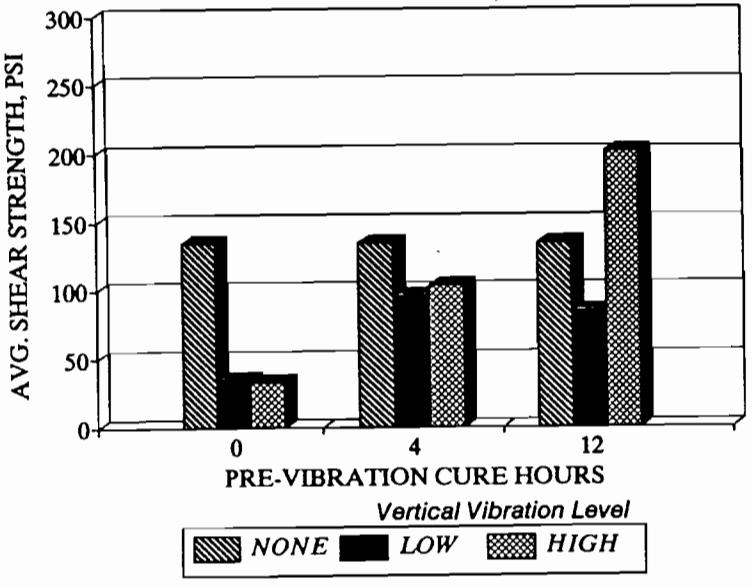


Figure E.22 Comparison of Average Shear Strengths for a 2-in. Overlay (Rough-Wet Interface) Under Vertical Vibration Mode

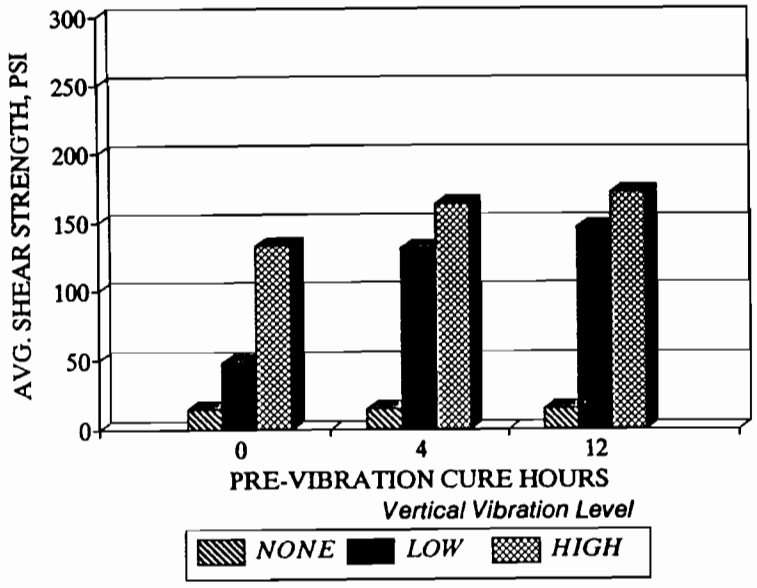


Figure E.23 Comparison of Average Shear Strengths for a 4-in. Overlay (Smooth-Dry Interface) Under Vertical Vibration Mode

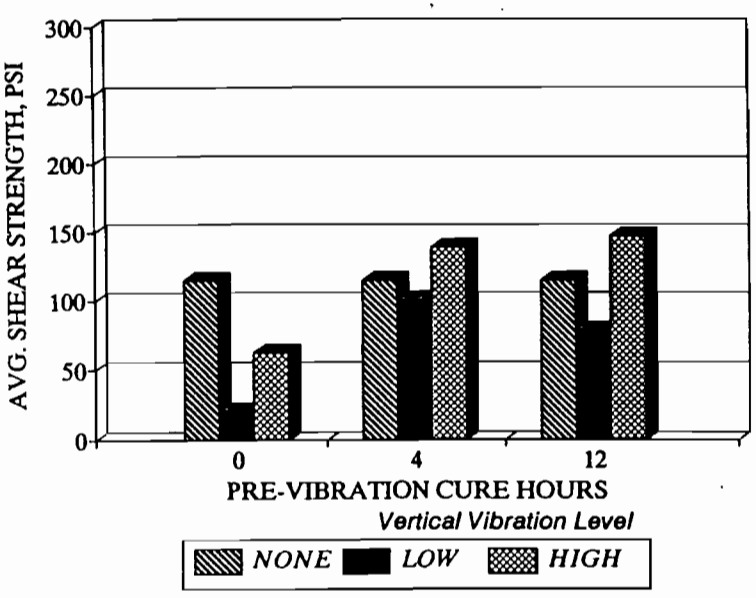


Figure E.24 Comparison of Average Shear Strengths for a 4-in. Overlay (Smooth-Wet Interface) Under Vertical Vibration Mode

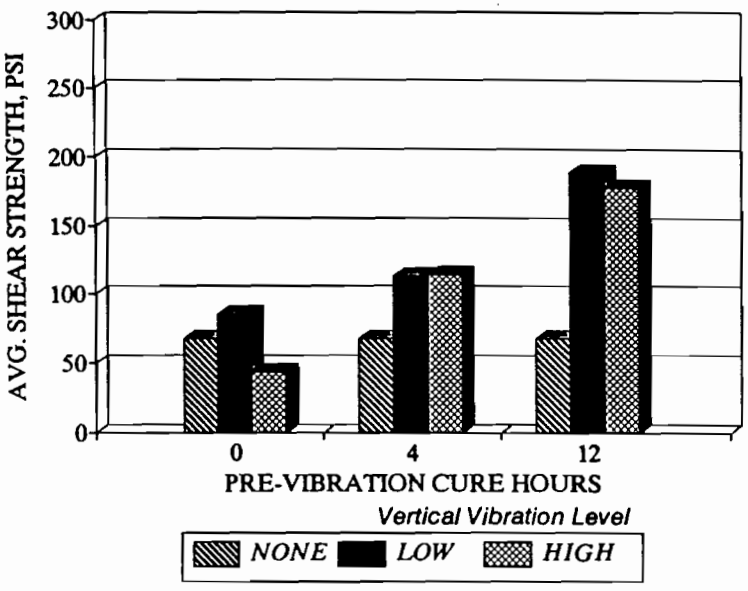


Figure E.25 Comparison of Average Shear Strengths for a 4-in. Overlay (Rough-Dry Interface) Under Vertical Vibration Mode

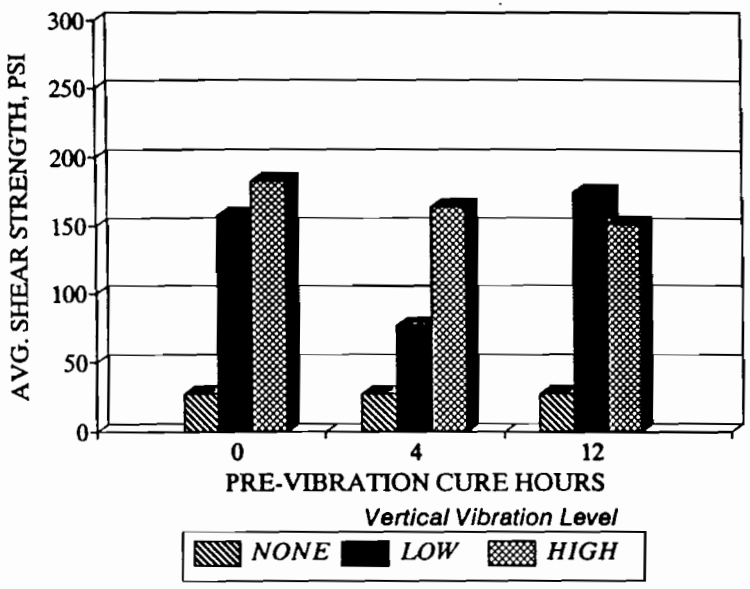


Figure E.26 Comparison of Average Shear Strengths for a 4-in. Overlay (Rough-Wet Interface) Under Vertical Vibration Mode

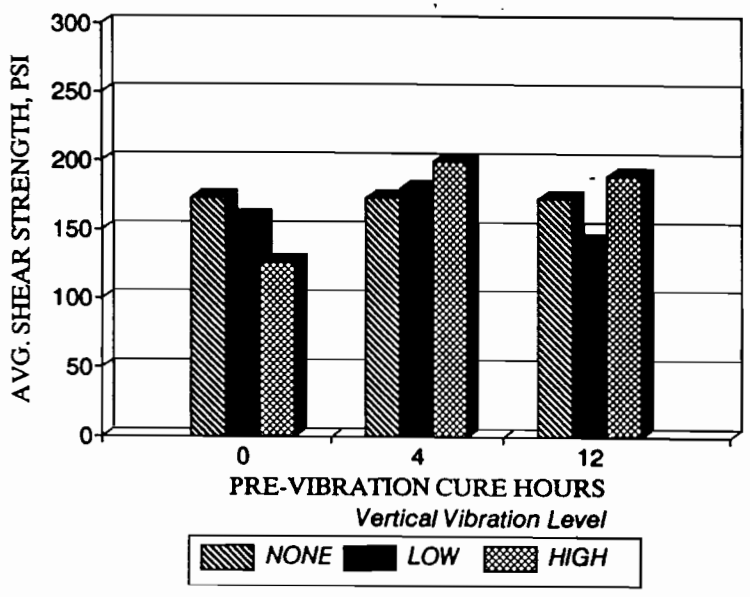


Figure E.27 Comparison of Average Shear Strengths for a 6-in. Overlay (Smooth-Dry Interface) Under Vertical Vibration Mode

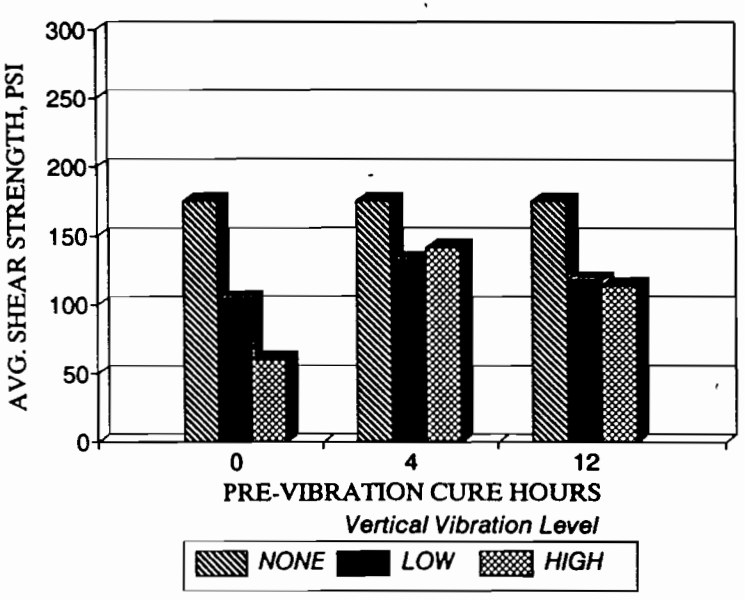


Figure E.28 Comparison of Average Shear Strengths for a 6-in. Overlay (Smooth-Wet Interface) Under Vertical Vibration Mode

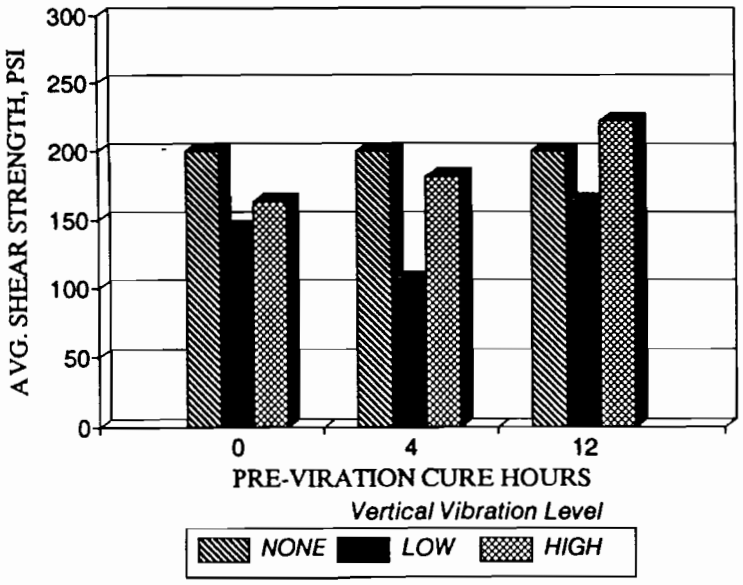


Figure E.29 Comparison of Average Shear Strengths for a 6-in. Overlay (Rough-Dry Interface) Under Vertical Vibration Mode

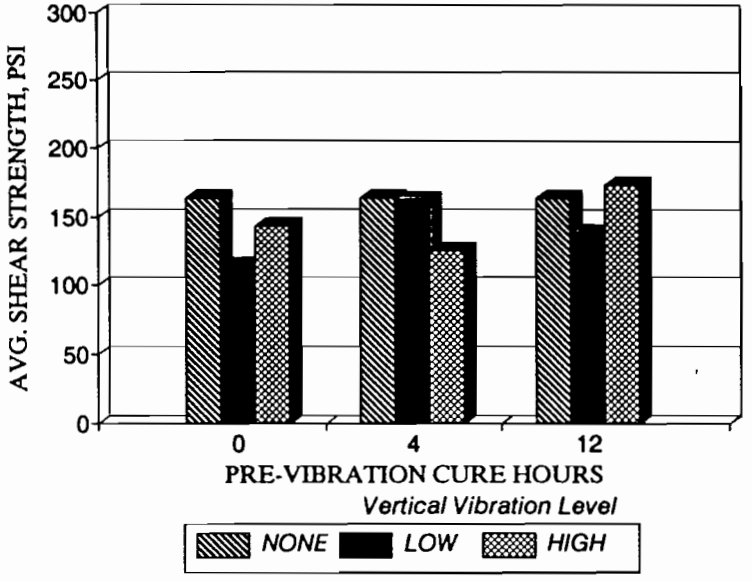


Figure E.30 Comparison of Average Shear Strengths for a 6-in. Overlay (Rough-Wet Interface) Under Vertical Vibration Mode

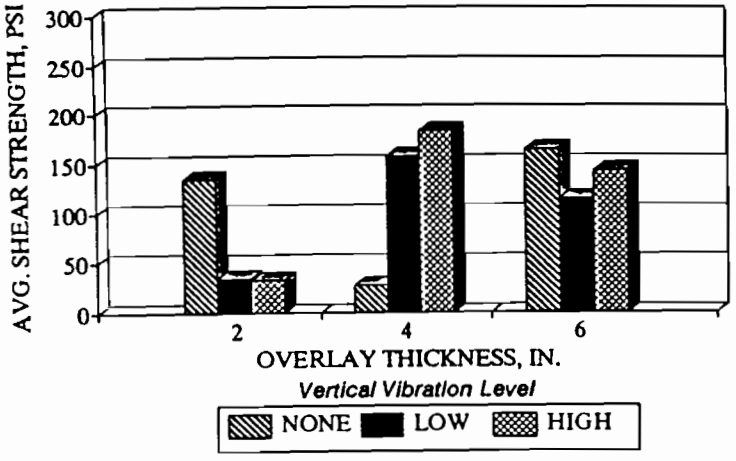


Figure E.31 Comparison of Average Shear Strengths After 0 Hrs. of Pre-Vibration Cure (Smooth-Dry Interface) Under Vertical Vibration Mode

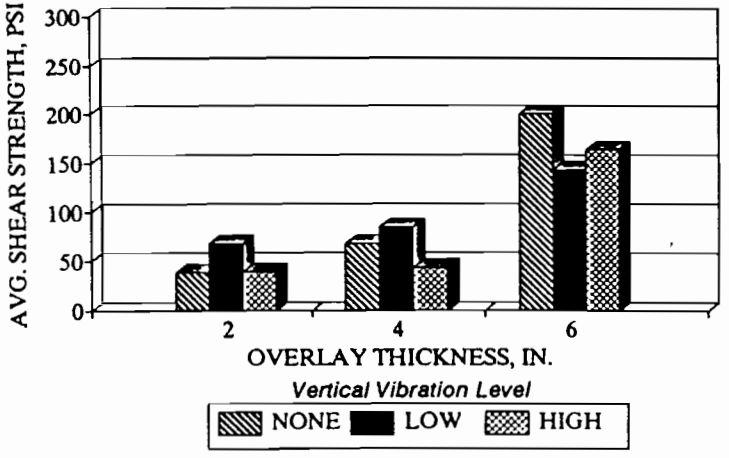


Figure E.32 Comparison of Average Shear Strengths After 0 Hrs. of Pre-Vibration Cure (Smooth-Wet Interface) Under Vertical Vibration Mode

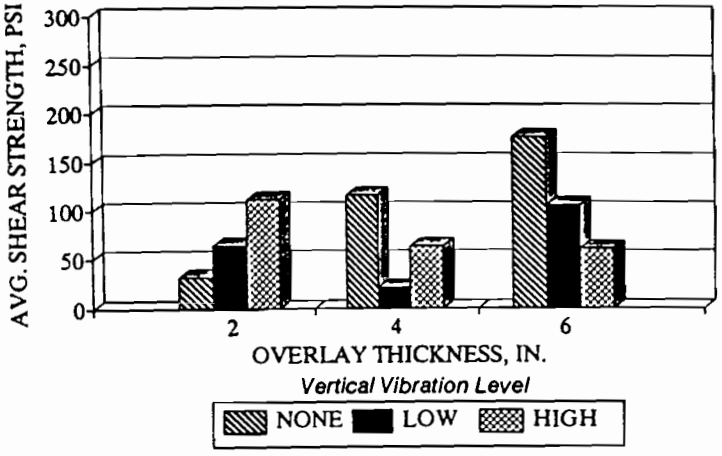


Figure E.33 Comparison of Average Shear Strengths After 0 Hrs. of Pre-Vibration Cure (Rough-Dry Interface) Under Vertical Vibration Mode

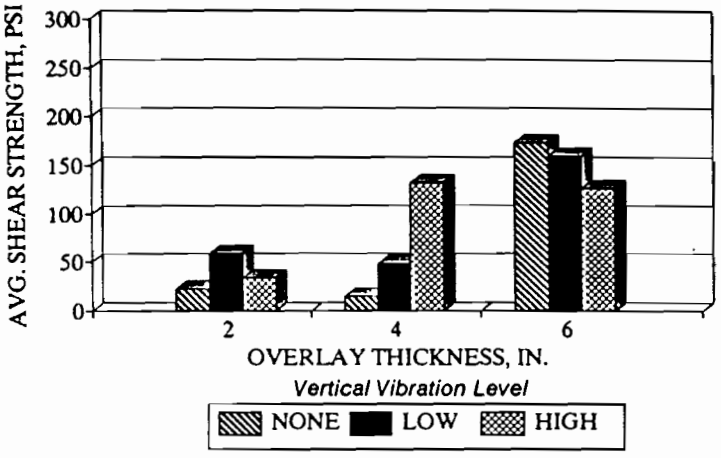


Figure E.34 Comparison of Average Shear Strengths After 0 Hrs. of Pre-Vibration Cure (Rough-Wet Interface) Under Vertical Vibration Mode

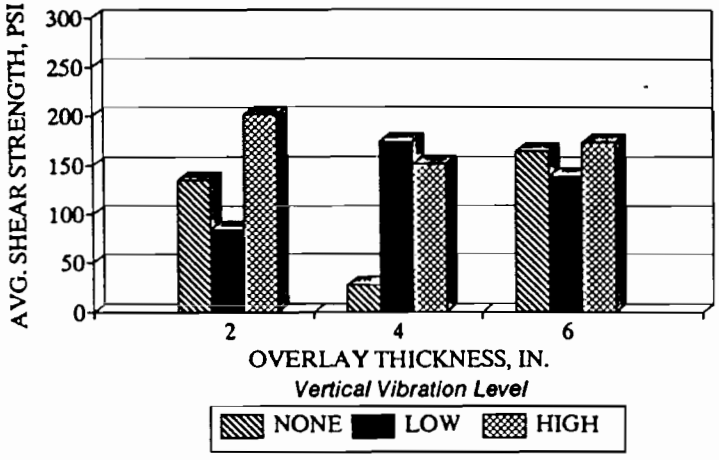


Figure E.35 Comparison of Average Shear Strengths After 4 Hrs. of Pre-Vibration Cure (Smooth-Dry Interface) Under Vertical Vibration Mode

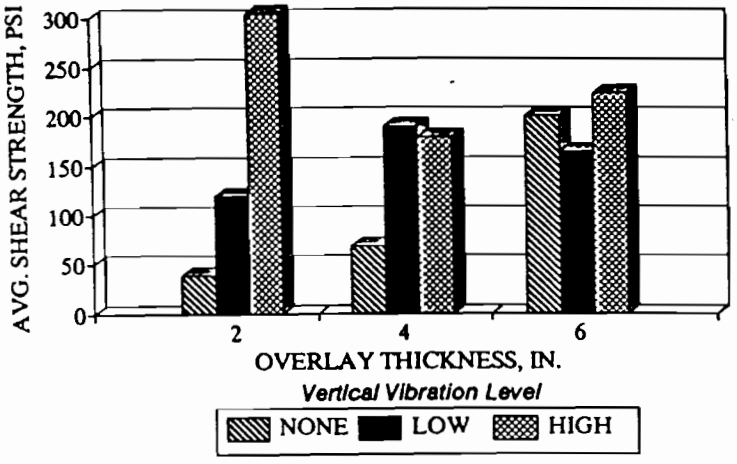


Figure E.36 Comparison of Average Shear Strengths After 4 Hrs. of Pre-Vibration Cure (Smooth-Wet Interface) Under Vertical Vibration Mode

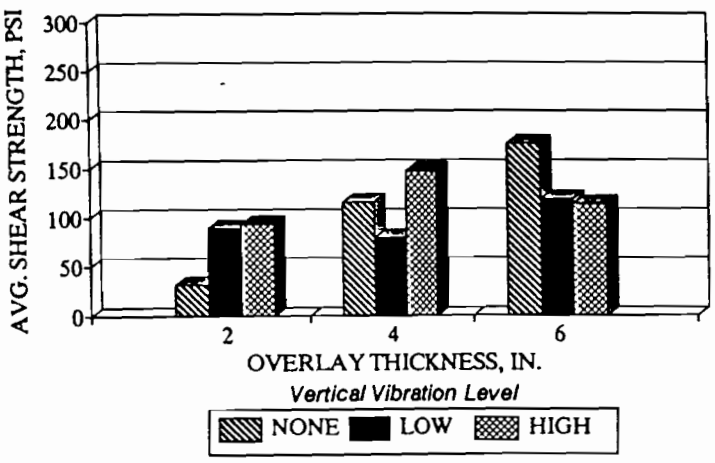


Figure E.37 Comparison of Average Shear Strengths After 4 Hrs. of Pre-Vibration Cure (Rough-Dry Interface) Under Vertical Vibration Mode

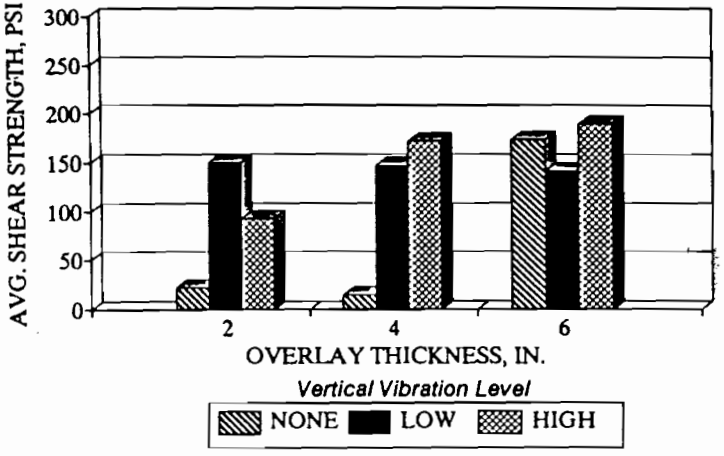


Figure E.38 Comparison of Average Shear Strengths After 4 Hrs. of Pre-Vibration Cure (Rough-Wet Interface) Under Vertical Vibration Mode

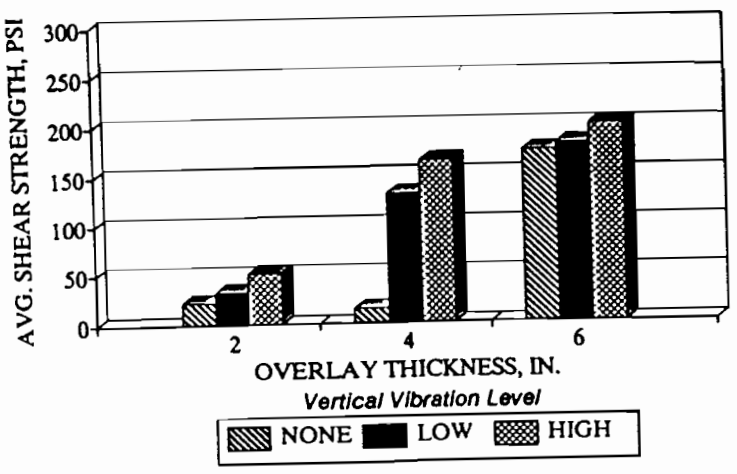


Figure E.39 Comparison of Average Shear Strengths After 12 Hrs. of Pre-Vibration Cure (Smooth-Dry Interface) Under Vertical Vibration Mode

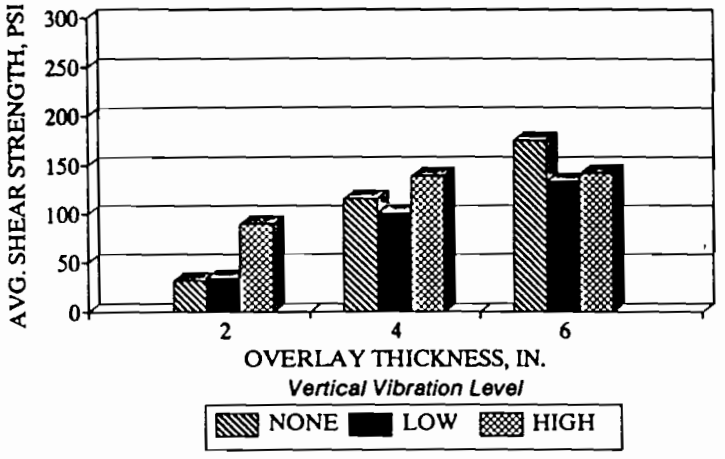


Figure E.40 Comparison of Average Shear Strengths After 12 Hrs. of Pre-Vibration Cure (Smooth-Wet Interface) Under Vertical Vibration Mode

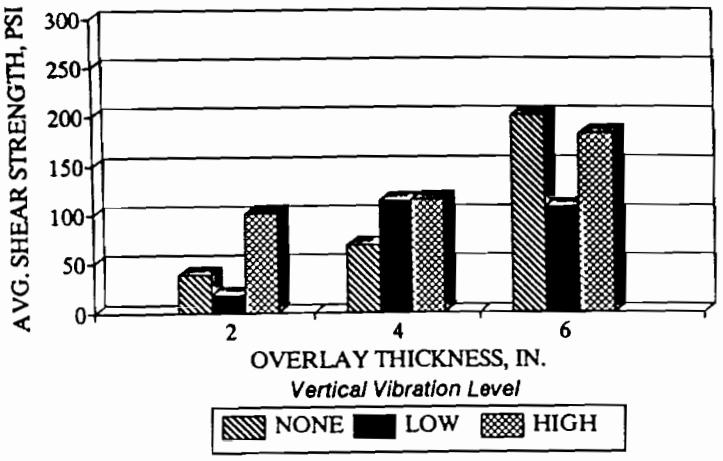


Figure E.41 Comparison of Average Shear Strengths After 12 Hrs. of Pre-Vibration Cure (Rough-Dry Interface) Under Vertical Vibration Mode

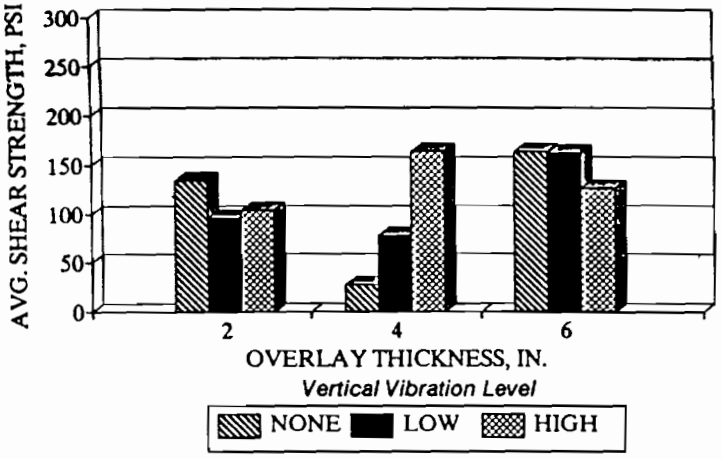


Figure E.42 Comparison of Average Shear Strengths After 12 Hrs. of Pre-Vibration Cure (Rough-Wet Interface) Under Vertical Vibration Mode

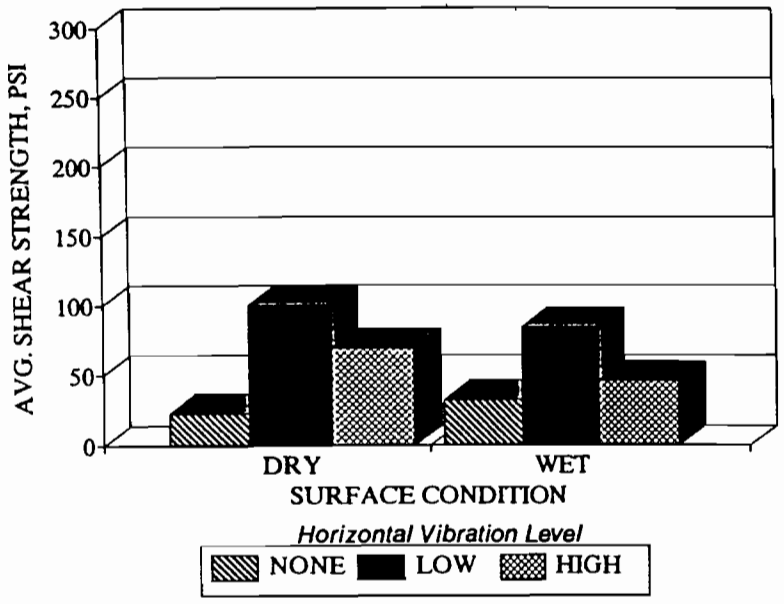


Figure E.43 Comparison of Average Shear Strengths for a 2-in. Overlay After 0 Hrs. of Pre-Vibration Cure (Smooth Interface) Under Horizontal Vibration Mode

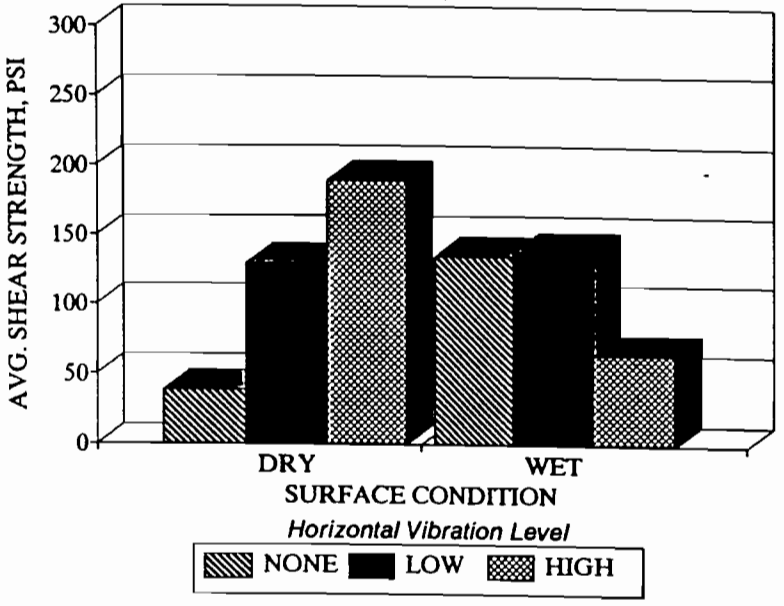


Figure E.44 Comparison of Average Shear Strengths for a 2-in. Overlay After 0 Hrs. of Pre-Vibration Cure (Rough Interface) Under Horizontal Vibration Mode

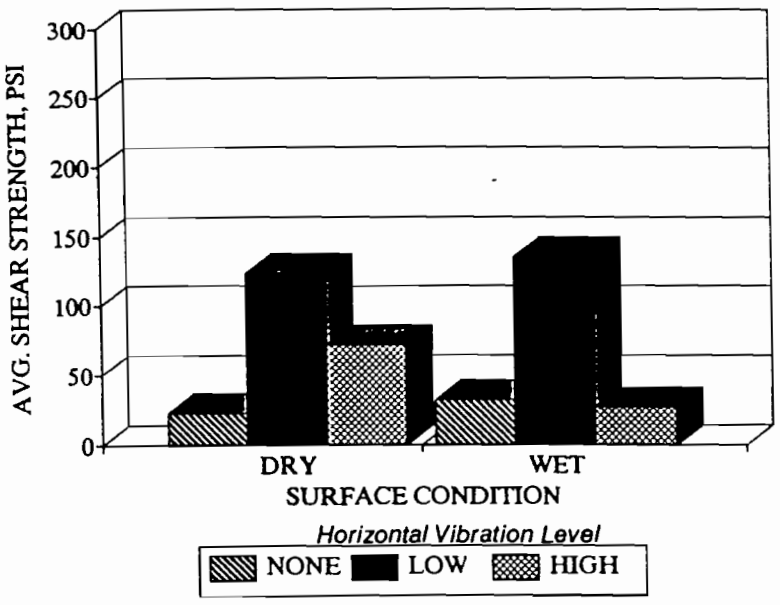


Figure E.45 Comparison of Average Shear Strengths for a 2-in. Overlay After 4 Hrs. of Pre-Vibration Cure (Smooth Interface) Under Horizontal Vibration Mode

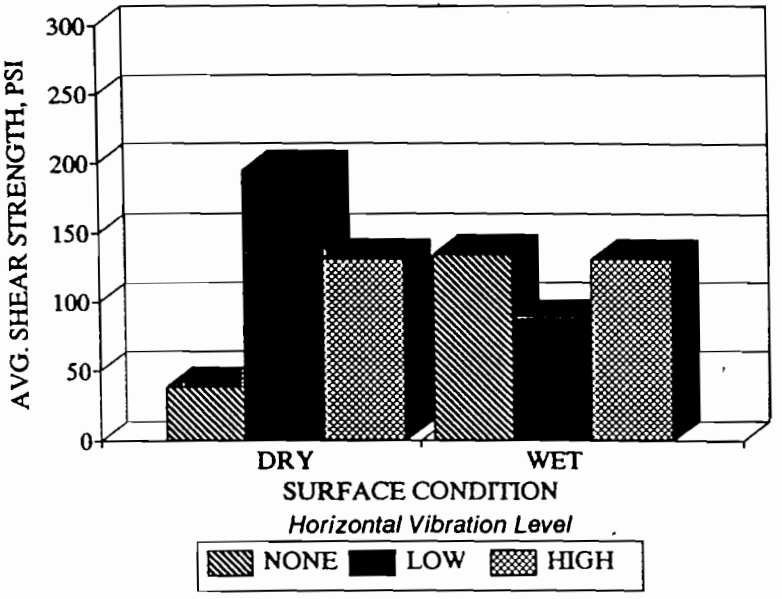


Figure E.46 Comparison of Average Shear Strengths for a 2-in. Overlay After 4 Hrs. of Pre-Vibration Cure (Rough Interface) Under Horizontal Vibration Mode

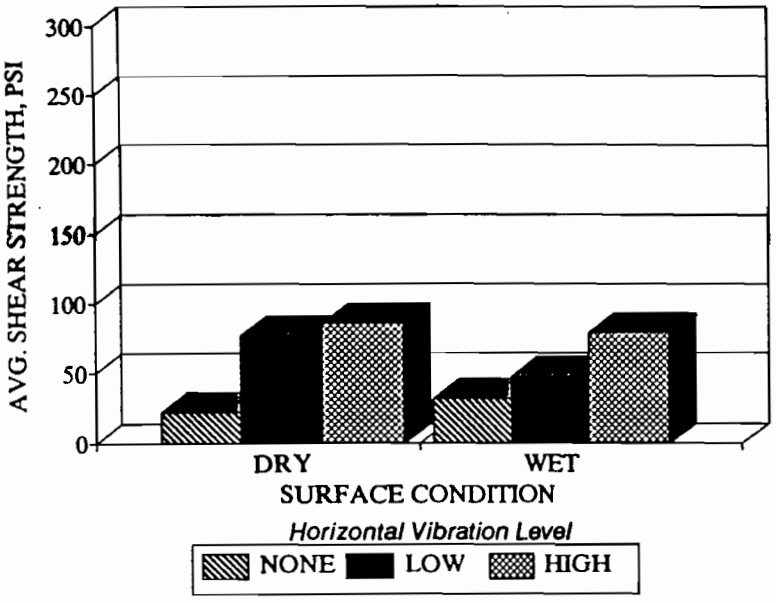


Figure E.47 Comparison of Average Shear Strengths for a 2-in. Overlay After 12 Hrs. of Pre-Vibration Cure (Smooth Interface) Under Horizontal Vibration Mode

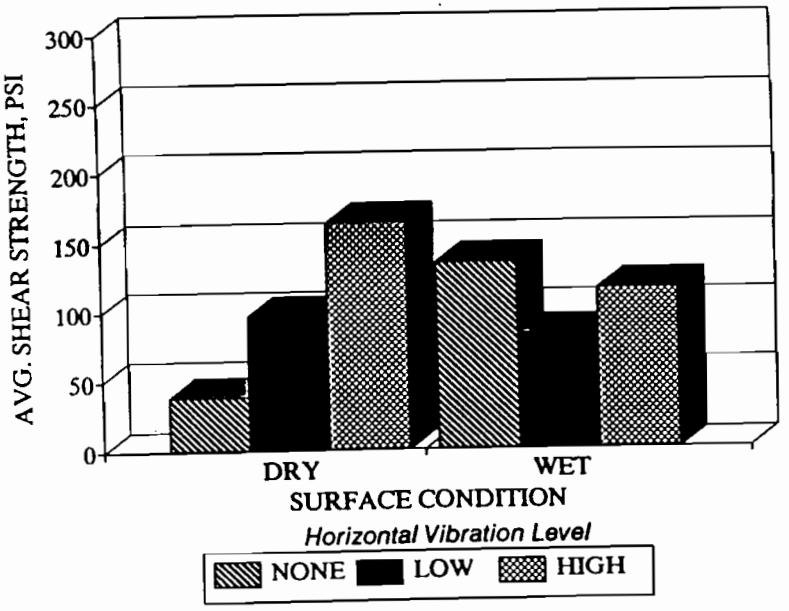


Figure E.48 Comparison of Average Shear Strengths for a 2-in. Overlay After 12 Hrs. of Pre-Vibration Cure (Rough Interface) Under Horizontal Vibration Mode

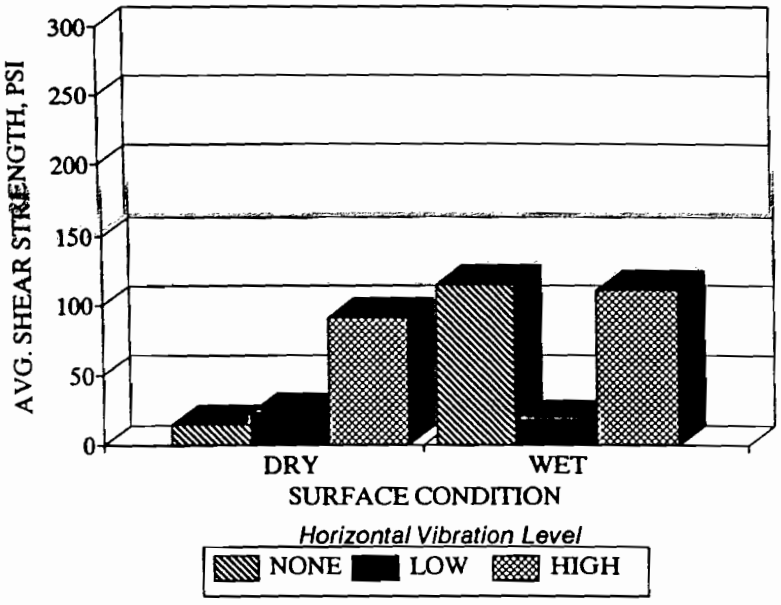


Figure E.49 Comparison of Average Shear Strengths for a 4-in. Overlay After 0 Hrs. of Pre-Vibration Cure (Smooth Interface) Under Horizontal Vibration Mode

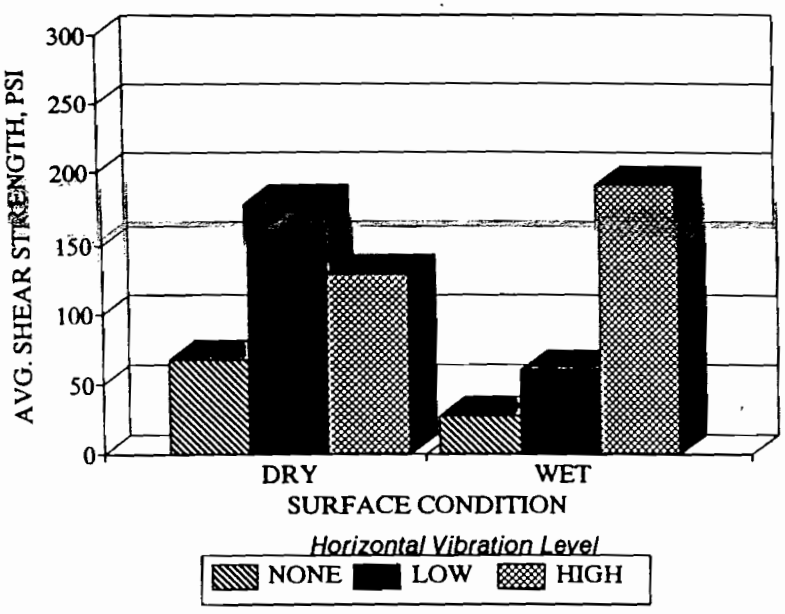


Figure E.50 Comparison of Average Shear Strengths for a 4-in. Overlay After 0 Hrs. of Pre-Vibration Cure (Rough Interface) Under Horizontal Vibration Mode

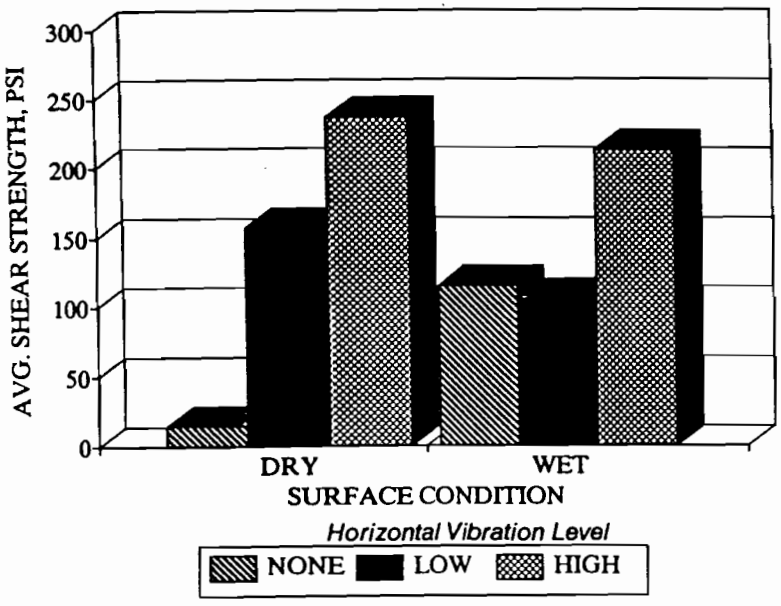


Figure E.51 Comparison of Average Shear Strengths for a 4-in. Overlay After 4 Hrs. of Pre-Vibration Cure (Smooth Interface) Under Horizontal Vibration Mode

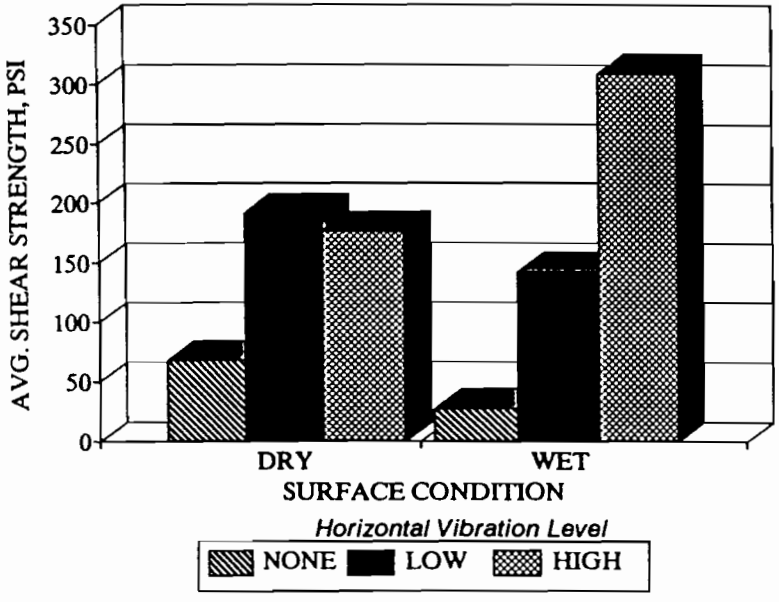


Figure E.52 Comparison of Average Shear Strengths for a 4-in. Overlay After 4 Hrs. of Pre-Vibration Cure (Rough Interface) Under Horizontal Vibration Mode

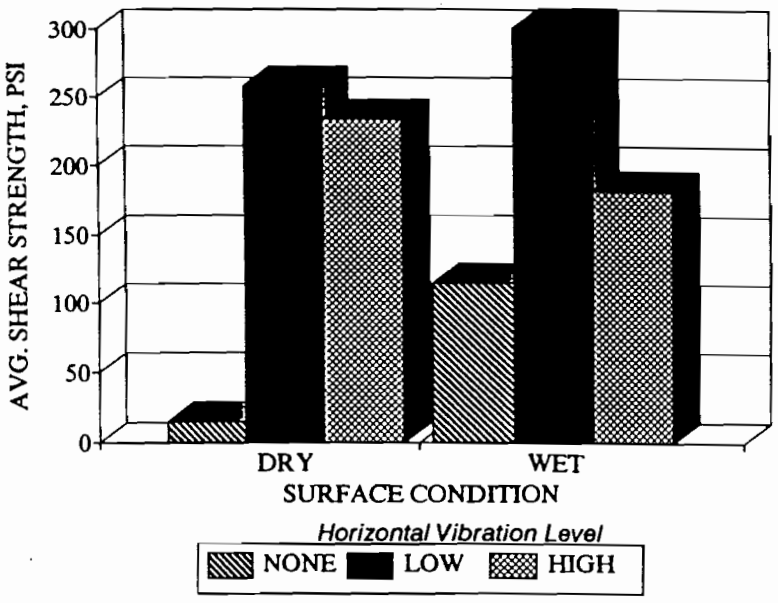


Figure E.53 Comparison of Average Shear Strengths for a 4-in. Overlay After 12 Hrs. of Pre-Vibration Cure (Smooth Interface) Under Horizontal Vibration Mode

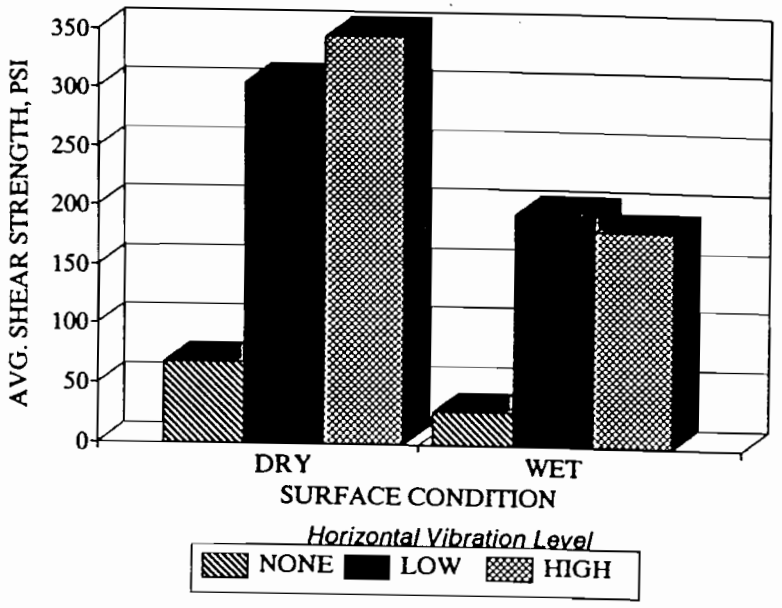


Figure E.54 Comparison of Average Shear Strengths for a 4-in. Overlay After 12 Hrs. of Pre-Vibration Cure (Rough Interface) Under Horizontal Vibration Mode

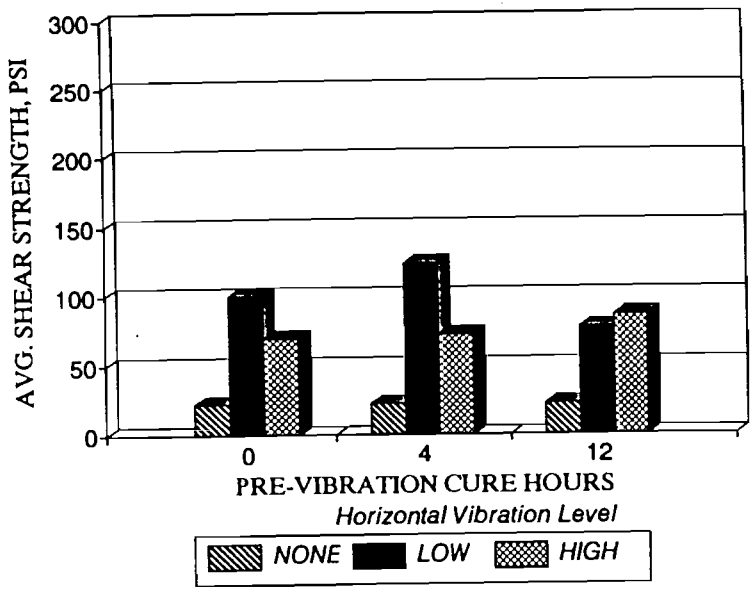


Figure E.55 Comparison of Average Shear Strengths for a 2-in. Overlay (Smooth-Dry Interface) Under Horizontal Vibration Mode

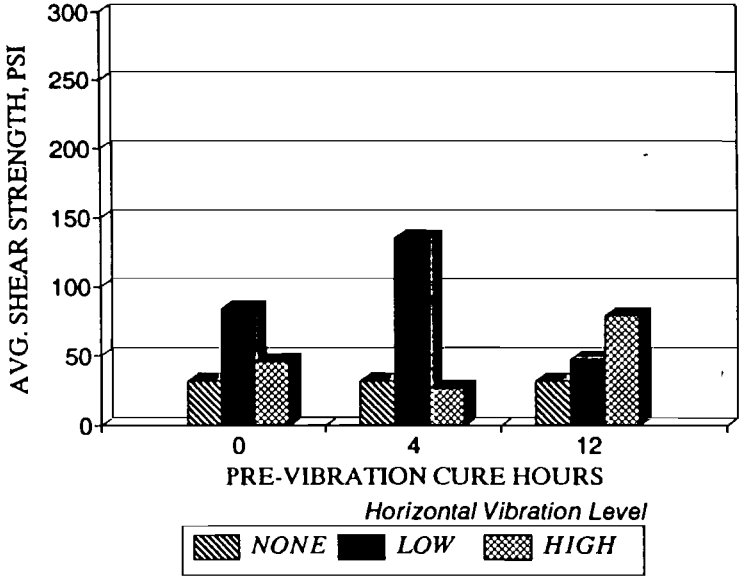


Figure E.56 Comparison of Average Shear Strengths for a 2-in. Overlay (Smooth-Wet Interface) Under Horizontal Vibration Mode

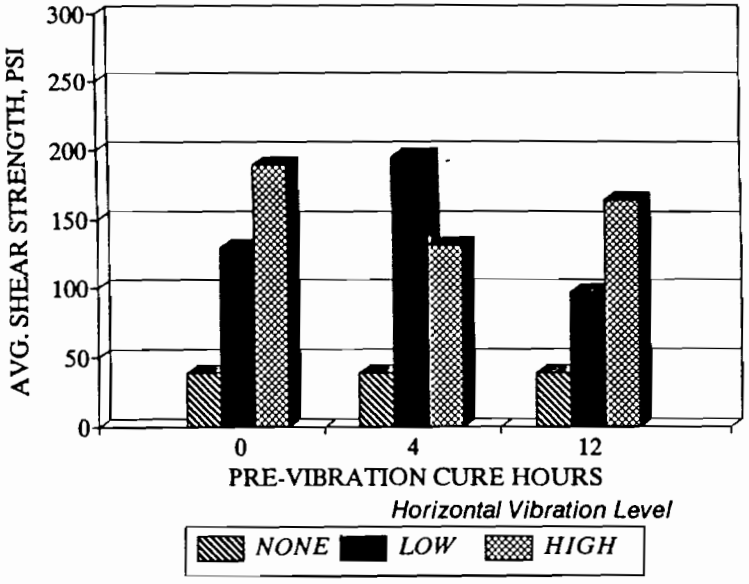


Figure E.57 Comparison of Average Shear Strengths for a 2-in. Overlay (Rough-Dry Interface) Under Horizontal Vibration Mode

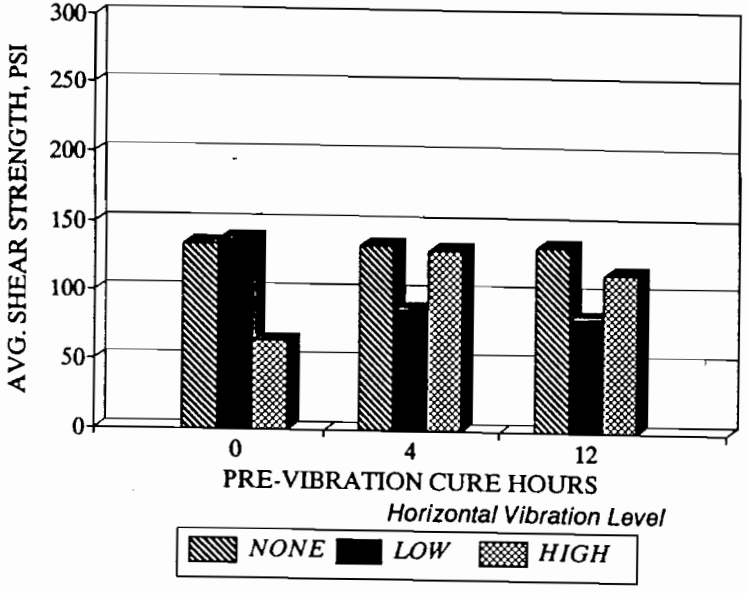


Figure E.58 Comparison of Average Shear Strengths for a 2-in. Overlay (Rough-Wet Interface) Under Horizontal Vibration Mode

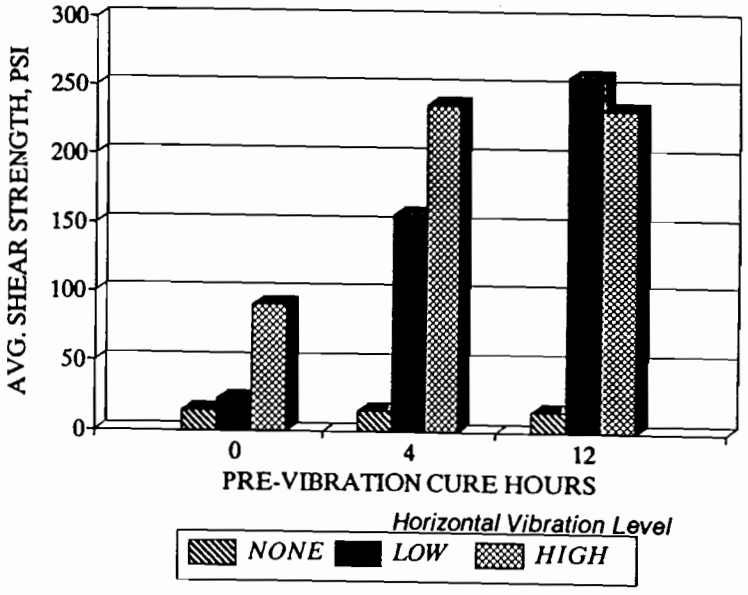


Figure E.59 Comparison of Average Shear Strengths for a 4-in. Overlay (Smooth-Dry Interface) Under Horizontal Vibration Mode

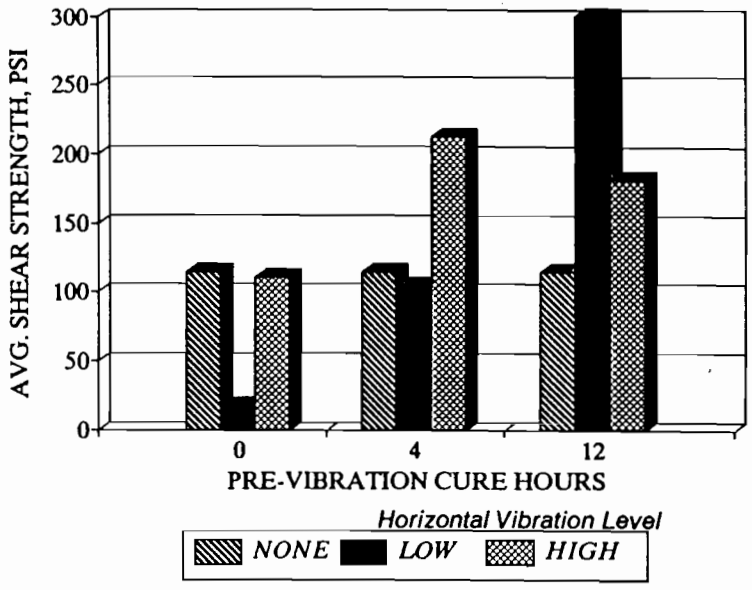


Figure E.60 Comparison of Average Shear Strengths for a 4-in. Overlay (Smooth-Wet Interface) Under Horizontal Vibration Mode

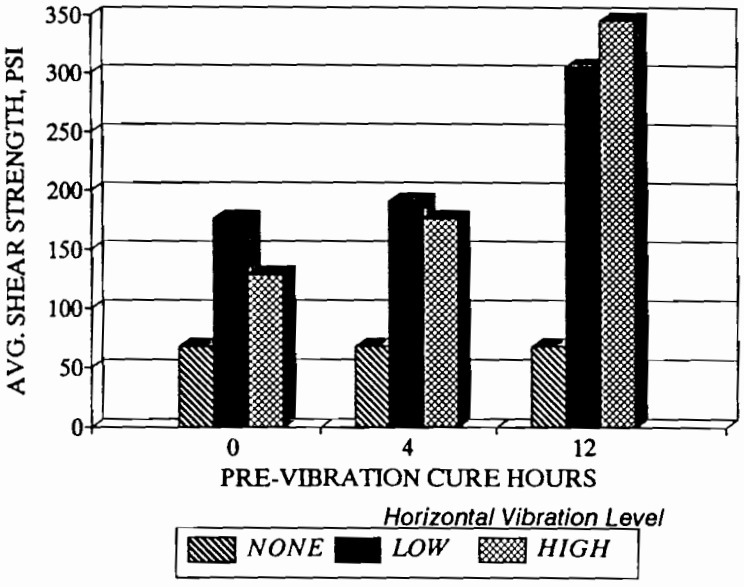


Figure E.61 Comparison of Average Shear Strengths for a 4-in. Overlay (Rough-Dry Interface) Under Horizontal Vibration Mode

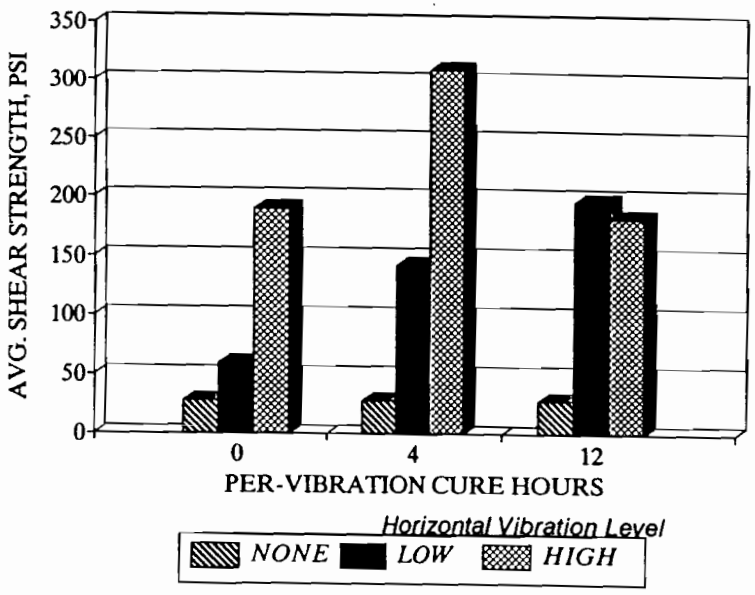


Figure E.62 Comparison of Average Shear Strengths for a 4-in. Overlay (Rough-Wet Interface) Under Horizontal Vibration Mode

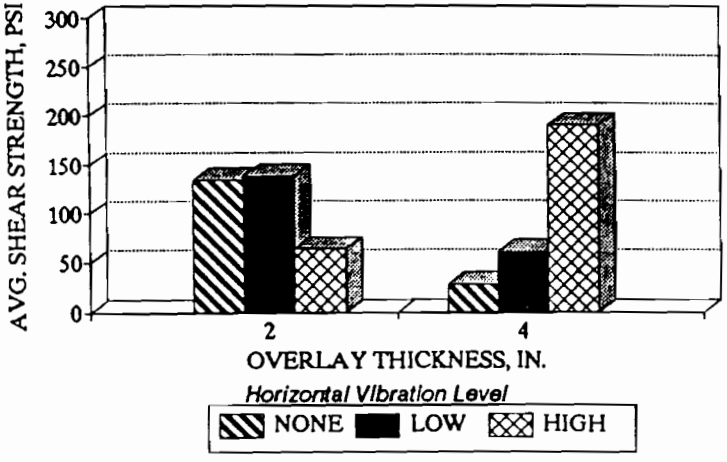


Figure E.63 Comparison of Average Shear Strengths After 0 Hrs. of Pre-Vibration Cure (Smooth-Dry Interface) Under Horizontal Vibration Mode

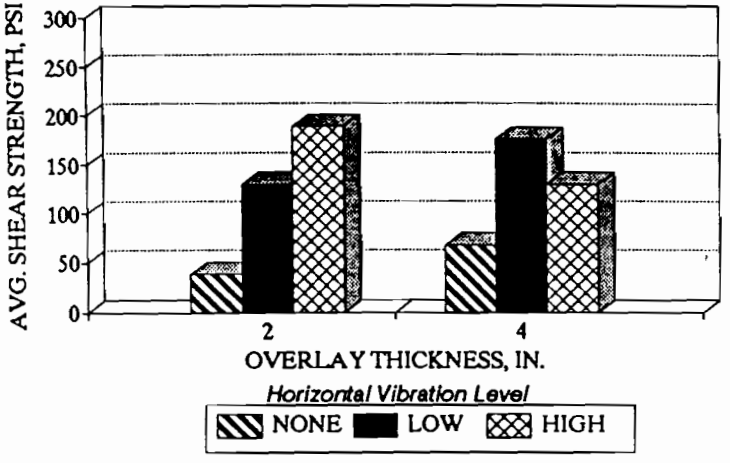


Figure E.64 Comparison of Average Shear Strengths After 0 Hrs. of Pre-Vibration Cure (Smooth-Wet Interface) Under Horizontal Vibration Mode

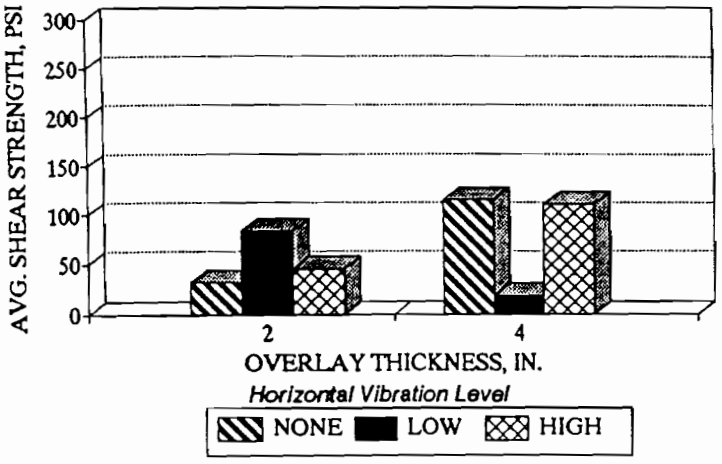


Figure E.65 Comparison of Average Shear Strengths After 0 Hrs. of Pre-Vibration Cure (Rough-Dry Interface) Under Horizontal Vibration Mode

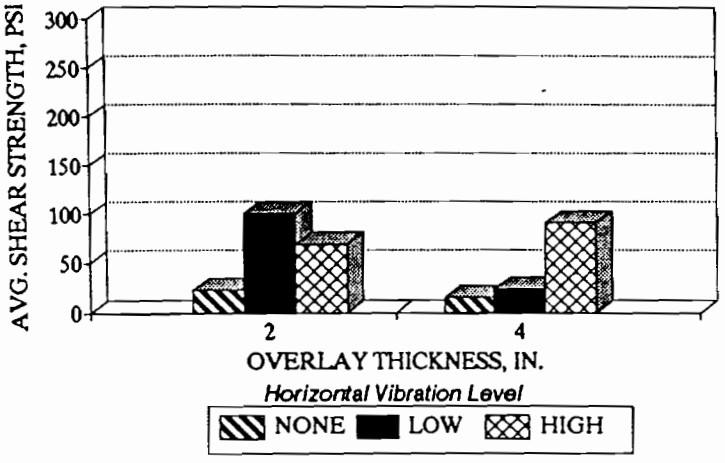


Figure E.66 Comparison of Average Shear Strengths After 0 Hrs. of Pre-Vibration Cure (Rough-Wet Interface) Under Horizontal Vibration Mode

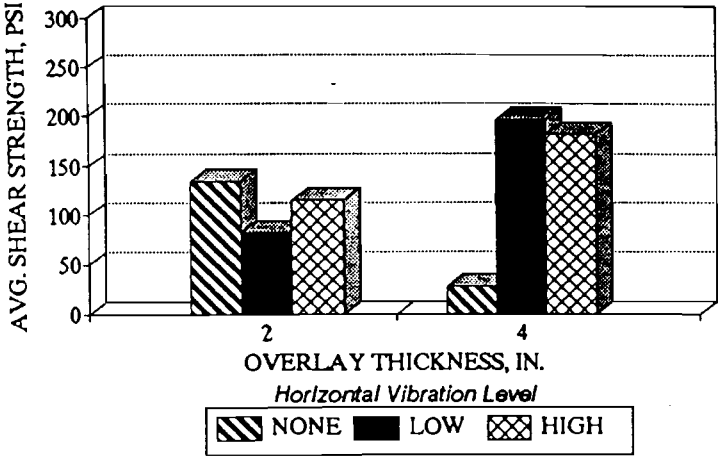


Figure E.67 Comparison of Average Shear Strengths After 4 Hrs. of Pre-Vibration Cure (Smooth-Dry Interface) Under Horizontal Vibration Mode

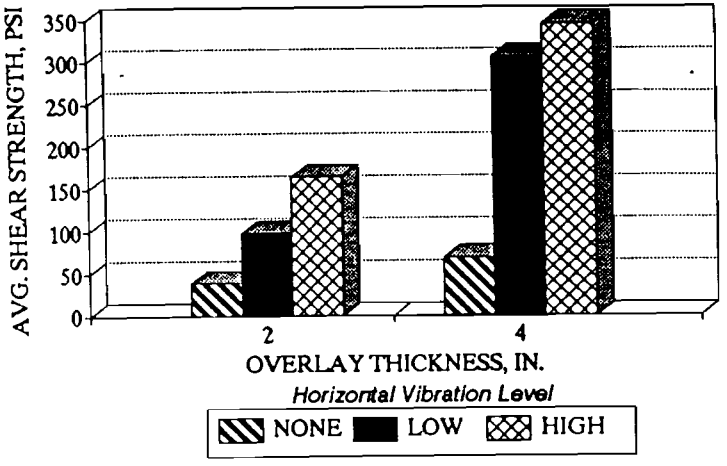


Figure E.68 Comparison of Average Shear Strengths After 4 Hrs. of Pre-Vibration Cure (Smooth-Wet Interface) Under Horizontal Vibration Mode

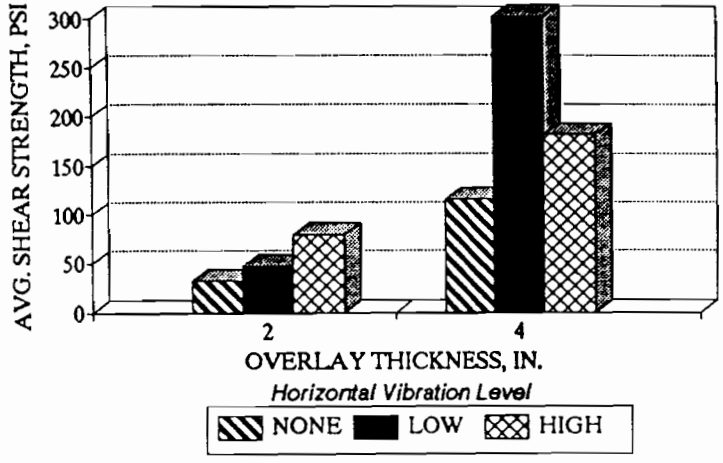


Figure E.69 Comparison of Average Shear Strengths After 4 Hrs. of Pre-Vibration Cure (Rough-Dry Interface) Under Horizontal Vibration Mode

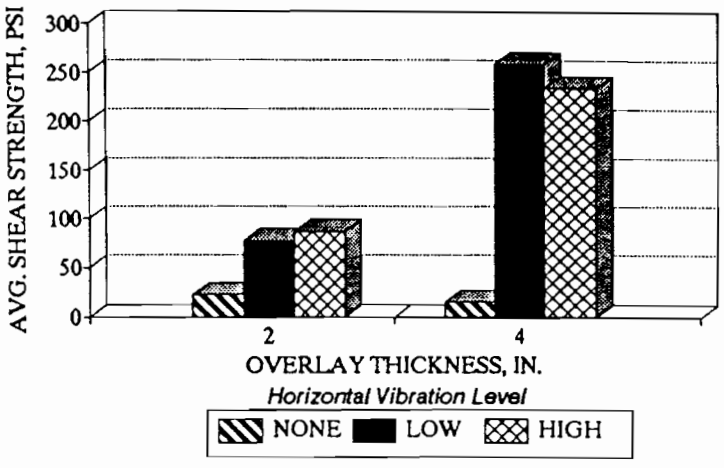


Figure E.70 Comparison of Average Shear Strengths After 4 Hrs. of Pre-Vibration Cure (Rough-Wet Interface) Under Horizontal Vibration Mode

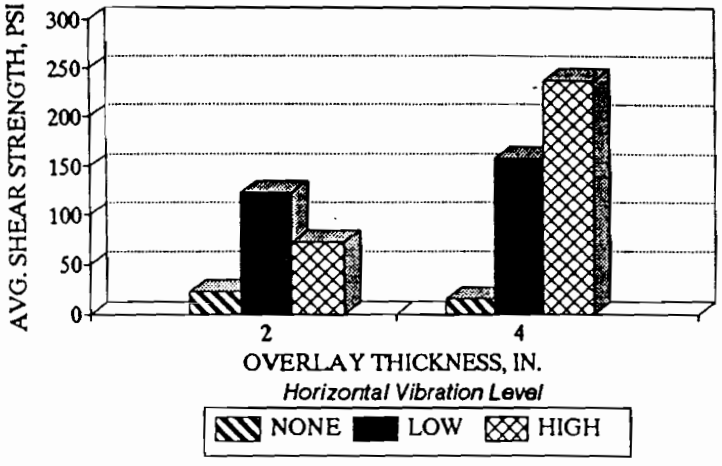


Figure E.71 Comparison of Average Shear Strengths After 12 Hrs. of Pre-Vibration Cure (Smooth-Dry Interface) Under Horizontal Vibration Mode

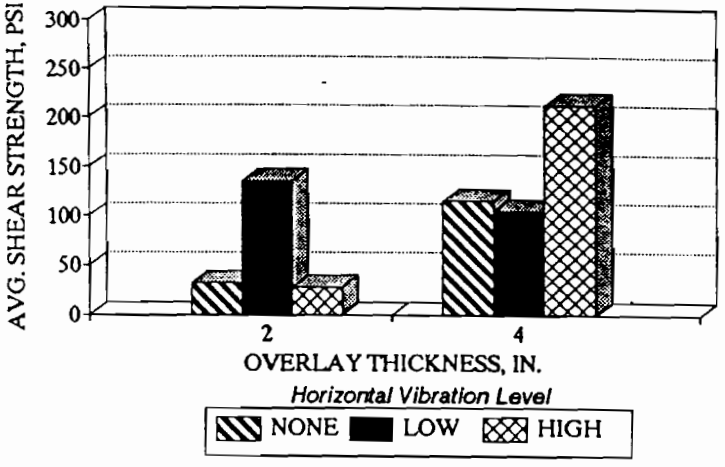


Figure E.72 Comparison of Average Shear Strengths After 12 Hrs. of Pre-Vibration Cure (Smooth-Wet Interface) Under Horizontal Vibration Mode

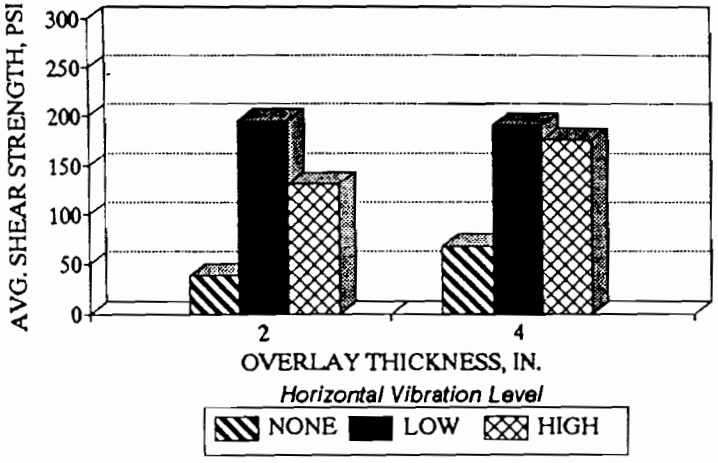


Figure E.73 Comparison of Average Shear Strengths After 12 Hrs. of Pre-Vibration Cure (Rough-Dry Interface) Under Horizontal Vibration Mode

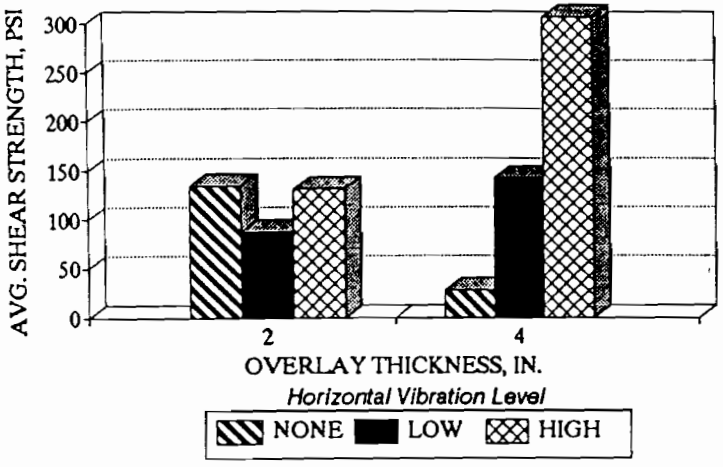


Figure E.74 Comparison of Average Shear Strengths After 12 Hrs. of Pre-Vibration Cure (Rough-Wet Interface) Under Horizontal Vibration Mode

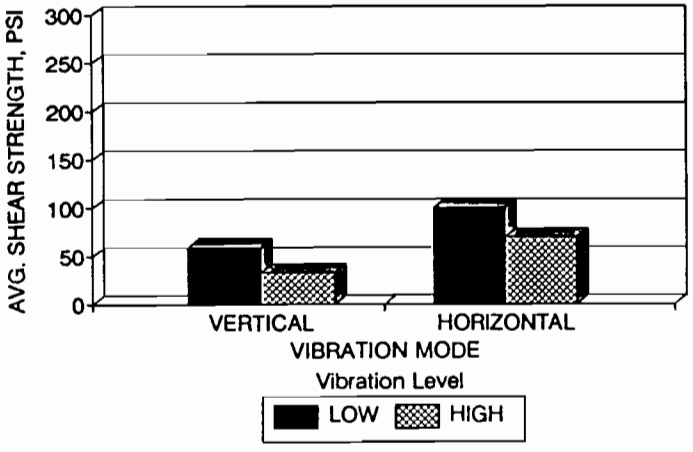


Figure E.75 Comparison of Average Shear Strengths for a 2-in. Overlay after 0 Hrs. of Pre-Vibration Cure (Smooth-Dry Interface) Under Vertical and Horizontal Vibration Modes

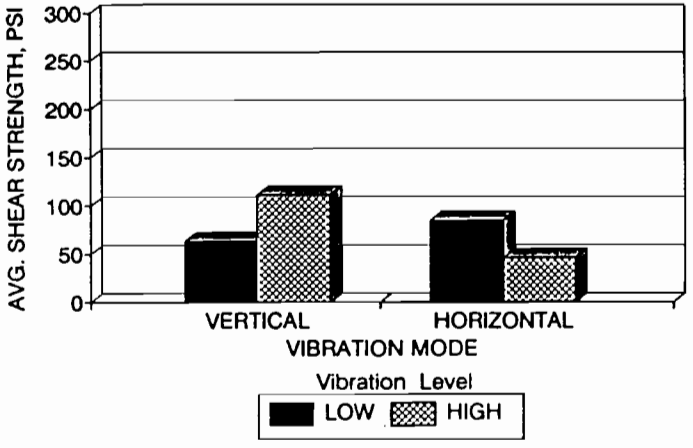


Figure E.76 Comparison of Average Shear Strengths for a 2-in. Overlay after 0 Hrs. of Pre-Vibration Cure (Smooth-Wet Interface) Under Vertical and Horizontal Vibration Modes

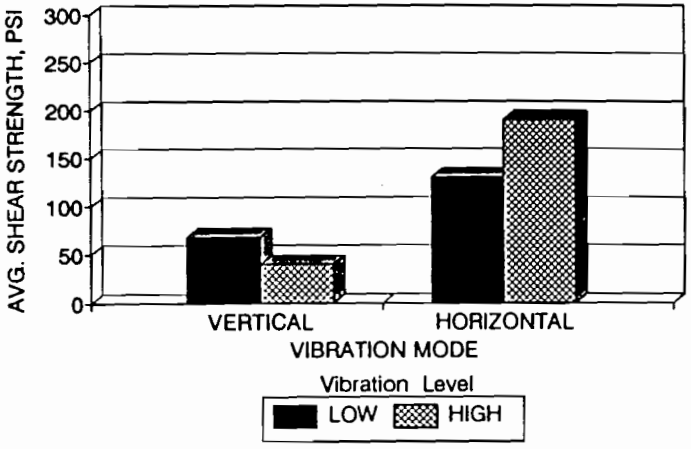


Figure E.77 Comparison of Average Shear Strengths for a 2-in. Overlay after 0 Hrs. of Pre-Vibration Cure (Rough-Dry Interface) Under Vertical and Horizontal Vibration Modes

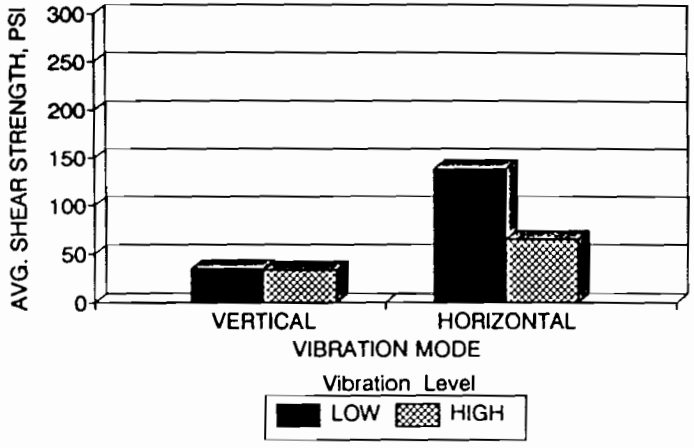


Figure E.78 Comparison of Average Shear Strengths for a 2-in. Overlay after 0 Hrs. of Pre-Vibration Cure (Rough-Wet Interface) Under Vertical and Horizontal Vibration Modes

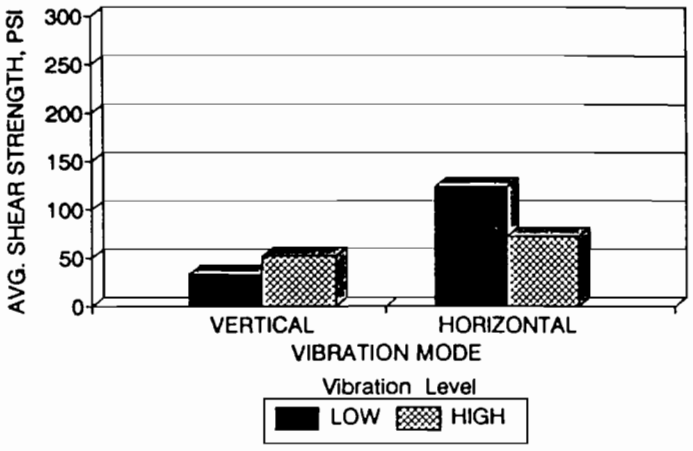


Figure E.79 Comparison of Average Shear Strengths for a 2-in. Overlay after 4 Hrs. of Pre-Vibration Cure (Smooth-Dry Interface) Under Vertical and Horizontal Vibration Modes

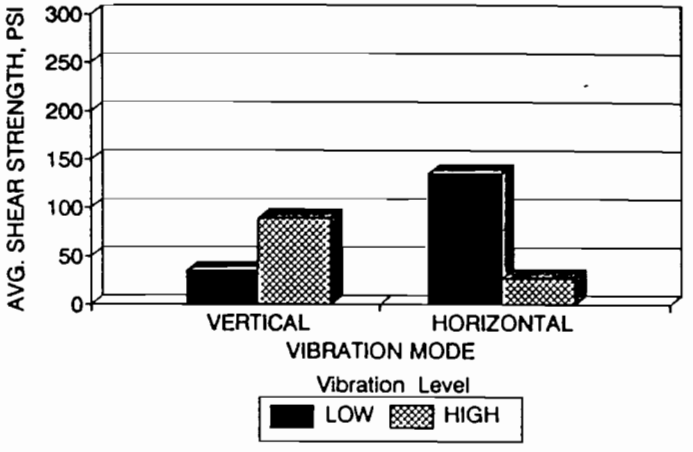


Figure E.80 Comparison of Average Shear Strengths for a 2-in. Overlay after 4 Hrs. of Pre-Vibration Cure (Smooth-Wet Interface) Under Vertical and Horizontal Vibration Modes

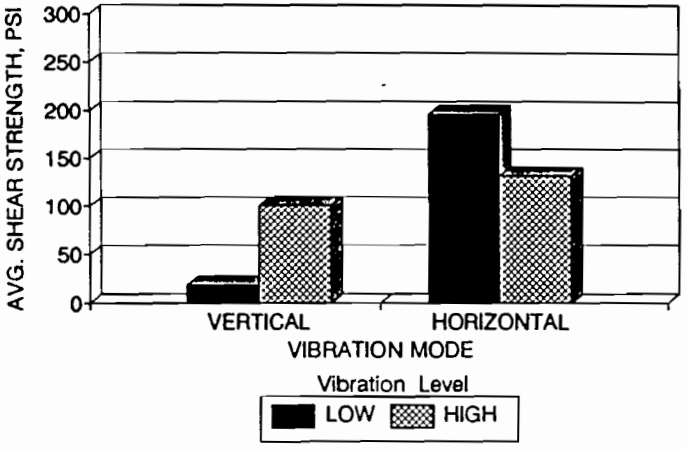


Figure E.81 Comparison of Average Shear Strengths for a 2-in. Overlay after 4 Hrs. of Pre-Vibration Cure (Rough-Dry Interface) Under Vertical and Horizontal Vibration Modes

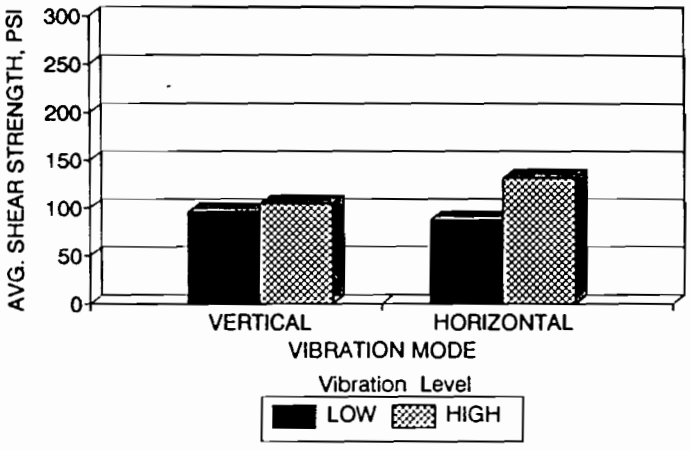


Figure E.82 Comparison of Average Shear Strengths for a 2-in. Overlay after 4 Hrs. of Pre-Vibration Cure (Rough-Wet Interface) Under Vertical and Horizontal Vibration Modes

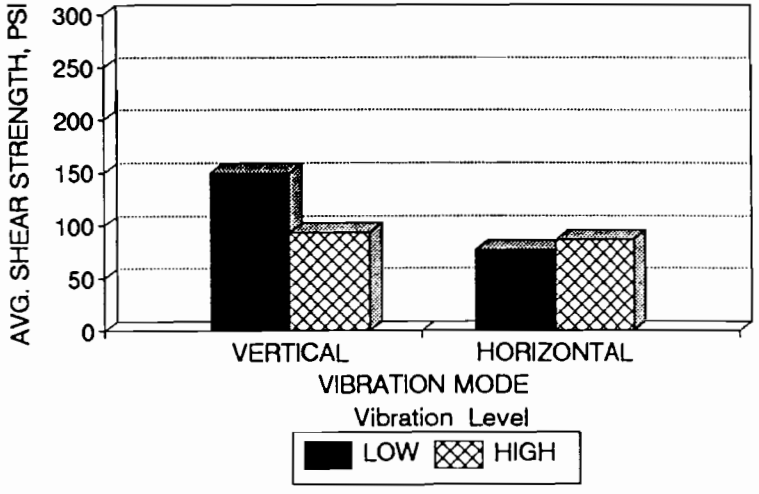


Figure E.83 Comparison of Average Shear Strengths for a 2-in. Overlay after 12 Hrs. of Pre-Vibration Cure (Smooth-Dry Interface) Under Vertical and Horizontal Vibration Modes

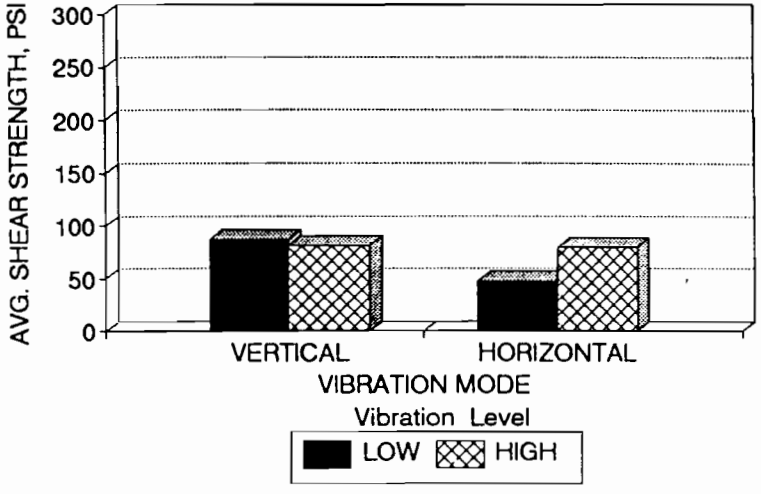


Figure E.84 Comparison of Average Shear Strengths for a 2-in. Overlay after 12 Hrs. of Pre-Vibration Cure (Smooth-Wet Interface) Under Vertical and Horizontal Vibration Modes

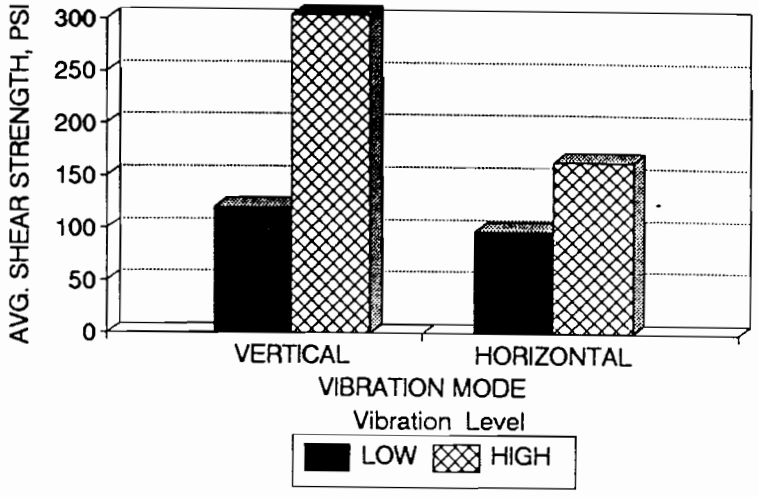


Figure E.85 Comparison of Average Shear Strengths for a 2-in. Overlay after 12 Hrs. of Pre-Vibration Cure (Rough-Dry Interface) Under Vertical and Horizontal Vibration Modes

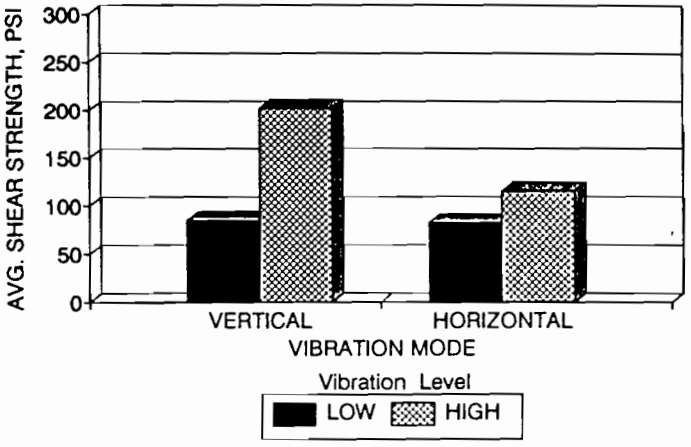


Figure E.86 Comparison of Average Shear Strengths for a 2-in. Overlay after 12 Hrs. of Pre-Vibration Cure (Rough-Wet Interface) Under Vertical and Horizontal Vibration Modes

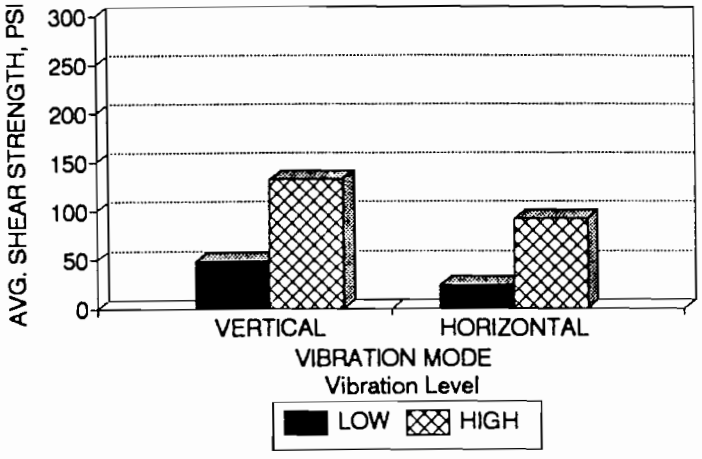


Figure E.87 Comparison of Average Shear Strengths for a 4-in. Overlay after 0 Hrs. of Pre-Vibration Cure (Smooth-Dry Interface) Under Vertical and Horizontal Vibration Modes

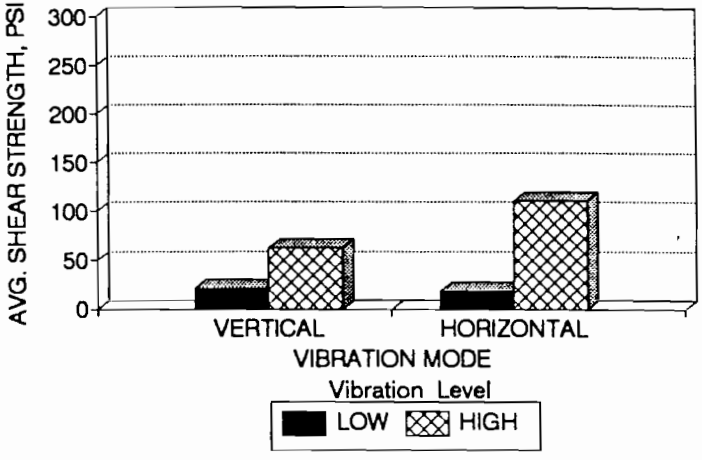


Figure E.88 Comparison of Average Shear Strengths for a 4-in. Overlay after 0 Hrs. of Pre-Vibration Cure (Smooth-Wet Interface) Under Vertical and Horizontal Vibration Modes

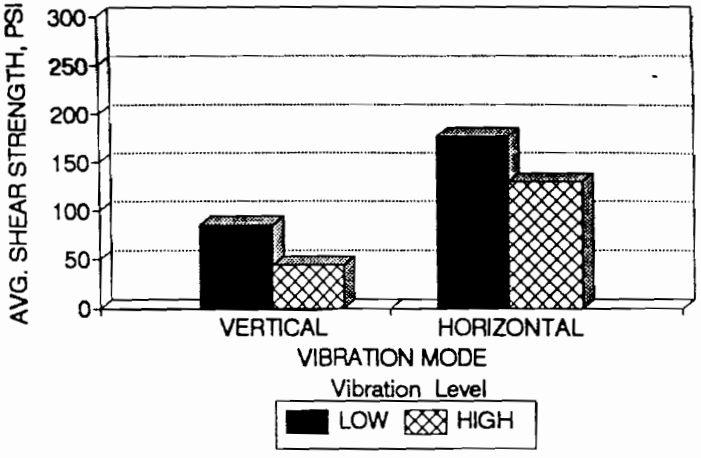


Figure E.89 Comparison of Average Shear Strengths for a 4-in. Overlay after 0 Hrs. of Pre-Vibration Cure (Rough-Dry Interface) Under Vertical and Horizontal Vibration Modes

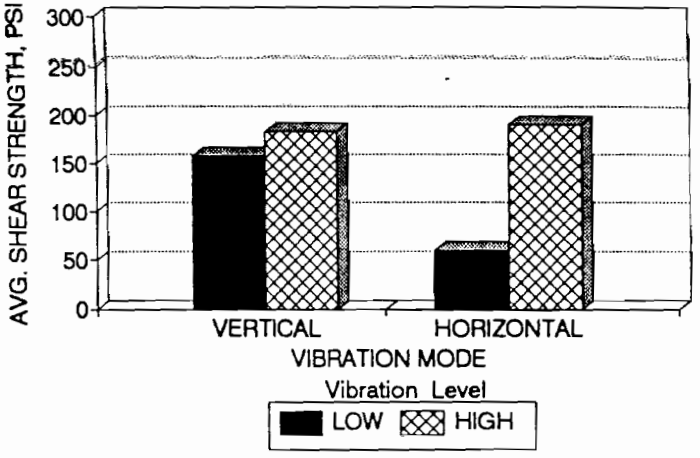


Figure E.90 Comparison of Average Shear Strengths for a 4-in. Overlay after 0 Hrs. of Pre-Vibration Cure (Rough-Wet Interface) Under Vertical and Horizontal Vibration Modes

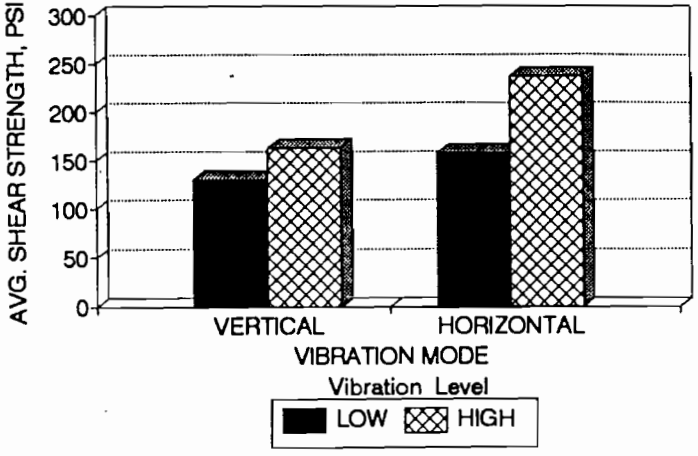


Figure E.91 Comparison of Average Shear Strengths for a 4-in. Overlay after 4 Hrs. of Pre-Vibration Cure (Smooth-Dry Interface) Under Vertical and Horizontal Vibration Modes

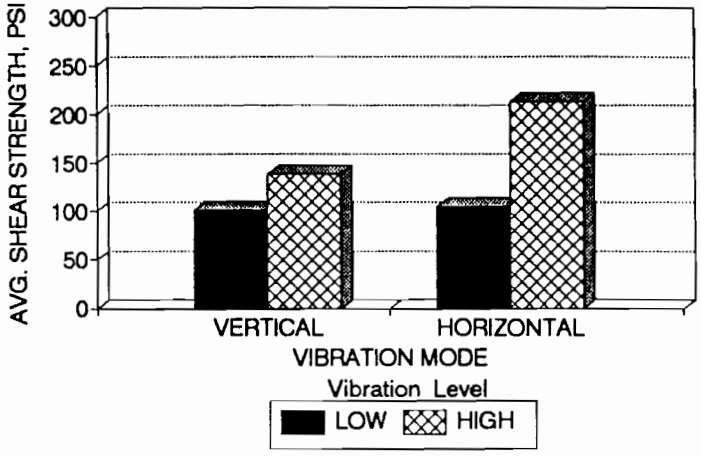


Figure E.92 Comparison of Average Shear Strengths for a 4-in. Overlay after 4 Hrs. of Pre-Vibration Cure (Smooth-Wet Interface) Under Vertical and Horizontal Vibration Modes

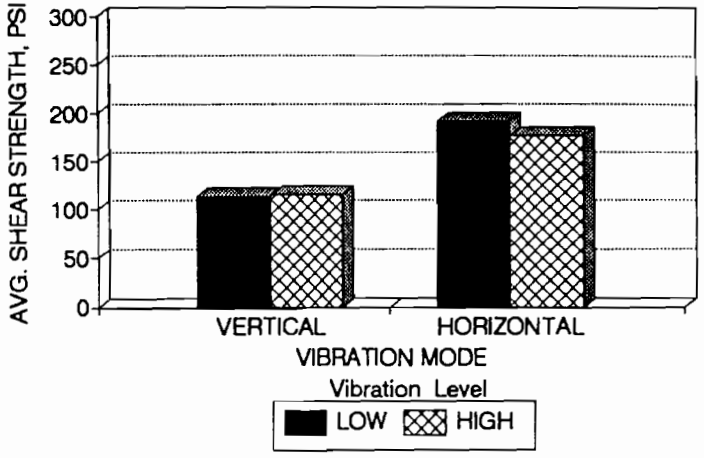


Figure E.93 Comparison of Average Shear Strengths for a 4-in. Overlay after 4 Hrs. of Pre-Vibration Cure (Rough-Dry Interface) Under Vertical and Horizontal Vibration Modes

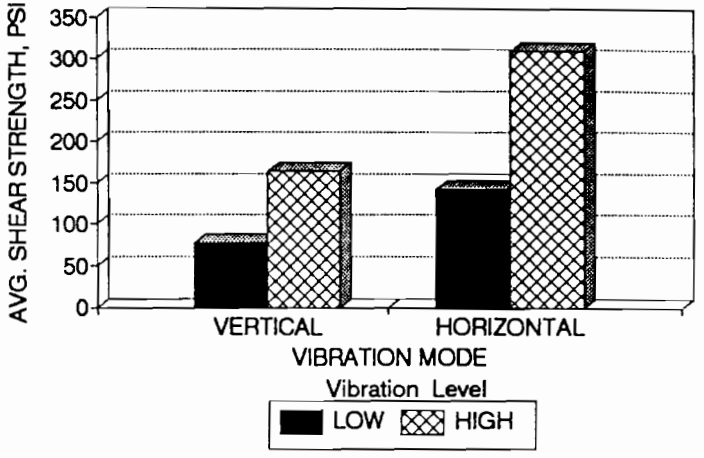


Figure E.94 Comparison of Average Shear Strengths for a 4-in. Overlay after 4 Hrs. of Pre-Vibration Cure (Rough-Wet Interface) Under Vertical and Horizontal Vibration Modes

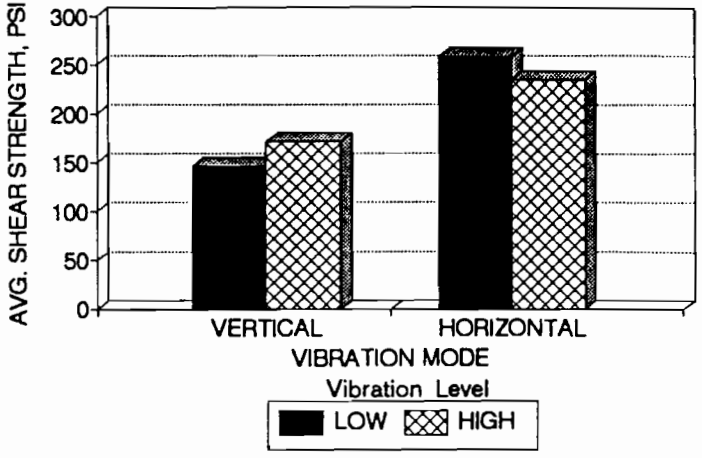


Figure E.95 Comparison of Average Shear Strengths for a 4-in. Overlay after 12 Hrs. of Pre-Vibration Cure (Smooth-Dry Interface) Under Vertical and Horizontal Vibration Modes

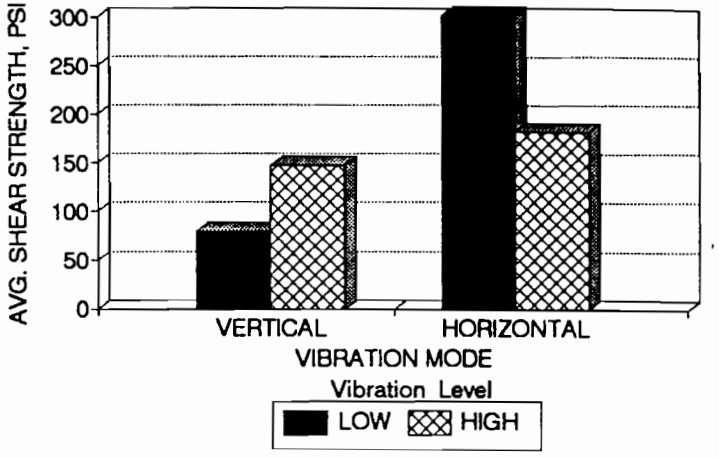


Figure E.96 Comparison of Average Shear Strengths for a 4-in. Overlay after 12 Hrs. of Pre-Vibration Cure (Smooth-Wet Interface) Under Vertical and Horizontal Vibration Modes

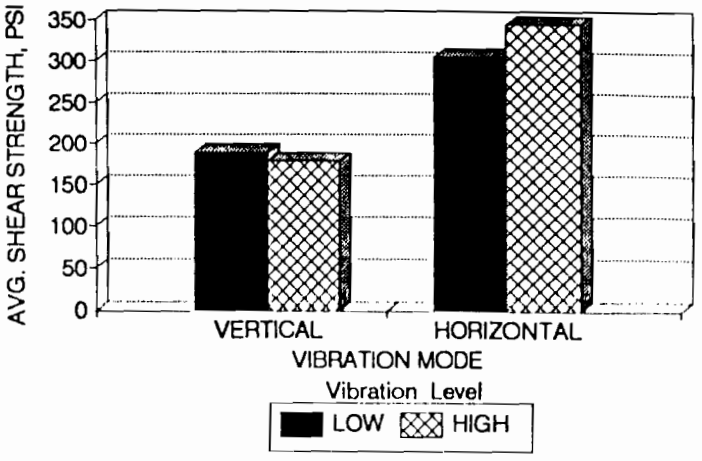


Figure E.97 Comparison of Average Shear Strengths for a 4-in. Overlay after 12 Hrs. of Pre-Vibration Cure (Rough-Dry Interface) Under Vertical and Horizontal Vibration Modes

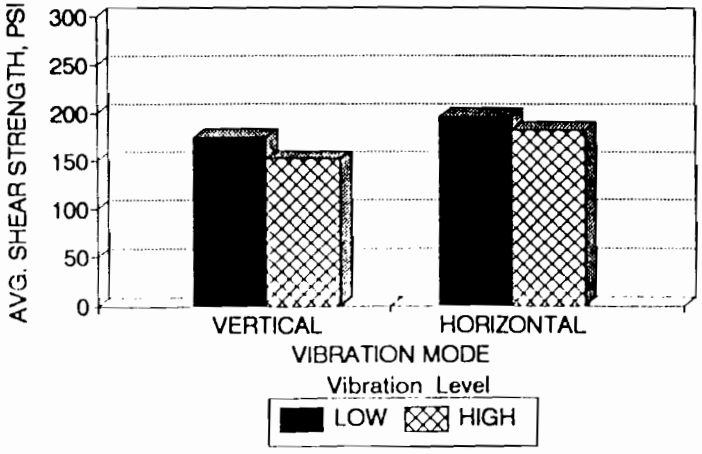


Figure E.98 Comparison of Average Shear Strengths for a 4-in. Overlay after 12 Hrs. of Pre-Vibration Cure (Rough-Wet Interface) Under Vertical and Horizontal Vibration Modes