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

by

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Research Project 1920

EFFECT OF VEHICULAR VIBRATION ON DEBONDING AND DELAMINATION OF CONCRETE OVERLAYS

Conducted for

Texas Department of Transportation

by

Center for Geotechnical and Highway Materials Research
The University of Texas at El Paso
Research Report 1920-1, Volume 1
March, 1992

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ACKNOWLEDGEMENTS

The authors would like to give their sincere appreciation to Dr. David Rozendal for his technical support. The authors would also like to thank Mr. Joe M. Battle, District Engineer of the Texas Department of Transportation, District 24, for the financial support of this research project and for allowing the first author to return to the University of Texas at El Paso to complete her Masters Degree. Thanks are also due to Mr. Mal Steinberg, Administrative Engineer of the Texas Department of Transportation, District 24, for his support as Project Coordinator. The author would also like to thank Johannes Makahaube and Vennalaganti Kristna Mohan, UTEP Graduate students, for their continuous help.

PREFACE

With the completion of the Interstate Highway System, the maintenance and reconstruction of the Interstates have become a priority. In many cases, existing bridges and overpasses on the Interstate system have deteriorated with age and require repair or replacement. Some of these existing structures must be widened in order to accommodate the increasing number of vehicles using the highways. Many of these structures are replaced or widened in phases. Thin-bonded concrete overlays are placed on these structures in phases also. The effects of the vehicular traffic vibrations on the adjacent lanes during the placement and curing of these concrete overlays is unknown.

During the widening of Interstate 10 in El Paso, Texas, the thin-bonded concrete overlay delaminated on the new structures which were constructed in two phases. The cause of this debonding and delamination was not clear but the effects of the vehicular vibration was suspected after an investigation of all construction records was conducted. Approximately, 31 percent of the original concrete overlay had to be replaced at a cost of $434,000.

To prevent a similar situation from occurring again, this research project will determine the effects of vehicular vibration on debonding and delamination of concrete overlays. Several parameters involved in the placement of concrete overlays are investigated.

ABSTRACT

This report presents the results of a study conducted on the effects of vehicular vibration on the debonding and delamination of concrete overlays placed on structures. The thin-bonded concrete overlay is used by the Texas Department of Transportation on several projects. The concrete overlays are subjected to vibrations during their placement and cure. These vibrations are caused by the traffic on the adjacent lanes when a structure is constructed in phases.

The parameters which were investigated are overlay thickness, cure time, vibration amplitude, vibration mode, surface texture, and surface wetness. These parameters were combined in different sequences and their effects on the shear strengths of the concrete overlays is reported. The shear strength results were compared based on surface wetness, overlay thickness, cure time and vibration mode.

EXECUTIVE SUMMARY

Thin-bonded concrete overlays have been used by the Texas Department of Transportation for many years. These overlays have been used for different applications. Many existing pavement sections have been overlaid with concrete for rehabilitation purposes. Concrete overlays are also used on structures to provide for a durable riding surface. Several research projects have been conducted to determine the best construction process for concrete overlays on different types of pavements. However, little research has been conducted on concrete overlays placed on structures.

During the widening of Interstate 10, in El Paso, Texas, the thin-bonded concrete overlays began to show signs of distress only 8 months after their placement. The overlays had delaminated and debonded to an extent which required replacement. These concrete overlays were placed on new structures which were constructed in phases. This construction phasing subjected the thin-bonded overlays to the vehicular vibrations from the adjacent lanes during the placement and curing of the concrete overlay. These vibrations were suspected as being partially responsible for causing the concrete overlays to delaminate and debond after an investigation of all construction records was conducted.

This research project was conducted in order to determine the effects of vehicular vibration on debonding and delamination of concrete overlay. Several other parameters involved in concrete overlays were investigated. The effects of the overlay thickness, pre-vibration cure time, surface wetness, surface texture, amplitude of vibration and vibration mode were studied. A laboratory experiment involving small concrete cylinder specimens was developed. Several tests were conducted on these specimens. The results were recorded and then analyzed to determine the parameters which affected the shear strength of the concrete overlays the most and determine under which conditions the best shear strength results were obtained.

The results of this study indicate that the thickness of the concrete overlay determines which parameters influence the shear strengths. As the thickness of the overlay was increased, higher shear strengths were generally obtained. Some of the parameters have similar affects on a 2-in., 4-in. and 6-in. overlay.

A 2-in. overlay is affected by the surface texture, pre-vibration cure time, and amplitude of vibration. A rough surface results in higher shear strengths than a smooth surface. The wetness of the surface did not produce consistent results i.e. a dry surface did not always produce higher shear strengths than a wet surface. The cure time controls the variability in the results. A 0 hour pre-vibration cure time gave inconsistent results whereas, a 4 and 12 hour pre-vibration cure gave fairly consistent shear strengths. The shear strengths increased as the cure time increased. A high level of vibration (high amplitude) usually resulted in the highest shear strengths especially after the specimens were allowed a pre-vibration cure of 4 or 12 hours. An overlay which was never subjected to vibrations (control specimen) generally gave the lowest shear strengths. A vertical vibration mode resulted in lower shear strengths than a horizontal vibration mode.

A 4-in. overlay was not as affected by the surface texture as the 2-in. overlay but the highest shear strengths were obtained on a rough surface. The surface wetness did not appear to significantly affect the shear strengths. Variable results were obtained when the specimens were vibrated immediately after pouring the overlay. The shear strengths became more consistent and higher strengths were obtained as the pre-vibration cure time increased. As with the 2-in. overlay, a high amplitude usually produced the largest shear strengths and no vibration gave the lowest results. The high amplitude vibration significantly increased the shear strengths after the overlays were cured for 4 or 12 hours prior to vibration. A vertical vibration mode generally resulted in lower shear strengths than a horizontal vibration mode.

The 6-in. overlay shear strengths were not significantly affected by surface texture, surface wetness, pre-vibration cure time, or vibration amplitude. The shear strength results obtained were fairly similar. That is, compared to the other two overlay thickness studied, the variability in the strengths was relatively small. A horizontal vibration mode test was not performed on a 6-in. overlay. However, because of the small variations caused by the other parameters, a change in the vibration direction would probably not affect the shear strength results either.

Large variation in the shear strengths of the concrete overlays were obtained in many cases. However, when working with concrete, large variations in the test results can be expected especially when the concrete is relatively "green" (fresh).

IMPLEMENTATION STATEMENT

The implementation of this research's results is not recommended at this time. The research should be completed by August, 1992 at which time implementation may begin.

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CHAPTER 1

INTRODUCTION

1.1 Problem Statement

Delamination and debonding of concrete layers overlying bridge decks and as used in thin-bond overlays have been occurring frequently. Existing studies show that these problems (debonding and delamination) significantly accelerate the rate of deterioration of the concrete and tremendously reduce its fatigue life. Unfortunately, this problem cannot be totally attributed to or described by the quality or type of cement and aggregates used. The construction records indicate that even under the tightest quality control programs, debonding of concrete has occurred very shortly after the completion of construction. One significant factor which has not been taken into account is the vibration of the member due to traffic in the vicinity of the freshly-poured concrete. Also, once debonding or delamination initiates for any reason, the vehicular vibration may result in the rapid extension and propagation of the defects.

1.2 Scope of Work

The main objective of this research is to investigate the effects of vibration on the initiation and propagation of debonding and delamination of concrete overlays. In more detail, the objectives are to study and evaluate the effects of several parameters which may contribute to delamination. These parameters are: amplitude of vibration; curing time; thickness of concrete overlay and; texture and wetness of the interface between the existing and freshly-poured concrete.

1.3 Organization

The following five chapters discuss in detail the procedures and the results of this study. Chapter 2 discusses the background information (or case study) which led to this research project. The findings of an extensive literature survey are also included in this chapter. A thorough description of the methodology utilized is found in Chapter 3. This includes the testing matrix, collection of field vibration measurements, sample preparation, and testing procedure. Chapter 4 gives a presentation of the results obtained from the testing described in the previous section. A discussion of all test results, along with their significance, is found in Chapter 5. This report closes with Chapter 6 containing a summary, conclusions, and recommendations for future work. Chapter 6 is followed by all appendices and references.

CHAPTER 2

BACKGROUND

2.1 Introduction

An investigation of the delamination of thin-bonded 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-in. 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 1987 (phase I; outside lanes) and in the spring of 1988 (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 placement, consolidation and curing.

Eight months after the thin-bonded concrete overlays (second phase) 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.

In January 1989, sounding of the overpasses was conducted and the extent of the delamination was recorded on a Deck Layout Plan Sheet. 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. Manning (1981) suggested that visible cracks which occur shortly after construction, imply improper construction procedures and inadequate inspection. Establishing the cause of cracks was to assign fault and that it was difficult to assemble all facts from construction records and personnel. Also, the quality and level of inspection are uneven within agencies and from one agency to another. However, in this case, the author had the advantage of being an inspector on this project and therefore, witnessed the construction method. The construction method was 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. During the construction of these structures, however, no through traffic was permitted and they consequently experienced no vibrations. The cores obtained from both 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. Some overpasses were found to have more delaminated areas than 3 months earlier. While others remained virtually the same except for new or more severe cracks. It was then clear that the delaminated concrete overlay would have to be removed and replaced or somehow sealed against moisture to prevent further damage from occurring.

An experimental test section was prepared to determine the repair procedure of the delaminated overlay. But before the test section was prepared, three types of concrete mixes were tested with different types of surface preparations. Type II, Type III and Pyrament cement concrete mixes were tested on a wood float finish and a cold chisel finish beam half. A saturated surface dry (SSD) and a dry surface along with beam halves with and without a bonding grout were all variants combined for the testing specimens to establish the best bonding results and the criteria used for the test section. These results showed that the Type III concrete had a better bonding strength when on a chisel, dry surface. However, no significant differences occurred when a bonding grout was or was not used.

The entire surface of the test section was scarified to roughen the box beam surface, then was lightly sandblasted to remove any contaminates and the final cleaning, prior to concrete placement, was by compressed, filtered, airblast. The eastern-most half of the test section (that intended for Pyrament Concrete) was maintained in a saturated surface dry (SSD) condition for 24 hours prior to the placement of the concrete, per Pyrament representatives. The western most half remained dry at all times up to and during the placement of the bonding grout or the concrete (1/2 with grout; 1/2 without grout).

The Type III Concrete was placed of 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). 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. Results in tensile, shear, compression, and flexure tests led 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.

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 strength value. However, this value of 119 psi was not much greater than the Type III with grout. The Pyrament result on a saturated surface dry condition was low, 80 psi. The results on a dry surface were much better than on the SSD but still with no significant advantage over either of the Type III results.

A direct shear test was also performed on 12 original concrete overlay core specimens and signified an important correlation. The average shear stress of the outside lane (construction Phase I) exceeds the average shear stress 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 IH-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 a 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 sounding. This sounding found considerably more delamination on the inside than on the outside lanes.

Therefore, this phenomenon can be partially attributed to the direct vibrations of IH-10 traffic on the adjacent 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 were caused by adjacent travel lane traffic.

A more detailed report on the background and significance of this work can be found in Appendix A.

2.2 Survey of Literature

Very little literature on thin-bonded concrete overlays placed on bridges was found. Most information regarding concrete overlays is for pavement overlays. However, some important and relevant information can be found in these pavement concrete overlay reports.

Several investigators (Peshkin, 1989; Kailasananthan, 1984; and Gausmann, 1986) have studied concrete pavement overlays of a thickness range between 2-in. and 4-in. Peshkin (1989) stated that in surveying and studying various overlay projects the nominal thickness were 3-in. or 4-in. and that a lack of variation in overlay thickness exists. Therefore, in addition to an overlay thickness of 2-in. and 4-in., a 6-in. overlay was investigated. Some engineers have also suggested that thicker overlays produce less of a possibility for debonding or delamination to occur. Debonding has been defined as failure at a joint between an overlay and an existing deck and delamination defined as a horizontal fracture plane in an existing deck (Manning, 1981).

A theoretical shear stress at the interface of a concrete pavement and a concrete overlay was determined to be in a range from 16 to 24 psi using program ELSYM5, a linear elastic analysis (Suh, 1988). AASHTO (1990) has established 250 psi as an acceptable bond strength when tested in direct tension. The tests should be conducted within 7 to 14 days of completion of the cure time of the overlay. A satisfactory bond has also been defined by Peshkin (1989) to be a bond strength greater than 200 psi after construction.

Manning (1981) surveyed several existing bridge overlays for the effect of traffic-induced vibrations and the frequency of these bridges. The frequencies in bridges usually were within the range from 1 to 20 Hz. This result is consistent with the findings from monitoring a local bridge. The largest amplitudes of vibration on a bridge occur when the natural frequencies of a vehicle and the bridge are the same, usually between 2 to 5 Hz. The same report also states that vehicle speed is not a significant factor in determining the response of highway bridges.

Therefore, reducing the speed limit on a bridge under construction would not reduce the bridge's amplitude of vibration. In order to minimize the amplitude of traffic vibrations, care must be exercised to ensure smooth transitions exist at expansion joints i.e. reduce dynamic impact. The amplitude of vibrations of a bridge seem more extensive than they actually are to a person standing on the bridge. This is because the human body is extremely sensitive to the presence of vibrations.

Peshkin (1989) suggested that debonding at cracks was caused by horizontal slab movement. The effects of a vertical and horizontal vibration mode on laboratory overlay specimens are investigated. A survey of bridge decks (Furr, 1981) has found no evidence of problems in concrete placed and cured while traffic was maintained on the bridge. No detrimental effects on the concrete, rebar nor the interaction between them was found. Manning (1981) also refers to a laboratory experiment conducted in Texas on reinforced beams. A 2-in. overlay was placed on a vibrating beam and subjected to cyclic loading for 48 hours. No loss in bond strength was found. Both of these cases involved reinforced concrete. The mean shear bond strength at the interface between an existing CRCP and a CRCP overlay was 204 psi on the 28th day after the overlay placement (Suh, 1988).

Kailasananthan (1984) conducted a lab experiment testing overlay shear strength cylinders and correlated these results to field testing. Several interface parameters and types of overlays were examined. These lab specimen overlays were not subjected to vibrations, as in this report, but provide a basis for direct shear strength results. Plain concrete overlays were found to be better than reinforced overlays and exposure to high temperatures was determined to not effect the mean shear stress. The overlays tested here will only be non-reinforced and exposed only to room temperature. Suh (1988) also studied the affects of several factors and interactions of these factors on the bond strength between a CRCP pavement and a CRCP overlay. A General Linear Model (GLM) assigned numerical values to the influence of these factors. These results will be used simply as a comparison to the shear stress results of a plain overlay subjected to vibrations.

CHAPTER 3

METHODOLOGY

3.1 Introduction

Several parameters which may contribute to the delamination of concrete overlays were investigated. These parameters include amplitude and direction of vibration, curing time, thickness of concrete overlay, and texture and wetness of the interface between the existing (base) and the freshly poured (overlay) concrete. These parameters were combined to form 72 different sample conditions. The testing matrices showing all these parameters are illustrated in Figures 3.1 and 3.2.

Concrete overlay thicknesses of 2-in., 4-in. and 6-in. were studied. Each overlay thickness was tested for its direct shear strength under different interface conditions and subjected to different vibration levels. The overlay-base interface was either a smooth surface or a rough surface. The rough surface was created by a wood float finish. The smooth surface was the bottom of the core sample or the side facing the forms. Before applying the overlay, the base concrete surface was kept dry or wetted with water.

Once the overlay was poured on top of the base, the sample was allowed to cure, without being subjected to vibrations, for 0, 4 or 12 hours. A 0 hour pre-vibration cure time (i.e. vibrating the sample immediately after preparation) would be similar to pouring a concrete overlay in the field while traffic was allowed on the adjacent lanes and consequently, subjected to traffic vibrations. A 12 hour pre-vibration cure time represents the field condition when an overlay would be poured and then allowed to cure, without being subjected to vibration from the adjacent traffic for 12 hours.

Surface	Surface	Curing time	0 Hours						4 Hours						12 Hours					
		Amplitude	High			Low			High			Low			High			Low		
		Thickness Overlay	2	4	6	2	4	6	2	4	6	2	4	6	2	4	6	2	4	6
Rough	Wet																			
	Dry																			
Smooth	Wet																			
	Dry																			

Figure 3.1 Vertical Vibration Mode Testing Matrix

Surface	Surface												
	Cure Time	0 Hours				4 Hours				12 Hours			
	Amplitude	High		Low		High		Low		High		Low	
	Thickness Overlay	2	4	2	4	2	4	2	4	2	4	2	4
Rough	Wet												
	Dry												
Smooth	Wet												
	Dry												

Figure 3.2 Horizontal Vibration Mode Testing Matrix

Control specimens which were allowed to cure for 24 hours without ever being subjected to vibration were also tested. These direct shear results established a basis for comparing those samples which were vibrated for a certain period of time.

As soon as the cure time was completed, the overlay samples were placed on a 50-lb shaker and vibrated in either a vertical or horizontal direction. With the shaker set up to subject the specimen to vertical vibration, amplitudes of vibration equal to the maximum deflection and half the maximum deflection of the span (see next section) were considered as high and low amplitudes, respectively. In the case of the horizontal vibration mode, peak amplitudes equal to 1/3 of the vertical amplitudes were used as high and low amplitudes. Lower amplitudes for the horizontal vibration mode were necessary because the smaller specimens were placed perpendicular to the shaker, not directly on top of the shaker. Therefore, the weight of the samples was not affecting the amount of motion in the shaker as in the case with the vertical vibration mode. In both cases, the frequency of the vibration was maintained as the fundamental frequency of vibration of the bridge. A complete discussion on how the vertical mode amplitudes were obtained is presented later.

The samples were tested after a total time (pre-vibration cure time + vibration time) of 24 hours from preparation of the concrete overlay. That is, a specimen with 0 hour pre-vibration cure time was vibrated for the entire 24 hours. While a specimen with 4 hour pre-vibration cure time was subjected to vibration for 20 hours and a specimen cured for 12 hours was vibrated for 12 hours. At the end of the 24 hours, the specimens were tested for their direct shear strength. This testing procedure is described in full in a following section.

3.2 Vibration Measurement in the Field

In order to obtain vibration measurements needed for the testing procedure, direct readings were taken and recorded on the IH-10 eastbound Hawkins Overpass in El Paso. This was one of the overpasses which was involved in the overlay delamination problem discussed in Chapter 2 and Appendix A.

Two geophones (velocity transducers) were placed on the outside shoulder lane of the overpass. One geophone was set on the short span and the other on the long span of the overpass, i.e. 57.5-ft and 85-ft, respectively. Because of the layout and location of the overpass, it was possible to place the geophones on the spans without the use of traffic control (see Figure 3.3). Therefore, the pattern of the daily traffic was not affected in any way.

The geophones were connected by coaxial cables to two channels of a Dynamic Signal Analyzer (see Figure 3.4). The analyzer was programmed to take readings from each geophone every 8

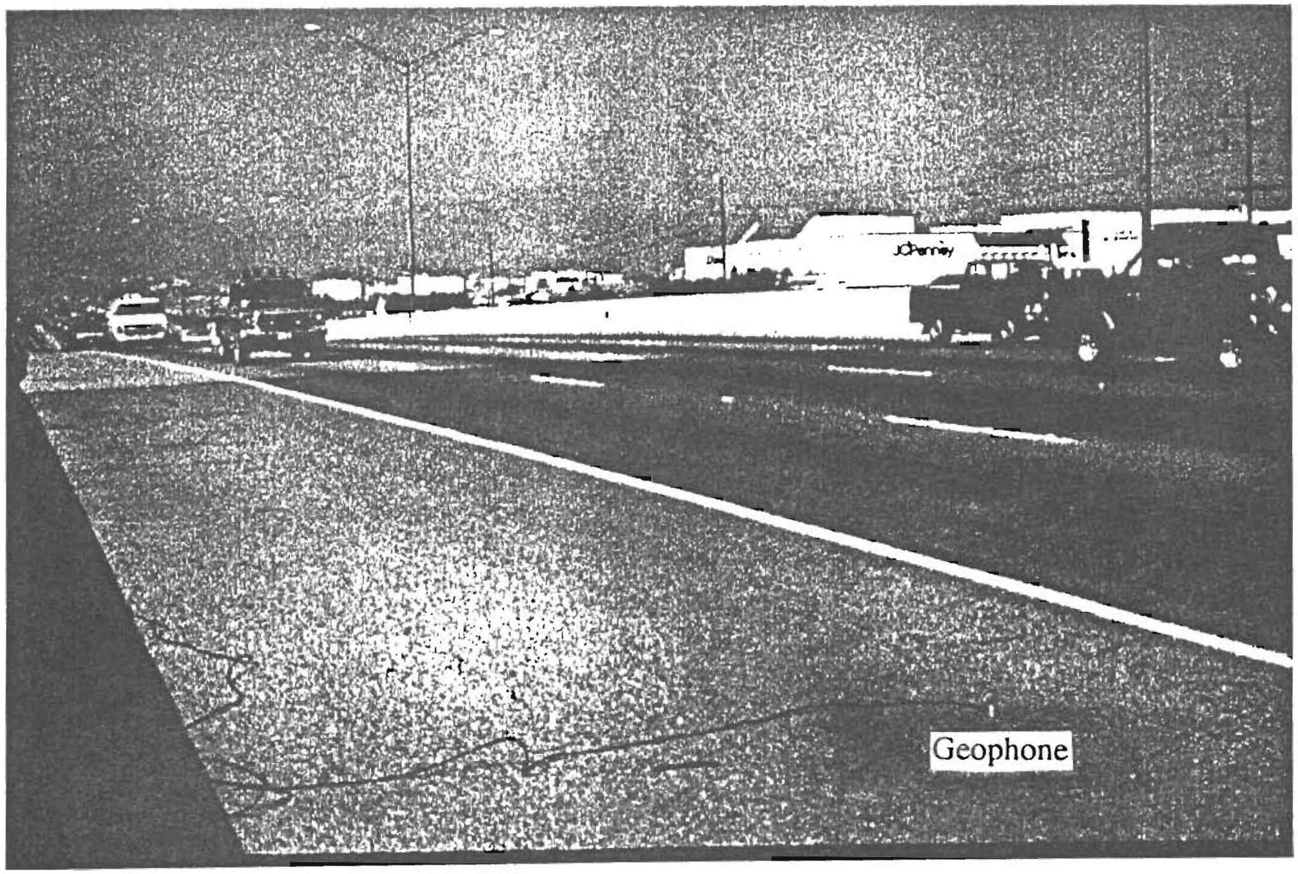

Figure 3.3 Geophones Placed on IH-10 Overpass

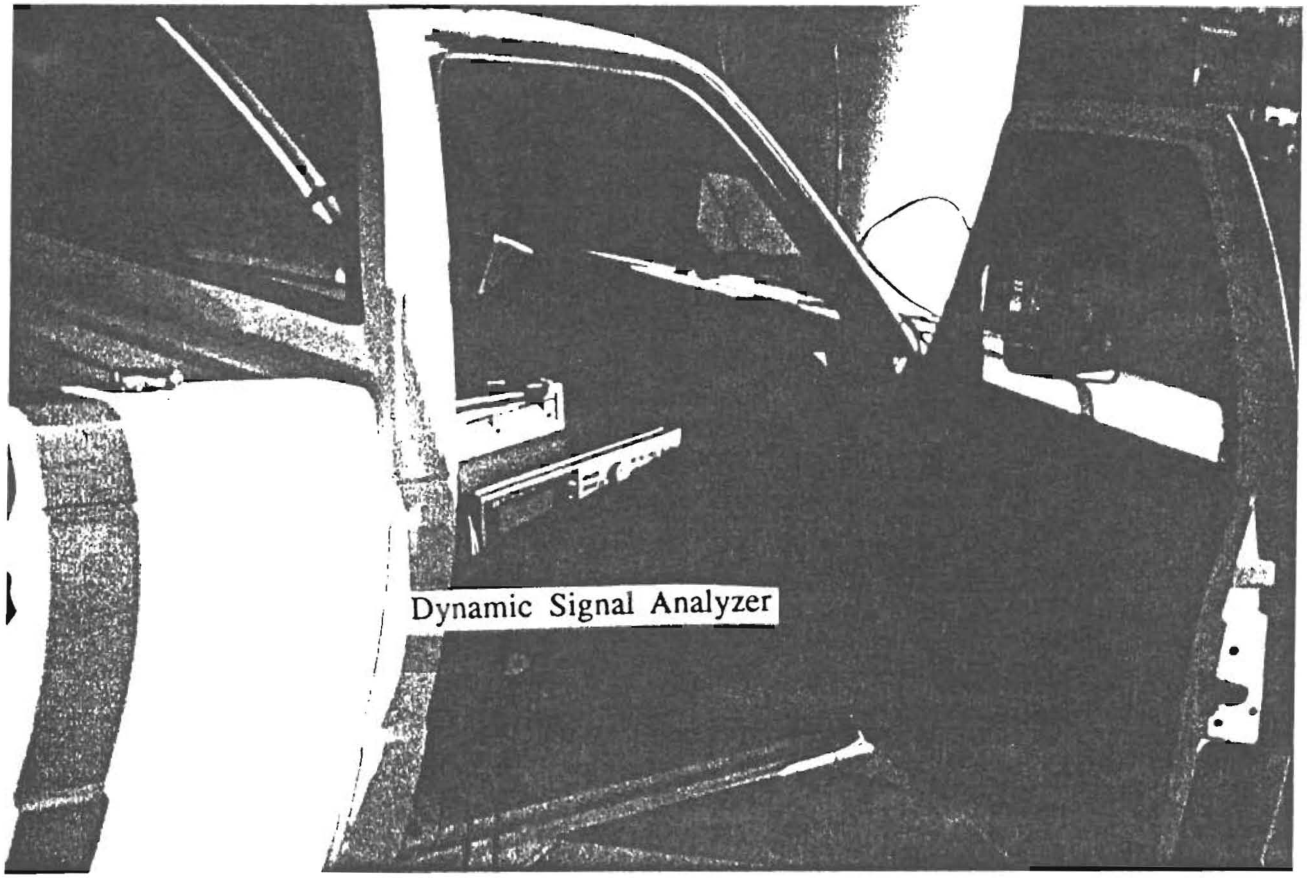

Figure 3.4 Dynamic Signal Analyzer in Field

minutes. Fifty signals were averaged to obtain one record. Readings were taken between 8:00 a.m. and 6:00 p.m. in order to get a good representation of the daily traffic. The morning, noon, and evening rush hours were obtained within this time period.

Based on this study, an amplitude of 80 mils was determined as representative of the vibration of the long span and 40 mils for the short span. Figure 3.5 gives an example of the vibration amplitude time history. In the 16 second time frame, three trucks and a small vehicle can be identified in this figure.

To better define the vibration characteristics of the bridges, 50 time records similar to that shown in Figure 3.5 were Fourier transferred and averaged to obtain the amplitude response spectrum of the vibration over an eight minute period. Also, to better characterize the volume of the traffic, two types of averaging techniques were used.

In the first technique, the so called "peak-hold" average was established (see Figure 3.6a). In the "peak-hold" technique the maximum amplitude occurring at each frequency is saved. Therefore, the record can be considered as the maximum envelop of all 50 records. Typically, the number of trucks would be immaterial in the results, as only one or two trucks can yield the same peak hold record as several hundred trucks. Shown in Figure 3.6b is the result of the arithmetic averaging of the identical 50 records used to develop Figure 3.6a. The arithmetic average varies substantially with the percentage of the trucks in the traffic flow. As the number of trucks increases, the arithmetic average would be closer to the "peak-hold" average. Let us assume that the level of vibration induced by an automobile is negligible when compared with that of a heavy truck. If the traffic is purely heavy trucks, the two figures (3.6a and 3.6b) would be very similar. Alternatively, if most of the traffic is considered as automobiles, the arithmetic average would be substantially less than the peak-hold average. In Figure 3.6, the peak amplitude is about 3 times larger than the average amplitude. Therefore, it can be approximated that about 1/3 of the traffic were trucks.

All the amplitude versus frequency plots obtained from the data collected all day are shown in Appendix B.

3.3 Sample Preparation

3.3.1 Base

The base concrete used for the specimens was a Class "H-H" concrete. This was the class of concrete used by the Highway Department for the Precast Concrete Box Beams used on the IH-10 project in which the concrete overlay was placed.

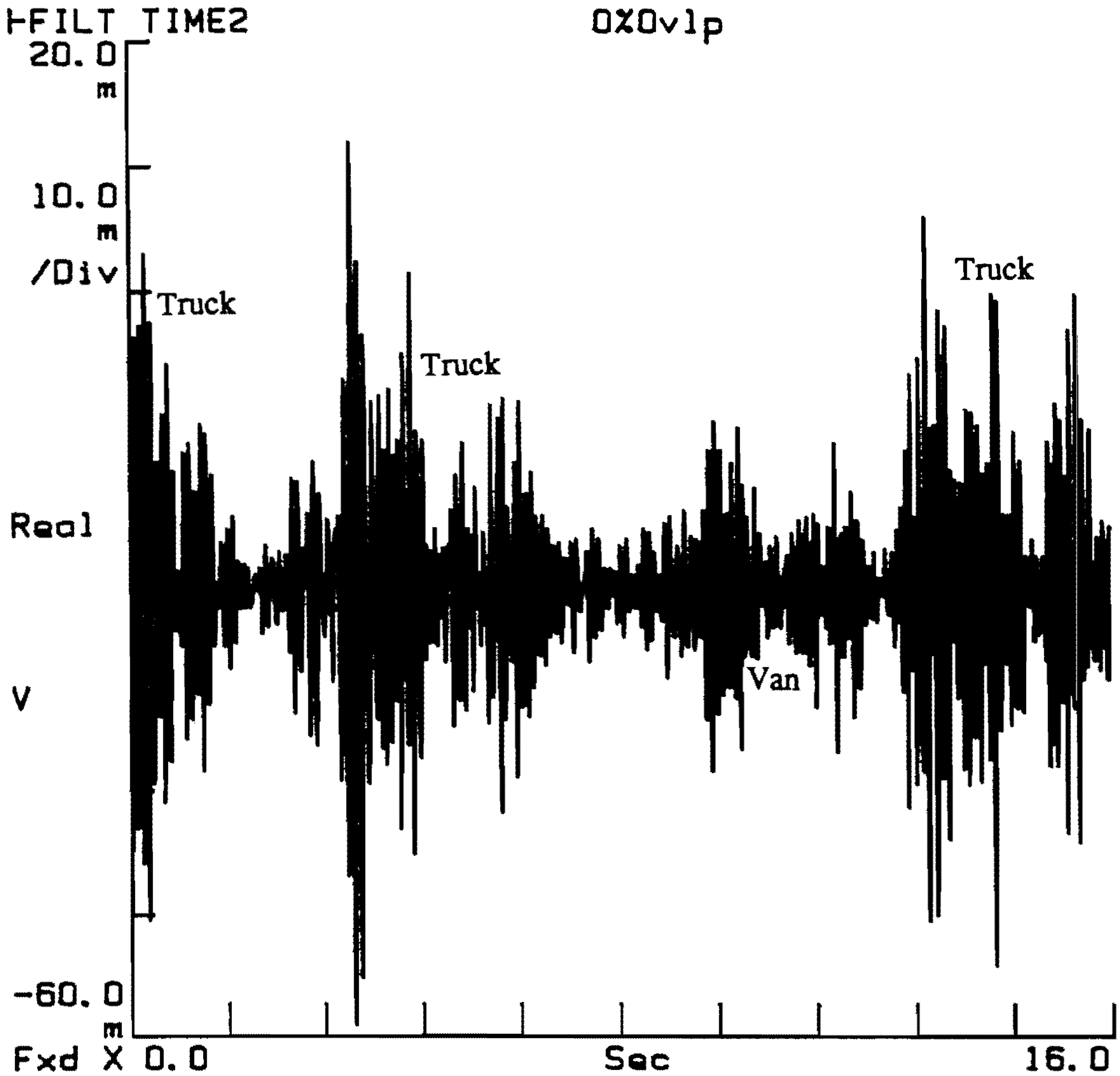

Figure 3.5 Vibration Amplitude Time History of Bridge Deck

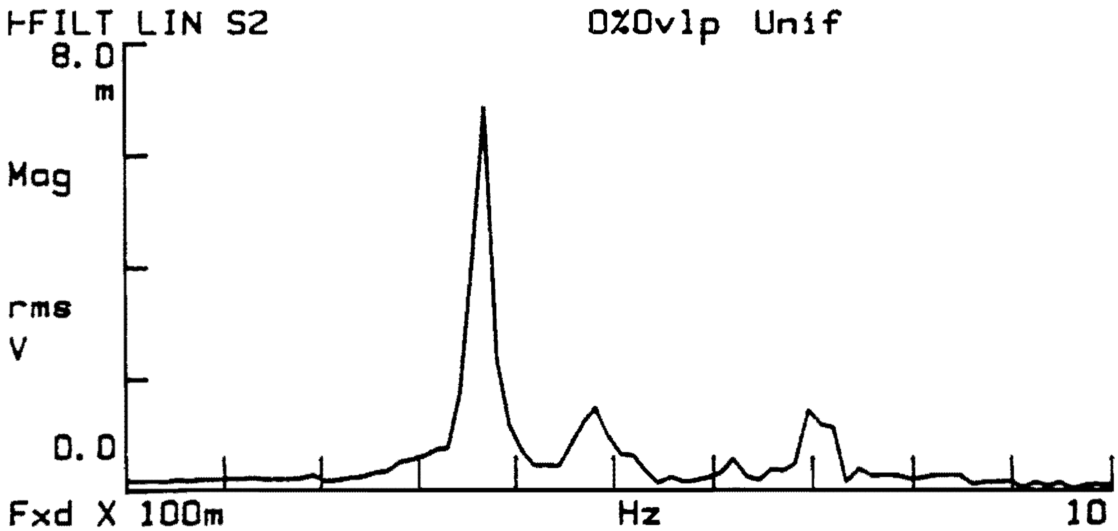

Figure 3.6a "Peak-Hold" Average Amplitudes

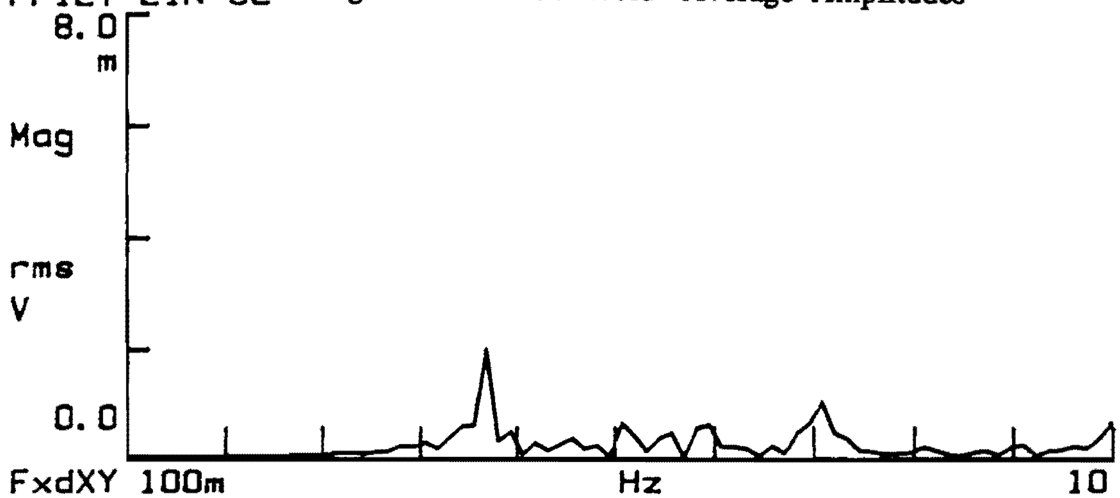

Figure 3.6b Arithmetic Average Amplitudes

Initially, standard 6-in. cylinders were going to be individually made with this concrete as the base samples. However, this would have required a lot of time and manpower. Also, variations in the preparation and strength of the concrete would occur in each cylinder. Therefore, it was decided that pouring one slab would be easier and would result in more consistency throughout the concrete and strength test results. An 8-ft X 8-ft X 7.5-in. slab was formed and the Class "H-H" concrete (delivered in a ready-mix truck) was poured, vibrated with hand-held spud vibrators, finished with wood floats, and then allowed to cure for 28 days. Burlap sacks and plastic were used to retain the concrete's moisture during the cure period. The burlap was checked everyday and wetted as necessary.

After the 28-day cure period, a concrete coring machine with a 4-in. diameter diamond bit core drill was used to obtain the base samples. All specimens had a 3 3/4-in. diameter and a 7 1/2-in. length.

The class "H-H" concrete design factors are as follows:

cement - 7 sacks/C.Y. concrete
coarse aggregate - 0.68
water - 5.25 gal/sack of cement
entrained air - 6.0%
1/2" maximum aggregate size
high range water reducer - manufacture's recommendation

The average 28-day compressive strength of this concrete was 4826 psi.

For the vertical vibration testing, the base core specimens were adhered to steel plates with a two-component epoxy (see Figure 3.7). These base plates could then be placed on a platform which was securely attached to the shaker. The platform was made of 1/2-in. plexi-glass and was capable of holding two specimens at a time.

The base core specimens used for the horizontal vibration testing were also obtained in the same manner from the same slab described above. The only difference was that these cores were saw-cut to a length of 4-in. Reducing the size of the cores, reduced the weight of the sample and therefore, minimized the stress on the shaker. A frame made of 1/8-in. steel plates was used. The two steel plates were welded together for form an "L" shape and the holes needed to support the frame to the shaker and to hold the sample in place were drilled-out. This frame was capable of holding only one sample at a time.

3.3.2 Overlay

The concrete overlay design mix was based on the Highway Departments Class "CO". This class of concrete was the same design used in the field on the IH-10 project where the original

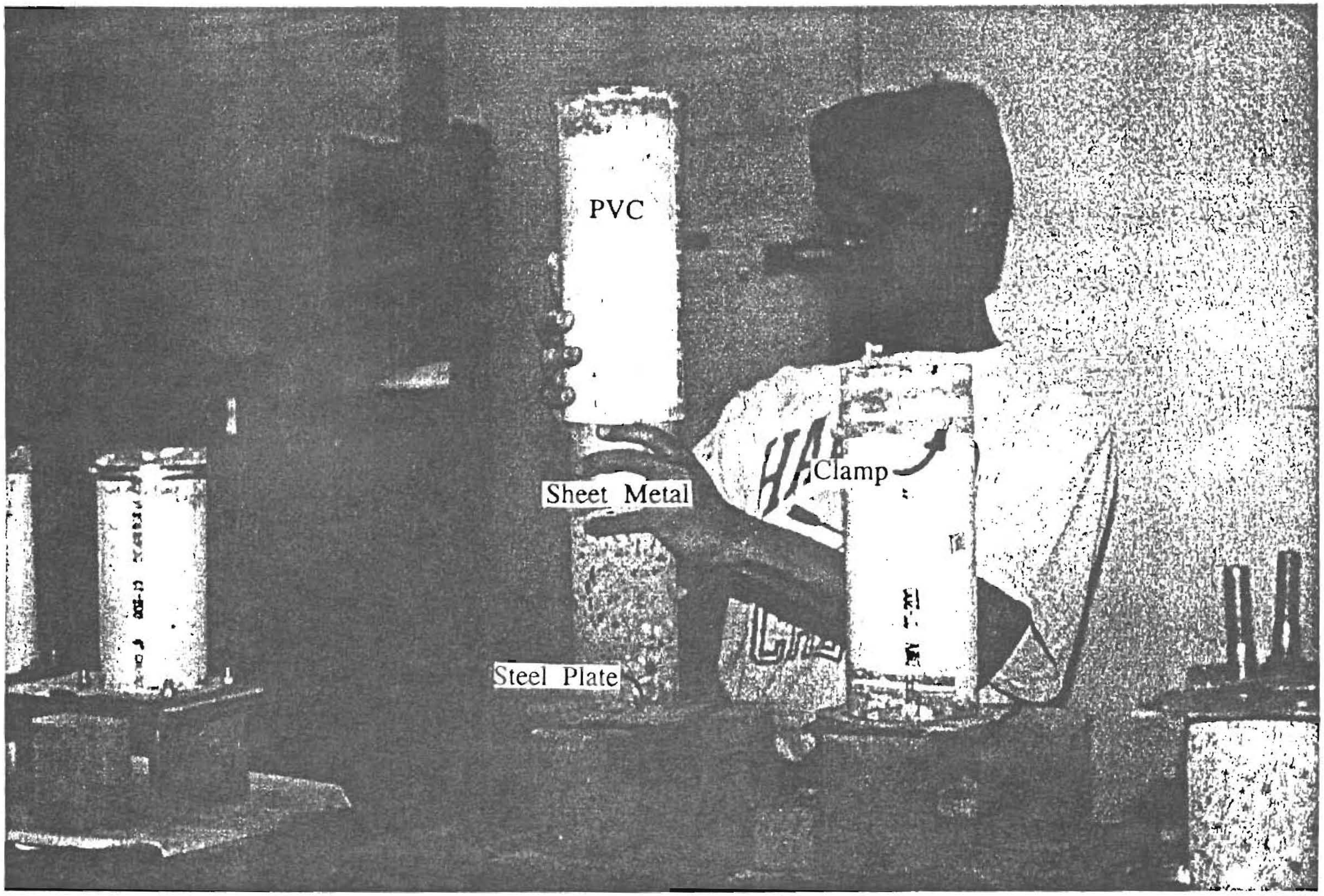

Figure 3.7 Placing PVC Form Over Base Sample

thin-bonded overlay delamination occurred.
For the vertical vibration testing, small amounts of the overlay concrete were prepared daily. Two similar samples were prepared at a time i.e. with the same surface texture, overlay thickness, cure time, etc.. Only two specimens were prepared at a given time because the shaker was limited to the weight of two samples. The dry concrete materials (sand, aggregate, cement, and fly-ash) were weighed on a scale and mixed by hand.

A piece of 4-in. diameter PVC pipe was placed over the entire base concrete core sample which had been previously placed on a steel plate. The length of the PVC depended on whether a 2-in., 4-in. or 6-in. overlay was being prepared. A seam was cut down the length of the PVC pipe to make the removal of the form easier. A piece of sheet metal was inserted between the PVC and the core sample and all the way to the top of the PVC to create a tight fitting form. Two clamps were placed around the PVC and tightened in order to prevent the forms from slipping.

With the overlay forms in place, the amount of water required for the overlay concrete was added. The materials were mixed by hand until the desired consistency was obtained. The concrete was placed in the PVC forms and compacted with a tamping rod (see Figure 3.8). If the sample being tested required a wet interface, the surface of the base core was sprinkled with water immediately prior to the placement of the overlay. In this manner, the water would not have time to evaporate. A similar procedure is followed in the field when a surface is required to be wet before the placement of concrete.

The two freshly-poured samples would be left undisturbed for the required cure time and then placed on the vibrator and subjected to the specified vertical vibration amplitude (see Figure 3.9). In the case of the 0 hour pre-vibration cure, the samples were placed on the vibrator immediately after the overlay pour. As mentioned before, the amount of time a sample was vibrated depended on the cure time.

A similar procedure for preparing the overlay concrete for the horizontal vibration testing was followed (see Figure 3.10). However, only 2-in. and 4-in. overlays were investigated and one sample was prepared at a time because of the shaker's limitations of holding specific weights in a perpendicular direction (i.e. limit amount of stress on the shaker). Again, the testing matrix is shown in Figure 3.2. The same type of forms were used and the same interface conditions and cure times were tested.

The 50-lb shaker, shown in Figures 3.9 and 3.10, was controlled by a Labwork Inc. Linear Power Amplifier (model PA-123) and Amplifier Control Panel (model CP-123) and a Wavetek Arbitrary Waveform Generator (model 75). The amplitude of the vibrator was set with the Amplifier Control Panel while the frequency and wave function (sine) were controlled with the Wavetek.

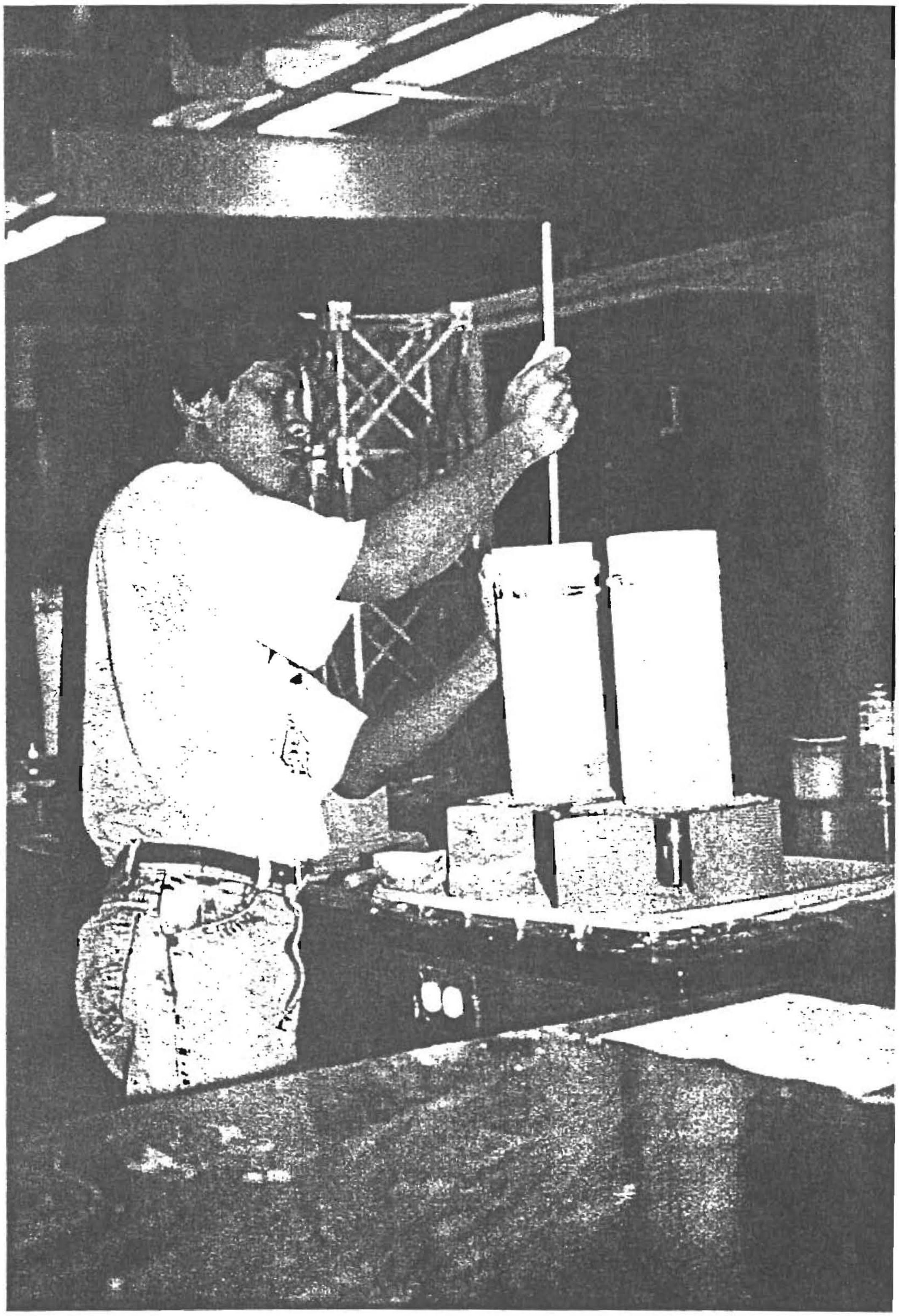

Figure 3.8 Tamping Fresh Concrete Overlay in PVC Forms

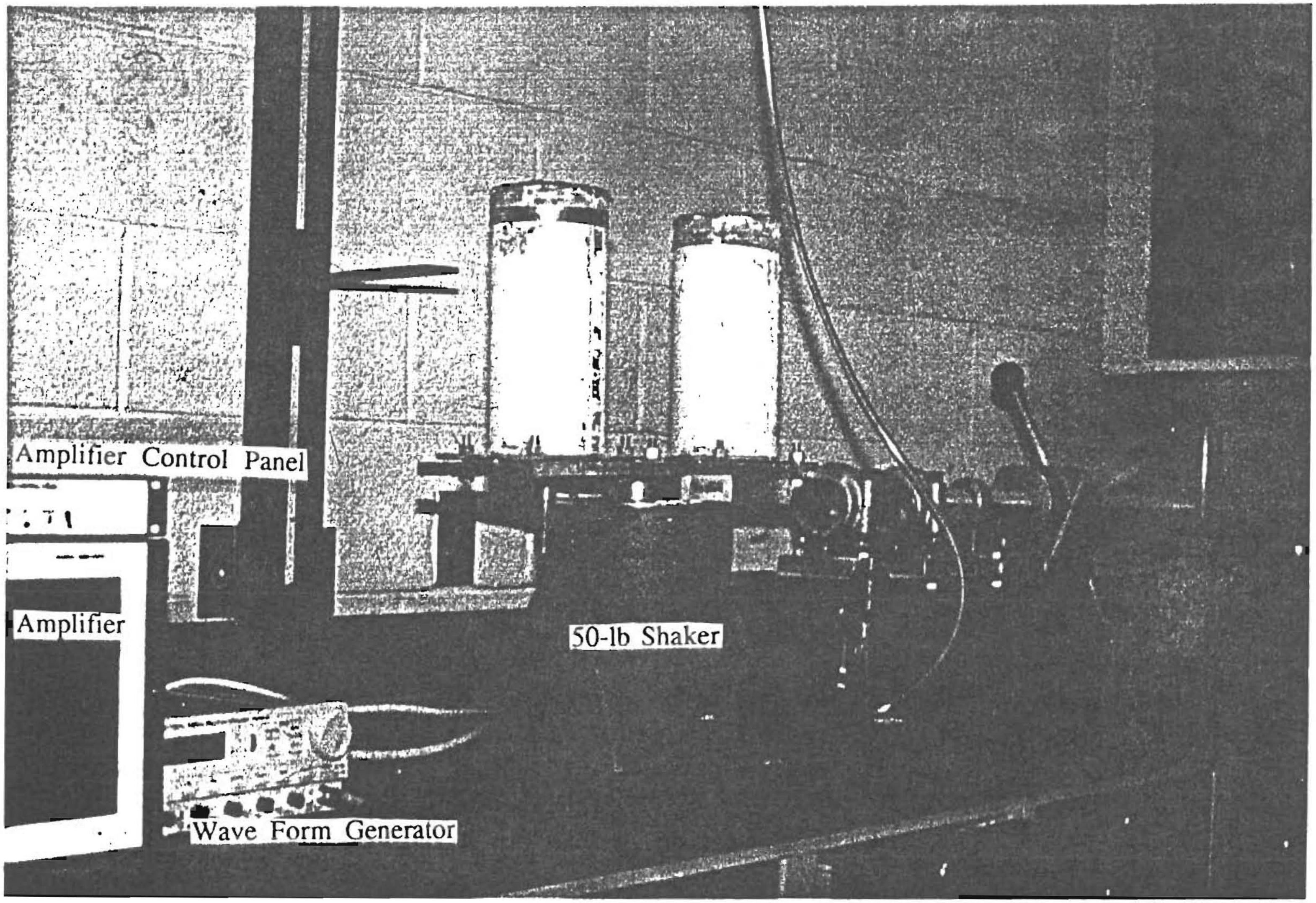

Figure 3.9 Concrete Overlay Samples Being Subjected to a Vertical Vibration Mode

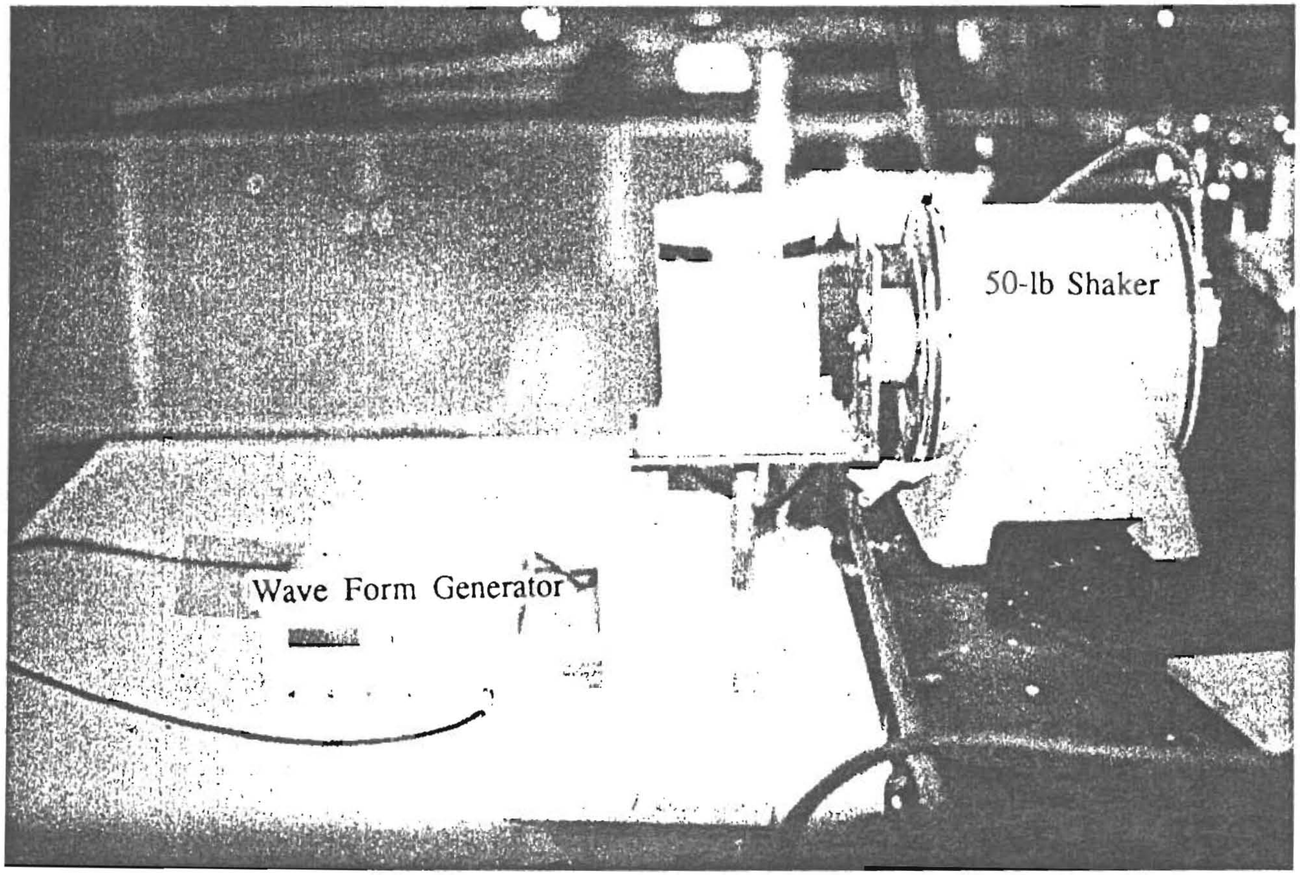

Figure 3.10 Concrete Overlay Sample Being Subjected to a Horizontal Vibration Mode

In all cases, the samples were removed from the shaker and tested in direct shear 24 hours after the overlay had been prepared and placed on the base concrete core.

The Class "CO" concrete design factors are as follows:

cement - 8 sacks/C.Y.
fly-ash - 25%
water - 4.5 gals/sack of cement
coarse aggregate - 0.67
entrained air - 6.0%
1/2" maximum aggregate size

An average 28-day compressive strength of 4754 psi was obtained on a trial batch.

3.4 Testing Procedure

At the end of the 24 hour period, the PVC form and sheet metal were removed from the specimen. The Guillotine Direct Shear Test Method, shown in Figure 3.11, was used to test the specimens. The design for this fixture for measuring the shear strength of concrete materials was obtained from the Center for Transportation Research at The University of Texas at Austin. The apparatus was slightly modified to suit the size of the core specimens and to simplify the construction. The complete dimensions and description of materials used are found in Appendix C.

The sample was placed in the shear apparatus with the moving plate and the top clamp piece off. The top clamp piece was then placed on top of the sample making sure that the interface between the base and overlay lay exactly at the edge. This ensured that only the shear strength at the interface was obtained and not any added strength from the older concrete (i.e. the base). If the length of the base core extended beyond the clamped section it was supported by a wooden block as shown in Figure 3.12. In this manner, the weight of the concrete would not affect the test. The top clamp piece was placed and then tightened until the sample was completely secured (see Figure 3.13). The two bolts were alternately tightened slowly otherwise, too much pressure, too quickly, would sometimes break the sample. The moving plate, or guillotine, was placed on top of the sample and the entire apparatus placed on a Riehle compression testing machine (see Figure 3.14). The moving plate was set directly and evenly under the loading block (see Figure 3.15). A load was applied to the guillotine, at a constant rate, until the overlay concrete was sheared from the base (see Figure 3.16). The load at which the break occurred was recorded and the shear strength, τ, calculated:

$$\tau = P/A$$

where P is the load at which the specimen broke (maximum load) and A is the cross sectional area of the specimen.

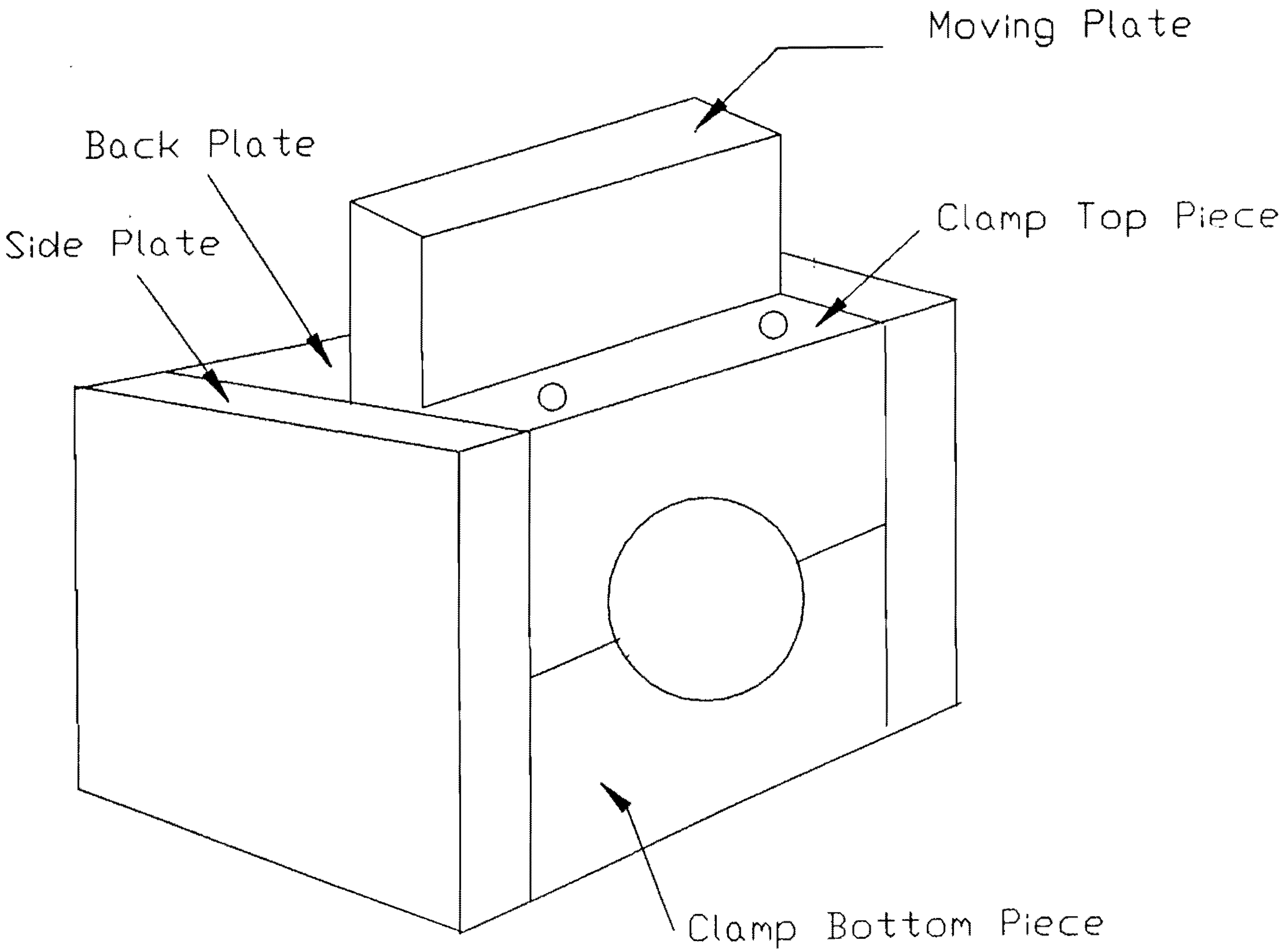

Figure 3.11 Guillotine Direct Shear Test Apparatus

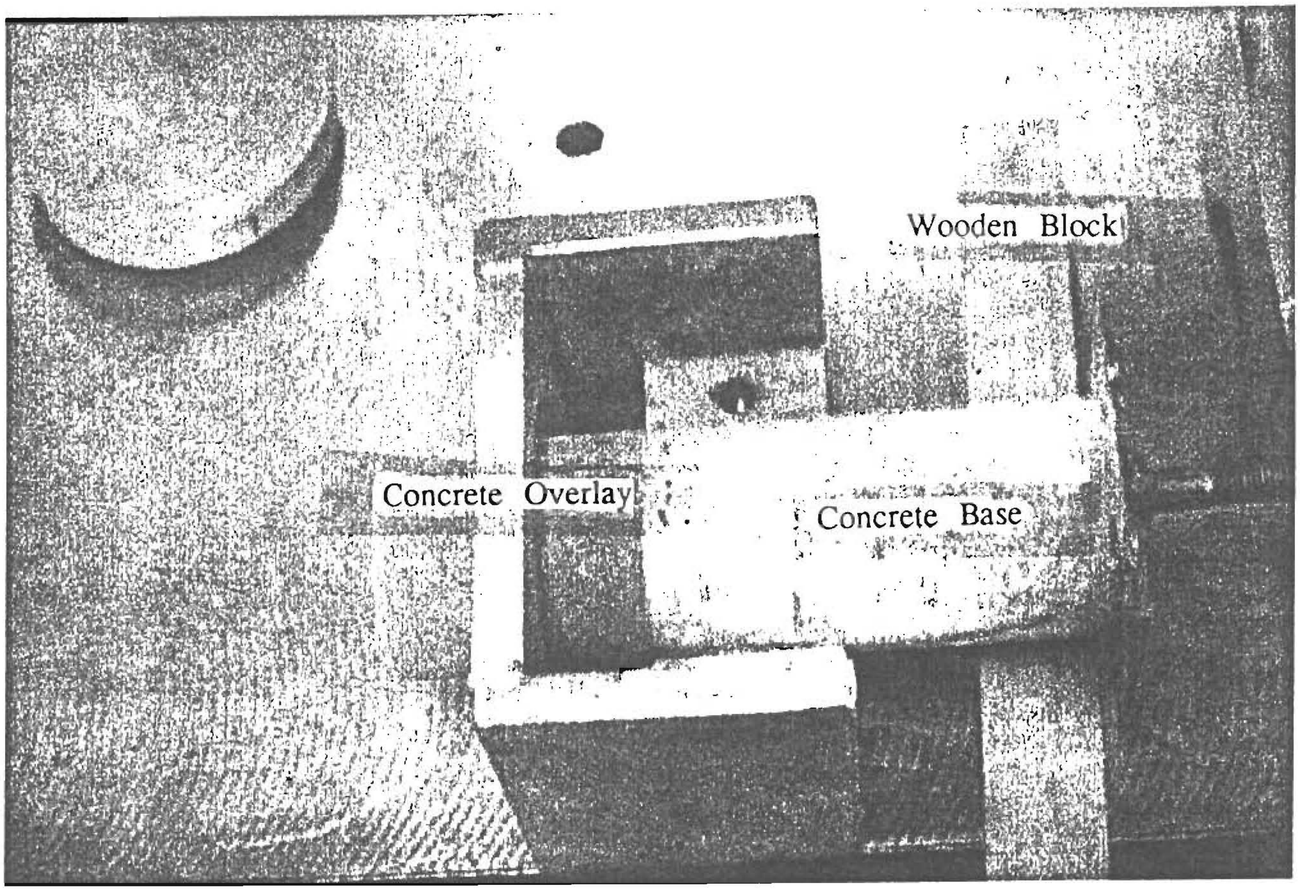

Figure 3.12 Concrete Overlay Specimen Placed in Shear Apparatus

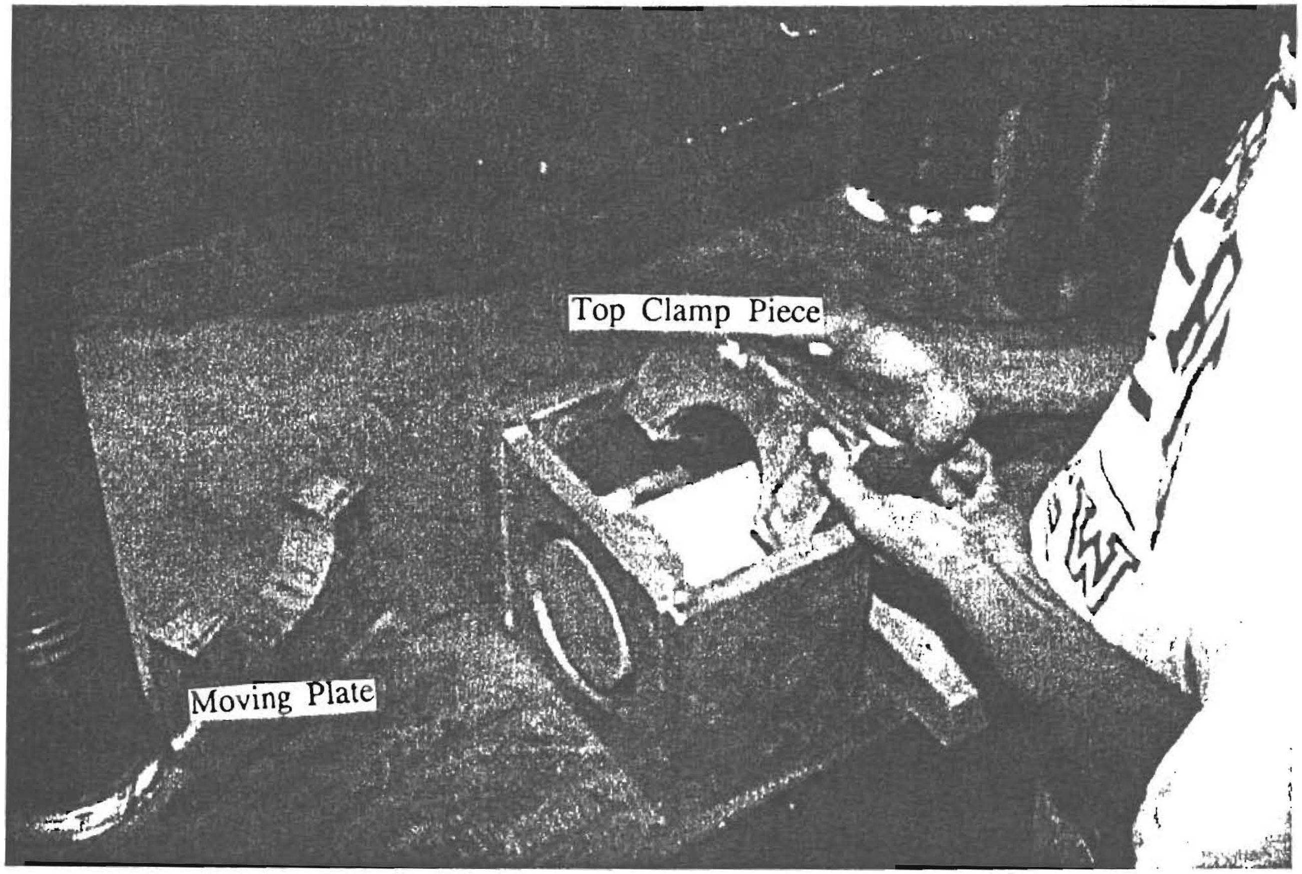

Figure 3.13 Placing Top Clamp Piece on Shear Apparatus

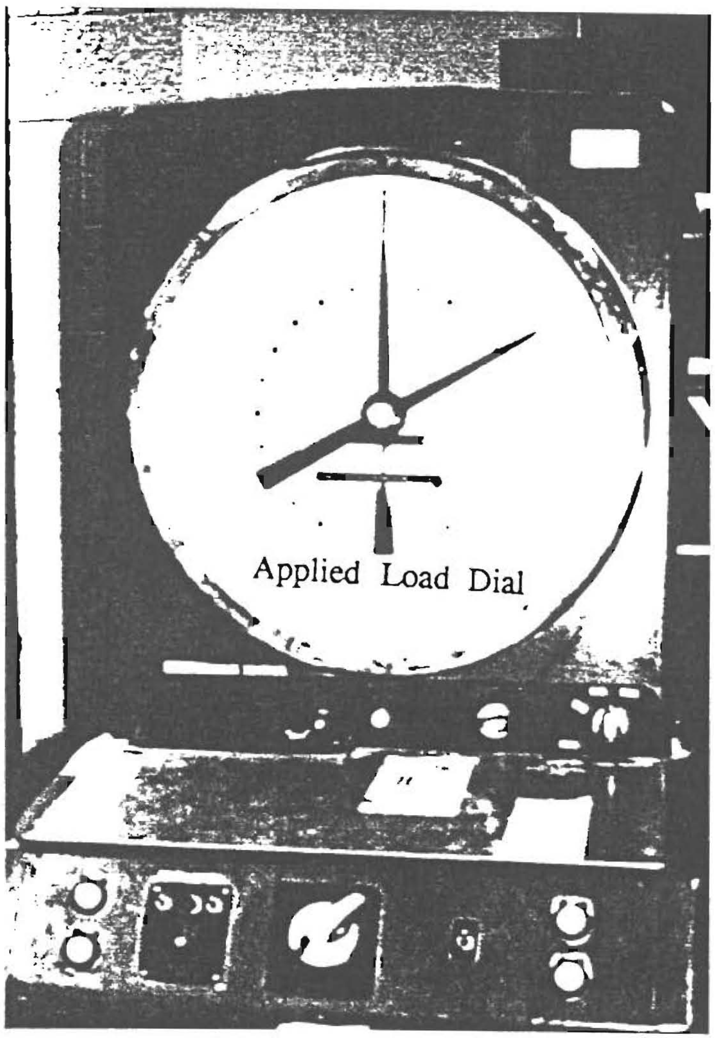

Figure 3.14 Riehle Compression Testing Machine Control

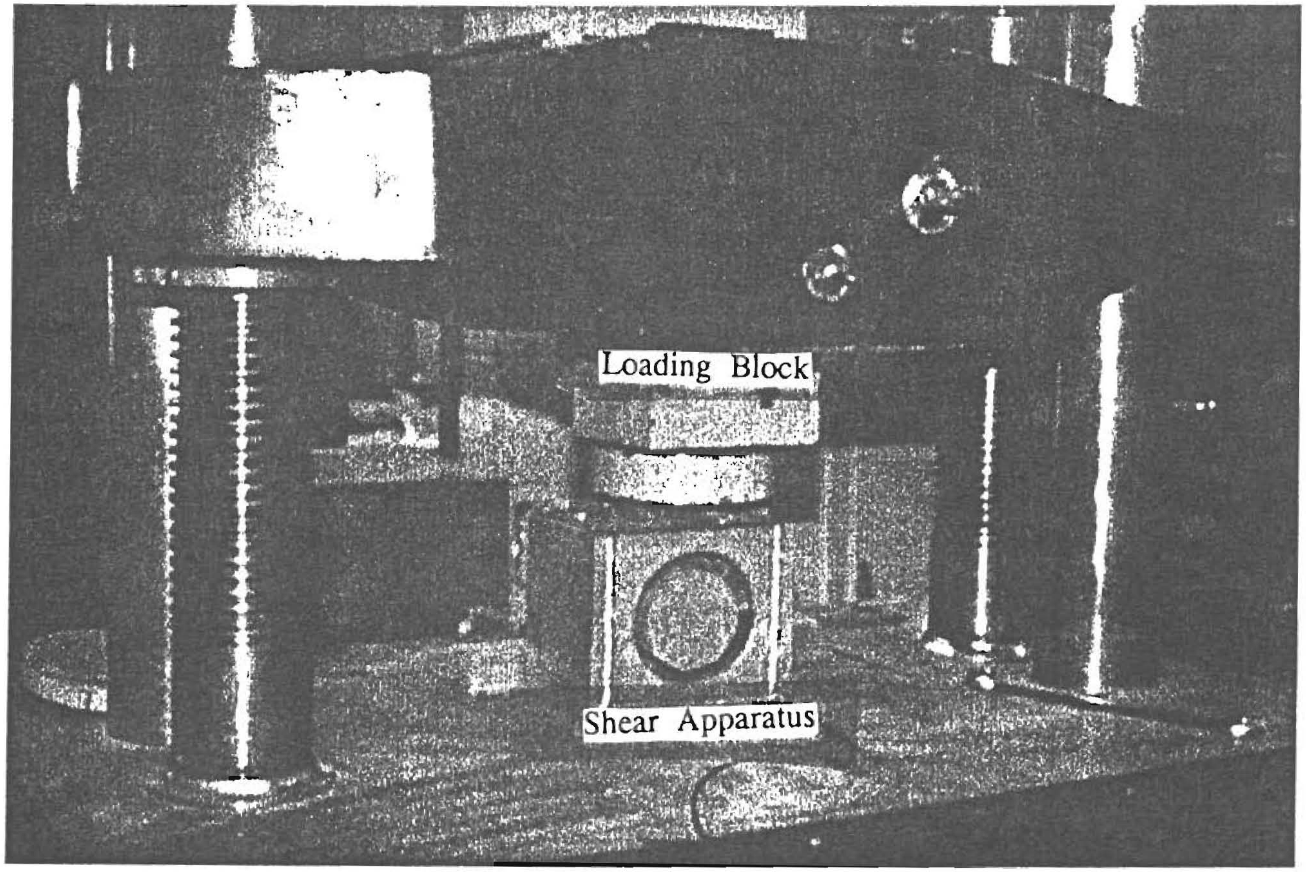

Figure 3.15 Shear Apparatus with Overlay Specimen Placed Under Loading Block of Riehle Compression Testing Machine

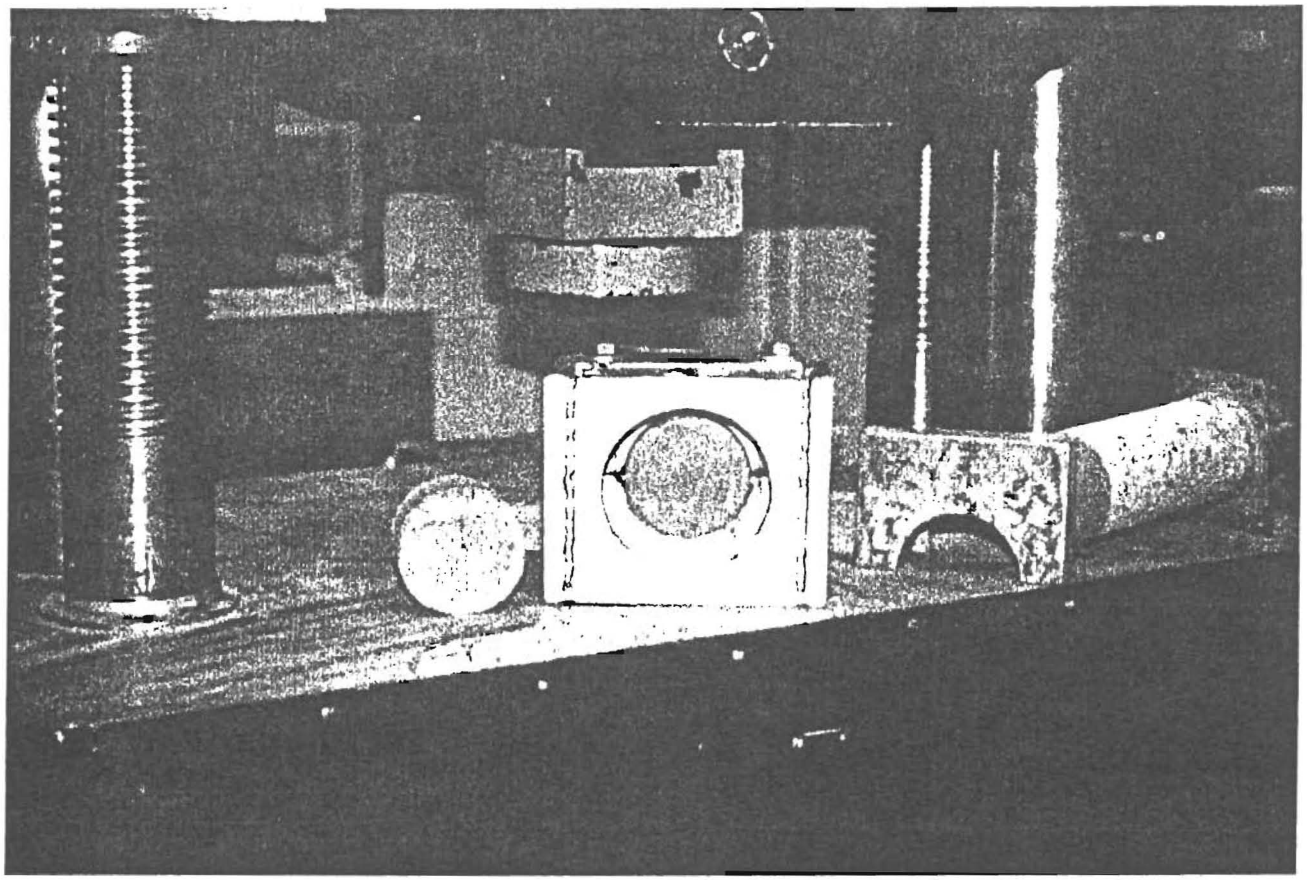

Figure 3.16 Concrete Overlay Specimen After Shearing

3.5 Future Work

3.5.1 Introduction

The next phase of this research project on the delamination of concrete overlays is to study the effects of vibration on larger specimens. These larger samples will be 3-ft X 6-in. X 2-in. beams and will be susceptible to flexural movement. The same interface conditions will be studied as well as the same cure times and vibration amplitudes. The only difference is that a 2-in. and 4-in. overlay will be examined and not a 6-in. overlay. So far, the testing apparatus forms have been designed and constructed and the base beams have been formed and poured.

3.5.2 Sample Preparation

3.5.2.1 Base

The concrete used for the base beams is the same class "H-H" concrete used for the base cores previously described. The size of these beams are 3-ft X 6-in. X 2-in.. A 2-in. depth was chosen in order to minimize the thickness and weight of the beam and therefore, allow for flexural movement to occur within the 3-ft length.

An 8-ft X 3-ft X 2-in. form was divided equally into twelve 6-in. wide areas. The beams were constructed using hand-made forms in order to have consistency throughout the concrete. If the individual standard beam molds would have been used variations in the concrete batches and the preparation of the samples would lead to variations in the strength of the beams. The class "H-H" concrete was delivered by a ready-mix truck to the site and poured into the oiled forms. The oil was used to ease the removal of the forms after the cure period. The concrete was consolidated with tamping rods because of the thin thickness and then finished with wooden floats. The beams were covered with wet burlap sacks and plastic and cured for 28 days. The burlap was checked everyday and wetted as necessary. After the cure period, the forms were striped and the beam specimens stored.

3.5.2.2 Platform

A steel plate platform was designed to hold the base beam samples and the overlay on a large 2000-lb. shaker (Ling Electronics Model B290) (see Figure 3.17). This platform is shown in Figure 3.18. A detailed drawing of this platform is found in Appendix D. The base beam is supported at the ends only and two pieces of 1/4-in. plexi-glass (3-ft X 6-in.) are placed along the length of the beam on both sides. The plexi-glass is supported at both ends by five large bolts and act as the forms for holding the freshly-poured overlay concrete in place. The plexi-

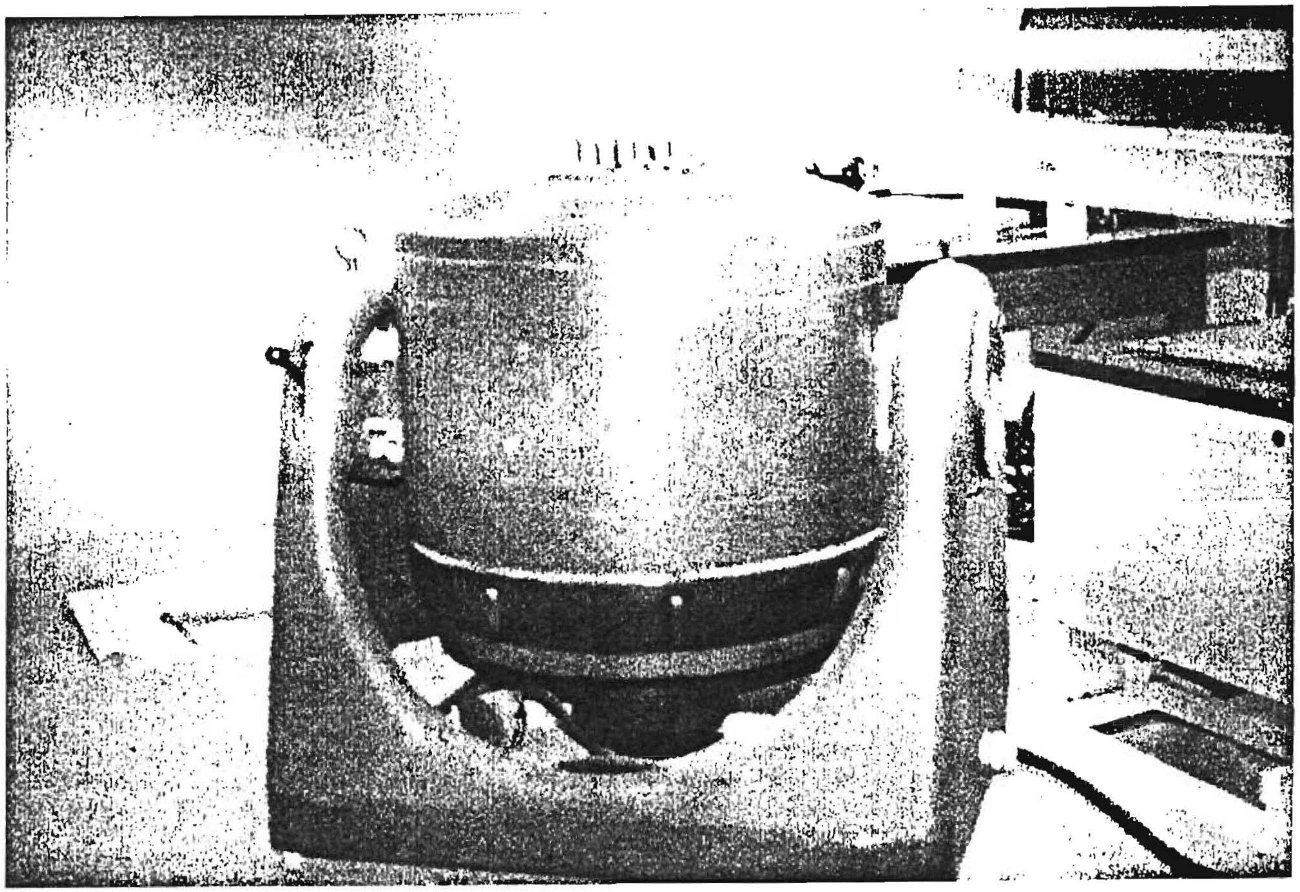

Figure 3.17 2000-lb Shaker

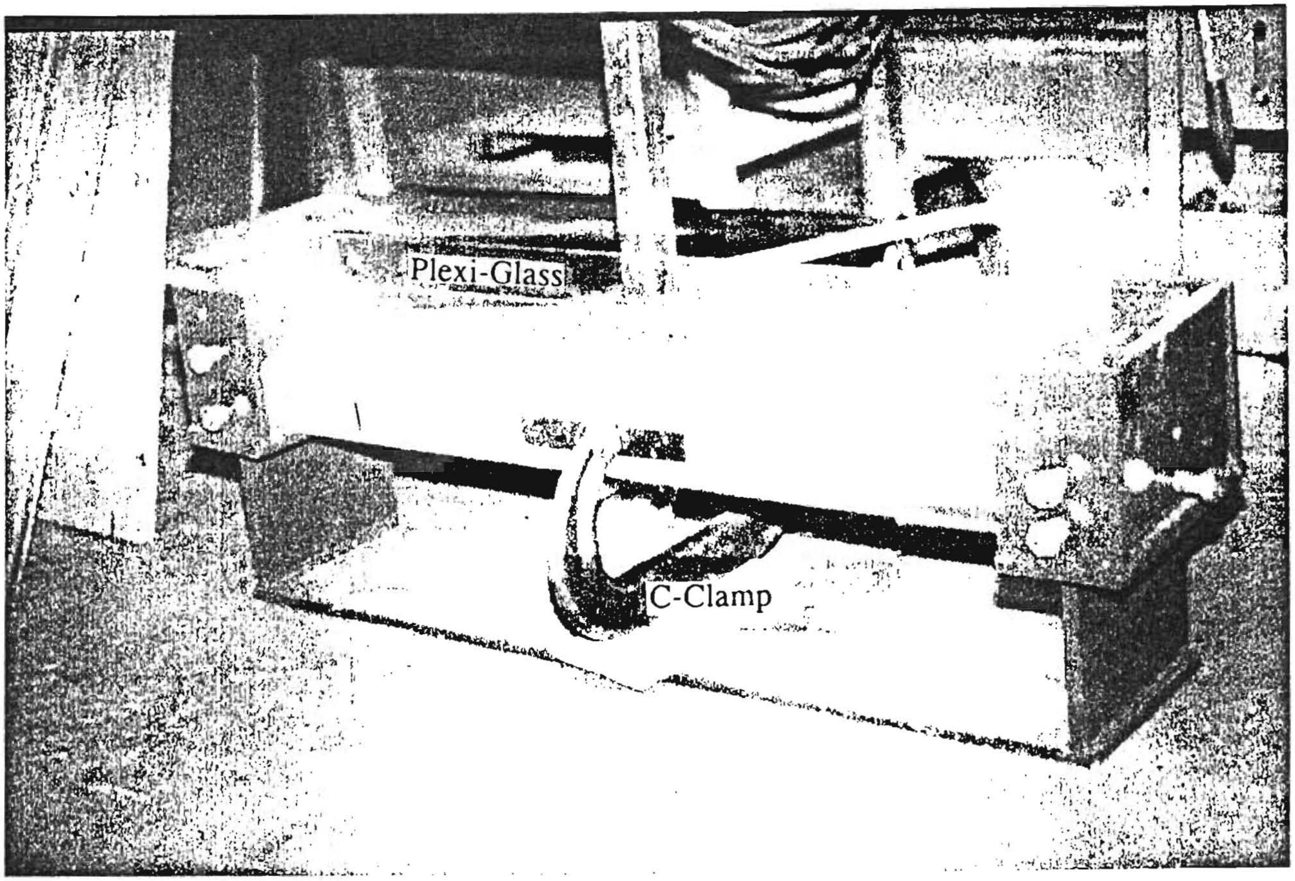

Figure 3.18 Platform Used to Place Beam Overlay Samples on 2000-lb Shaker

glass is marked longitudinally at a point 4-in. from the bottom in order to mark the limits for a 2-in. overlay. Concrete placed to the top of the plexi-glass would be a 4-in. overlay. A large C-clamp is placed in the middle of the span for extra support of the plexi-glass. The large bottom plate is drilled to match the holes on the top of the shaker for anchoring purposes.

3.5.2.3 Overlay

The same class "CO" concrete used for the core overlays is used for the beam overlay. Again, the overlay concrete is measured, mixed and placed by hand. The overlay concrete is placed on top of the beam in the frame. Consolidation is obtained with a tamping rod and finishing is done with a wood-float. The sample is allowed to set without being subjected to vibrations for the designated cure time and then placed on the shaker for the remaining time. This procedure is exactly the same as that followed for the core specimens.

The shaker is controlled by several Ling Electronics components which consist of: Control Selector DA-10; Power Amplifier CP 5/6; Cycling Oscillators CO-10-A and CO-10-B; Preamplifier 111; Servco Control Amplifier S-10; and Amplifier S-12-D and G. These components allow for the control of the needed amplitudes and frequencies and are shown in Figure 3.19.

3.5.3 Testing Procedure

Currently, the testing procedure is being established and refined for determining the shear strength of the overlay-base interface. The beam is simply supported with 6-inches between the supports. A load is then applied at the center point of the beam and deflection readings are recorded. Different compression machines have been tested to date in order to get consistent results i.e. deflection versus load graphs. The 3-ft beam is broken in half and then each half is also tested in the same manner. A theoretical solution is being developed as well as a finite-element solution to the problem of determining the shear strength.

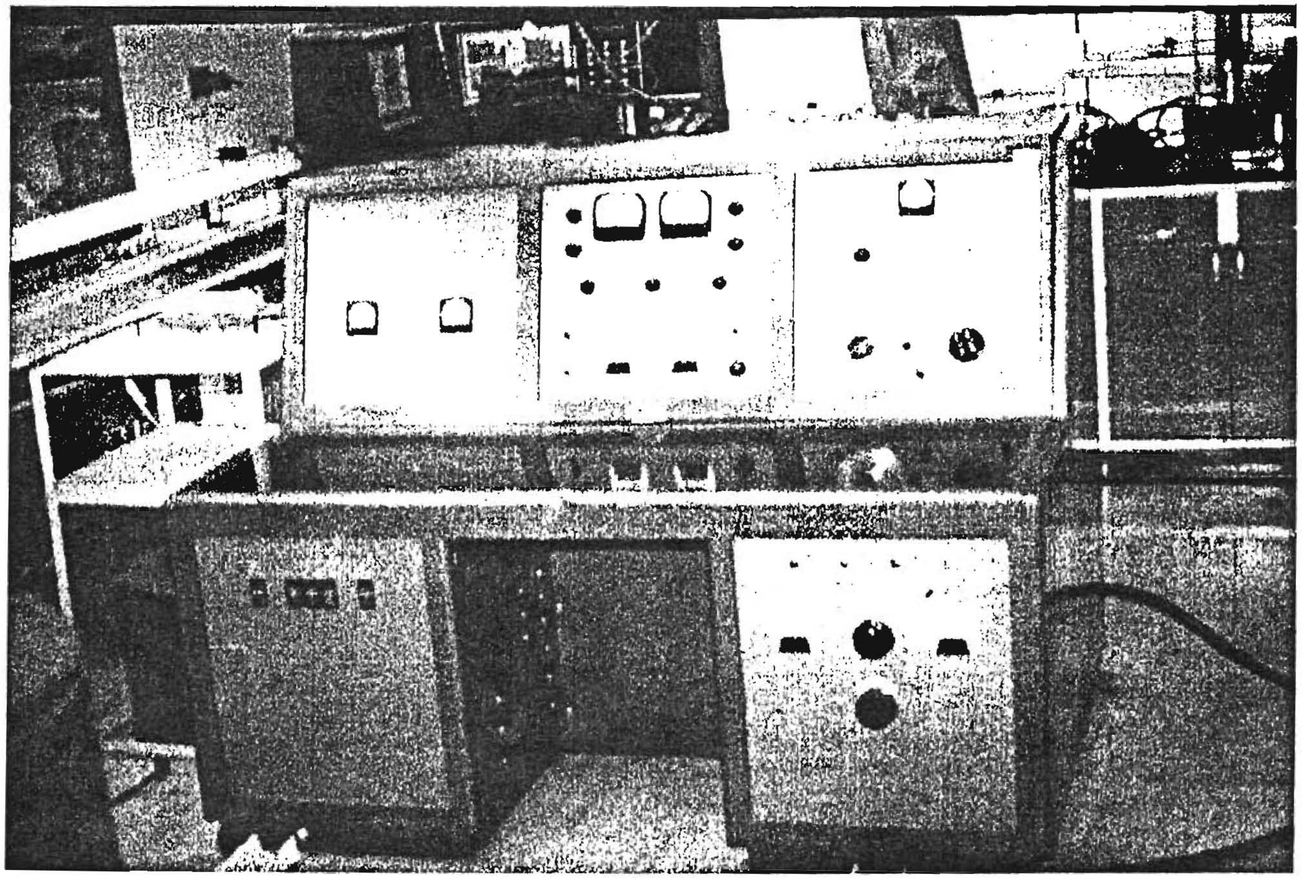

Figure 3.19 2000-lb Shaker Control Components

CHAPTER 4

PRESENTATION OF RESULTS

4.1 Vertical Vibration Mode

Shear strengths obtained from shear tests on all specimens subjected to vertical vibration mode are shown in Tables 4.1 through 4.3. As mentioned before, the effects of thickness of the overlay, pre-vibration cure time, surface preparation were experimentally investigated. Shear strengths obtained under different conditions are also graphically compared and are shown in Appendix E. For example, plots were created which show the differences in the shear strengths for a dry surface and a wet surface with all other parameters (i.e. pre-vibration cure time, overlay thickness, and surface texture) maintained constant. The shear strengths are also compared for similar specimens subjected to 0, 4 and 12 hours of pre-vibration cure. The differences in shear strengths for overlay thickness of 2-in., 4-in., and 6-in. are also discussed. Similar comparisons are carried out when the specimens were subjected to horizontal vibration. Finally, the variation in results solely due to the mode of vibration (horizontal vs vertical) are discussed.

4.1.1 Surface Conditions

The shear strengths for a dry surface and a wet surface before pouring the overlay are compared here. This was studied to determine whether the surface on which a concrete overlay is placed should be wet or dry immediately before the overlay placement.

Based on the results reflected in Table 4.1, the average shear strengths for a 2-in. overlay and a 0 hour pre-vibration cure time (i.e. vibrated for 24 hours) on smooth and rough surfaces are not very consistent. On a dry surface, the low vibration levels produced a slightly higher shear

Table 4.1 Average Shear Strength for a 2-in Overlay Under Vertical Vibration Mode

Cure Time (HR)	Surface Texture	Surface Wetness	Vibration Level	Shear Strength (PSI)
0	Smooth	Dry	None *	22.5
0	Smooth	Dry	Low	58.5
0	Smooth	Dry	High	33.0
0	Smooth	Wet	None *	32.0
0	Smooth	Wet	Low	63.5
0	Smooth	Wet	High	110.5
0	Rough	Dry	None *	38.0
0	Rough	Dry	Low	67.5
0	Rough	Dry	High	39.0
0	Rough	Wet	None *	134.0
0	Rough	Wet	Low	34.5
0	Rough	Wet	High	32.5

* - Control Specimen

Table 4.1 Con't. Average Shear Strength for a 2-in Overlay Under Vertical Vibration Mode

Cure Time (HR)	Surface Texture	Surface Wetness	Vibration Level	Shear Strength (PSI)
4	Smooth	Dry	Low	32.5
4	Smooth	Dry	High	51.0
4	Smooth	Wet	Low	34.0
4	Smooth	Wet	High	88.5
4	Rough	Dry	Low	18.5
4	Rough	Dry	High	100.5
4	Rough	Wet	Low	95.5
4	Rough	Wet	High	103.5

Table 4.1 Con't. Average Shear Strength for a 2-in Overlay Under Vertical Vibration Mode

Cure Time (HR)	Surface Texture	Surface Wetness	Vibration Level	Shear Strength (PSI)
12	Smooth	Dry	Low	150.0
12	Smooth	Dry	High	92.5
12	Smooth	Wet	Low	86.5
12	Smooth	Wet	High	81.0
12	Rough	Dry	Low	119.5
12	Rough	Dry	High	303.5
12	Rough	Wet	Low	84.0
12	Rough	Wet	High	201.0

Table 4.2 Average Shear Strength for a 4-in Overlay Under Vertical Vibration Mode

Cure Time (HR)	Surface Texture	Surface Wetness	Vibration Level	Shear Strength (PSI)
0	Smooth	Dry	None *	14.5
0	Smooth	Dry	Low	48.0
0	Smooth	Dry	High	132.0
0	Smooth	Wet	None *	115.0
0	Smooth	Wet	Low	21.0
0	Smooth	Wet	High	62.5
0	Rough	Dry	None *	68.0
0	Rough	Dry	Low	85.0
0	Rough	Dry	High	43.5
0	Rough	Wet	None *	27.5
0	Rough	Wet	Low	157.5
0	Rough	Wet	High	182.5

* - Control Specimen

Table 4.2 Con't. Average Shear Strength for a 4-in Overlay Under Vertical Vibration Mode

Cure Time (HR)	Surface Texture	Surface Wetness	Vibration Level	Shear Strength (PSI)
4	Smooth	Dry	Low	130.5
4	Smooth	Dry	High	163.5
4	Smooth	Wet	Low	101.0
4	Smooth	Wet	High	138.5
4	Rough	Dry	Low	113.0
4	Rough	Dry	High	114.5
4	Rough	Wet	Low	77.0
4	Rough	Wet	High	164.0

Table 4.2 Con't. Average Shear Strength for a 4-in Overlay Under Vertical Vibration Mode

Cure Time (HR)	Surface Texture	Surface Wetness	Vibration Level	Shear Strength (PSI)
12	Smooth	Dry	Low	146.0
12	Smooth	Dry	High	171.5
12	Smooth	Wet	Low	79.0
12	Smooth	Wet	High	147.0
12	Rough	Dry	Low	189.0
12	Rough	Dry	High	178.0
12	Rough	Wet	Low	174.0
12	Rough	Wet	High	151.0

Table 4.3 Average Shear Strength for a 6-in Overlay Under Vertical Vibration Mode

Cure Time (HR)	Surface Texture	Surface Wetness	Vibration Level	Shear Strength (PSI)
0	Smooth	Dry	None *	173.0
0	Smooth	Dry	Low	159.0
0	Smooth	Dry	High	126.0
0	Smooth	Wet	None *	175.0
0	Smooth	Wet	Low	104.5
0	Smooth	Wet	High	60.5
0	Rough	Dry	None *	200.0
0	Rough	Dry	Low	143.0
0	Rough	Dry	High	163.5
0	Rough	Wet	None *	164.0
0	Rough	Wet	Low	114.5
0	Rough	Wet	High	143.0

* - Control Specimen

Table 4.3 Con't. Average Shear Strength for a 6-in Overlay Under Vertical Vibration Mode

Cure Time (HR)	Surface Texture	Surface Wetness	Vibration Level	Shear Strength (PSI)
4	Smooth	Dry	Low	180.0
4	Smooth	Dry	High	200.0
4	Smooth	Wet	Low	132.5
4	Smooth	Wet	High	141.5
4	Rough	Dry	Low	106.5
4	Rough	Dry	High	181.5
4	Rough	Wet	Low	162.5
4	Rough	Wet	High	126.0

Table 4.3 Con't. Average Shear Strength for a 6-in Overlay Under Vertical Vibration Mode

Cure Time (HR)	Surface Texture	Surface Wetness	Vibration Level	Shear Strength (PSI)
12	Smooth	Dry	Low	141.5
12	Smooth	Dry	High	189.5
12	Smooth	Wet	Low	118.0
12	Smooth	Wet	High	113.5
12	Rough	Dry	Low	163.5
12	Rough	Dry	High	222.5
12	Rough	Wet	Low	139.0
12	Rough	Wet	High	173.5

strength on both smooth and rough surface conditions. On the other hand, on a wet-smooth surface, the high vibration levels produced the highest shear strength (110.5 psi). This is reflected in Figure 4.1. Even though not shown here, on a wet-rough surface, the no vibration resulted in the highest shear strength (134 psi).

Similar inconsistent results were obtained for a 2-in. overlay thickness and a 4 hour pre-vibration cure time. Low shear strengths were obtained on the smooth surface as shown in Figure 4.2. Typically, shear strengths increased on a rough surface. In general, for a 2-in. overlay and 4 hour pre-vibration cure, the highest shear strength was obtained on a rough-wet surface when the specimen was subjected to no vibration.

When a 2-in. overlay was allowed a pre-vibration cure of 12 hours, no vibration on a smooth surface produced the lowest shear strengths on both wet and dry surfaces. Low vibration levels resulted in an increase in the shear strength on a smooth-dry surface (150 psi). On a smooth-wet surface, low and high vibration levels caused similar shear strengths. Shown in Figure 4.3 are the shear strengths of specimens subjected to vibration after 12 hours of pre-vibration cure. On a rough surface, shear strengths due to high vibration levels were greater than the no and low vibration levels. On a rough-dry and rough-wet surface, the introduction of high vibration levels after 12 hours of pre-vibration cure produced shear strengths of 303.5 psi and 201 psi, respectively.

The shear strengths of specimens with 4-in. overlays on both dry and wet surfaces are variable. For a 0 hour pre-vibration cure time on a smooth-dry interface, the specimens subjected to high vibration levels produced the highest shear strengths (132 psi average). However, on a smooth-wet surface, specimens not vibrated yielded the highest shear strengths (115 psi). Figure 4.4 illustrates that on a rough interface and a 0 hour pre-vibration cure time, better shear strengths are obtained on a wet interface than on a dry interface. As the pre-vibration cure time increased, i.e. 4 and 12 hours, the differences in shear strengths for dry and wet surfaces are generally small, on both smooth and rough surfaces. Typically, 4 and 12 hours of pre-vibration cure with high vibration levels produced the highest shear strengths. However, the shear strengths obtained from low levels of vibration were not much lower than those obtained from the high vibration levels.

Typical comparisons of the shear strengths of 6-in. overlays poured on dry and wet interfaces are shown in Figure 4.6. Typically, on both wet and dry surfaces, the pre-vibration cure time, surface roughness and vibration levels, resulted in similar shear strengths. The largest variation in shear strengths between the three vibration levels occurred on a smooth-wet interface with a 0 hour pre-vibration cure time.

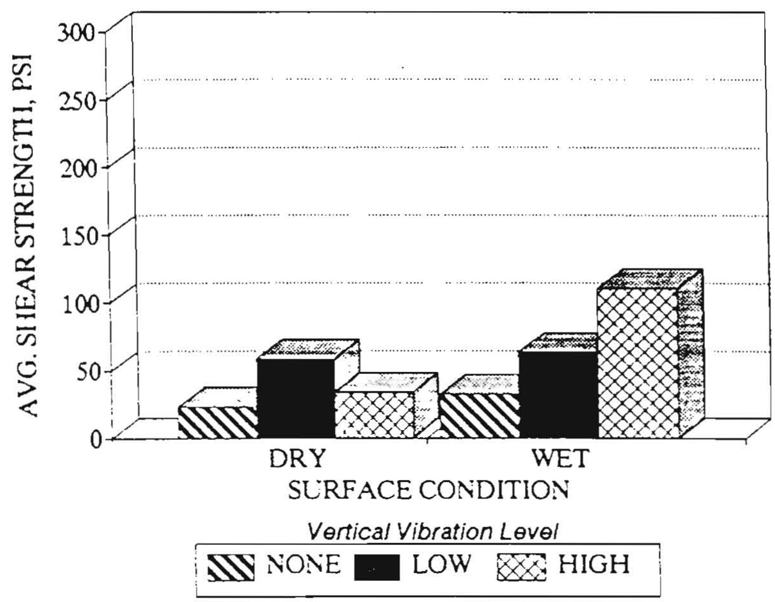

Figure 4.1 Comparison of Average Shear Strengths for a 2-in Overlay After 0 Hrs. of Pre-vibration Cure (Smooth Interface) Under Vertical Vibration Mode

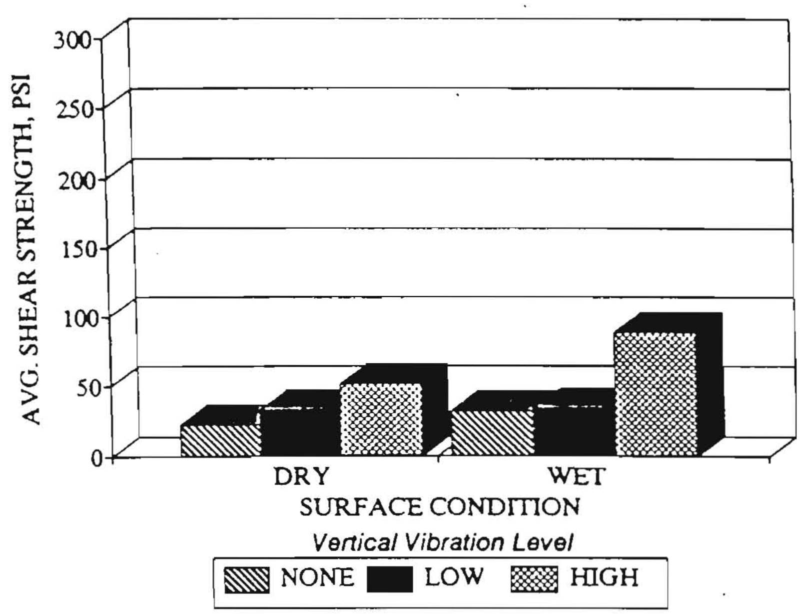

Figure 4.2 Comparison of Average Shear Strengths for a 2-in Overlay After 4 Hrs. of Pre-vibration Cure (Smooth Interface) Under Vertical Vibration Mode

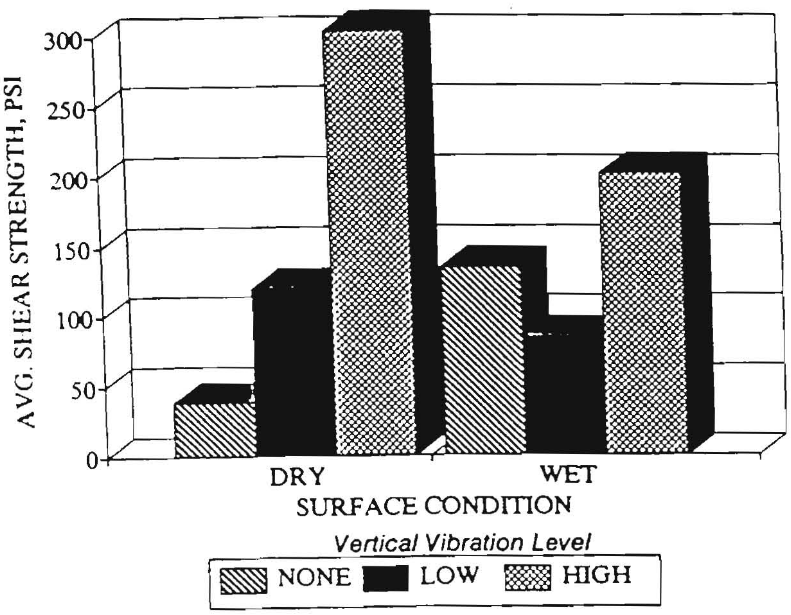

Figure 4.3 Comparison of Average Shear Strengths for a 2-in Overlay After 12 Hrs. of Pre-Vibration Cure (Rough Interface) Under Vertical Vibration Mode

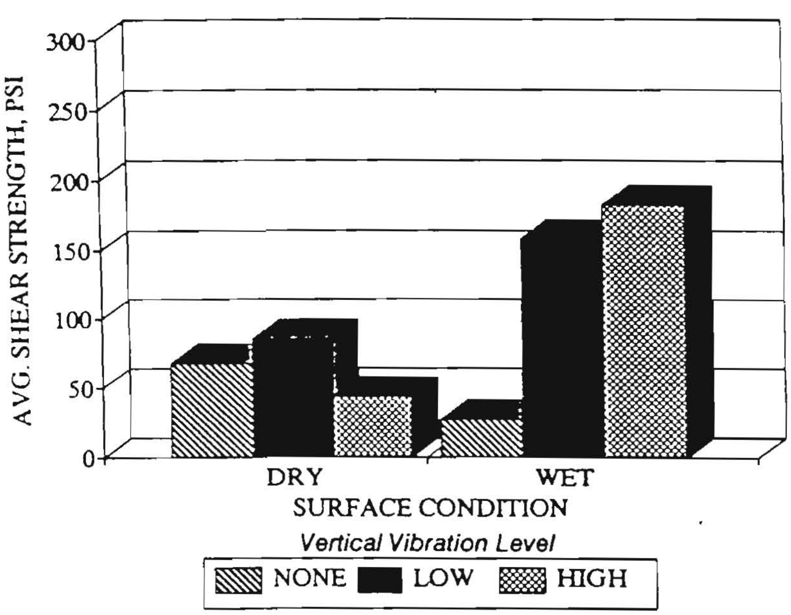

Figure 4.4 Comparison of Average Shear Strengths for a 4-in Overlay After 0 Hrs. of Pre-Vibration Cure (Rough Interface) Under Vertical Vibration Mode

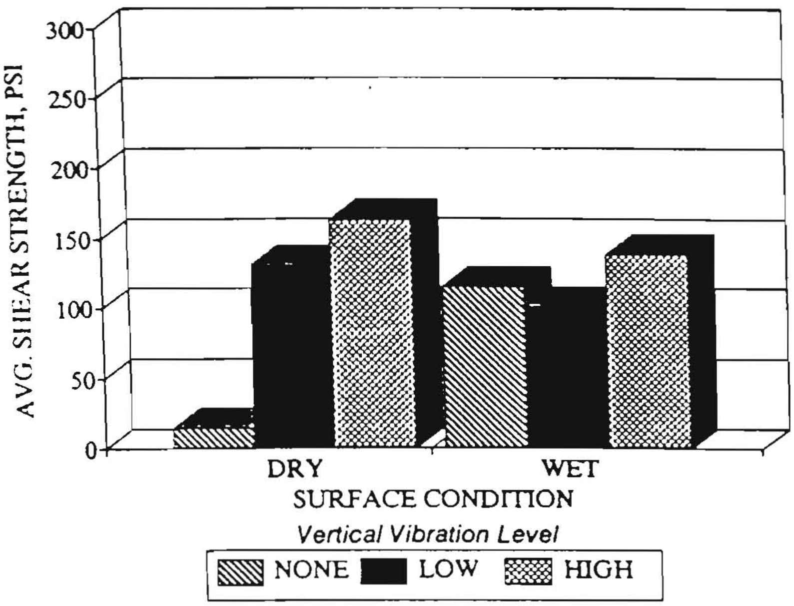

Figure 4.5 Comparison of Average Shear Strengths for a 4-in Overlay After 4 Hrs. of Pre-Vibration Cure (Smooth Interface) Under Vertical Vibration Mode

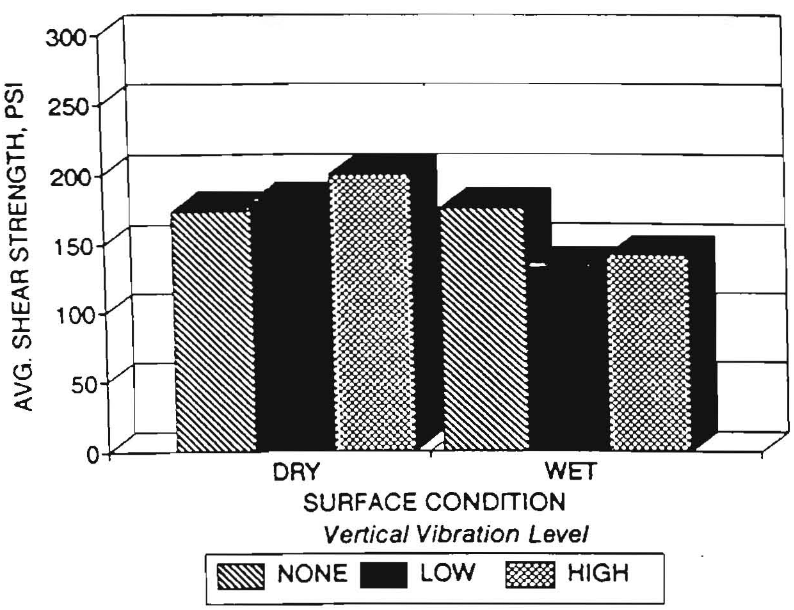

Figure 4.6 Comparison of Average Shear Strengths for a 6-in Overlay After 4 Hrs. of Pre-Vibration Cure (Smooth Interface) Under Vertical Vibration Mode

4.1.2 Pre-Vibration Cure Times

The results presented in this section give an overall view of the effects that the pre-vibration cure time may have on the shear strengths. Typically, all other specimen parameters are kept constant and only the effects of vibration levels for each condition are reflected.

The shear strengths for specimens not subjected to vibration for all pre-vibration cure time are the same on the graphs shown in the preceding sections. Because the graphs show the shear strengths of a specific overlay thickness and interface condition, these shear strengths do not change with a change in pre-vibration cure time.

The shear strengths of a 2-in. overlay on a smooth-dry, rough-dry and rough-wet surface at high vibration levels increased with an increase in pre-vibration cure time. Figure 4.7 shows that on the rough-dry surface, the shear strength increased 3 times when the pre-vibration cure was increased from 4 hours to 12 hours. However, on the smooth-wet surface, the high vibration levels resulted in shear strengths which decreased slightly (approximately 30 psi) as the pre-vibration cure time increased.

The shear strengths due to low levels of vibration on a smooth-dry, rough-dry and rough-wet surface, decreased when pre-vibration cure was increased from 0 to 4 hours, and then increased (2 or 3 times) at a 12 hour pre-vibration cure time. On a rough-wet surface, for the low levels of vibration, the shear strengths were slightly higher at 4 hours pre-vibration cure than at 12 hours pre-vibration cure. No vibration on a smooth-dry, smooth-wet and rough-dry surface, generally, produced the lowest shear strengths of the three vibration levels. However, on a rough-wet surface, no vibration resulted in the highest shear strength of the three vibration levels at 0 and 4 hour pre-vibration cure and the second highest shear strength at 12 hour pre-vibration cure.

For 4-in. overlays subjected to high levels of vibration on smooth-dry (see Figure 4.8), smooth-wet and rough-dry interfaces, the shear strengths increased with increased pre-vibration cure time. Typically, low vibration levels resulted in a similar trend. On a rough-wet surface subjected to high vibration levels, the shear strengths decreased slightly as the pre-vibration cure time increased. The low vibration level shear strengths, on the same interface, were similar for a 0 and 12 hour pre-vibration cure and for a 4 hour pre-vibration cure time resulted in the lowest shear strength of the three vibration levels. Generally, no vibration produced the lowest shear strengths except on smooth-wet surfaces.

Typically, for the 6-in. overlays, the shear strengths for all interface conditions and vibration levels, increased from the average shear strengths of the 2-in. and 4-in. overlays. In general, for both the low and high vibration levels, the shear strengths increased with an increase in pre-

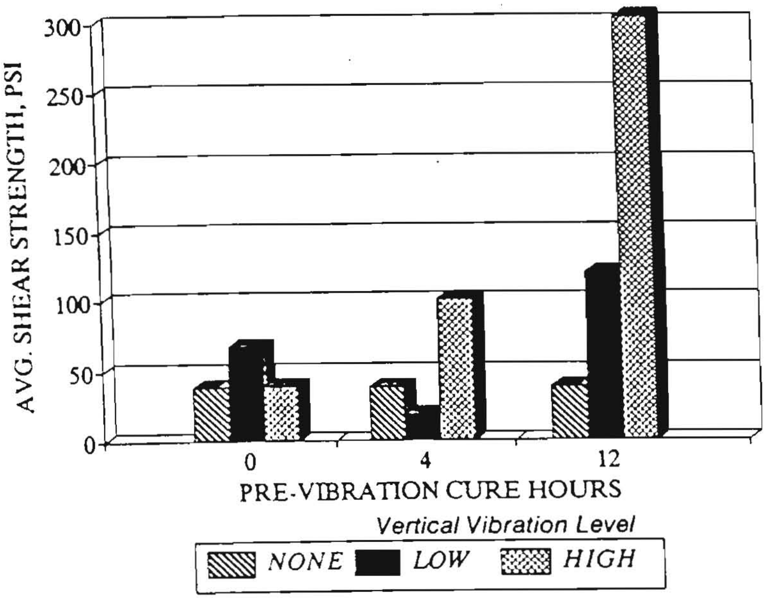

Figure 4.7 Comparison of Average Shear Strengths for a 2-in. Overlay (Rough-Dry Interface) Under Vertical Vibration Mode

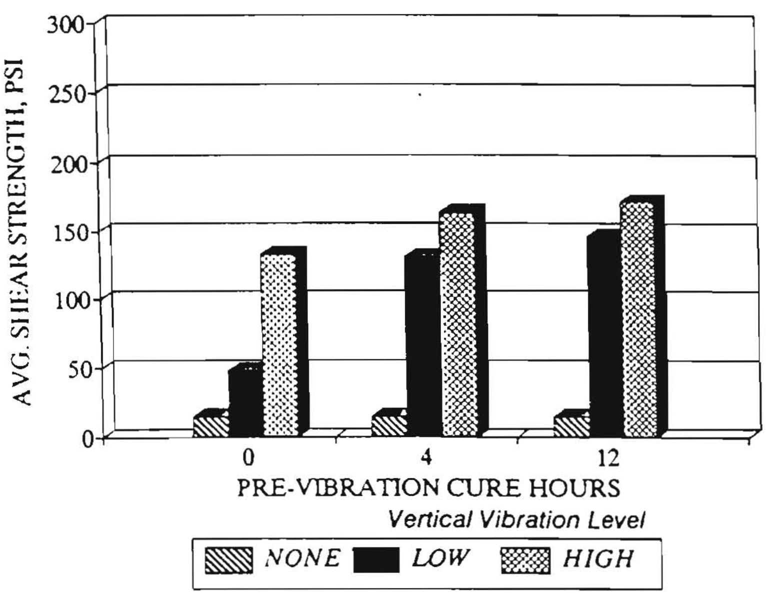

Figure 4.8 Comparison of Average Shear Strengths for a 4-in. Overlay (Smooth-Dry Interface) Under Vertical Vibration Mode

vibration cure time. However, the difference in shear strengths from one pre-vibration cure time to another was not very significant. Unlike the results for 2-in. and 4-in. overlays, Figure 4.9 shows that no vibration on specimens yielded shear strengths that were lower or similar to the results obtained for low and high vibration levels.

4.1.3 Overlay Thickness

The shear strengths from a 0 hour pre-vibration cure time were variable. Large and small differences between all three vibration level shear strengths exist for an overlay thickness of 2-in. and 4-in. on all surface conditions. Figure 4.10 illustrates this variability. High vibration levels produced the highest shear strengths for a 4-in. overlay and no vibration produced the highest shear strengths for 2-in. and 6-in. overlays. Generally, shear strengths of 6-in. overlays were more or less independent of vibration level; that is, the shear strength is not affected by the vibration level.

Less variability in the shear strengths occurred for the 4 hour pre-vibration cure time. Typically, the shear strengths for all three vibration levels increased with an increase in overlay thickness. A high vibration level for a 2-in. overlay on a smooth-dry (see Figure 4.11), smooth-wet and rough-dry surface, gave the highest shear strengths. However, on a rough-wet surface, no vibration produced the highest shear strength (approximately 30 psi greater than the high vibration level shear strength).

With a 12 hour pre-vibration cure period, the difference between the highest shear strengths of a 2-in., 4-in. and 6-in. overlay thickness was, typically, smaller than the difference between shear strengths of a 0 and 4 hour pre-vibration cure time. Figure 4.12 illustrates that larger vibration-related variations in shear strengths occurred for 2-in. overlays than for 4-in. or 6-in. overlays. In this figure (a rough-dry surface) the shear strength more than doubled between a no vibration (38 psi) and low vibration level (120 psi). The shear strength then increased, almost 3 times, between a low vibration level and a high level vibration (304 psi). This was the highest shear strength of all vertical vibration mode conditions studied. The 4-in. overlays produced similar shear strengths from low and high vibration levels. These results were much greater than those strengths obtained from the no vibration levels. The 6-in. overlay produced similar shear strengths amongst all three vibration levels.

4.2 Horizontal Vibration Mode

The shear strengths obtained for all specimens subjected to horizontal vibration under different surface and curing conditions are shown in Tables 4.4 and 4.5. The same type of comparisons as those for the vertical vibration mode were made. However, only 2-in. and 4-in. overlays

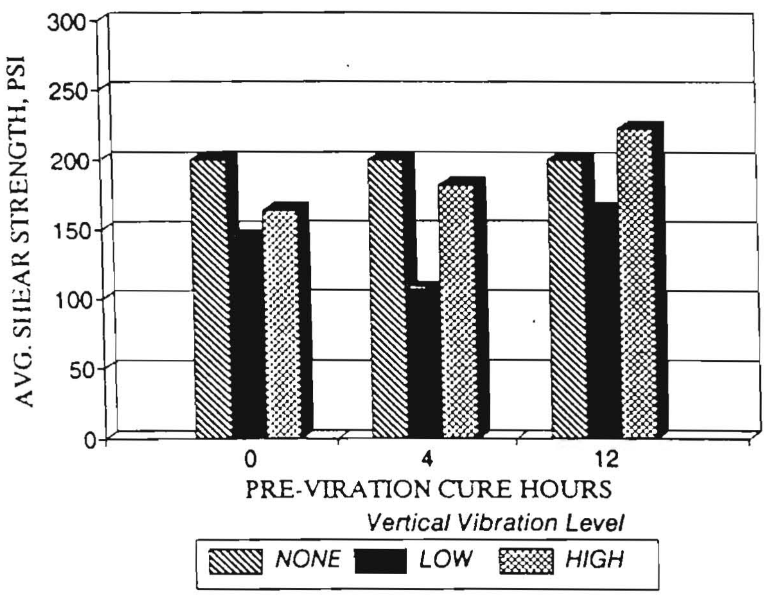

Figure 4.9 Comparison of Average Shear Strengths for a 6-in. Overlay (Rough-Dry Interface) Under Vertical Vibration Mode

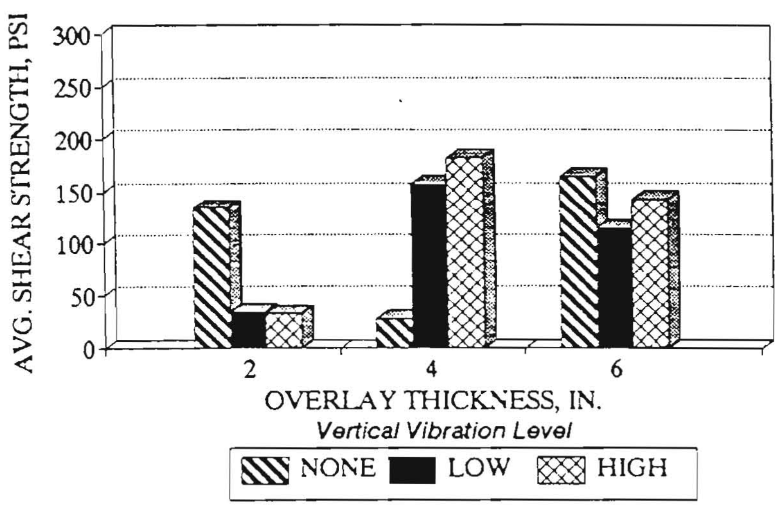

Figure 4.10 Comparison of Average Shear Strengths After 0 Hrs. of Pre-Vibration Cure (Rough-Wet Interface) Under Vertical Vibration Mode

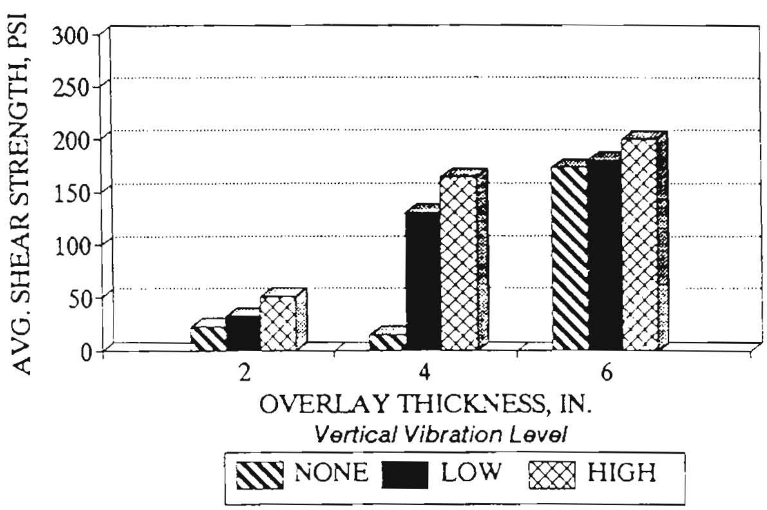

Figure 4.11 Comparison of Average Shear Strengths After 4 Hrs. of Pre-Vibration Cure (Smooth-Dry Interface) Under Vertical Vibration Mode

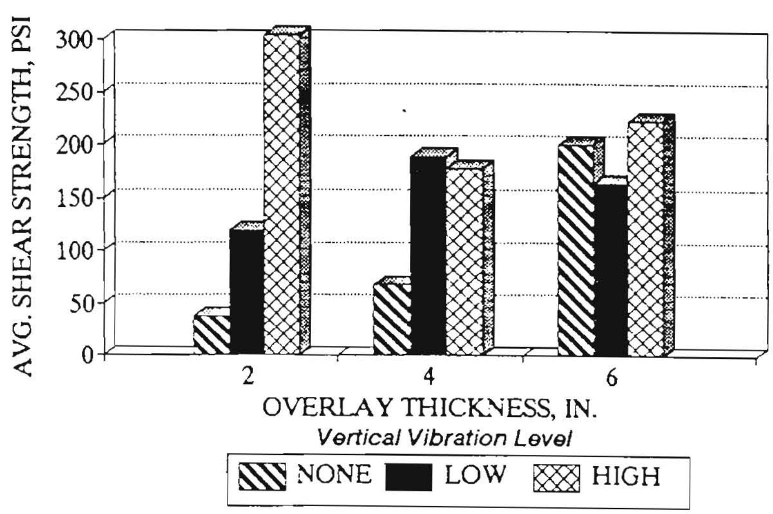

Figure 4.12 Comparison of Average Shear Strengths After 12 Hrs. of Pre-Vibration Cure (Rough-Dry Interface) Under Vertical Vibration Mode

Table 4.4 Average Shear Strength for a 2-in Overlay Under Horizontal Vibration Mode

Cure Time (HR)	Surface Texture	Surface Wetness	Vibration Level	Shear Strength (PSI)
0	Smooth	Dry	None *	22.5
0	Smooth	Dry	Low	100.0
0	Smooth	Dry	High	69.0
0	Smooth	Wet	None *	32.0
0	Smooth	Wet	Low	84.0
0	Smooth	Wet	High	45.5
0	Rough	Dry	None *	38.0
0	Rough	Dry	Low	129.0
0	Rough	Dry	High	189.0
0	Rough	Wet	None *	134.0
0	Rough	Wet	Low	138.0
0	Rough	Wet	High	64.0

* - Control Specimen

Table 4.4 Con't. Average Shear Strength for a 2-in Overlay Under Horizontal Vibration Mode

Cure Time (HR)	Surface Texture	Surface Wetness	Vibration Level	Shear Strength (PSI)
4	Smooth	Dry	Low	123.0
4	Smooth	Dry	High	72.0
4	Smooth	Wet	Low	135.0
4	Smooth	Wet	High	27.0
4	Rough	Dry	Low	195.0
4	Rough	Dry	High	131.0
4	Rough	Wet	Low	87.0
4	Rough	Wet	High	131.0

Table 4.4 Con't. Average Shear Strength for a 2-in Overlay Under Horizontal Vibration Mode

Cure Time (HR)	Surface Texture	Surface Wetness	Vibration Level	Shear Strength (PSI)
12	Smooth	Dry	Low	77.0
12	Smooth	Dry	High	86.0
12	Smooth	Wet	Low	47.0
12	Smooth	Wet	High	79.0
12	Rough	Dry	Low	97.0
12	Rough	Dry	High	164.0
12	Rough	Wet	Low	82.0
12	Rough	Wet	High	115.0

Table 4.5 Average Shear Strength for a 4-in Overlay Under Horizontal Vibration Mode

Cure Time (HR)	Surface Texture	Surface Wetness	Vibration Level	Shear Strength (PSI)
0	Smooth	Dry	None *	14.5
0	Smooth	Dry	Low	23.0
0	Smooth	Dry	High	91.0
0	Smooth	Wet	None *	115.0
0	Smooth	Wet	Low	18.0
0	Smooth	Wet	High	111.0
0	Rough	Dry	None *	68.0
0	Rough	Dry	Low	176.0
0	Rough	Dry	High	129.0
0	Rough	Wet	None *	27.5
0	Rough	Wet	Low	60.0
0	Rough	Wet	High	190.0

* - Control Specimen

Table 4.5 Con't. Average Shear Strength for a 4-in Overlay Under Horizontal Vibration Mode

Cure Time (HR)	Surface Texture	Surface Wetness	Vibration Level	Shear Strength (PSI)
4	Smooth	Dry	Low	157.0
4	Smooth	Dry	High	237.0
4	Smooth	Wet	Low	105.0
4	Smooth	Wet	High	213.0
4	Rough	Dry	Low	191.0
4	Rough	Dry	High	176.0
4	Rough	Wet	Low	142.0
4	Rough	Wet	High	309.0

Table 4.5 Con't. Average Shear Strength for a 4-in Overlay Under Horizontal Vibration Mode

Cure Time (HR)	Surface Texture	Surface Wetness	Vibration Level	Shear Strength (PSI)
12	Smooth	Dry	Low	258.0
12	Smooth	Dry	High	234.0
12	Smooth	Wet	Low	301.0
12	Smooth	Wet	High	182.0
12	Rough	Dry	Low	305.0
12	Rough	Dry	High	345.0
12	Rough	Wet	Low	196.0
12	Rough	Wet	High	182.0

were studied under a horizontal vibration mode. A 6-in. overlay was not included.

4.2.1 Surface Conditions

For a 2-in. overlay and all three pre-vibration cure times, higher shear strengths were generally found on rough surfaces. At 0, 4 and 12 hour pre-vibration cure times, the rough-dry surface produced the highest shear strength. The shear strengths from specimens not subjected to pre-vibration cure are shown in Figure 4.13. The shear strengths of specimens subjected to high vibration levels were the highest for 0 and 12 hour pre-vibration cure and the shear strengths at the low vibration levels were the highest at a 4 hour pre-vibration cure. Figure 4.14 is an example of a smooth interface in which the shear strengths between a dry and wet surface were similar. These shear strengths were less variable than the same results for a vertical vibration mode.

Four-in. overlays with 0 hour pre-vibration cure time, on both smooth and rough surfaces, resulted in similar maximum shear strengths on wet and dry surfaces. The level of vibration which produced the highest shear strength was variable. Figure 4.15 shows that after 4 hours of pre-vibration cure time, high levels of vibration created similar shear strengths for a smooth-wet (213 psi) and smooth-dry (237 psi) interface. However, Figure 4.16 illustrates that on rough-wet surfaces, high vibration levels caused higher shear strength (309 psi) than on a rough-dry interface (176 psi). Figure 4.17 shows that after 12 hours of pre-vibration cure time, the low vibration level on a smooth-wet surface resulted in the highest shear strength. However, on a rough surface (see Figure 4.18), under dry surface conditions, much higher shear strengths for both low and high vibration levels were obtained (when compared to wet surfaces). Typically, for a 4-in. overlay, both low and high vibration levels caused higher shear strengths than the no vibration.

4.2.2 Pre-Vibration Cure Times

The shear strengths for 2-in. overlays significantly varied for 0, 4 or 12 hours pre-vibration cure times. For example, for some surface conditions, certain vibration level shear strengths increased with longer pre-vibration cure times and other vibration level shear strengths decreased with increased pre-vibration cure time. Figure 4.19 shows the variability in shear strengths for 0, 4 and 12 hour pre-vibration cure times. The overall average shear strengths were similar for each pre-vibration cure time.

For 4-in. overlays, an increased pre-vibration cure time produced an increase in shear strengths for low and high vibration levels. On a smooth-dry (shown in Figure 4.20), smooth-wet and rough-wet interface, high vibration levels produced the highest shear strengths for 0 and 4 hour pre-vibration cures. For a 12 hour pre-vibration cure, the shear strengths for low and high

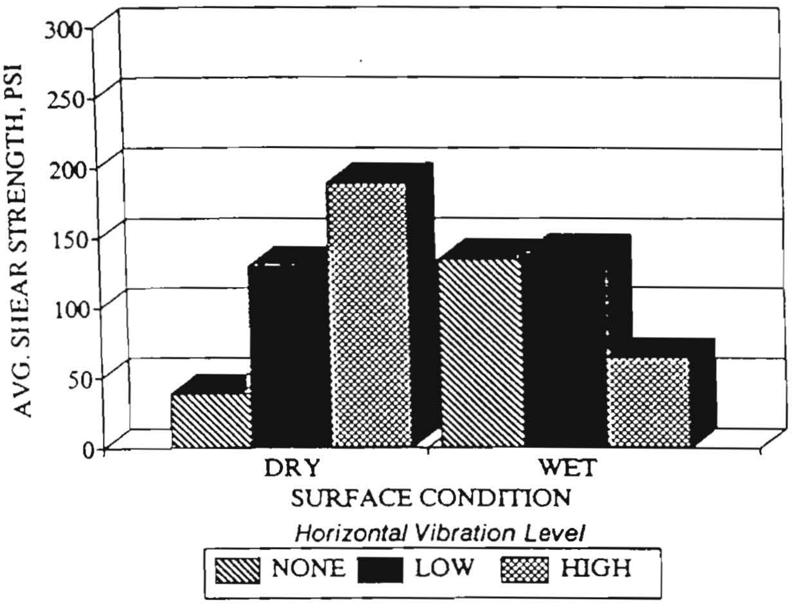

Figure 4.13 Comparison of Average Shear Strengths for a 2-in Overlay After 0 hrs. of Pre-Vibration Cure (Rough Interface) Under Horizontal Vibration Mode

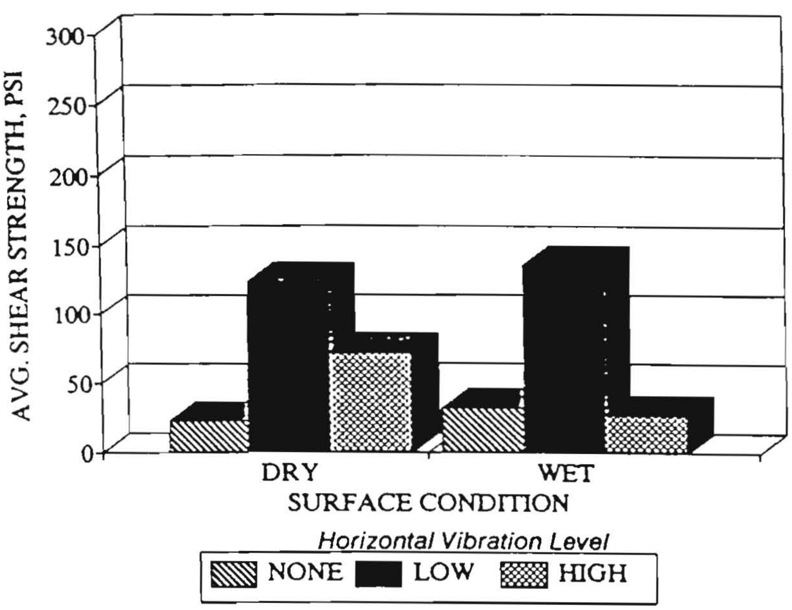

Figure 4.14 Comparison of Average Shear Strengths for a 2-in Overlay After 4 hrs. of Pre-Vibration Cure (Smooth Interface) Under Horizontal Vibration Mode

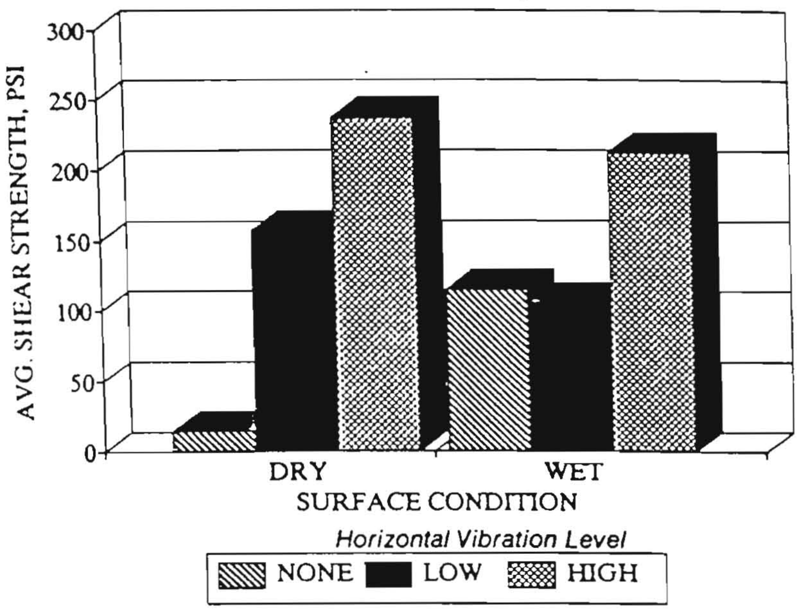

Figure 4.15 Comparison of Average Shear Strengths for a 4-in Overlay After 4 hrs. of Pre-Vibration Cure (Smooth Interface) Under Horizontal Vibration Mode

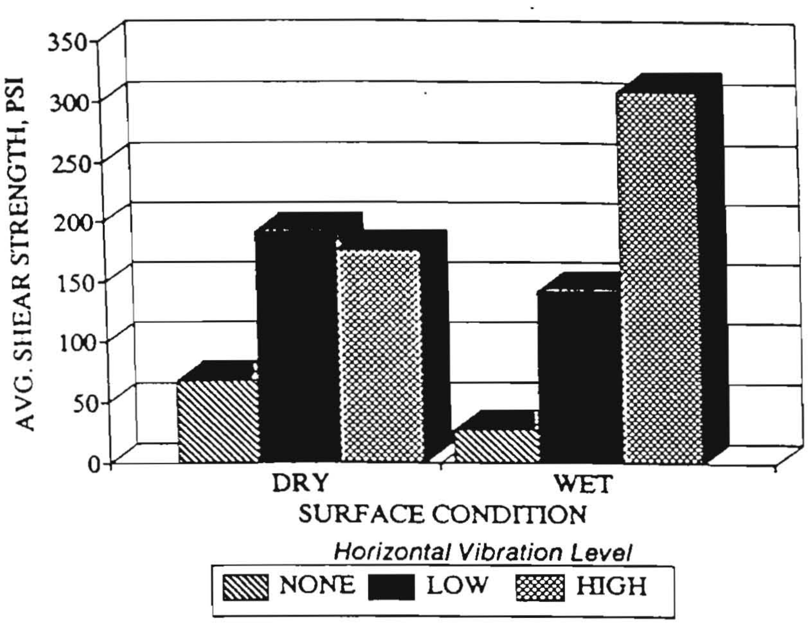

Figure 4.16 Comparison of Average Shear Strengths for a 4-in Overlay After 4 hrs. of Pre-Vibration Cure (Rough Interface) Under Horizontal Vibration Mode

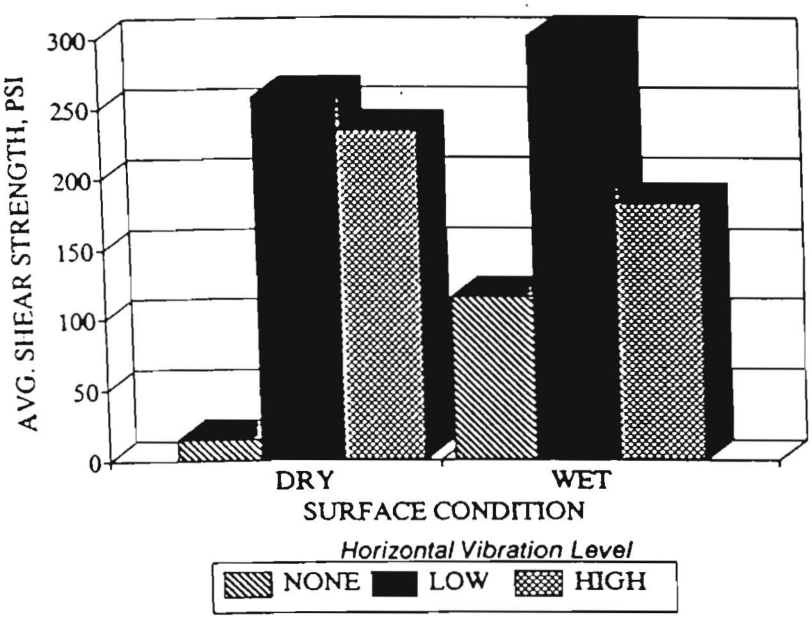

Figure 4.17 Comparison of Average Shear Strengths for a 4-in Overlay After 12 hrs. of Pre-Vibration Cure (Smooth Interface) Under Horizontal Vibration Mode

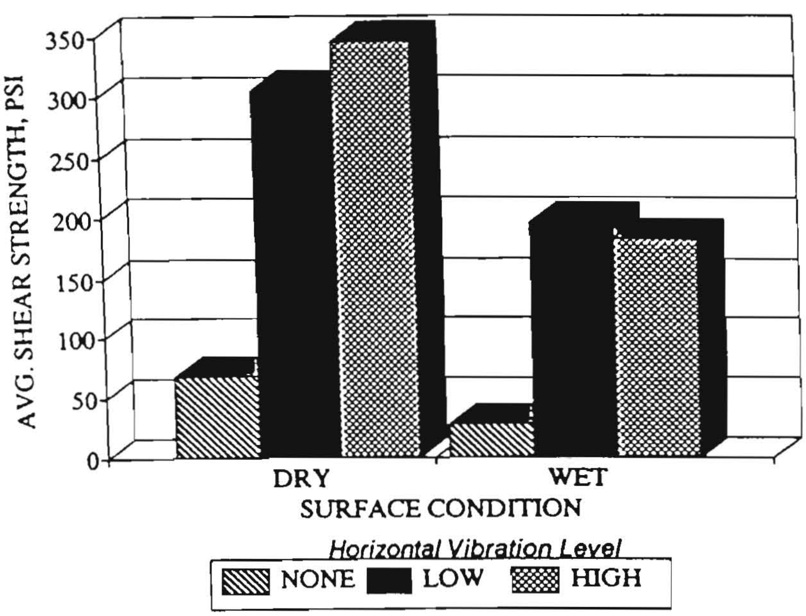

Figure 4.18 Comparison of Average Shear Strengths for a 4-in Overlay After 12 hrs. of Pre-Vibration Cure (Rough Interface) Under Horizontal Vibration Mode

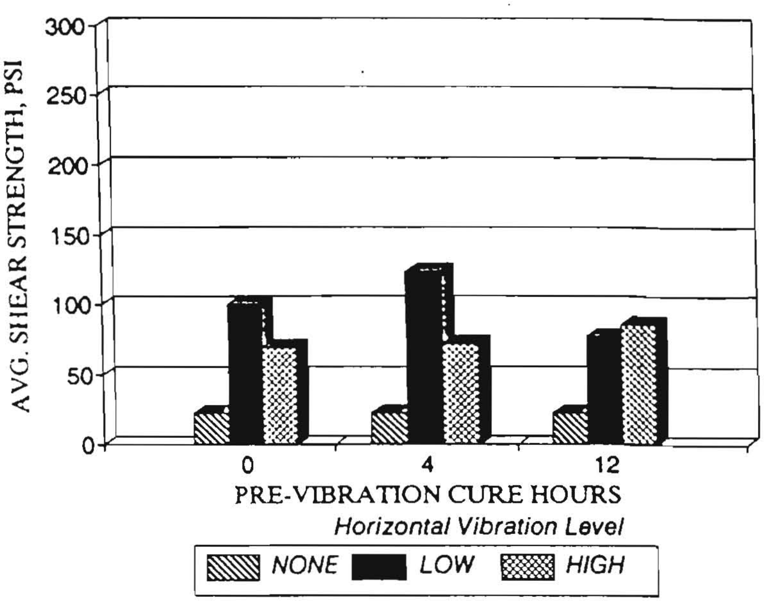

Figure 4.19 Comparison of Average Shear Strengths for a 2-in Overlay (Smooth-Dry Interface) Under Horizontal Vibration Mode

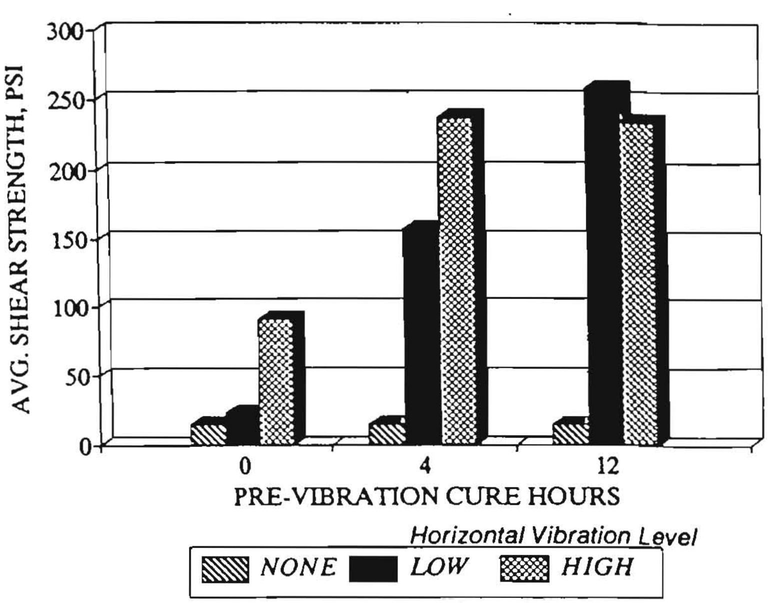

Figure 4.20 Comparison of Average Shear Strengths for a 4-in Overlay (Smooth-Dry Interface) Inerface) Under Horizontal Vibration Mode

pre-vibration cures. For a 12 hour pre-vibration cure, the shear strengths for low and high vibration levels were similar except on a smooth-wet surface. The highest shear strength for a 4-in. overlay subjected to a horizontal vibration mode was obtained on a rough-dry surface and with a 12 hour pre-vibration cure (345 psi).

4.2.3 Overlay Thickness

The shear strengths from 2-in. and 4-in. overlays, at a 0 hour pre-vibration cure produced variable results. On smooth-dry, smooth-wet and rough-wet surfaces, and at low vibration levels, the shear strengths decreased as the overlay thickness increased. Whereas, Figure 4.21 shows that at high vibration levels, shear strengths increased as the thickness of the overlay increased. At high vibration levels, shear strengths were similar on the smooth-dry and smooth-wet interfaces. On the rough-dry interfaces, and at low levels of vibration, shear strengths decreased as the thickness increased. Typically, shear strengths of specimens not subjected to vibration were the lowest of the three vibration levels. A 4-in. overlay on a smooth-wet surface and a 2-in. overlay on a rough-wet surface were the only exceptions. However, in both of these cases, the no vibration shear strengths did not exceed the highest recorded shear strength yielded by either the low or high vibration levels.

Specimens having pre-vibration cures of 4 and 12 hours, produced shear strengths which increased as the overlay thickness increased. In Figure 4.22 typical shear strengths obtained after 4 hours of pre-vibration cure are presented. At high vibration levels, shear strengths increased more significantly from a 2-in. overlay specimen to a 4-in. overlay specimen than the low level vibration shear strengths. The highest shear strength (300 psi) after a 4 hour pre-vibration cure was obtained on a rough-wet surface.

Specimens with a 12 hour pre-vibration cure, typically, yielded significantly higher shear strengths for both low and high vibration levels. Figure 4.23 shows the highest 12 hour pre-vibration cure shear strength (on a rough-dry surface) of 345 psi. Generally, when the specimens were not subjected to vibration, the lowest shear strengths were obtained (relative to other vibration levels). Specimens poured on smooth interfaces with 4 or 12 hours of pre-vibration cure resulted in shear strength variations between a 2-in. and 4-in. overlay which were larger than the variations of the rough interfaces.

4.3 Vertical Versus Horizontal Vibration Modes

Only the shear strengths at low and high vibration levels were compared. The shear strengths from the two vibrational modes were plotted together to determine which mode had more effect on the shear strengths under the different conditions studied. This may help to determine which

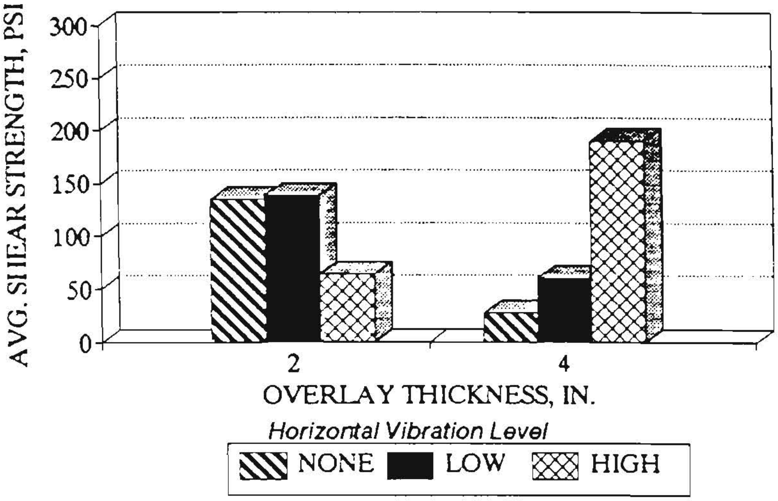

Figure 4.21 Comparison of Average Shear Strengths After 0 hrs. of Pre-Vibration Cure (Rough-Wet Interface) Under Horizontal Vibration Mode

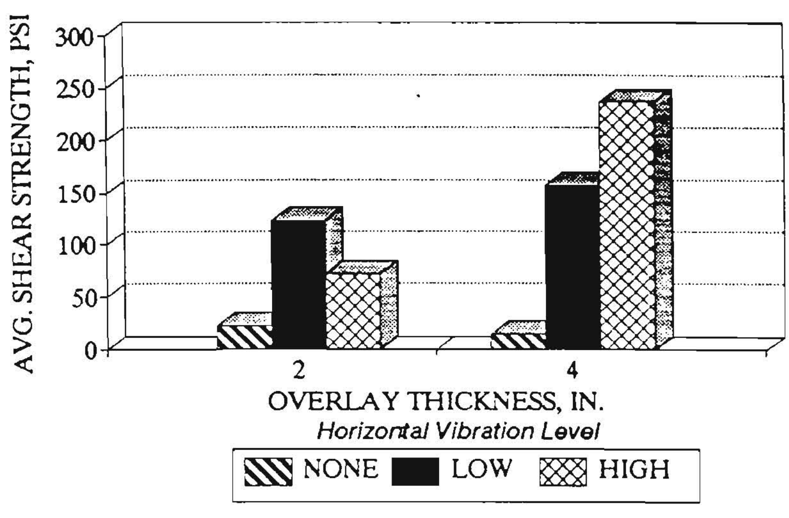

Figure 4.22 Comparison of Average Shear Strengths After 4 hrs. of Pre-Vibration Cure (Smooth-Dry Interface) Under Horizontal Vibration Mode

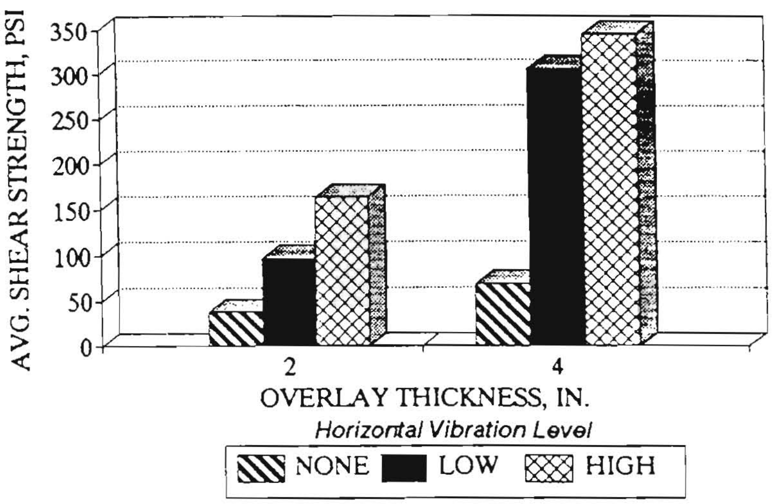

Figure 4.23 Comparison of Average Shear Strengths After 12 hrs. of Pre-Vibration Cure (Rough-Dry Interface) Under Horizontal Vibration Mode

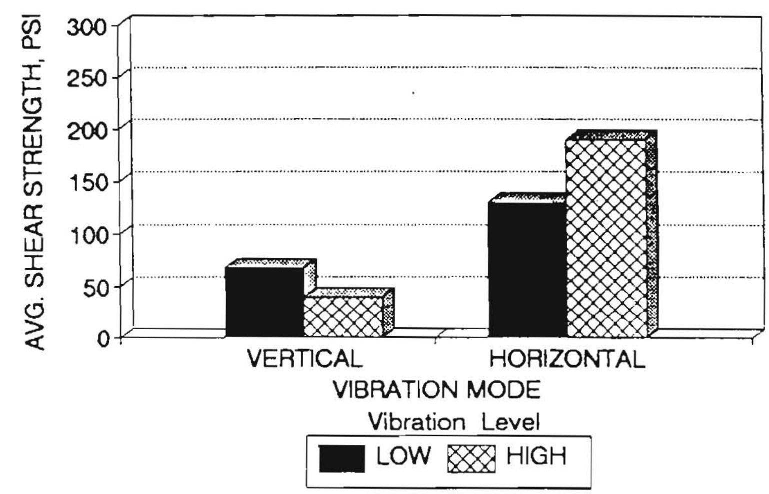

Figure 4.24 Comparison of Average Shear Strengths for a 2-in Overlay after 0 hrs. of Pre-Vibration Cure (Rough-Dry Interface) Under Vertical and Horizontal Vibration Modes

vibration mode is most detrimental to the delamination or debonding of a fresh concrete overlay.

Typically, specimens with a 2-in. overlay and a 0 hour pre-vibration cure time, yielded higher shear strengths under a horizontal vibration mode than under a vertical vibration mode. A smooth-wet surface was the only interface condition in which the vertical vibration mode resulted in slightly higher shear strengths than those of horizontal vibration mode. Figure 4.24 illustrates the large variation in shear strengths for vertical and horizontal modes on rough surfaces.

Specimens with 2-in. overlay and 4 hour pre-vibration cure time also yielded higher shear strengths in the horizontal vibration mode than in the vertical vibration mode. Again, a smooth-wet surface was the only interface condition at which vertical vibration levels yielded higher shear strengths. Figure 4.25 exemplifies the larger variation in the low level vibration shear strengths than the variation in the high level vibration shear strengths. This occurred on all interface conditions except the rough-wet surface.

The shear strengths obtained from specimens with a 2-in. overlay and subjected to 12 hours of pre-vibration cure time were different than those previously discussed. On smooth surfaces and low vibration levels, shear strengths were lower in the horizontal vibration mode than in the vertical mode. On the contrary, at high vibration levels, shear strengths remained similar. Figure 4.26 shows that on rough surfaces and low vibration levels, shear strengths were similar for the vertical and horizontal modes. Whereas, at high vibration levels, shear strengths decreased significantly from the vertical vibration mode to the horizontal mode, i.e. the shear strengths from vertical vibrations were approximately 2 times higher than the those of the horizontal vibrations.

The shear strengths for 4-in. overlays and 0 hour pre-vibration cure time were variable. On a smooth-dry surface (see Figure 4.27), shear strengths due to vertical vibration mode were slightly higher than the horizontal mode results. The opposite was true on the smooth-wet surfaces. At both low and high vibration levels, shear strengths were higher for the horizontal vibration mode, on the rough-dry interfaces, than for the vertical vibration mode. On the rough-wet surface and high vibration levels, shear strengths were similar for the vertical and horizontal vibration modes. At low vibration levels,
strengths were higher for the vertical mode than the horizontal mode.

Less variability in the shear strengths occurred for 4-in. overlay specimens with a 4 hour pre-vibration cure time. For all surface conditions, higher shear strengths were obtained in the horizontal vibration mode than the vertical mode. Figure 4.28 shows how, typically, at high vibration levels, shear strengths increased more than those of low vibration levels from the vertical vibration mode to the horizontal mode. All interface conditions with a 4 hour pre-vibration cure, except the rough-dry surface, yielded higher shear strengths with the high vibration levels than with the low vibration levels.

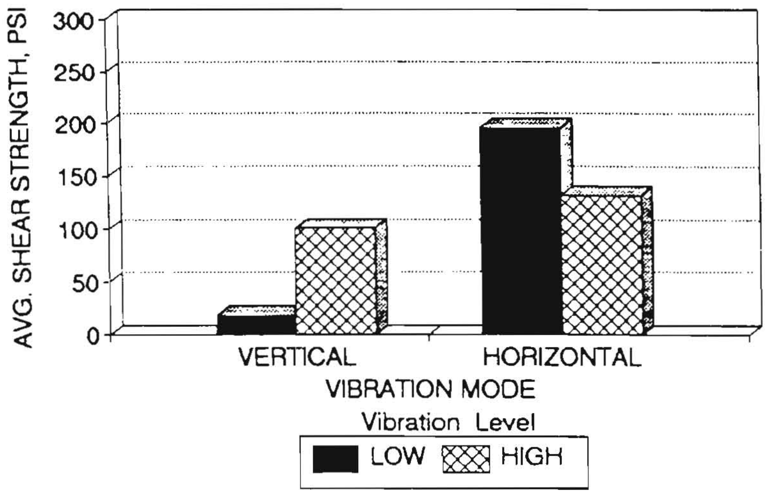

Figure 4.25 Comparison of Average Shear Strengths for a 2-in Overlay After 4 hrs. of Pre-Vibration Cure (Rough-Dry Interface) Under Vertical and Horizontal Vibration Modes

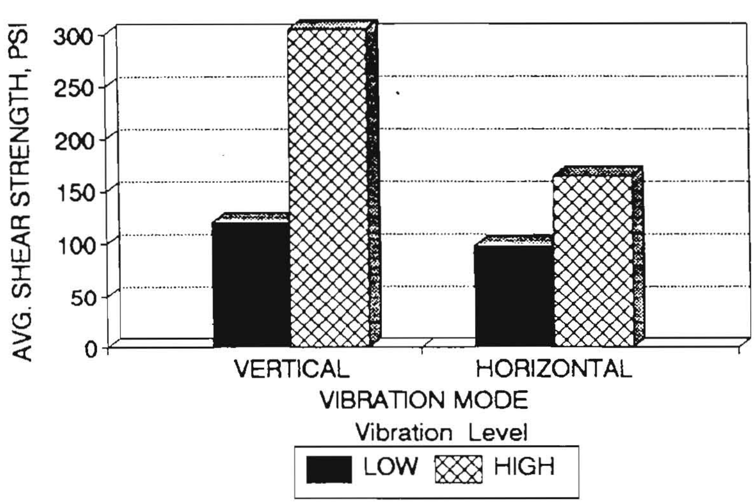

Figure 4.26 Comparison of Average Shear Strengths for a 2-in Overlay After 12 hrs. of Pre-Vibration Cure (Rough-Dry Interface) Under Vertical and Horizontal Vibration Modes

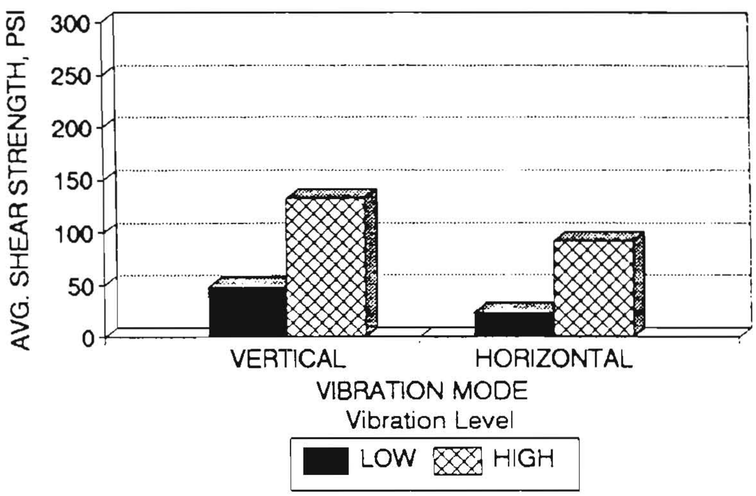

Figure 4.27 Comparison of Average Shear Strengths for a 4-in Overlay after 0 hrs. of Pre-Vibration Cure (Smooth-Dry Interface) Under Vertical and Horizontal Vibration Modes

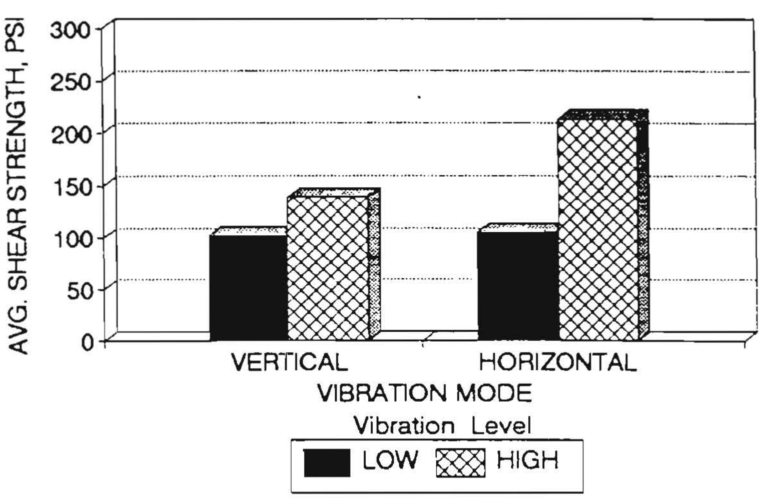

Figure 4.28 Comparison of Average Shear Strengths for a 4-in Overlay After 4 hrs. of Pre-Vibration Cure (Smooth-Wet Interface) Under Vertical and Horizontal Vibration Modes

Specimens with 4-in. overlay and 12 hour pre-vibration cure yielded higher shear strengths in the horizontal vibration mode than in the vertical mode (as with the 4 hour pre-vibration cure results). However, at low vibration levels, shear strengths were similar to, or higher than, those of high vibration levels as shown in Figure 4.29. Typically, the variation between the vertical and horizontal mode shear strengths were significant. The rough-wet interface was the only surface condition in which the shear strengths for both vibration modes were similar.

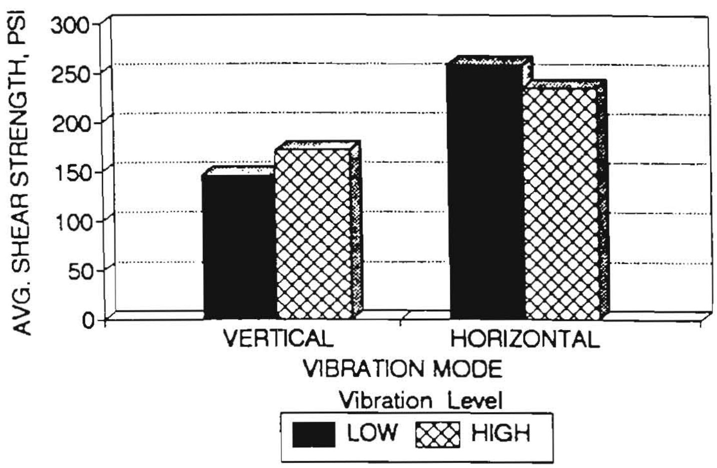

Figure 4.29 Comparison of Average Shear Strengths for a 4-in Overlay After 12 hrs. of Pre-Vibration Cure (Smooth-Dry Interface) Under Vertical and Horizontal Vibration Modes

CHAPTER 5

DISCUSSION OF RESULTS

5.1 Vertical Vibration Mode

5.1.1 Effects of Surface Conditions

In most cases, no specific pattern in shear strengths was established. That is, no one combination of surface conditions, e.g. smooth-wet or rough-dry, gave consistent low or high shear strengths.

The most variable test results were obtained for 2-in. and 4-in. overlays when no pre-vibration curing was permitted. The combined surface conditions and vibration levels did not produce consistent results. Therefore, a large variability existed between the shear strengths of a specific specimen conditions. For example, a rough-dry surface and a high vibration level did not produce the highest shear strengths for all overlay thickness and cure times.

This variability in the results for the 0 hour pre-vibration cure time may reflect what occurred on the IH-10 widening project as described in Chapter 2 and Appendix A. Although the surface condition (smooth-wet) was the same throughout the original placement of the concrete overlay, some areas of the overlay delaminated while other areas were intact or well-bonded. A 0 hour pre-vibration cure time condition existed in the field, i.e. the concrete overlay was placed and cured while traffic remained on the adjacent lanes and thus, the overlay was subjected to different vibration levels. With such a large variation and no specific combination of parameters combining to form consistent shear strength results, one can only guess and hope for a good bond to form.
For a thicker overlay (6-in.) and longer pre-vibration cure times (4 and 12 hours), less variation

in strength occurred between wet and dry surfaces. There was more consistency in the shear strengths but this seems to be caused by the increased overlay thickness and increased cure times not the wet or dry surface condition. These parameters will be fully discussed in the following sections.

5.1.2 Effects of Pre-Vibration Cure Time

The shear strengths of specimens with 2-in. and 4-in. overlays generally increased with an increase in cure time. The only exceptions to this finding, a 2-in. overlay on a smooth-wet surface at high vibration levels and a 4-in. overlay on rough-wet surface at high vibration levels, yielded minimal decrease in shear strengths.

The other significant finding was that specimens subjected to low or high vibration levels, applied after 4 or 12 hour pre-vibration cure, developed shear strengths which were greater than those specimens which were never subjected to vibration. However, in a few cases, specimens which were not vibrated produced slightly higher shear strengths than those subjected to high vibration levels. These exceptions occurred on specimens with a rough-wet surface of 2-in. overlay and on the smooth-wet surface of 4-in. overlay.

The specimens with a 6-in. overlay showed a similar pattern. An increase in the pre-vibration cure time resulted in an increase in shear strength. However, all three vibration levels produced similar results and the differences in shear strengths amongst specimens cured for 0, 4 and 12 hours before vibration were generally small.

Based on these results, an overlay which is allowed to cure for 12 hours and is then subjected to vibrations for 12 hours will produce the best shear strengths after a 24 hour period. The average shear strength which can be expected is approximately 150 psi.

When dealing with a 2-in. overlay thickness, cured for 12 hours before vibration, the highest shear strengths appear to occur on a roughened surface. As the overlay thickness increased, the condition of the surface seemed to become less of a factor in the outcome of the shear strengths. With a 6-in. overlay, the cure time also became less of a factor in determining the shear strengths obtained.

5.1.3 Effects of Overlay Thickness

The results presented in Appendix E illustrate the sole effect of increase in the overlay thickness. The combination of cure time and overlay thickness seemed to determine the outcome of the shear strengths. A definite increase in shear strength occurred with an increase in overlay thickness, especially with 0 hour pre-vibration cure time. Again, as the pre-vibration cure time increased, the differences in shear strengths for 4-in. and 6-in. overlay thicknesses decrease. The specimens with 2-in. overlays tended to obtain high shear strengths with a 12 hour pre-vibration cure time when poured on a rough surface (wet and dry) and at high vibration levels.

5.2 Horizontal Vibration Mode

5.2.1 Effects of Surface Conditions

A more consistent pattern in shear strengths was found for horizontal vibration mode (compared to the vertical vibration mode). Specimens with 2-in. overlays at any pre-vibration cure time were found to have higher shear strengths on a rough-dry surface. Specimens with 4-in overlays at 0 hour pre-vibration cure time on a rough (dry or wet) yielded higher shear strengths than on the smooth surface. Shear strengths of specimens with 4-in. overlays with 4 and 12 hours of pre-vibration curing were less affected by the surface condition whether rough or smooth and wet or dry. For both specimens with 2-in. and 4-in. overlays, low or high vibration levels generally produced better or equal shear strengths to those specimens which were never subjected to vibration. This finding is similar to that observed for a vertical vibration mode.

In general, test results from the horizontal vibration mode seemed to produce more consistent shear strengths, especially for specimens with 2-in. and 4-in. overlay at 0 hour pre-vibration cure time.

5.2.2 Effects of Pre-Vibration Cure Time

The pre-vibration cure times studied in the horizontal vibration mode affected the shear strengths in a different manner (when compared with those of the vertical vibration mode). For all surface conditions, the specimens with a 2-in. overlay yielded similar shear strengths at low and high vibration levels, irrespective of the pre-vibration cure time. In most cases, the shear strengths of specimens with a 4-in. overlay increased slightly as the pre-vibration cure time increased. However, the results of specimens on a smooth-dry surface yielded large differences between the 0 hour pre-vibration cure shear strength and the 4 hour pre-vibration cure shear strength.

Overall, the horizontal vibration mode had a significantly less effect on shear strengths obtained at different pre-vibration cure times than the vertical vibration mode. These results may indicate that the horizontal vibration mode associated with bridges is of less concern than the vertical vibrations created by traffic.

5.2.3 Effects of Overlay Thickness

As in the case of the vertical vibration mode, the shear strengths for a 0 hour pre-vibration cure time were not very consistent. The effects of overlay thickness were very hard to determine when the specimens were subjected to vibration immediately after the samples are prepared, i.e. 0 hour pre-vibration cure. For no pre-vibration cure time, the thickness of the overlay did not control the shear strength.

More consistency was found in the results when specimens were cured 4 or 12 hours before being subjected to vibrations. The thicker overlays (4-in.) resulted in higher shear strengths. For specimens with 4-in. overlays, the shear strength improved when the overlay was placed on a roughened surface and subjected to high vibration levels.

The specimens with 2-in. overlays produced lower shear strengths on smooth surfaces, regardless of the vibration level when compared to the results from the 4-in. overlays. This indicates that, for thin overlays, shear strength can be improved if placed on a roughened surface. The thicker overlays were less affected by the surface condition. After 4 and 12 hour pre-vibration cures, the highest shear strengths were obtained on rough interfaces.

5.3 Vertical Versus Horizontal Vibration Modes

The 2-in. overlays after 0 and 4 hour pre-vibration cure resulted in shear strengths which were generally higher in the horizontal vibration mode than the vertical vibration mode. The high vibration level shear strengths on a smooth-wet surface with a 0 and 4 hour pre-vibration cure were the only exceptions. This indicates that the shear strength of an overlay poured on a smooth-wet interface, combined with a short pre-vibration cure time, was affected more by a horizontal vibration mode. The variations between the shear strengths obtained with vertical and horizontal vibration modes, generally, increased on rough surfaces. Therefore, a roughened surface is less affected by horizontal vibration modes.

When a 2-in. overlay was allowed a pre-vibration cure of 12 hours, the shear strengths in the vertical vibration mode were higher than those in the horizontal vibration mode. The largest variation in shear strengths for the two vibration modes occurred when the overlay specimens were poured on rough interfaces and subjected to high levels of vibration. The shear strengths obtained under horizontal vibration modes were similar for low and high vibration levels after 4 and 12 hour pre-vibration cure periods. Therefore, the shear strengths were not affected by pre-vibration cure time under horizontal vibration modes. Due to vertical vibrations, shear strengths increased significantly from 4 to 12 hour pre-vibration cures. Therefore, when a 2-in. overlay was allowed a 12 hour pre-vibration cure, the vertical vibration movement actually improved the shear strengths on a rough surface creating a much better bond.

On a smooth-wet and rough-dry interface, a 4-in. overlay with a 0 hour pre-vibration cure, the shear strengths were higher for a horizontal vibration mode than for a vertical mode. The other two surfaces (smooth-dry and rough-wet) resulted in high shear strengths under a vertical vibration mode than a horizontal mode. This variation in results can possibly be attributed to the 0 hour pre-vibration cure time as previously discussed.

Shear strengths obtained on all surface conditions for 4-in. overlays after a 4 and 12 hour pre-vibration cure were higher with a horizontal vibration mode than the vertical mode. Again, this indicates that a vertical vibration mode affects the shear strengths more than a horizontal vibration mode. Typically, the high vibration levels produced higher shear strengths than the low vibration levels. Therefore, subjecting an overlay to high amplitudes of vibration after a pre-vibration cure period, improves the shear strengths. This increase in strength may be caused through a reconsolidation process of the concrete as was suggested by Manning (1981).

5.4 General Discussion

The variables which affected the concrete overlays varied from one overlay thickness to another. The thinnest overlay studied (2-in.) was affected by more variables than the 4-in. or 6-in. overlays. A rough surface texture generally produced higher shear strengths than a smooth surface. Kailasananthan (1984) also found that "milled or scarified surfaces" (rough) produced a better bond than a surface without "any special treatment". A conclusive determination of whether a wet or dry surface produced higher shear strengths was difficult to ascertain. The highest shear strengths obtained varied from one surface wetness condition to another.

The pre-vibration cure time definitely had an affect on the shear strengths of the overlay specimens. The longer the concrete overlay was allowed to cure before being subjected to vibration, the less variable and the higher the shear strengths were obtained. At a 0 hour pre-vibration cure time, a large variability occurred in the shear strengths. In some cases, when a 2-in. overlay was cured for 12 hours prior to vibration, shear strengths of 200 psi and higher were obtained.

Typically, a high vibration level produced higher shear strengths than low vibration levels. Much higher shear strengths were yielded by high vibration levels than no vibration (i.e. control specimens). This agrees with results obtained by Manning (1981). Manning stated that cylinders subjected to vibrations during curing had considerably higher strengths than control cylinders. However, at a 12 hour pre-vibration cure time, the variation between no, low and high vibration levels decreased. Also, a vertical vibration mode, generally, produced lower shear strengths than a horizontal vibration mode.

The 4-in. overlays were not as affected by surface conditions as the 2-in. overlays. However, the highest shear strengths obtained were usually on rough interfaces. As previously stated, shear strengths of a dry surface were not found to be consistently higher or lower than shear strengths of a wet surface. As the pre-vibration cure time increased, results were less variable and higher shear strengths were yielded. High level vibration introduced to the concrete overlay specimens after a pre-vibration cure period, increased the shear strengths more than the introduction of low level vibration. No vibration (or control specimen) usually produced the lowest shear strengths. Similar to the 2-in. overlay, the variation between the no, low and high vibration level shear strengths decreased at a 12 hour pre-vibration cure. Generally, shear strengths yielded by vertical vibration modes were less than shear strengths obtained by horizontal vibration modes.

The thickness of the concrete overlay significantly affected the shear strengths. The thicker overlays produced higher shear strengths, especially after a 0 and 4 hour pre-vibration cure. Consequently, an overlay of 6 inches produced the least amount of variability in shear strengths, regardless of pre-vibration cure time, surface condition or vibration level.

Based on shear strengths variability only, a 6-in. overlay would be an ideal thickness to use. However, the use of a 6-in. concrete overlay on a bridge is very uncommon. This amount of overlay would produce a larger dead load than a typical 2-in. or 4-in. overlay. If a 4-in. overlay were used, the highest shear strengths could be expected, and the least amount of variation in the shear strengths would occur, if the overlay were allowed to cure for 12 hours before being subjected to the vibrations of traffic on adjacent lanes. If a 2-in. overlay were used, higher shear strengths could be expected if the bridge surface were roughened (during the casting process or scarified prior to the overlay placement) and the concrete overlay were allowed to cure for 12 hours before being subjected to traffic vibrations. If it were physically impossible to reroute traffic, allowing for a 12 hour pre-vibration cure period, then a structural analysis could be performed to determine the effects of placing a 6-in. overlay on the structure. A cost analysis could also be performed to obtain a monetary comparison between placing a 6-in. concrete overlay and building or finding a detour route.

CHAPTER 6

CLOSURE

6.1 Summary

Thin-bonded concrete overlays have been used by the Texas Department of Transportation for many years. These overlays have been used for different applications. Many existing pavement sections have been overlaid with concrete for rehabilitation purposes. Concrete overlays are also used on structures to provide for a durable riding surface. Several research projects have been conducted to determine the best construction process for concrete overlays on different types of pavements. However, little research has been conducted on concrete overlays placed on structures.

During the widening of Interstate 10, in El Paso, Texas, the thin-bonded concrete overlays began to show signs of distress only 8 months after their placement. The overlays had delaminated and debonded to an extent which required replacement. These concrete overlays were placed on new structures which were constructed in phases. This construction phasing subjected the thin-bonded overlays to the vehicular vibrations from the adjacent lanes during the placement and curing of the concrete overlay. These vibrations were suspected as being partially responsible for causing the concrete overlays to delaminate and debond after an investigation of all construction records was conducted.

This research project was conducted in order to determine the effects of vehicular vibration on debonding and delamination of concrete overlay. Several other parameters involved in concrete overlays were investigated. The effects of the overlay thickness, pre-vibration cure time, surface wetness, surface texture, amplitude of vibration and vibration mode were studied. A laboratory experiment involving small concrete cylinder specimens was developed. Several tests were conducted on these specimens. The results were recorded and then analyzed to determine the parameters which affected the shear strength of the concrete overlays the most and to determine under which conditions the best shear strength results were obtained.

The results of this study indicate that the thickness of the concrete overlay determines which parameters influence the shear strengths. As the thickness of the overlay was increased, higher shear strengths were generally obtained. Some of the parameters have similar affects on a 2-in., 4-in. and 6-in. overlay.

A 2-in. overlay is affected by the surface texture, pre-vibration cure time, and amplitude of vibration. A rough surface results in higher shear strengths than a smooth surface. The wetness of the surface did not produce consistent results i.e. a dry surface did not always produce higher shear strengths than a wet surface. The cure time controls the variability in the results. A 0 hour pre-vibration cure time gave inconsistent results whereas, a 4 and 12 hour pre-vibration cure gave fairly consistent shear strengths. The shear strengths increased as the cure time increased. A high level of vibration (high amplitude) usually resulted in the highest shear strengths especially after the specimens were allowed a pre-vibration cure of 4 or 12 hours. An overlay which was never subjected to vibrations (control specimen) generally gave the lowest shear strengths. A vertical vibration mode resulted in lower shear strengths than a horizontal vibration mode.

A 4-in. overlay was not as affected by the surface texture as the 2-in. overlay but the highest shear strengths were obtained on a rough surface. The surface wetness did not appear to significantly affect the shear strengths. Variable results were obtained when the specimens were vibrated immediately after pouring the overlay. The shear strengths became more consistent and higher strengths were obtained as the pre-vibration cure time increased. As with the 2-in. overlay, a high amplitude usually produced the largest shear strengths and no vibration gave the lowest results. The high amplitude vibration significantly increased the shear strengths after the overlays were cured for 4 or 12 hours prior to vibration. A vertical vibration mode generally resulted in lower shear strengths than a horizontal vibration mode.

The 6-in. overlay shear strengths were not significantly affected by surface texture, surface wetness, pre-vibration cure time, or vibration amplitude. The shear strengths obtained were fairly similar. That is, compared to the other two overlay thickness studied, the variability in the strengths was relatively small. A horizontal vibration mode test was not performed on a 6-in. overlay. However, because of the small variations caused by the other parameters, a change in the vibration direction would probably not affect the shear strength results either.

Large variation in the shear strengths of the concrete overlays were obtained in many cases. However, when working with concrete, large variations in the test results can be expected especially when the concrete is relatively "green" (fresh).

6.2 Conclusions

The following conclusions can be drawn from the series of tests which were performed. The conclusions listed below apply to both the vertical and horizontal vibration mode results unless otherwise stated.

Typically, the shear strengths of the concrete overlays increased with an increase in overlay thickness. However, the shear strengths of the overlay specimens subjected to a horizontal vibration mode produced variable results for 2-in. and 4-in. overlays after a 0 hour pre-vibration cure. That is, the shear strengths for the 4-in. overlays were not consistently higher than the shear strengths of the 2-in. overlays. Each overlay thickness was affected by different parameters. These parameters will be discussed in the following paragraphs. Typically, the shear strengths of the 2-in. and 4-in. overlays were lower for a vertical vibration mode than for a horizontal vibration mode.

A specimen with a 2-in. overlay produced higher shear strengths on a roughened surface than on a smooth interface. The wetness condition of the surface did not produce consistent results i.e. a dry surface did not always yield higher shear strengths than a wet surface or visa versa. Variable shear strengths were obtained with a 0 hour pre-vibration cure. However, the shear strengths increased and became less variable with an increase in pre-vibration cure time. A high amplitude vibration generally produced the highest shear strengths especially as the pre-vibration cure time increased. Generally, the control specimens, i.e. no vibration, yielded the lowest shear strengths. In the few cases where no vibration produced the highest shear strengths, the second highest shear strength (whether yielded by a low or high vibration level) was relatively similar.

A 4-in. overlay was not as affected by the surface texture or surface wetness as a 2-in. overlay. Although, the highest shear strengths were obtained on a roughened surface. The shear strengths increased and became less variable with an increase in pre-vibration cure time. A high amplitude vibration usually gave the highest shear strengths especially when applied after a pre-vibration cure period.

The shear strengths of a 6-in. overlay were not affected significantly by surface texture, surface wetness, pre-vibration cure time or vibration amplitude. The shear strengths obtained under all conditions were relatively close i.e. less variability in the shear strengths yielded than for the results of a 2-in. or 4-in. overlay.

6.3 Recommendations for Future Work

The concrete overlay parameters studied in this research report should be applied to larger laboratory specimens. Typical laboratory beam size specimens should examined under the same variables used for the concrete core samples. The results of the beam samples should then be compared to this report's results. The conditions which are found to be the most important i.e. most critical, should then be studied in larger pavement sections under direct field conditions. The most favorable condition(s) which a concrete overlay would develop a sufficient bond strength and therefore, not be susceptible to delamination or debonding should be determined.

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