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16. Abstract

This report presents the results from the third phase of a study dealing with the effects of vehicular vibrations on the interface bonding of thin concrete overlays on bridge decks. In this phase of the project, beams 90-cm long, 15-cm wide and 5-cm thick reinforced with 6.5-mm-diameter bars placed 5-cm apart were used. A 5-cm-thick or a 10-cm-thick overlay was placed on top of a base concrete. The specimens were tested by one-point line load flexural testing. The parameters investigated were surface condition, surface texture, pre-vibration cure time, overlay thickness, and vibration amplitude. These parameters were combined in different sequences to study their effects on the interface bonding of concrete overlays. Some recommendations are included so that the best bond strength can be obtain during construction.

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INTERFACE BONDING OF THIN CONCRETE OVERLAYS DUE TO VEHICULAR VIBRATION

by

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Research Project 1920

EFFECTS 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 1920-3F
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NOT INTENDED FOR CONSTRUCTION, BIDDING, OR PERMIT PURPOSES

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IMPLEMENTATION STATEMENT

In this report some recommendations have been made which may be utilized during construction to maximize the bond strength of thin-bonded overlays. These recommendations may be implemented to determine if they are applicable to larger scale bridges.

ABSTRACT

This report presents the results from the third phase of a study dealing with the effects of vehicular vibrations on the interface bonding of thin concrete overlays on bridge decks. In this phase of the project, beams 90-cm long, 15-cm wide and 5-cm thick reinforced with 6.5-mm-diameter bars placed 5-cm apart were used. A 5-cm-thick or a 10-cm-thick overlay was placed on top of a base concrete. The specimens were tested by one-point line load flexural testing. The parameters investigated were surface condition, surface texture, pre-vibration cure time, overlay thickness, and vibration amplitude. These parameters were combined in different sequences to study their effects on the interface bonding of concrete overlays.

Some general conclusions were drawn from the tests performed. Dry interfaces performed better for control specimens and those specimens that were subjected to low levels of vibration. For thinner overlays, the surface texture did not affect the bond strength. For thicker overlays rough interfaces yielded higher values of bond strength. For smooth surfaces increase in pre-vibration cure time increased the bond strength. For rough interfaces the pre-vibration cure time had a small effect on the bond strength. Generally, the no vibration cases yielded the highest bond strengths. Typically, thinner overlays were more effective (bond strengths were closer to the shear stress at failure) in the interface bonding. An increase in pre-vibration cure time increased the bond effectiveness for thinner overlays. For the 10-cm-thick overlays, the static condition and a rough texture resulted in the highest effectiveness.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Figure	Description	Page

Figure	Description	Page

CHAPTER ONE

INTRODUCTION

Problem Statement

This report contains the results from the third phase of a study dealing with the effects of vehicular vibration on the interface bonding of thin concrete overlays on bridge decks. The first phase of this investigation, which was conducted by Rodriguez-Gomez and Nazarian (1992), consisted of testing small concrete cylinder specimens. These specimens were 10 cm in diameter and were subjected to pure vertical and horizontal modes of vibration. The guillotine direct shear test was used to find the shear strength at the interface of the base and the overlay. The parameters investigated were surface condition, surface texture, pre-vibration cure time, overlay thickness and vibration amplitude. These parameters were combined in different sequences and their effects on the interface bonding of concrete overlays were reported.

In the second phase of this study, a more realistic mode of vibration, bending mode, was used. The effects of the important parameters reported by Rodriguez-Gomez and Nazarian (1992), on the interface bonding of larger specimens were studied. In that stage, the specimens were 90-cm long, 15-cm wide, and 5-cm thick. A 5-cm-thick or 10-cm-thick overlay was placed on top of a base concrete. The specimens were subjected to a line load such that flexural failure would occur. Testing was conducted for three different spans, 75 cm , 30 cm and 15 cm. All failures were reported to occur in excess tensile stresses at the bottom fibre of the beam.

In this phase of the project beams 90-cm long, 15-cm wide, and 5-cm thick were also used. However, these beams were reinforced with 6.5-mm-diameter bars placed 5 cm apart. The specimens were tested by one-point line load flexural testing very similar to Phase II study. The parameters studied were the same as those studied by Rodriguez-Gomez and Nazarian (1992) and Makahaube et al (1993).

Scope of Work

The main objective of this research was to determine the influence of reinforcement combined with the parameters reported by Rodriguez-Gomez and Nazarian (1992), and Makahaube et al (1993) on debonding and delamination of concrete overlays. These parameters were overlay thickness, pre-vibration cure time, surface wetness, surface texture and amplitude of vibration.

A direct comparison of the bond strength obtained from this study with those from the previous investigations conducted by Rodriguez-Gomez and Nazarian (1992) and Makahaube et al (1993) is not possible because each method used has its own limitations (see Chapter Three). However, based upon the relative changes in the bond strengths from all three tests, the variations in the bond strengths are assumed to be valid. Practical recommendations based on the results of this study are also included in this report.

Organization

This report consists of six chapters. Chapter Two discusses the summary of the previous work and the background information related to this research. The testing methodology including the testing matrix and the specimen preparation for this and previous work is discussed in Chapter Three. The presentation of the results is discussed in Chapter Four. Chapter Five contains summary conclusions and recommendations based on the results of this study.

CHAPTER TWO

BACKGROUND

Introduction

During the widening of Interstate Highway 10, in El Paso, Texas, the thin-bonded concrete overlays placed on the bridge decks began to show signs of distress only eight months after their placement. The overlays had delaminated and debonded to an extent that required replacement. The case study is well-described in Rodriguez-Gomez and Nazarian (1992). The concrete overlays were placed on new structures which were constructed in phases. The overlay for the first phase (outside lanes), which was placed during the summer of 1987, was on the average 9-cm thick. Phase II (inside lanes) were constructed during spring of 1988. This construction phasing subjected the thin-bonded overlays constructed during the second phase to the vehicular vibrations from the adjacent lanes during the placement and curing of the concrete overlay. An extensive investigation by the TxDOT personnel could not relate the problem to any of the traditional reasons (e.g. poor-quality concrete, excessive thermal gradient, surface preparation) for the failure of an overlay. The only parameter not considered was the vehicular vibration.

To study the effects of vehicular vibration on debonding and delamination of thin-bonded overlays a study was initiated by Rodriguez-Gomez and Nazarian (1992) and then expanded by

Makahaube et al (1993). Several parameters such as overlay thickness, pre-vibration cure time, surface texture and amplitude of vibration were studied. The results were recorded and analyzed to determine the parameters which affected the shear strengths at the interface of the base and overlay layers. These two studies are summarized below.

Results from Phase I Study

As reported by Rodriguez-Gomez and Nazarian (1992), specimens 10-cm in diameter were tested to determine their bond strengths under different interface conditions, subjected to different vibration levels. Two modes of vibration, vertical and horizontal, were studied. In each mode of vibration, the effects of surface condition, pre-vibration cure time, and overlay thickness were experimentally investigated. The procedures followed and the conclusions are summarized below.

Test Procedures

To obtain the base specimens, a 2.5 m x 2.5 m x 20 cm slab was poured and allowed to cure for 28 days. A concrete coring machine was then used to obtain the base specimens for all experiments.

To perform the tests, the base specimens were adhered to steel plates with a two-component epoxy. The base plates could then be placed on a platform which was securely attached to a shaker (see Figure 2.1).

Small amounts of the overlay concrete were prepared daily. Two similar specimens (i.e. with same surface texture, overlay thickness, and cure time, etc) were simultaneously prepared. A piece of 10-cm-diameter PVC pipe was placed over the entire base concrete core specimen which had been previously placed on the steel plate. The concrete representing the overlay was placed in the PVC forms. The two freshly-poured specimens would be left undisturbed and then placed on the vibrator and subjected to a specified vibration amplitude.

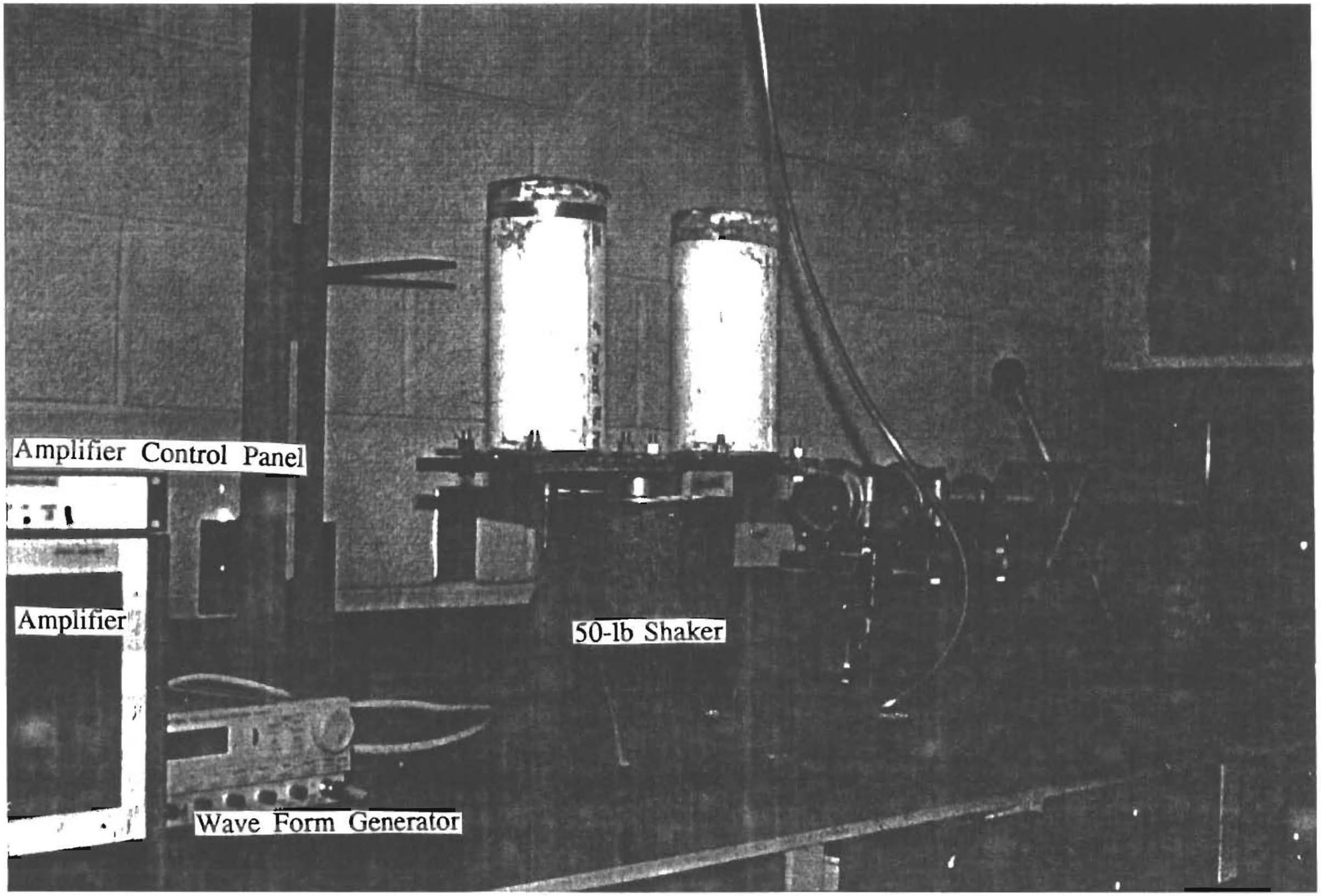


Figure 2.1 Small Concrete Specimens Being Subjected to Vibration

To apply vibration, a 50-lb shaker was used (see Figure 2.1). The amplitude of the vibrator was set by an amplifier control panel, while the frequency amplitude function was controlled with a function generator (see Rodriguez-Gomez and Nazarian, 1992 for more detail).

At the end of the 24-hour period, the specimens were tested. As shown in Figure 2.2, a guillotine direct shear device was used to determine the shear strength at the interface of the base concrete and the overlay. A load was applied to the guillotine, at a constant rate, until the overlay concrete was sheared. The load at which the base concrete and the overlay separated, P, was recorded and the shear strength, τ, calculated as:

$$\tau = P/A \tag{2.1}$$

where A is the cross sectional area of the specimen.

Conclusions

Typically the bond strengths of the concrete overlays increased with an increase in the overlay thickness. The bond strengths of the overlay specimens subjected to horizontal vibration mode produced variable results for 5-cm-thick and 10-cm-thick overlays after a 0 hour pre-vibration cure time. That is, the bond strengths for the 10-cm-thick overlays were not consistently higher than the bond strengths of the 5-cm-thick overlays. Typically, the bond strengths of the 5-cm-thick and 10-cm-thick overlays were lower for vertical vibration mode than for horizontal vibration mode.

A specimen with a 5-cm-thick overlay produced higher bond strengths on a roughened surface than on a smooth interface. The moisture at the interface did not produce consistent results. A dry surface did not always yield higher shear strengths than a wet surface or vice versa. Bond strengths considerably varied for specimens subjected to 0 hour pre-vibration cure time. However, the bond strengths increased and became less dependent on other variables with an increase in pre-vibration cure time.

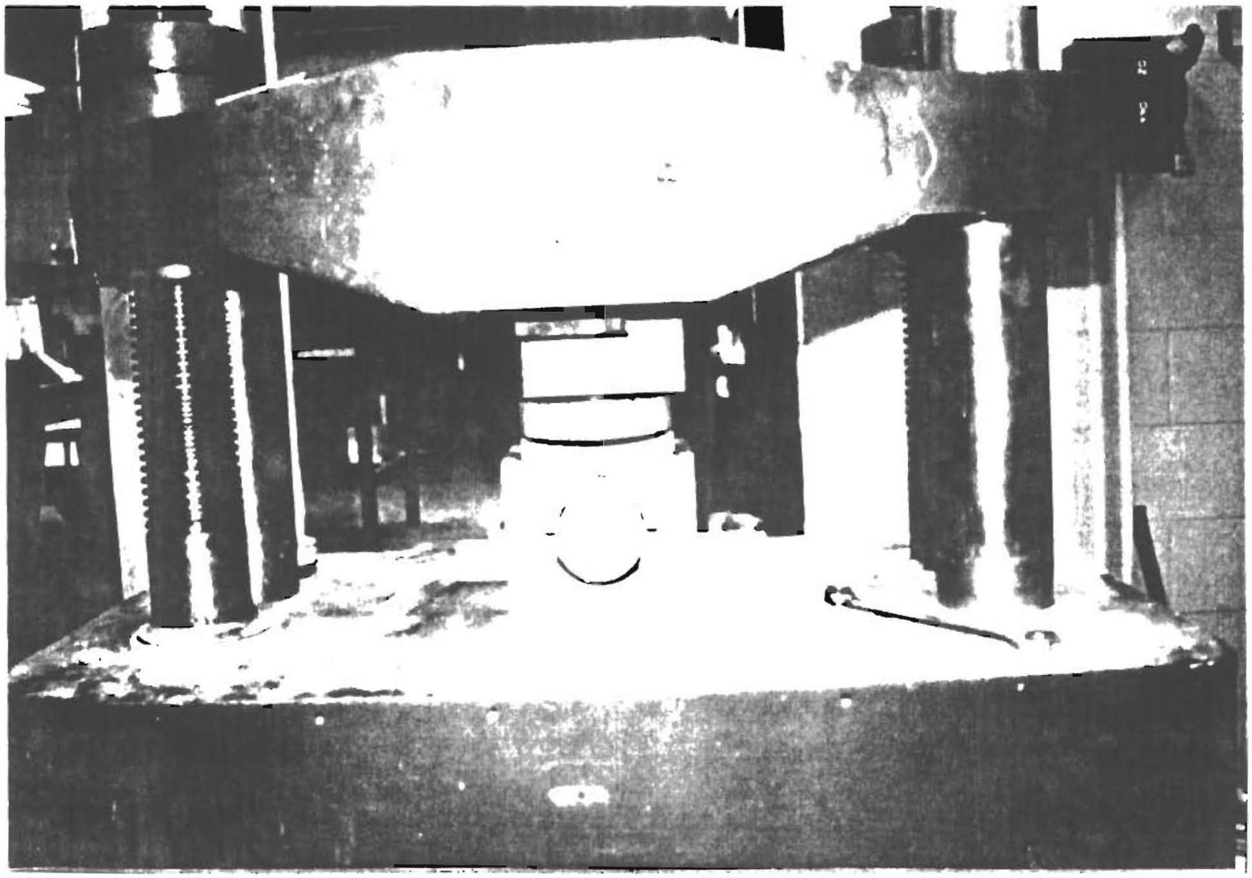


Figure 2.2 Specimen Subjected to Guillotine Direct Shear Test

High-amplitude vibration levels generally produced the highest shear strengths especially as the pre-vibration cure time increased. Generally, the control specimens, i.e. those not subjected to vibration, yielded the lowest shear strengths.

The interface bond of a 10-cm-thick overlay was not as affected by the surface texture or surface wetness as that of a 5-cm-thick overlay. Although the highest bond strengths were obtained on a roughened surface, the bond strength increased and became less variable with an increase in pre-vibration cure time.

The bond strength of a 15-cm-thick overlay was not significantly affected by the surface texture, surface wetness, cure time or vibration amplitude. The bond strengths obtained under different conditions studied were relatively similar.

One of the shortcomings of the guillotine shear device is that the specimen may experience some tensile forces at the interface on top of the shear forces. Practically speaking, this means that the overlay may "peel off" (as opposed to "shear off") the base concrete. As a result of this action, the bond strength measured with this test method may be lower than expected. However, since all specimens were tested following the same procedure, the relative relationships were assumed to be valid.

Results from Phase II Study

In the second phase of this study conducted by Makahaube et al (1993) a more realistic mode of vibration and larger specimens were used to determine the interface bond. These specimens were 90-cm long, 15-cm wide, and 5-cm thick. The parameters identified by Rodriguez-Gomez and Nazarian were used in that testing program as well. A 5-cm-thick or 10-cm-thick overlay was placed on top of the base concrete. The specimens were then tested by one-point line load flexural testing conducted in three different spans. These spans were 75 cm, 30 cm, and 15 cm. The procedures followed and the conclusions are summarized below.

Procedures

The base specimens, 90-cm (length) x 15-cm (width) x 5-cm (height), were poured on a piece of plywood retrofitted with appropriate dividers. Specimens were cured for 28 days, after which the beams were separated from the mold and stored.

To prepare for testing, a base beam was placed on a platform before pouring the overlay (see Figure 2.3). The overlay was placed on the top of the base beam and consolidated with a tamping rod. For wet conditions, water was applied to the beam surface before pouring the overlays. For the dry conditions, the base specimen was inspected to ensure that the surface was moisture free. The finishing process was done with a wooden float. The overlay was allowed to cure for 0 hour, 4 hours or 12 hours before being subjected to vibration.

The platform used was built in two parts. The steel frame held the base beam and the plexi-glass which was attached to the frames edges with bolts. The steel frame was then connected to the shaker (see Figure 2.4). The plexi-glass, which was used to hold the fresh concrete in place, was supported by five large bolts at both ends of the steel frame and was marked longitudinally at a point 10 cm from the bottom of the steel frame in order to mark the limits for a 5-cm-thick overlay. The 10-cm-thick overlay was constructed by placing concrete into the plexi-glass. A large C-clamp was placed in the middle of the span for extra support of the plexi-glass. This platform and its detail are shown in Makahaube et al (1993).

As shown in Figure 2.5, a 9-kN shaker and its accessories built by Ling Electronics were used in this study. A 27-kN tension/compression testing machine made by Forney was used to break the specimens (see Figure 2.6).

All specimens were tested by one point line load until they reached their flexural strength. Each specimen was first tested with a 75-cm span. During testing, the load was applied with a constant speed until the beam failed. The load at failure was recorded. A portion of failed specimen was then tested for 30-cm and 15-cm spans, respectively. Given the fact that none of the specimens failed in shear at the interface, it was decided to utilize the shear stress at tensile failure as a measure of minimum bond at the interface of the overlay and the base concrete.

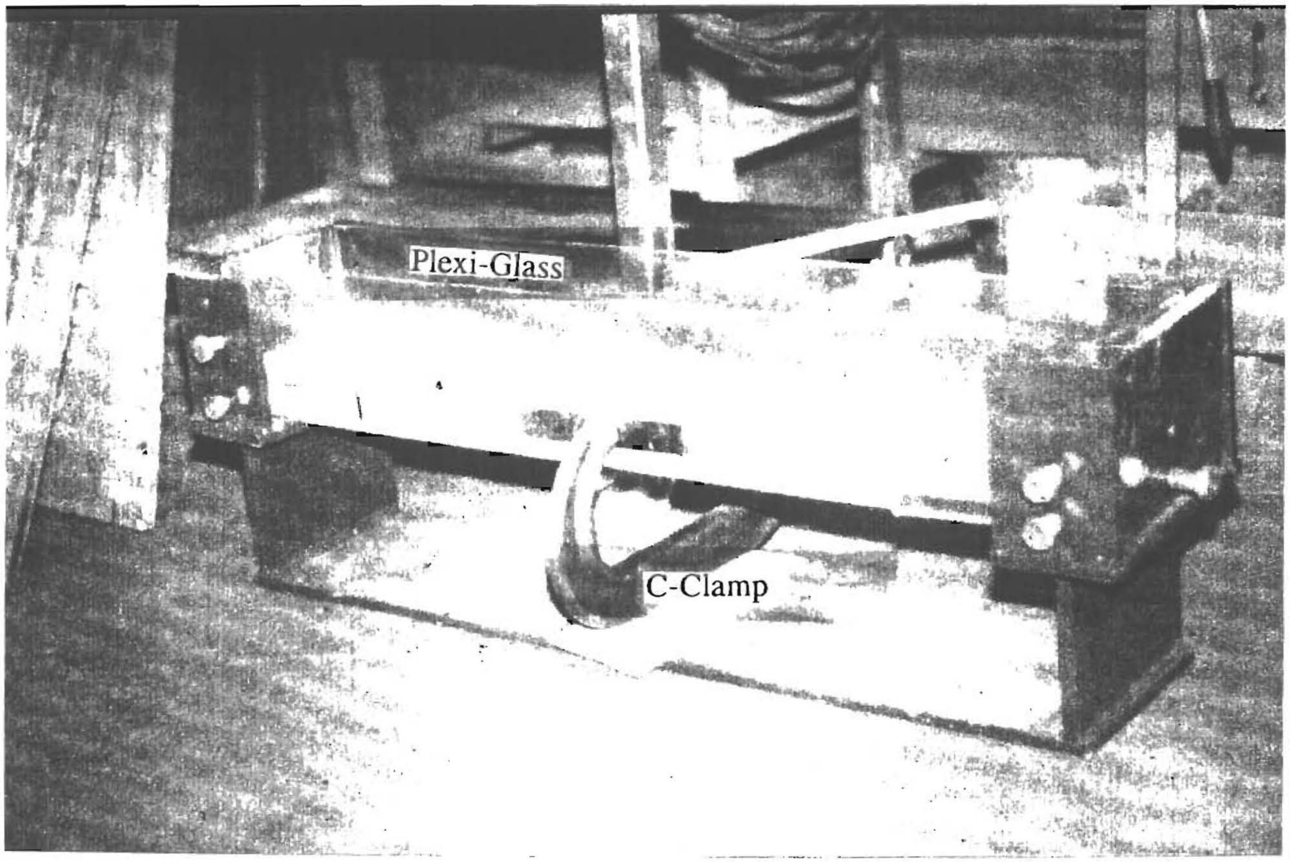


Figure 2.3 Platform Used to Place Large Specimens on 9-kN Shaker

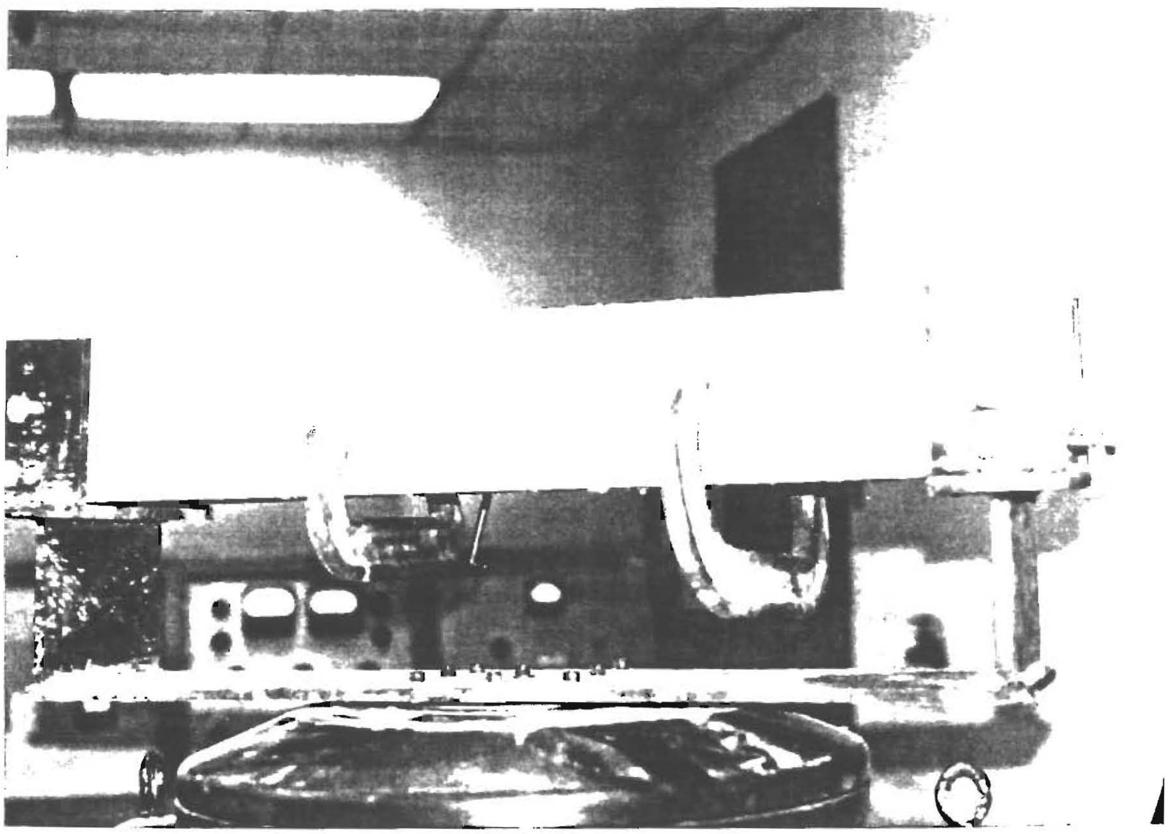


Figure 2.4 Large Specimens Being Subjected to Vibration

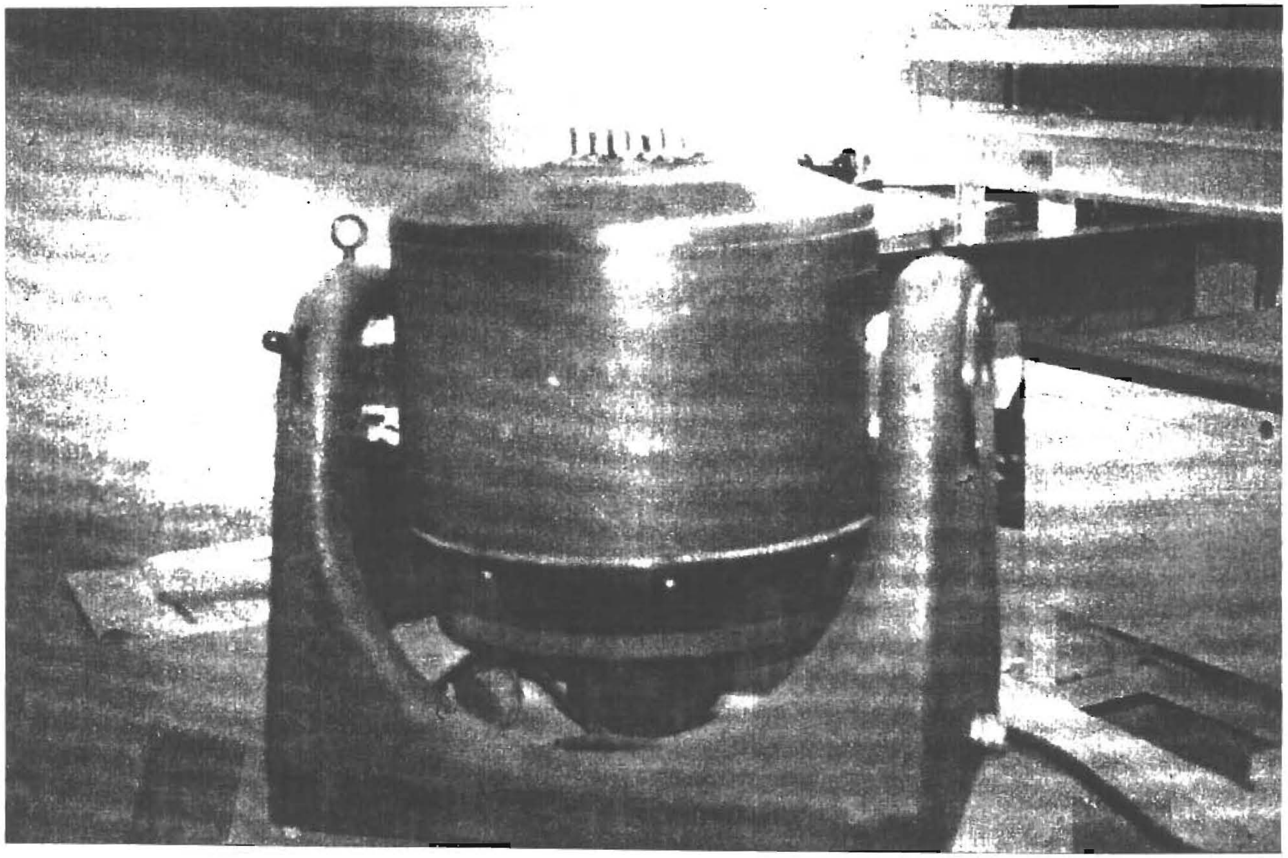


Figure 2.5 9-kN Shaker Used in This Study

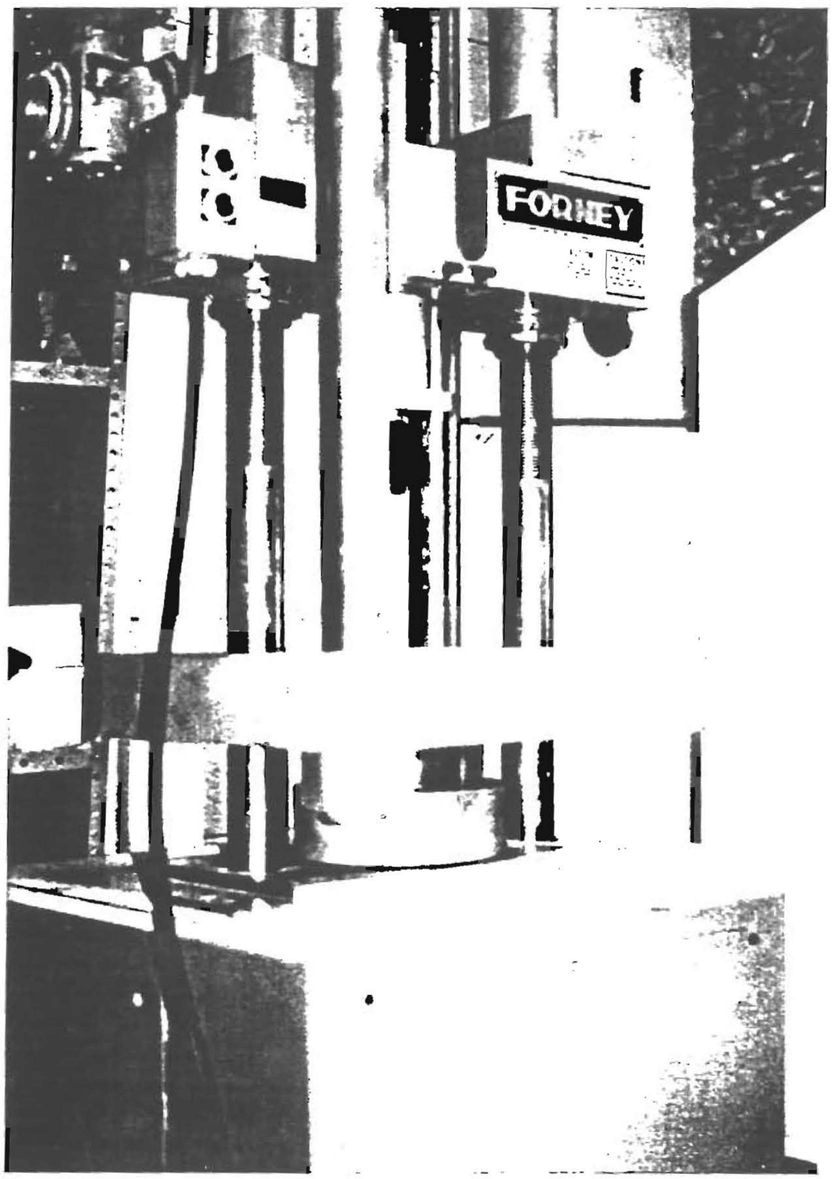


Figure 2.6 27-kN Forney Tension/Compression Testing Machine

The shear strengths were calculated using equation below:

$$\tau = \frac{VQ}{Ib} \tag{2.2}$$

where: V = the shear at failure,

Q = the first moment of area above the overlay-base concrete interface,

I = the moment of inertia, and

b = the width of the beam

The specimens tested consisted of two different materials with two different moduli of elasticity. The first layer, which was the base beam, had aged at least 28 days and the second layer, the overlay, was 24 hours old at the time the specimen was tested. The modulus of elasticity of the base specimen was about 27.3 GPa based upon compression tests. The modulus of elasticity of the overlay after 1 day was experimentally determined as 12.6 GPa. The results from this study are presented in detail in Makahaube et al (1993).

Conclusions

Surface Condition. Wet surfaces for thinner overlays (5-cm) yielded better or equal bond strengths when compared with dry surfaces for both low and high amplitude vibrations. However, for control specimens (not subjected to vibrations) dry interface produced slightly better bond. For thicker overlays the smooth, wet interfaces were not recommended as they were more affected by vibrations. For 10-cm-thick overlays on rough surfaces less variation in strength occurred between rough and dry surfaces. In this case, surface moisture condition did not affect the interface bond.

Surface Texture. Thinner overlays were not significantly affected by surface texture. Smooth, wet surfaces yielded slightly higher values of shear stresses at failure when subjected to low-amplitude vibration levels. High-amplitude vibration levels did not result in consistent values for bond strengths. Similarly, for thicker overlays on dry interfaces the surface texture was again of no consequence. Smooth texture produced better bond strength when cured for 12 hours and then subjected to low or high-amplitude of vibration. Smooth, wet interfaces were more affected by vibrations when compared with rough, wet interfaces. Bond strength (independent of surface texture) decreased when pre-vibration cure time was increased from 4 to 12 hours. Specimens not subjected to vibration produced the highest values of bond strength for smooth, wet interfaces.

Pre-vibration Cure Time. Vibration generally improved the bond between base and overlays for 5-cm-thick overlays. Specimens subjected to low-amplitude vibrations exhibited higher bond strengths. Independent of surface texture and surface condition, an increase in the pre-vibration cure time resulted in a decrease in the bond strength for both 5-cm-thick and 10-cm-thick overlays.

Thicker overlays yielded higher bond strengths when specimens were not subjected to vibration. High-amplitude vibrations generally produced better or equal bond strength for thicker overlays when compared with low-amplitude vibrations. Smooth, wet interfaces were more affected by vibrations. On rough surfaces (wet or dry) short periods of cure time were recommended.

Effect of Overlay Thickness. The bond strength of the concrete overlays increased with an increase in overlay thickness. However, 10-cm-thick overlays were less effective in bond development than 5-cm-thick overlays i.e the bond strength was a lower percentage of the shear stress at failure of a solid beam at the same fibre.

Amplitude of vibration and pre-vibration cure time were the controlling parameters in determining the bond effectiveness. For smooth, dry interfaces the bond effectiveness was constant for both 5-cm-thick and 10-cm-thick overlays. For smooth, wet interfaces, the bond effectiveness varied with vibration levels and pre-vibration cure time. For 5-cm-thick overlays highest effectiveness was achieved when the specimens were subjected to low-amplitude vibration.

One limitation of this test program was that none of the specimens developed a shear failure at the interface of the base and the overlay materials. To compare the bond strength, shear stress at the of tensile failure of the combined cross section was used as an indication of the bond strength. Therefore, once again, the absolute values are of small value, but the trends observed should be a good indication of the variations in the bond strength.

CHAPTER THREE

METHODOLOGY

Introduction

As indicated before, this study was conducted in three phases. In the first phase, small specimens were subjected to pure vertical or horizontal vibration, and tested in pure shear. In the second phase, the specimens were subjected to the bending mode of vibration, and tested in the bending mode. The last phase, this study, was a repeat of the tests performed in phase two but on reinforced specimens. The procedures followed in this phase (i.e. the third phase) are included.

All three phases share several common aspects. First, all specimens in all phases were subjected to the same vibration levels. The vibration levels were based upon actual field measurements on one bridge which experienced debonding. In addition, the same base and overlay concrete mixes were used in all three phases.

General Procedures

Irrespective of the shape of the specimen or the mode of vibration, each specimen was tested at 24 hours after its making. Each overlay thickness was tested 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 beam on the side facing the form. Before pouring the overlay, the base beam surface was kept dry or wet. After the overlay was poured on the top of the base beam, the specimen was allowed to cure without being subjected to vibrations for 0, 4, 12 or 24 hours. A 0-hour pre-vibration cure time (i.e. vibrating the specimen immediately after preparation) would be similar to pouring a concrete overlay in the field while traffic is being allowed on the adjacent lanes and consequently being subjected to traffic vibrations. A 12-hour pre-vibration cure time represents the field condition when an overlay is being poured and then allowed to cure without being subjected to vibration from the adjacent traffic for 12 hours. A 24 hours cure time represents the field condition when an overlay is allowed to cure for 24 hours without being subjected to vibration.

The testing matrix, showing all parameters tested, is illustrated in Figure 3.1. These parameters include amplitude of vibration, curing time, thickness of overlay, texture and wetness of interface between existing (base) and freshly poured (overlay) concrete. These specimens were combined in different sequences to form at least 56 different specimens (ignoring the repeat tests).

The base concrete in all three phases has a class designation of "H-H" as per TxDOT. The mix design parameters for this concrete are included in Table 3.1. The average 28-day compressive strength of this concrete was about 33 MPa. The base concrete for each phase was poured at the same time for all specimens, using ready-mix concrete.

A concrete with a class designation of "CO" was used for the overlay. This concrete was measured, mixed and placed by hand. The design parameters for this concrete are also shown in Table 3.1. The average 28-day compressive strength of this concrete was also about 33 MPa.

CURE TIME, Hours		0				4				12				24	
VIBRATION		HIGH		LOW		HIGH		LOW		HIGH		LOW		NONE	
THICKNESS, cm		5	10	5	10	5	10	5	10	5	10	5	10	5	10
SURFACE TEXTURE	SURFACE CONDITION														
ROUGH	WET														
	DRY														
SMOOTH	WET														
	DRY														

Figure 3.1 Testing Matrix Used in This Study

Table 3.1 Mix Design Parameters for Class "H-H" Concrete and Class "CO" Concrete.

Design Factor	Class "H-H" Concrete	Class "CO" Concrete
Cement	7sacks/C.Y. concrete	8sacks/C.Y. concrete
Coarse Aggregate	0.68	0.67
Water	5.25 gal/sack of cement	4.5 gals/sack of cement
Entrained Air	6.0 percent	6.0 percent
Aggregate Size	1/2 in. max.	1/2 in. max.
Additives	High range water reducer	Fly ash 25%

Vibration Measurements in the Field

To subject the specimens to realistic vibration amplitudes and frequency contents, the vibration characteristics of one bridge which had experienced debonding were measured. The procedure for measuring the vibration amplitude is described in Rodriguez-Gomez and Nazarian (1992) in detail. Amplitudes of 2 mm and 1 mm were determined as representative of the vibration of a long span and a short span, respectively.

Two averaging techniques were used to characterize the traffic volume. The first technique was "peak-hold" average and the second was the arithmetic average. In the first technique, the maximum amplitude which occurred at each frequency was saved. An example is shown in Figure 3.2a. The record can be considered as the maximum envelope for 8 minutes of traffic.

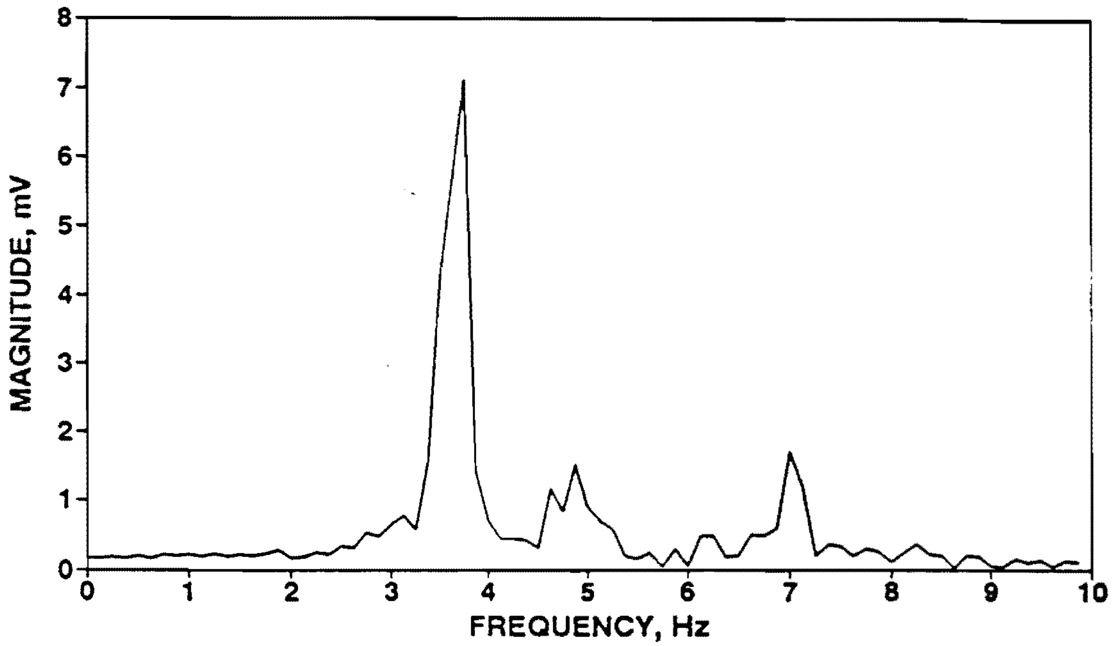
In the second technique, the arithmetic average was taken from the same 8 minutes of traffic (see Figure 3.2b). The result varied substantially with the percentage of the trucks in the traffic flow. As the number of trucks increases, the arithmetic average would be closer to the "peak-hold" average.

To better understand this, let us assume that the vibrations produced by an automobile are negligible as compared to those of a heavy truck. These figures would be similar if all the traffic is purely heavy truck. The result of the arithmetic average would be smaller than those of the peak-hold average if most of the traffic is considered to be automobiles. The peak-hold amplitude (Figure 3.2a) is 3 times larger than the arithmetic amplitude (Figure 3.2b). Therefore, it can be approximated that, for that time frame, about 1/3 of the traffic were trucks.

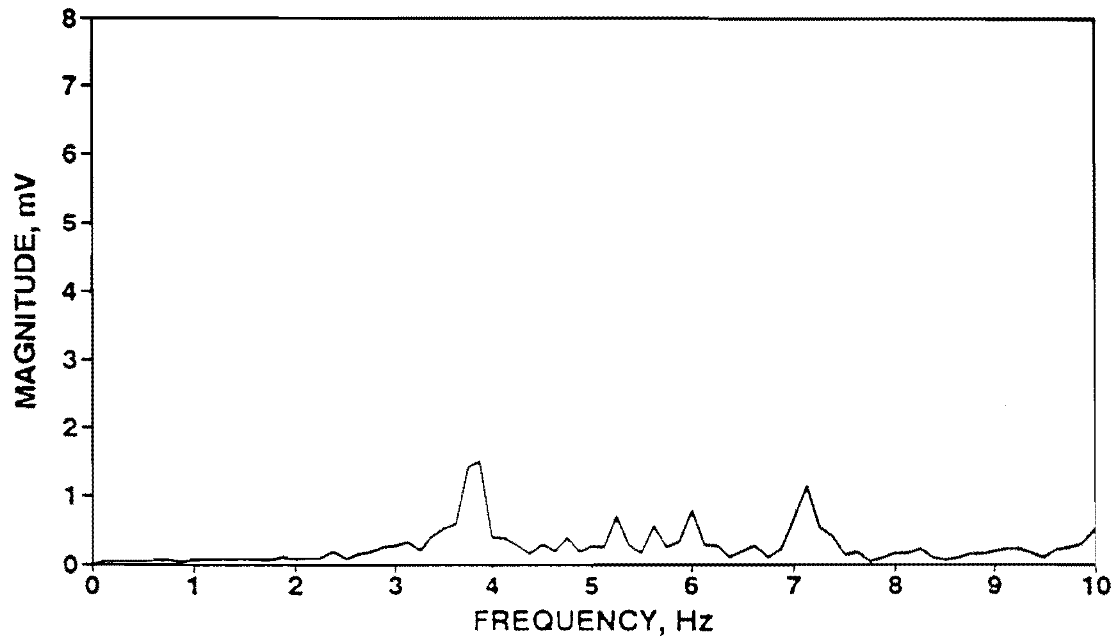
Methodology for Present Work

The beams used here were very similar in size (i.e. 90 cm x 15 cm x 5 cm) and concrete mix (Class H-H) to those used by Makahaube et al (1993). The major difference was that these beams were reinforced with 6.5-mm-diameter bars placed at 5-cm intervals.

The same testing apparatus and procedures followed by Makahaube et al were also utilized here. However, the data reduction was slightly different. Tests over a 75-cm span were



a) "Peak-Hold" Average



b) Arithmetic Average

Figure 3.2 Typical Vibration Characteristics of Bridges That Debonded carried out first. One half of 75-cm span was then tested for 30-cm span and other for 15-cm span. A 75-cm span is rather flexible. Therefore, the failure would occur in tension. The shear stress at the interface when tensile failure occurs is rather small. Typically, the shear stresses were on the order of 5 percent of tensile strengths.

For a 30-cm span the failure is again due to excessive tensile stresses. In this case, the tensile strengths are more or less the same as those from the 75-cm span. However, the shear stresses at failure were increased by 60 to 65 percent. Typically, the shear stresses were 15 to 20 percent of the tensile strengths.

Tests with the 15-cm span were carried out to maximize the possibility of failure in shear. In this case, the shear stresses at failure were almost 25 percent of the tensile strengths. Unfortunately, no signs of failure in shear could be seen for this span either. Based upon the visual observation and the study of the cracks that were mapped all failures occurred in tension.

For each test, the deflection of the beam as a function of the applied load was recorded at the neutral axis of every specific span. Load-deflection curves were then plotted for each span. A typical load-deflection curve is illustrated in Figure 3.3. A sudden change in the slope of the curve is apparent. The load at which the change in slope occurred usually coincided with the load when first crack appeared on the specimen. This load was used to calculate shear stress and tensile stress for each specific span. In addition, as done by Makahaube et al, the ultimate load to failure was also noted. The load-deflection curves from all tests are included in Appendix A.

Given the fact that no failure in shear could be achieved, it was decided to utilize the shear stress at which the first crack appeared as a measure of bond strength at the interface of the overlay and the base concrete.

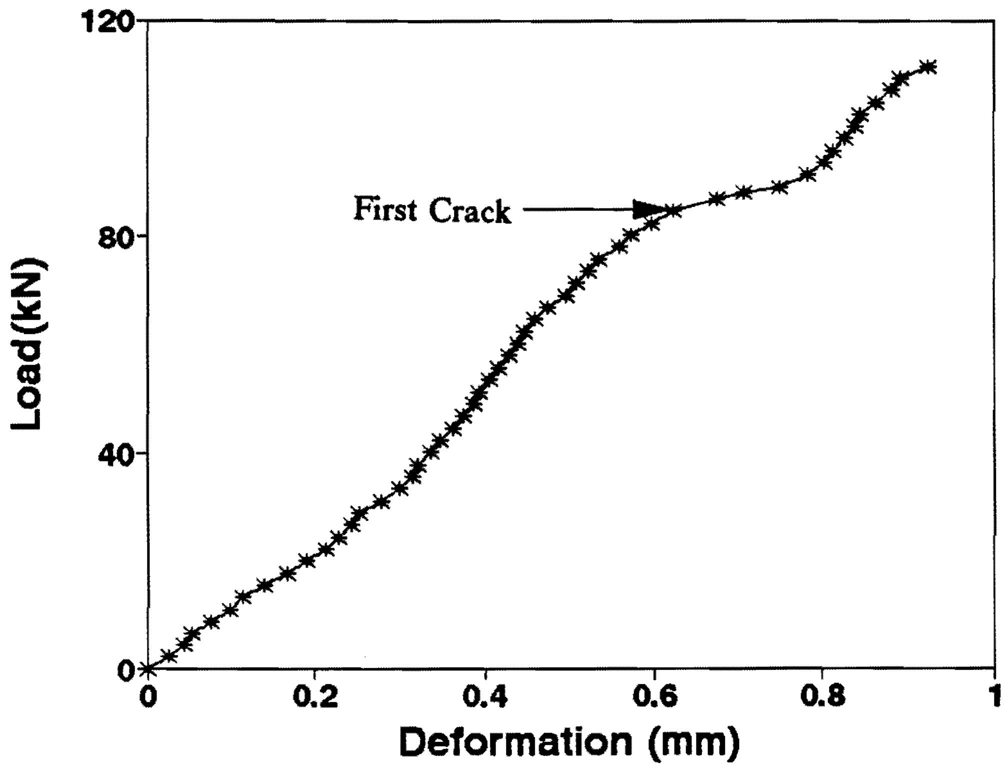


Figure 3.3 Typical Load Deformation Curve from Bending Tests

The bond strengths were calculated using equation:

$$\tau = \frac{VQ}{Ib} \tag{3.1}$$

where : V = the shear force at failure (load taken from the change in slope of deflection curve),

Q = the first moment of area above the overlay and base concrete interface,

I = the moment of inertia, and

b = the width of the beam

The tensile stresses were calculated using equation:

$$\sigma = \frac{MC}{I} \tag{3.2}$$

where M = the moment at failure caused by the point load,

C = the distance from the neutral axis to the bottom extreme fiber, and

I = the moment of inertia of the transformed section.

The tensile strengths and the bond strengths for all tests are summarized in Appendix B. The tensile strengths were not directly utilized in this study, but are presented for completeness. In the following chapter only the results from the 15-cm span are discussed, because these are the most critical in terms of shear failure.

Typical results to be discussed in the next chapter are shown in Figure 3.4 as an example. The bond strengths at the base concrete-overlay concrete interface are shown on the y-axis. Also shown on the figure is the highest theoretical shear stress at failure that one can expect should the whole cross-section have been constructed from the base material and cured for at least 28 days. The most desirable conditions is of course when the bond strengths are close to this value. The abscissa varies with the condition under study. For each case, the parameter of interest is selected for this axis. Typically, the results from several vibration levels are shown on the same graph.

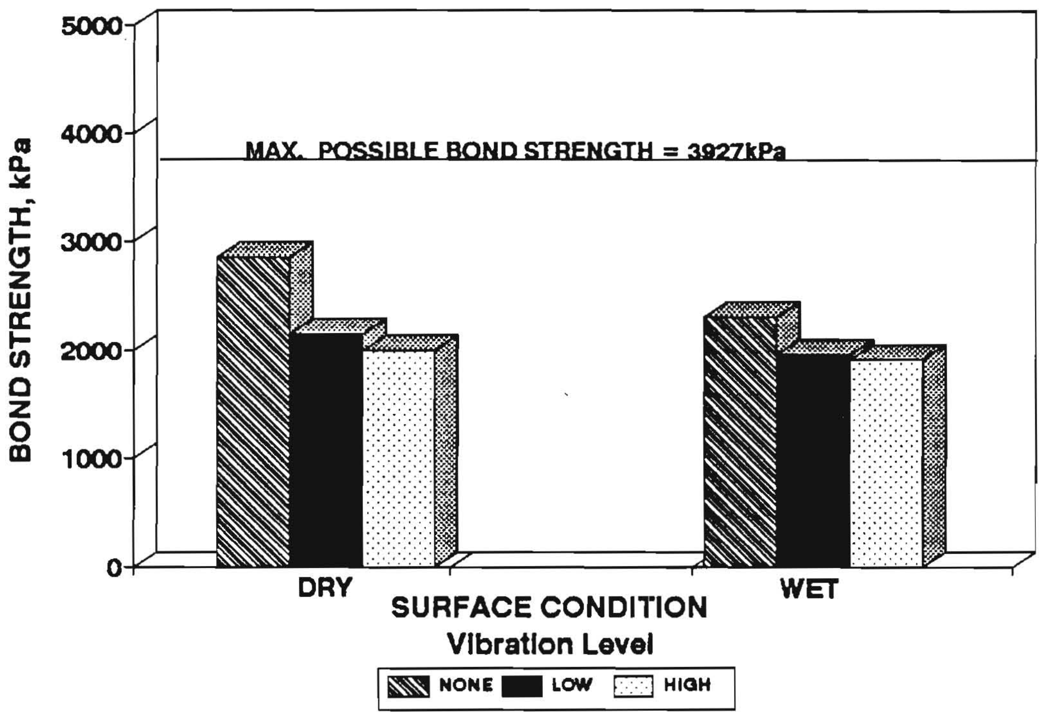


Figure 3.4 Typical Results Obtained from This Study

CHAPTER FOUR

PRESENTATION OF RESULTS

Introduction

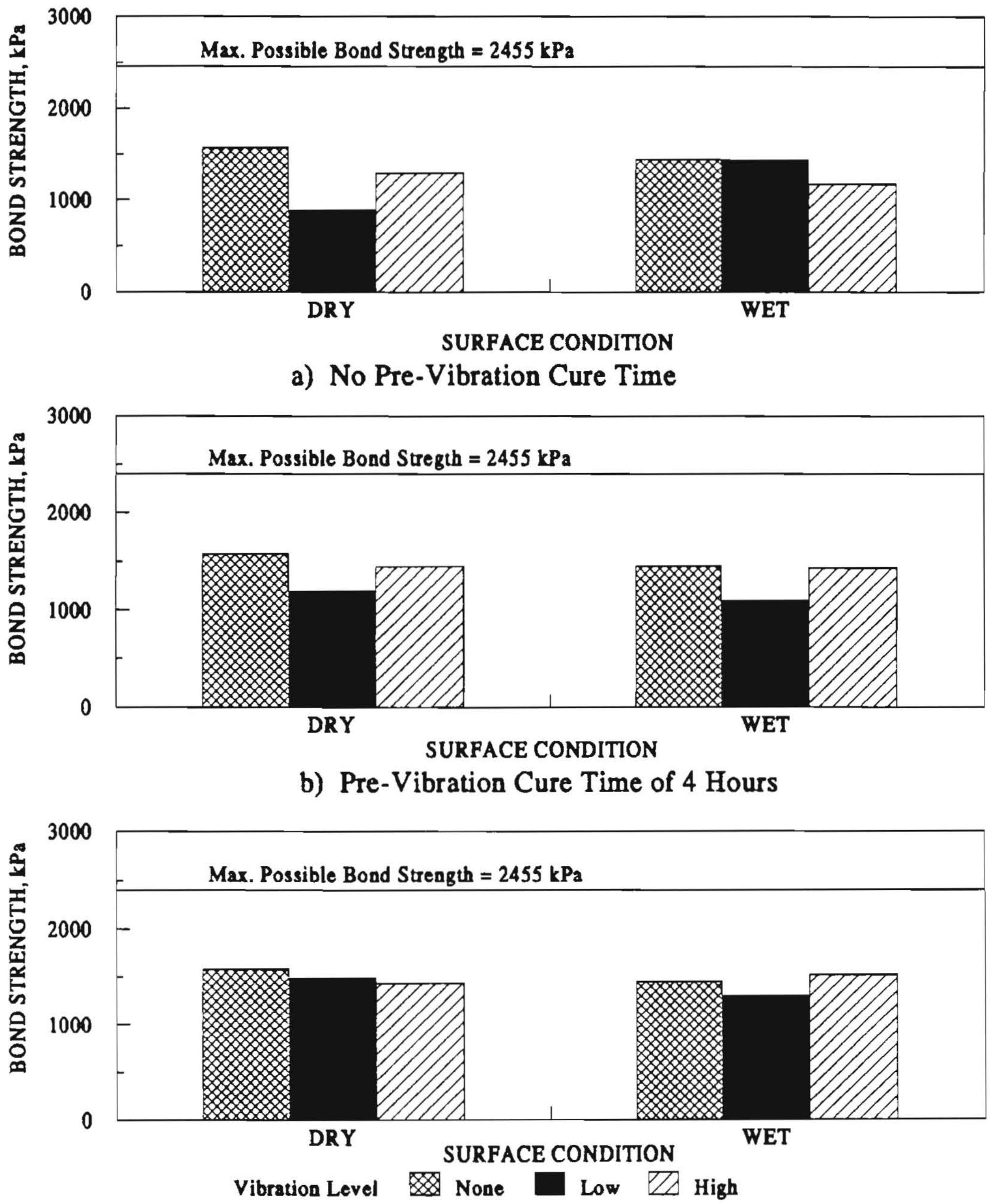
The results from the tests performed following the procedures described in the previous chapter are presented here. The shear stresses at failure as well as the shear stresses when the first crack appeared are included in Appendix B. The appendix also contains the tensile stresses at failure. In this chapter, the discussions are limited to the shear stresses when the first crack appeared in the 15-cm spans. This value will be called the bond strength from here on.

The parameters that are investigated in the rest of this chapter are: surface moisture, surface texture, pre-vibration cure time and thickness of overlays.

Surface Moisture (Dry vs Wet)

The effects of surface moisture just before pouring the concrete on the bond strength are discussed here. The bond strengths obtained for smooth surfaces when 5-cm-thick overlays were used are presented in Figure 4.1. For static conditions (i.e. when the specimens were not subjected to vibration at all), the dry interfaces produced slightly better bonds.

As reflected in Figure 4.1, for specimens subjected to low levels of vibration the bond strengths were typically higher for the dry surfaces as compared with the wet surfaces. The



a) No Pre-Vibration Cure Time

b) Pre-Vibration Cure Time of 4 Hours

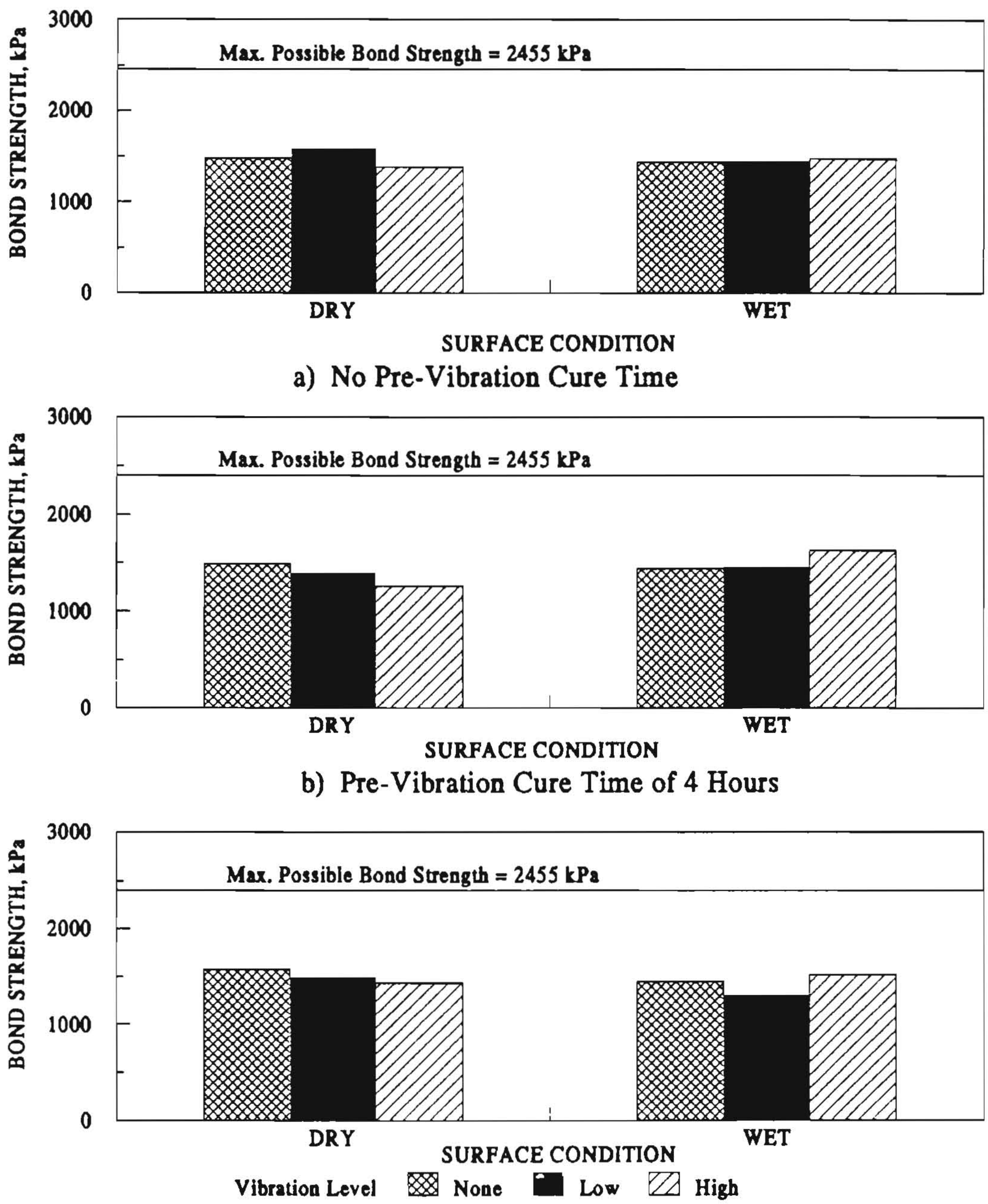
c) Pre-Vibration Cure Time of 12 Hours

Figure 4.1 Impact of Surface Condition on Bond Strength for 5-cm-Thick Overlays (Smooth Surface) exception was when no pre-vibration cure time was allowed. In that condition, the wet surfaces seemed to develop better bonds relative to the dry surfaces. At high vibration levels, the bond strengths were not much influenced by the moisture at the interface (see Figure 4.1). Practically speaking, at each pre-vibration cure time studied, the wet and dry surfaces yielded similar results.

The bond strengths for 5-cm-thick overlays with rough interfaces are presented in Figure 4.2. For static conditions, dry and wet interfaces yeilded similar bond strengths. Practically speaking, little relative (wet relative to dry) variations in the bond strengths were observed when low levels of vibration were utilized. For high vibration levels, the wet surfaces performed slightly better. However, for 12 hours of cure time and high vibration levels rough wet interfaces were not desirable.

The results from tests on specimens with smooth, dry interfaces when 10-cm-thick overlays were used are summarized in Figure 4.3. Under static conditions, the specimens with dry interfaces yielded slightly higher bond strengths than those measured under wet conditions. For specimens subjected to low levels of vibration, when no curing was allowed before vibration, the wet surfaces yielded slightly stronger bond as compared to the dry surfaces. However, as the cure time was increased, the dry surfaces seemed to be more desirable. For higher levels of vibration, the bond strengths did not exhibit an appreciable pattern. The highest value (of about 2100 kPa) was recorded for the specimen with a dry interface. The lowest value (of about 1600 kPa) also corresponded to a dry interface.

The results from tests on specimens with 10-cm-thick overlays on rough interfaces are presented in Figure 4.4. In this case, dry surfaces generally resulted in better or equally good interface bonds when compared to wet ones.



a) No Pre-Vibration Cure Time

b) Pre-Vibration Cure Time of 4 Hours

c) Pre-Vibration Cure Time of 12 Hours

Figure 4.2 Impact of Surface Condition on Bond Strength for 5-cm-Thick Overlays (Rough Surface)

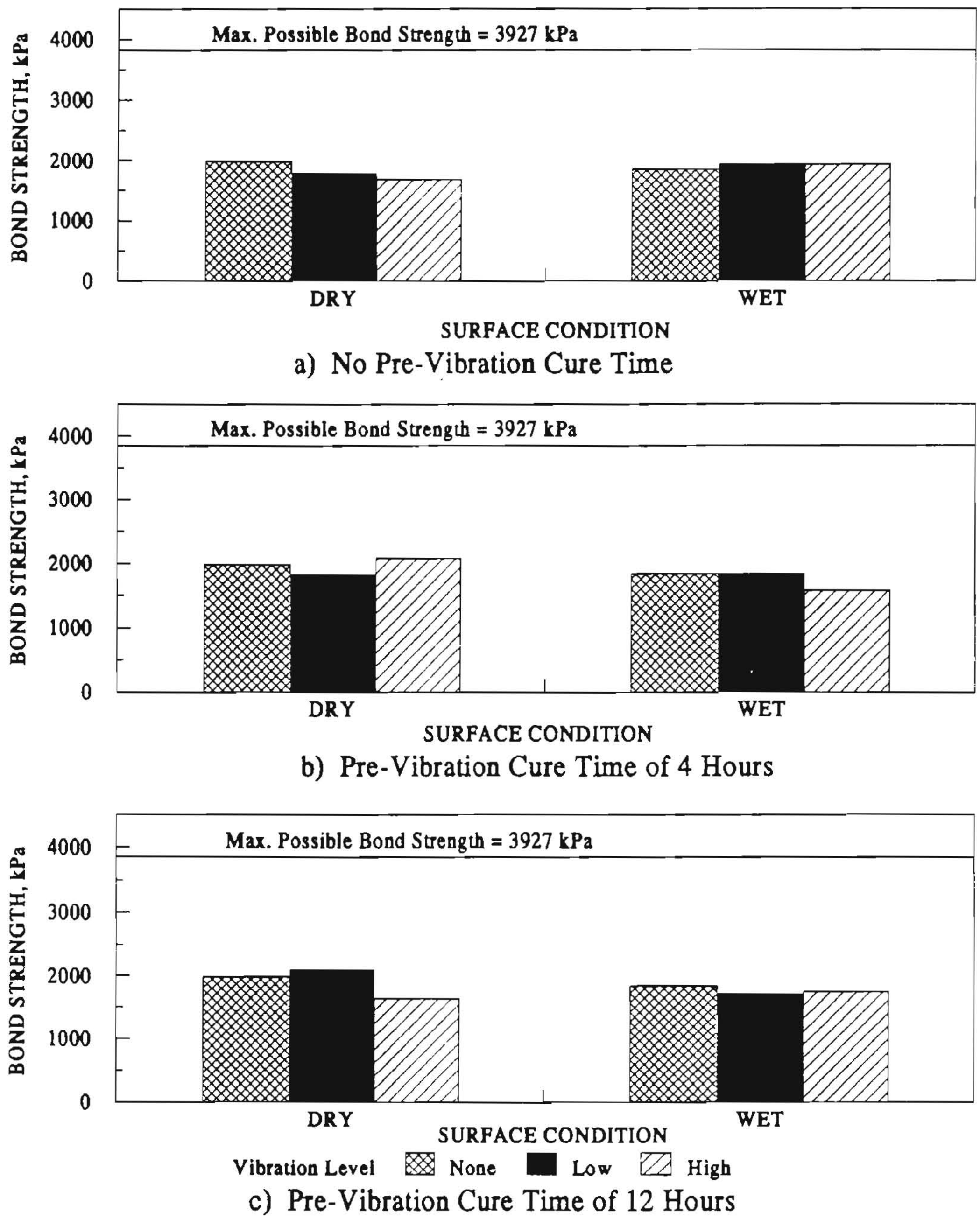
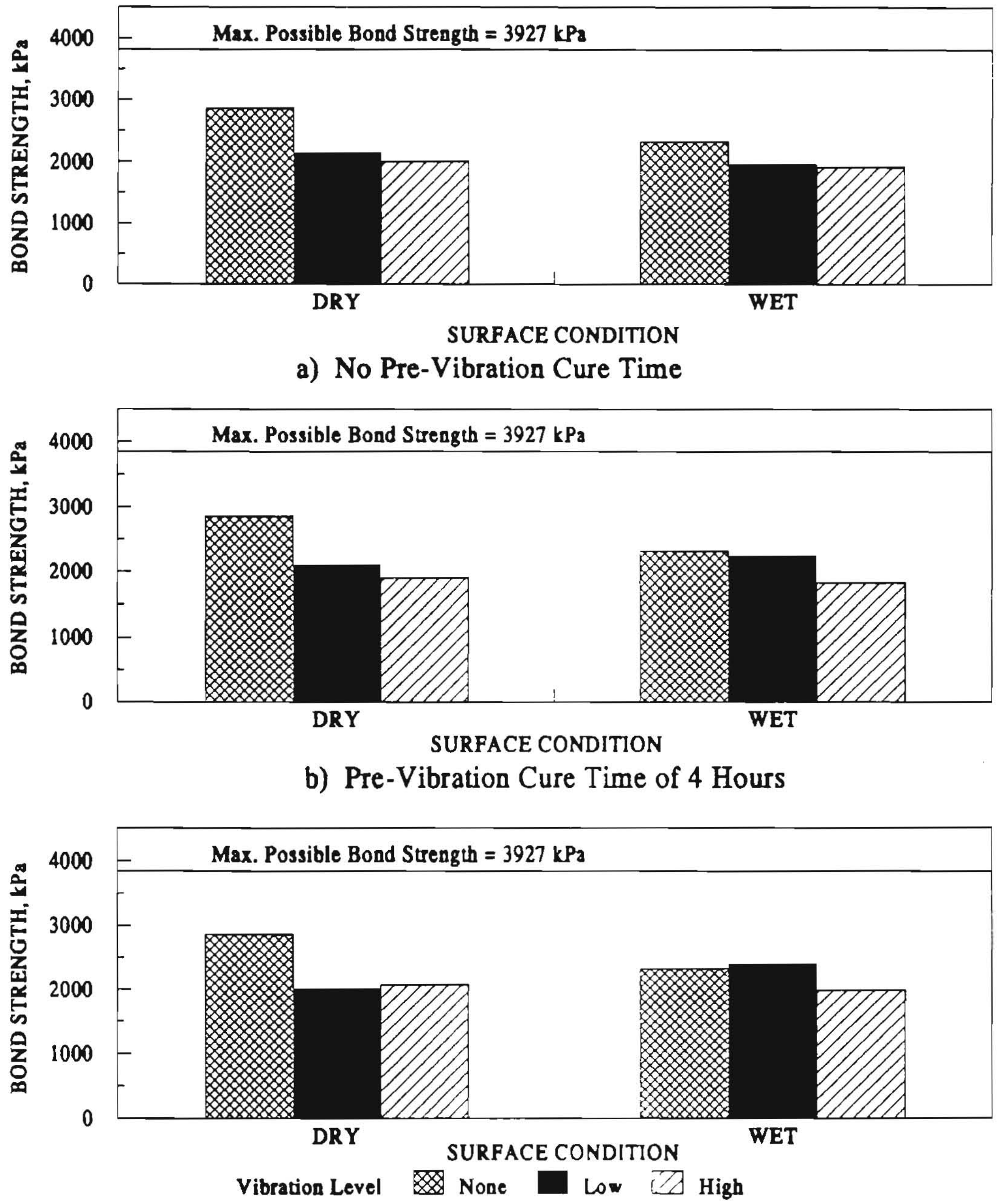


Figure 4.3 Impact of Surface Condition on Bond Strength for 10-cm-Thick Overlays (Smooth Surface)



a) No Pre-Vibration Cure Time

b) Pre-Vibration Cure Time of 4 Hours

c) Pre-Vibration Cure Time of 12 Hours

Figure 4.4 Impact of Surface Condition on Bond Strength for 10-cm-Thick Overlays (Rough Surface)

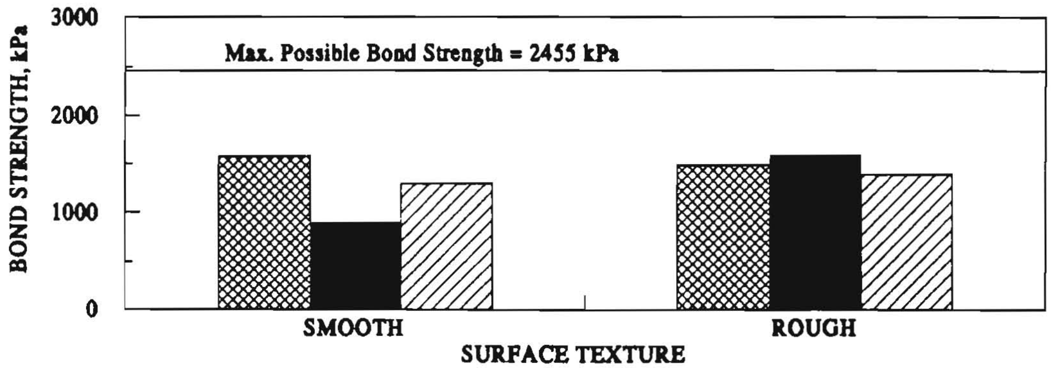
Surface Texture (Rough vs Smooth)

Figure 4.5 illustrates the effects of surface texture combined with pre-vibration cure time for 5-cm-thick overlays on dry interfaces. When tested after static curing conditions, the smooth interfaces yielded slightly higher bond as compared to the rough interfaces. For low levels of vibration, on rough interfaces, the bond strength was relatively insensitive to the pre-vibration cure time. However, for the smooth interfaces, the longer pre-vibration cure times resulted in higher bond strengths. Therefore, for thin overlays placed on dry base concrete, the rough interface may be more appropriate. At high levels of vibration, the texture did not seem to play a role and the smooth and rough interfaces produced equivalent bond strengths.

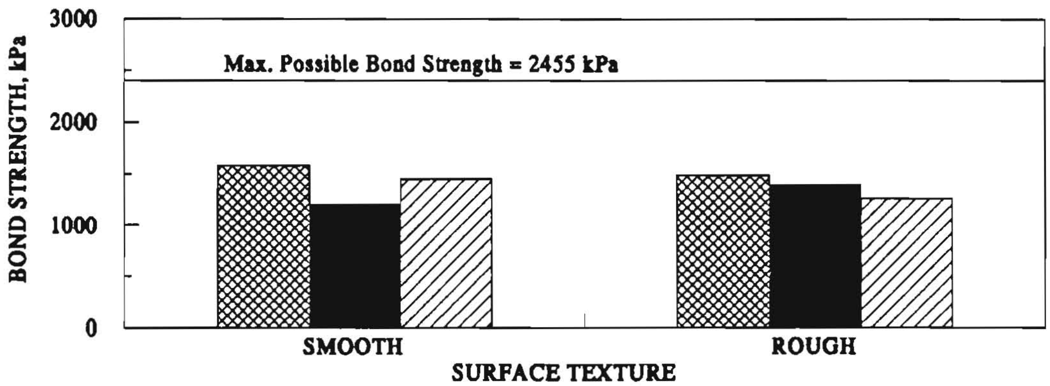
For wet interfaces and 5-cm-thick overlays, the bond strength was found to be less dependent on the surface texture (see Figure 4.6). However, for the smooth interfaces, once again the bond strength was dependent on the pre-vibration cure time. Therefore, once again, it may be concluded that when the interface is moistened, a rough surface may be more appropriate.

The effects of surface texture combined with the effects of pre-vibration cure time for 10-cm-thick overlays placed on dry interfaces are shown in Figure 4.7. Under static conditions, the rough interfaces exhibited higher bond strengths. The bond strengths for the low and high levels of vibration were more or less independent of the pre-vibration cure time for rough interfaces. However, for the smooth interfaces a trend towards the increase in bond strength with pre-vibration cure time could be detected.

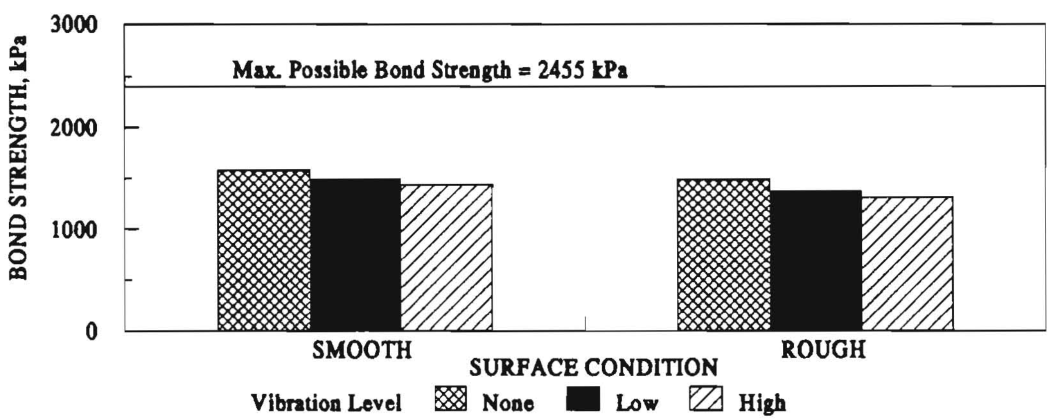
More consistent results were obtained for specimens with 10-cm-thick overlays on wet interfaces (see Figure 4.8). The bond strength for the static case was higher when a rough surface was utilized. The same trend was generally applicable to the cases when high and low vibration levels were used. In general, the roughened, wet surfaces for the thick overlays yielded a better bond strength.



a) No Pre-Vibration Cure Time



b) Pre-Vibration Cure Time of 4 Hours



c) Pre-Vibration Cure Time of 12 Hours

Figure 4.5 Impact of Surface Texture on Bond Strength for 5-cm-Thick Overlays (Dry Interface)

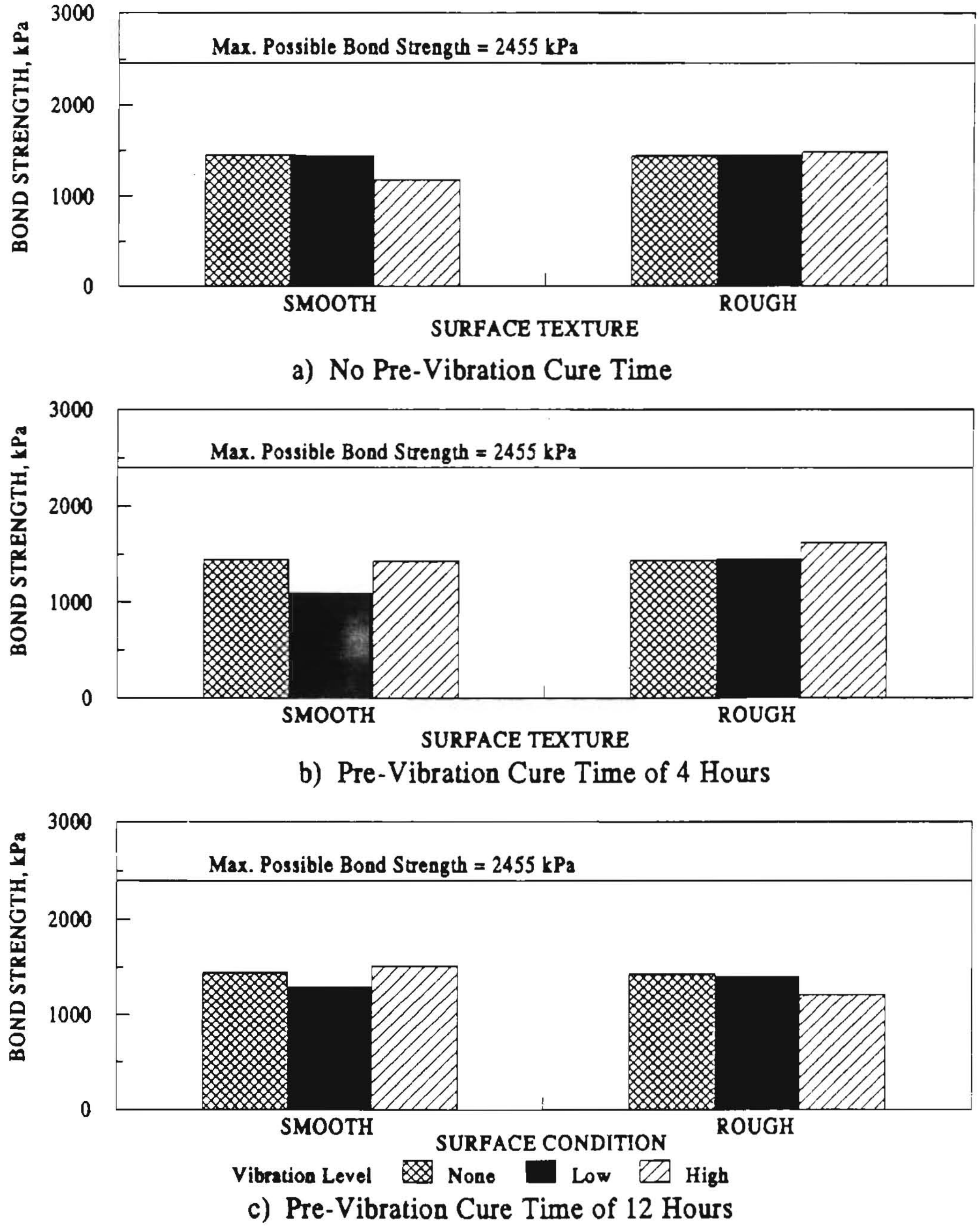
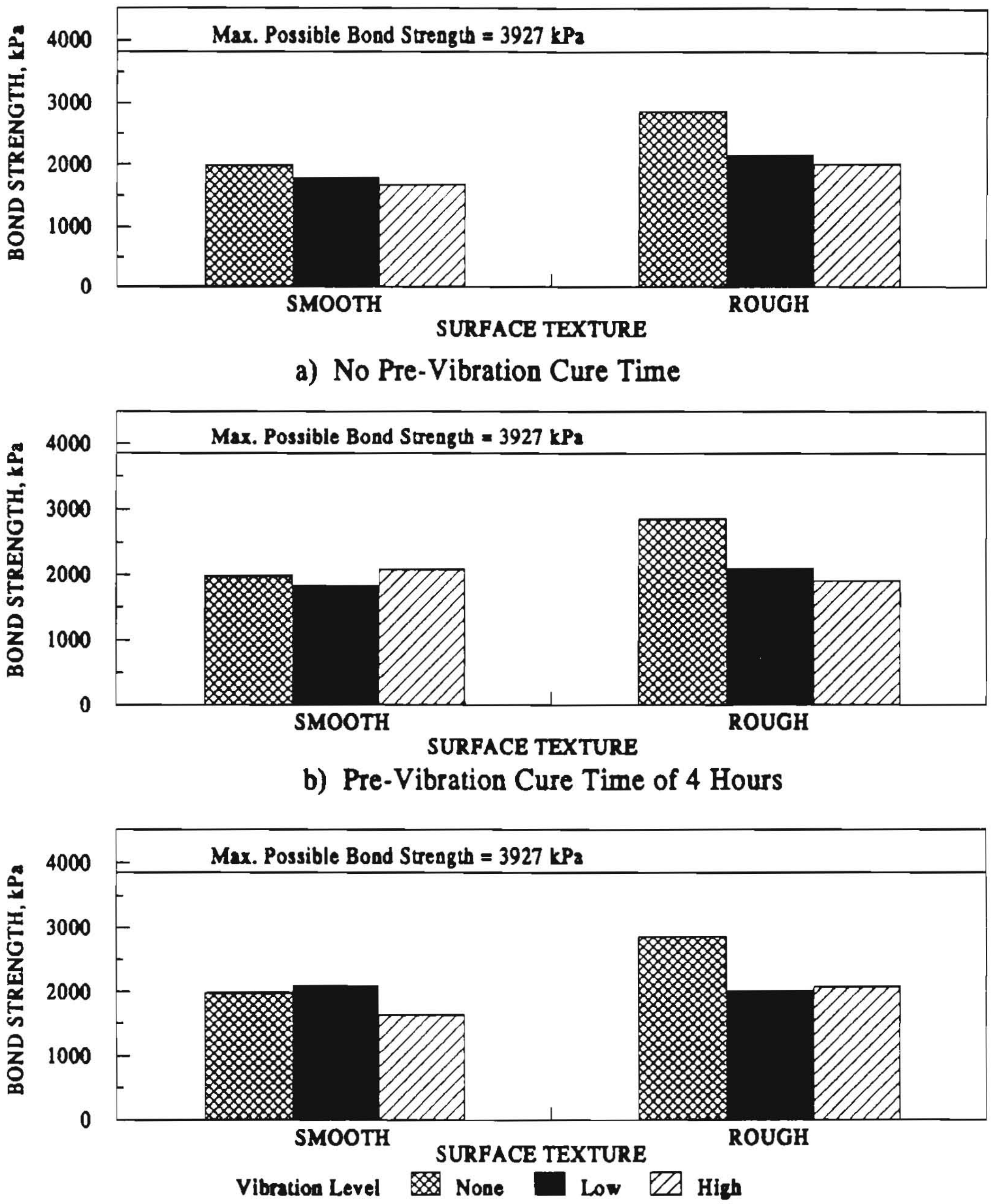


Figure 4.6 Impact of Surface Texture on Bond Strength for 5-cm-Thick Overlays (Wet Interface)

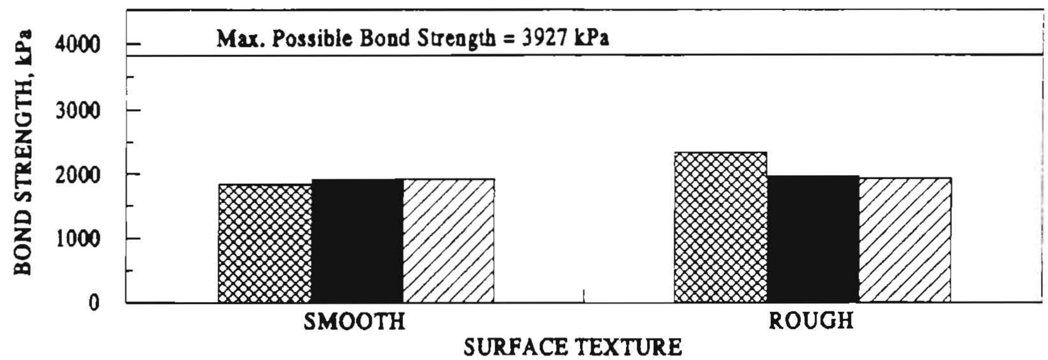


a) No Pre-Vibration Cure Time

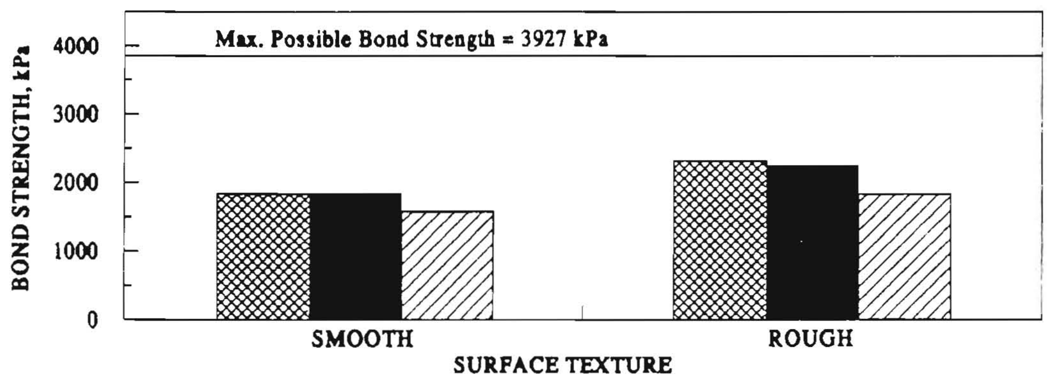
b) Pre-Vibration Cure Time of 4 Hours

c) Pre-Vibration Cure Time of 12 Hours

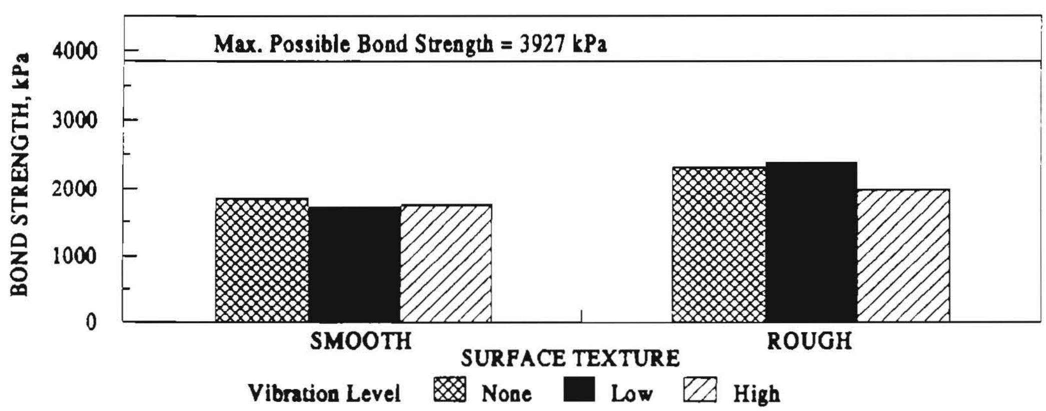
Figure 4.7 Impact of Surface Texture on Bond Strength for 10-cm-Thick Overlays (Dry Interface)



a) No Pre-Vibration Cure Time



b) Pre-Vibration Cure Time of 4 Hours



c) Pre-Vibration Cure Time of 12 Hours

Figure 4.8 Impact of Surface Texture on Bond Strength for 10-cm-Thick Overlays (Wet Interface)

Pre-Vibration Cure Time

The effect of the pre-vibration cure time on the bond strength, was one of the major parameters that needed to be addressed. As discussed before, the pre-vibration cure time corresponds to the traffic closure after pouring the overlay.

In Figure 4.9 the variation in the bond strength as a function of pre-vibration cure time for 5-cm-thick overlays is shown. For overlays placed on smooth, dry surfaces subjected to high levels of vibration (Figure 4.9a), the bond strength was more or less independent of the pre-vibration cure time. The bond strengths for all pre-vibration cure times were about 1400 kPa which is slightly lower than the case when the specimens were not vibrated. For low vibration levels, the bond strength gradually increased with the increase in the pre-vibration cure time. The bond strength increased from about 900 kPa to about 1500 kPa as the pre-vibration cure time increased from none to 12 hours, respectively.

For rough, dry interfaces, as shown in Figure 4.9b, the pre-vibration cure time had small effects. Basically, the highest bond strengths were usually achieved for the static conditions. Subjecting the specimens to low levels of vibration resulted in strengths that were either equal or slightly lower than those obtained from the no vibration cases. Finally, the specimens subjected to high vibration levels yielded bond strengths that were generally lower than those obtained either at low or no vibration levels irrespective to the pre-vibration cure time.

The results for 5-cm-thick overlays placed on wet interfaces as a function of pre-vibration cure time are illustrated in Figure 4.10. As shown in the figure for smooth interfaces the bond strengths were rather unpredictable and did not follow a certain pattern with the level of vibration or the pre-vibration cure time (see Figure 4.10a).

Contrary to the results with smooth surfaces, rough, wet interfaces yielded bond strengths that were more or less independent of the pre-vibration cure time or the level of vibration. Therefore, this type of surface may be more favorable.

The bond strengths measured for 10-cm-thick overlays as a function of pre-vibration cure time are shown in Figures 4.11 and Figure 4.12 for dry and wet surfaces, respectively. For smooth, dry interfaces, the bond strengths were more or less constant with a value of about 2000

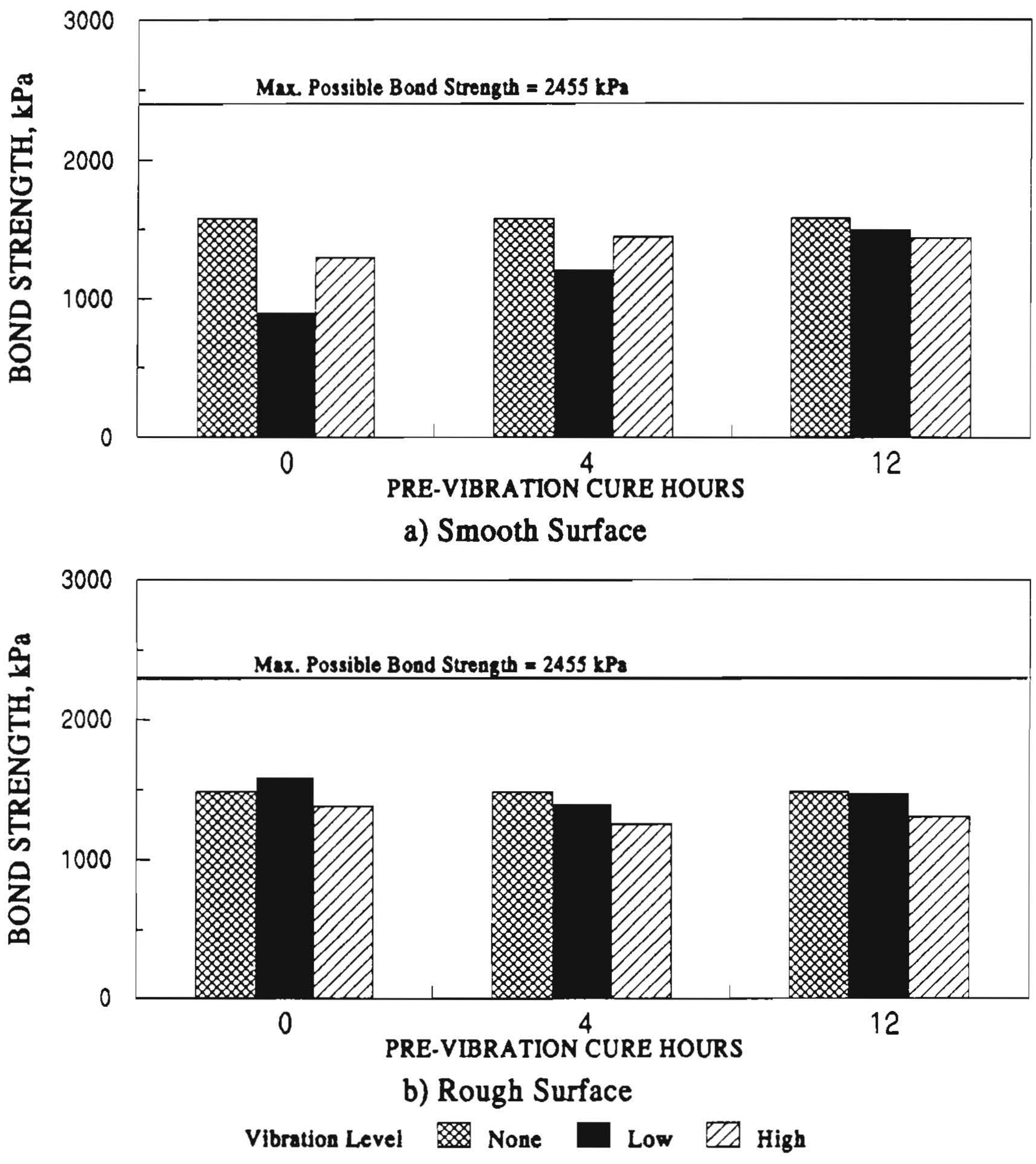


Figure 4.9 Impact of Pre-Vibration Cure Time on Bond Strength for 5-cm-Thick Overlays (Dry Interface)

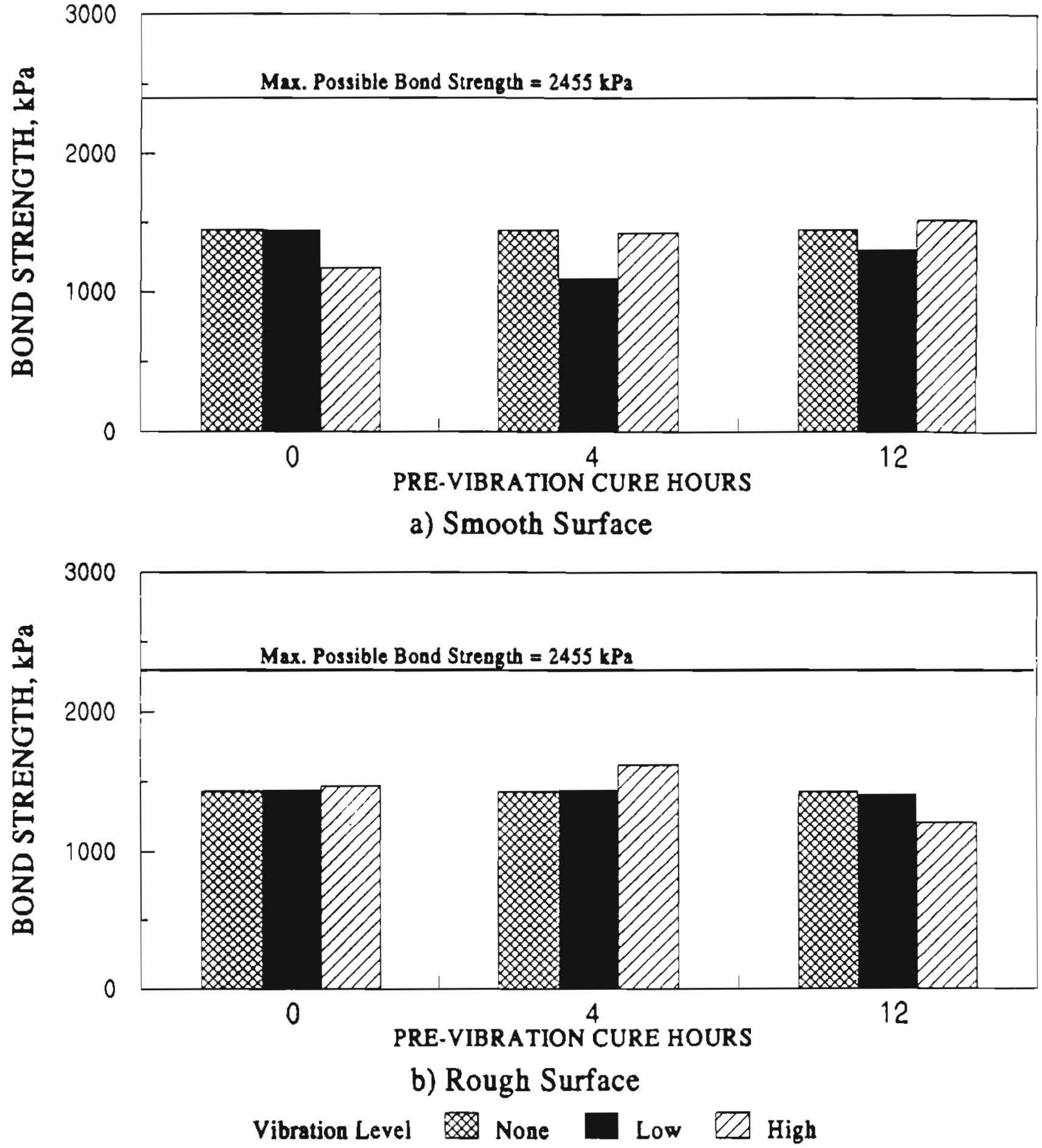


Figure 4.10 Impact of Pre-Vibration Cure Time on Bond Strength for 5-cm-Thick Overlays (Wet Interface)

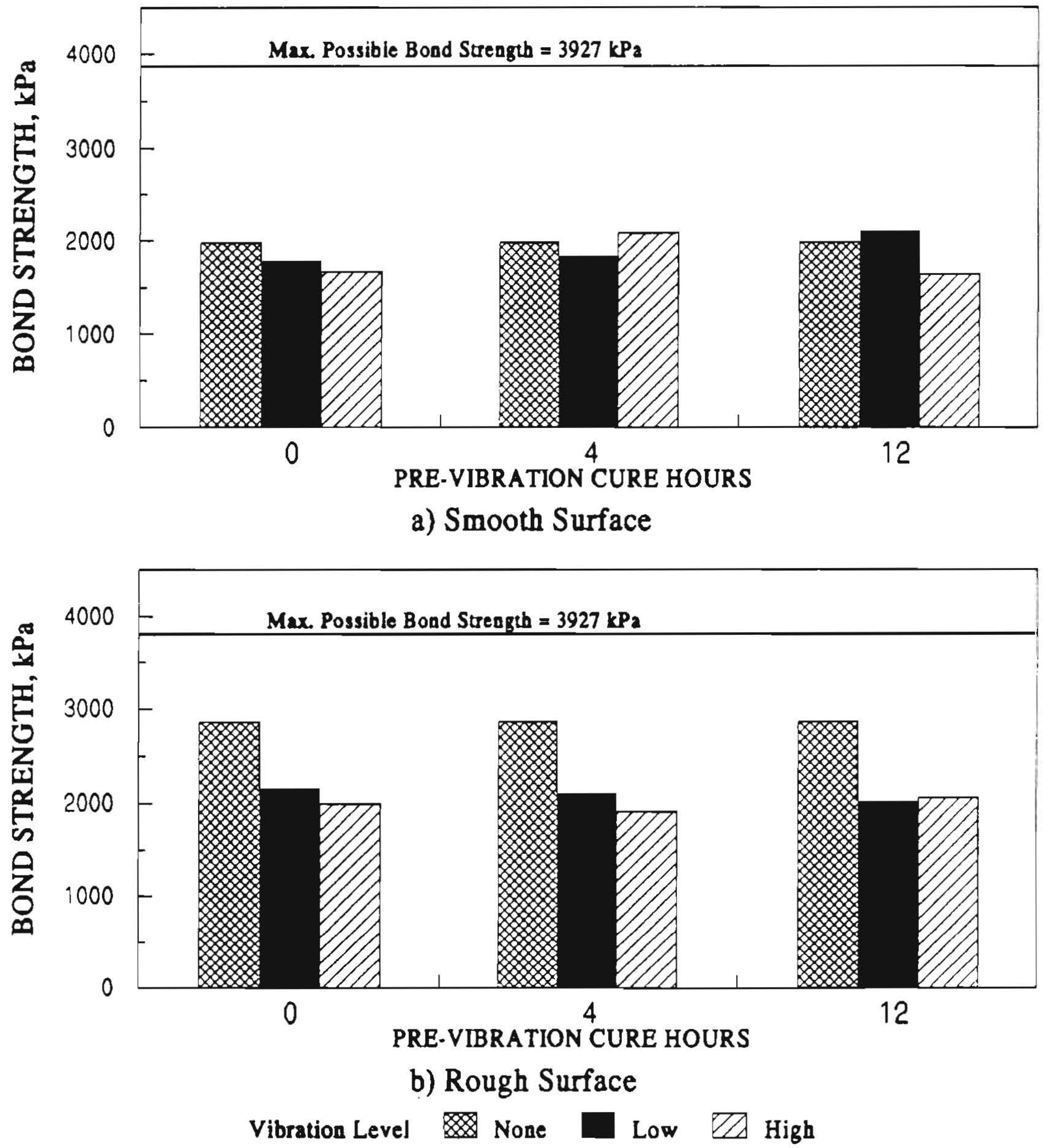


Figure 4.11 Impact of Pre-Vibration Cure Time on Bond Strength for 10-cm-Thick Overlays (Dry Interface)

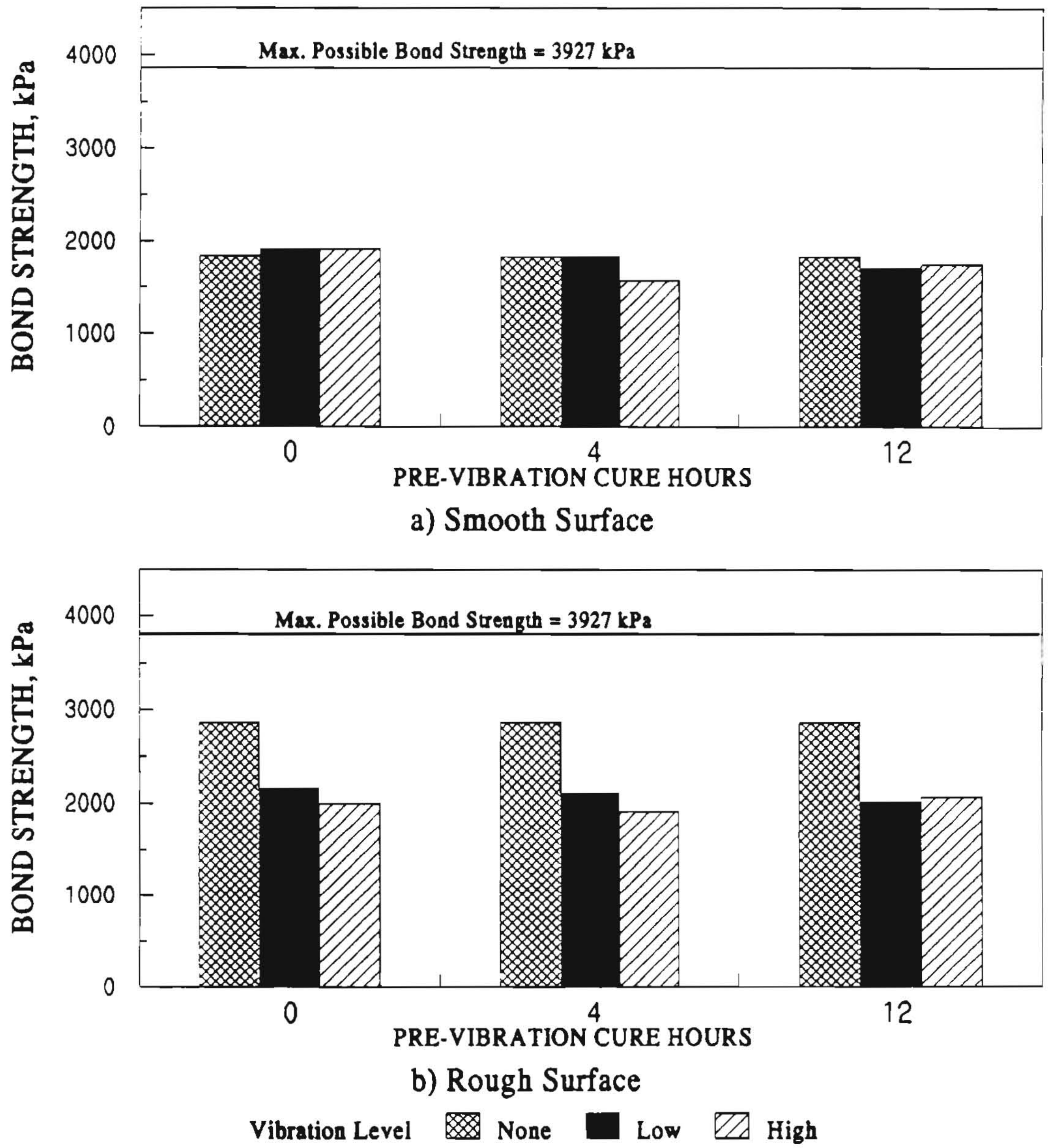


Figure 4.12 Impact of Pre-Vibration Cure Time on Bond Strength for 10-cm-Thick Overlays (Wet Interface)

kPa. In general, some indications of loss of bond strength with an increase in the vibration level could be noticed. However, the pre-vibration cure time had a small effect on the bond strength.

As shown in Figure 4.11b, the rough, dry surfaces yielded consistent results. Even though either low or high vibration levels resulted in decreases in the bond strengths, the reduction in strength was independent of the pre-vibration cure time.

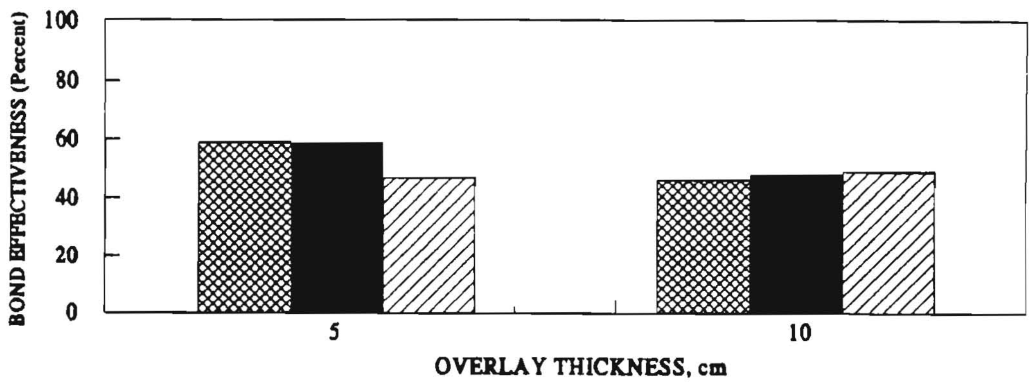
In Figure 4.12b, the results from tests performed on specimens with rough, wet interfaces are presented. In these cases, the low or high vibration levels only slightly affected the bond strengths. The change in pre-vibration cure time virtually caused no change in the bond strength.

Thickness of Overlay

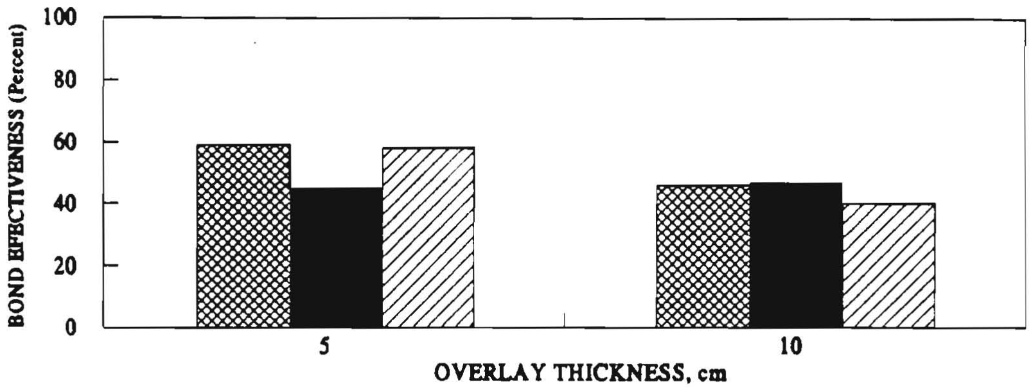
In this section, the impact of increasing the overlay thickness is analyzed by comparing the effectiveness of interface bond between 5-cm-thick and 10-cm-thick overlays. The effectiveness of the interface bond is defined as the ratio of the bond strength of specimens to the shear stresses at first crack of a solid beam made from the base material with the same height and at the same fiber as the interface of base and overlay.

Bond strengths from the 5-cm-thick and 10-cm-thick overlays with smooth, dry interfaces are compared in Figure 4.13. Typically, for the 5-cm-thick overlays, the bond effectiveness was more or less constant and varied between 50 percent and 60 percent. Similarly for the 10-cm-thick overlays the bond effectiveness was more or less constant and varied from 50 to 60 percent. Therefore, it may be concluded that for the dry, smooth interfaces the bond effectiveness is the same for the thin and thick overlays.

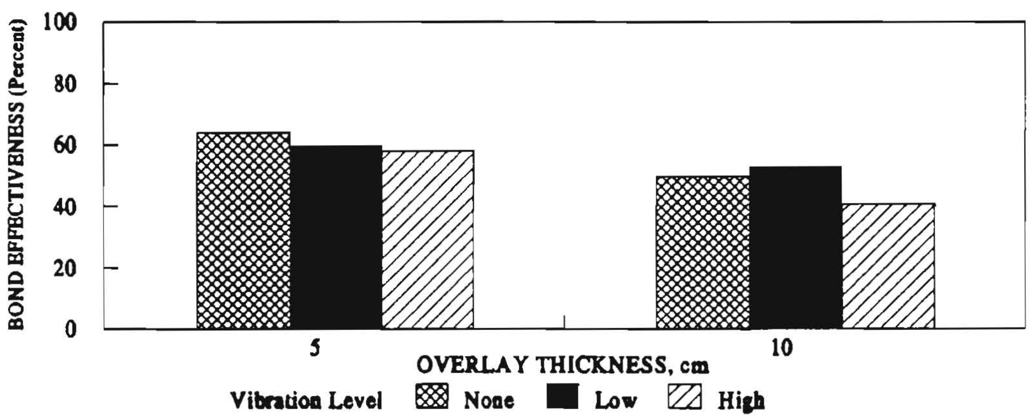
Figure 4.14 illustrates the bond effectiveness as a function of overlay thickness for the smooth, wet interfaces. Once again, for 5-cm-thick overlays, the bond effectiveness varied between 50 to 60 percent. For the 10-cm-thick overlays, the effectiveness was less than those for the thinner overlays for all three pre-vibration cure times studied. The effectiveness varies between 50 to 55 percent.



a) No Pre-Vibration Cure Time

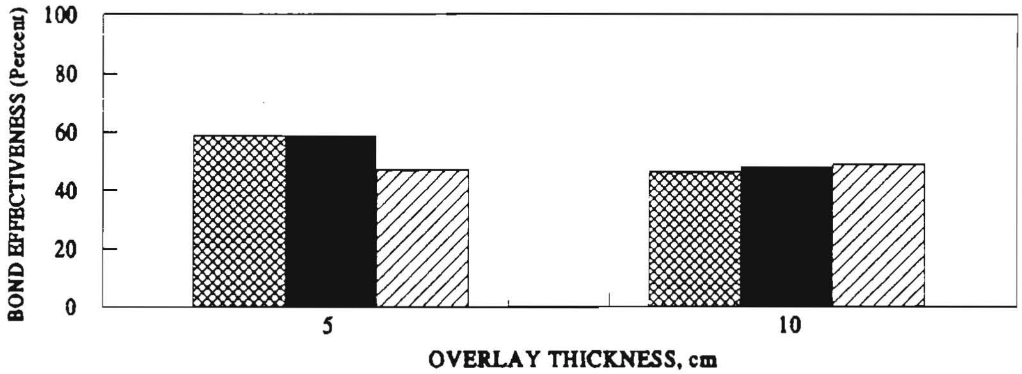


b) Pre-Vibration Cure Time of 4 Hours

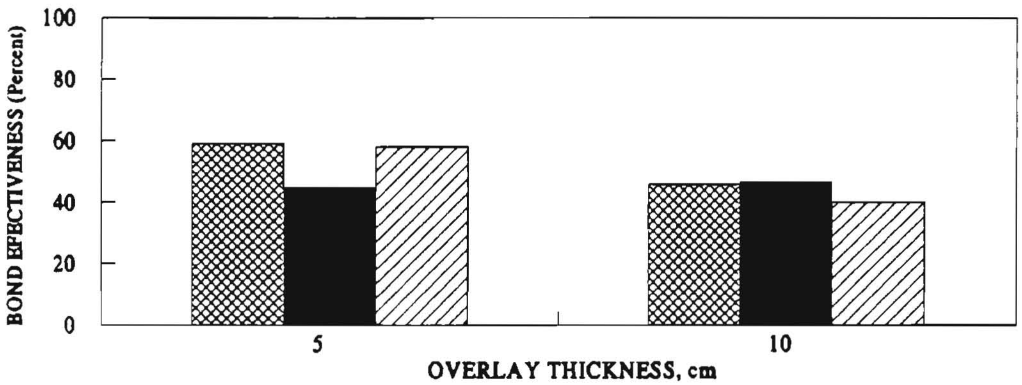


c) Pre-Vibration Cure Time of 12 Hours

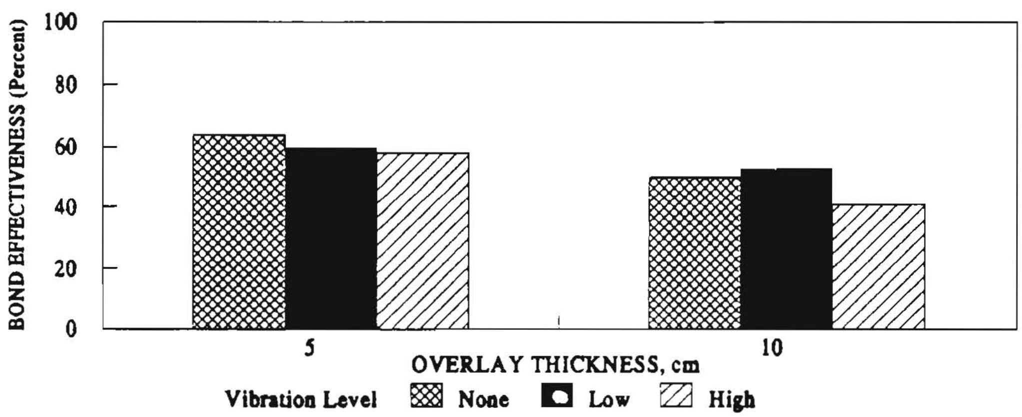
Figure 4.13 Impact of Overlay Thickness on Bond Effectiveness for Specimens with Smooth, Dry Interface



a) No Pre-Vibration Cure Time



b) Pre-Vibration Cure Time of 4 Hours



c) Pre-Vibration Cure Time of 12 Hours

Figure 4.14 Impact of Overlay Thickness on Bond Effectiveness for Specimens with Smooth, Wet Interface

For the rough, dry interfaces, the bond effectiveness as a function of overlay thickness for different pre-vibration cure times is shown in Figure 4.15. For 5-cm-thick overlays, the amplitude of vibration had marginal impact on the bond effectiveness. The bond effectiveness varied between 55 to 60 percent. Typically, the static conditions yielded the highest bond effectiveness. The effectiveness for the low and high vibration levels usually slightly decreased relative to the static conditions. When 10-cm-thick overlays were used, the static condition yielded the highest effectiveness. Due to the low and high levels of vibration, the effectiveness significantly decreased relative to the static condition. Comparing the results between the 5-cm-thick and 10-cm-thick overlays, the thinner overlays generally yielded slightly higher effectiveness.

The results for the rough, wet interfaces are presented in Figure 4.16. For the 5-cm-thick overlays, the increase in vibration level did not result in a significant increase or decrease in the effectiveness for almost all pre-vibration cure times. The effectiveness was about 60 percent in all cases. Contrary to the cases when 5-cm-thick overlays were used, the effectiveness for the 10-cm-thick overlays decreased (relative to the static conditions) for the specimens that were vibrated at high vibration levels. When low levels of vibration were applied to the specimens after a pre-vibration cure time of more than 4 hours, the effectiveness was more or less equal to the static conditions. Once again, the 5-cm-thick overlays yielded higher or equal effectiveness when compared to the 10-cm-thick overlays. This occurred in almost all pre-vibration cure times. In general it can be concluded that for 5-cm-thick overlays the level of vibration and the pre-vibration cure time have little influence on the bond effectiveness. For the 10-cm-thick overlays, the static condition and a rough surface tend to provide the highest effectiveness.

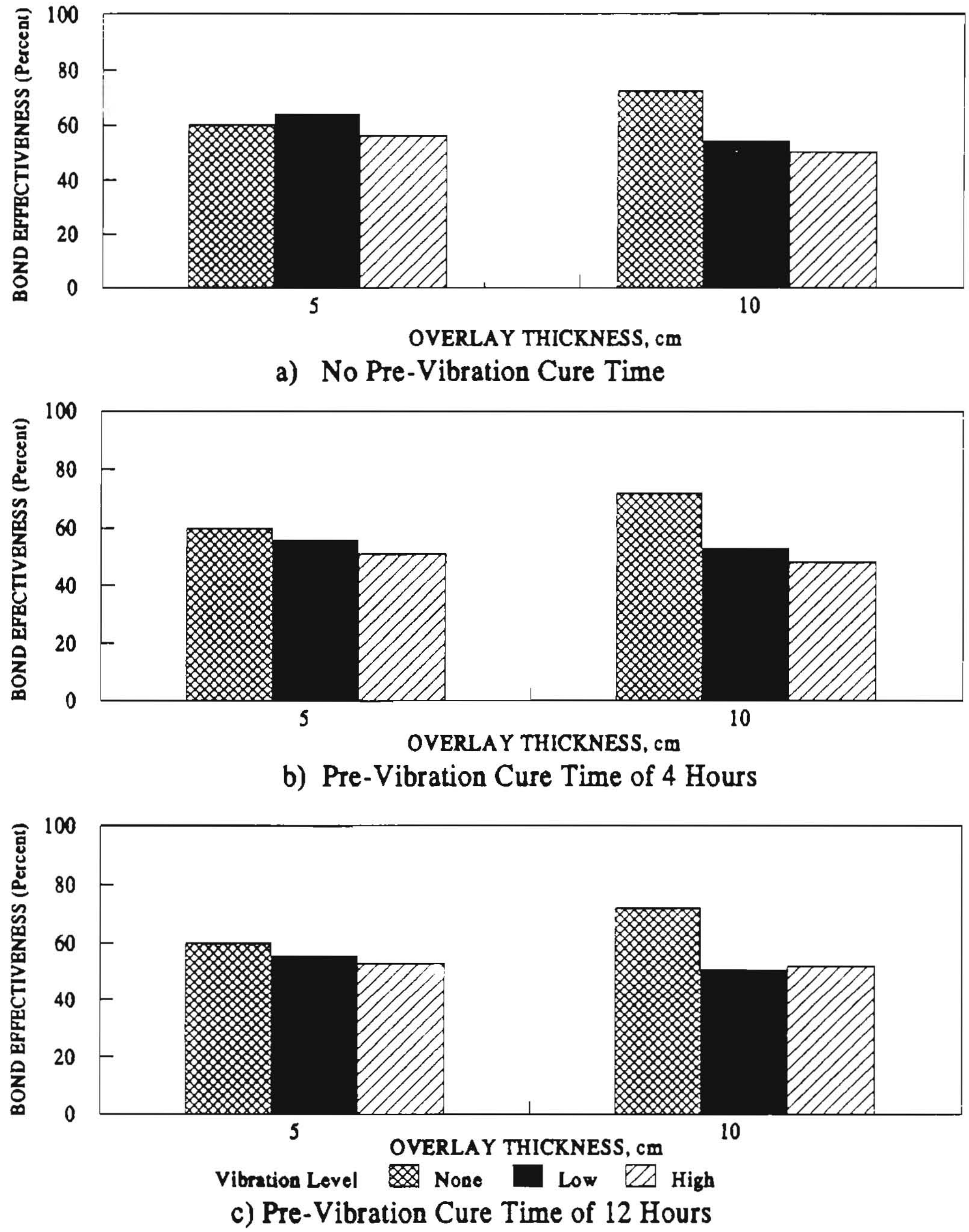
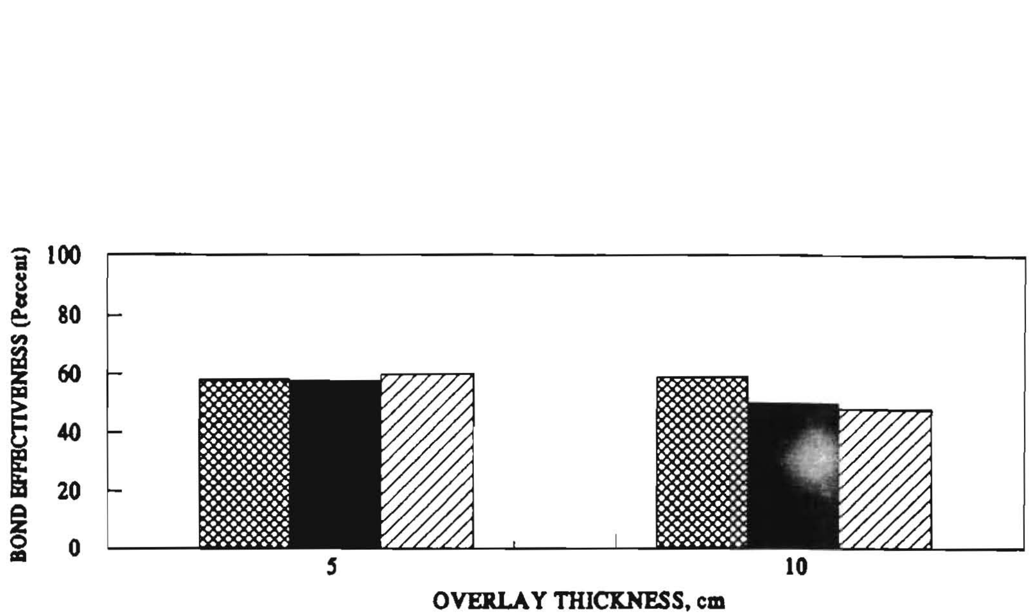
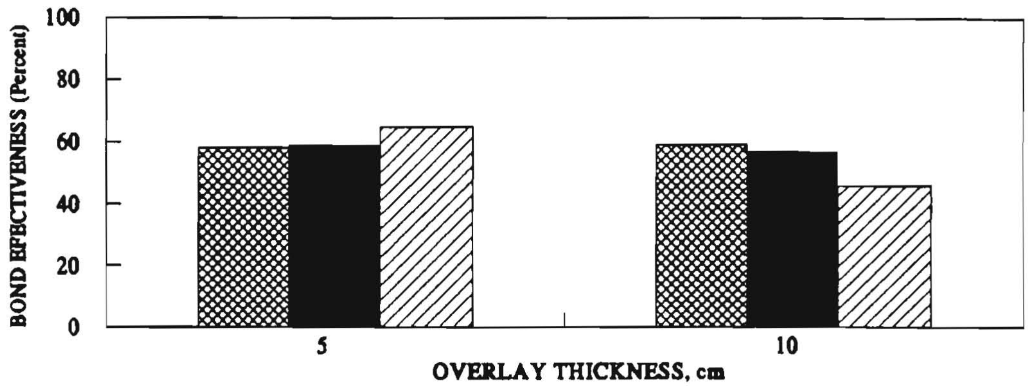


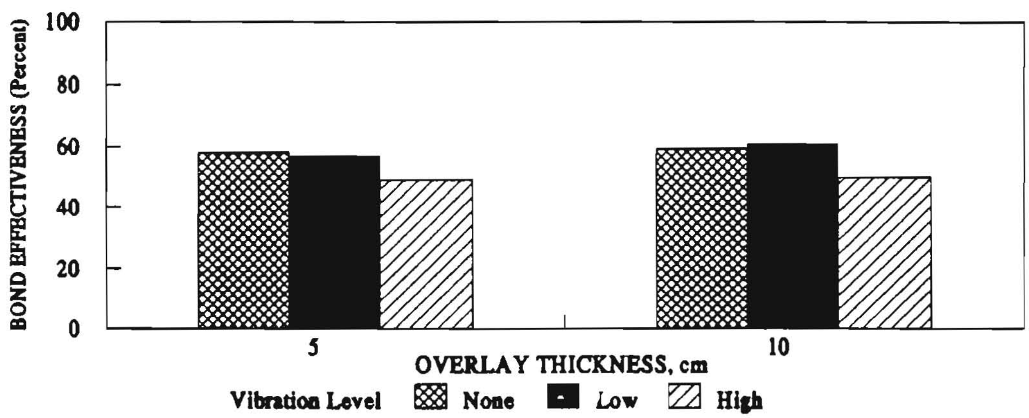
Figure 4.15 Impact of Overlay Thickness on Bond Effectiveness for Specimens with Rough, Dry Interface



a) No Pre-Vibration Cure Time



b) Pre-Vibration Cure Time of 4 Hours



c) Pre-Vibration Cure Time of 12 Hours

Figure 4.16 Impact of Overlay Thickness on Bond Effectiveness for Specimens with Rough, Wet Interface

CHAPTER FIVE

CLOSURE

Summary

The widening of overpasses on Interstate 10 in El Paso, Texas was conducted in two phases. The Phase I overlays were placed in a manner so that they were not subjected to vibrations caused by IH-10 traffic. The Phase II overlays were placed after traffic had been diverted to the newly completed section and were subjected to the direct vibration of IH-10 traffic on the adjacent lanes during placement, consolidation and curing. The Phase II overlays delaminated and debonded to an extent that required replacement. The causes for this debonding were not clear but the vehicular vibrations was suspected as a primary candidate after all construction records were investigated.

To study the effects of vehicular vibration on the interface bonding of thin concrete overlays a study was initiated by Rodriguez-Gomez and Nazarian (1992) and then expanded by Makahaube et al (1993). In the first phase, Rodriguez-Gomez and Nazarian (1992) subjected 10-cm-diameter specimens to two modes of vibrations (vertical and horizontal) and then tested the specimens in pure shear at the interface of base and concrete.

In the Phase II study conducted by Makahaube et al (1993), larger specimens 90-cm long, 15-cm wide and 5-cm thick were subjected to the bending mode of vibration and tested in the bending mode.

In this phase of the project beams 90-cm long, 15-cm wide and 5-cm thick were also used. However, these beams were reinforced with 6.5-mm-diameter bars placed 5-cm apart. The intention was to investigate the effects of reinforcement on the shear failure at the interface of the base and the concrete overlay. The specimens were subjected to an increasing line load in the mid span until flexural failure occurred. Almost all the failures were similar to those of the Phase II study, i.e. due to excess tensile stresses at the bottom fibre of the beam. The bond strength was therefore defined as the shear stress at the interface of the overlay and base concrete when the first crack appeared. The bond strengths were compared based on surface wetness, surface texture, pre-vibration cure time and overlay thickness. The results were recorded and analyzed to determine under which conditions best bonds were obtained.

Recommendations

The recommendations based on the test results are:

Surface Moisture

For conditions when the vibration is not permitted, the dry interfaces are more desirable independent of the surface texture or the overlay thickness. For low levels of vibration, the dry interface typically perform better except for thinner overlays on smooth surfaces with zero pre-vibration cure time. For high levels of vibration, the surface moisture does not seem to exhibit a trend. However, the interface bonds for all dry and wet interfaces (when all other parameters are same) are similar.

Surface Texture

For thinner overlays the rough and smooth interfaces yield more or less similar bond strengths. However, in many occasions the rough interfaces exhibit slightly higher bond strength.

For thicker overlays the rough interfaces are clearly more desirable. For all levels of vibrations and surface moisture the rough surfaces yielded higher bond strength.

Pre-Vibration Cure Time

For overlays placed on a smooth interface, the effects of pre-vibration cure time for low and high vibration levels can typically be defined as a gain in the bond strength.

For overlays placed on a rough interface, the pre-vibration cure time is of less importance and only slightly contribute to the gain in the bond strength. Generally the no vibration cases yield the highest bond strengths.

Overlay Thickness

Typically, thinner overlays yield bond strengths that are closer to the maximum possible theoretical bond strengths. For smooth interfaces this matter is even more significant. As the pre-vibration cure time increases the bond effectiveness for thinner overlays increases.

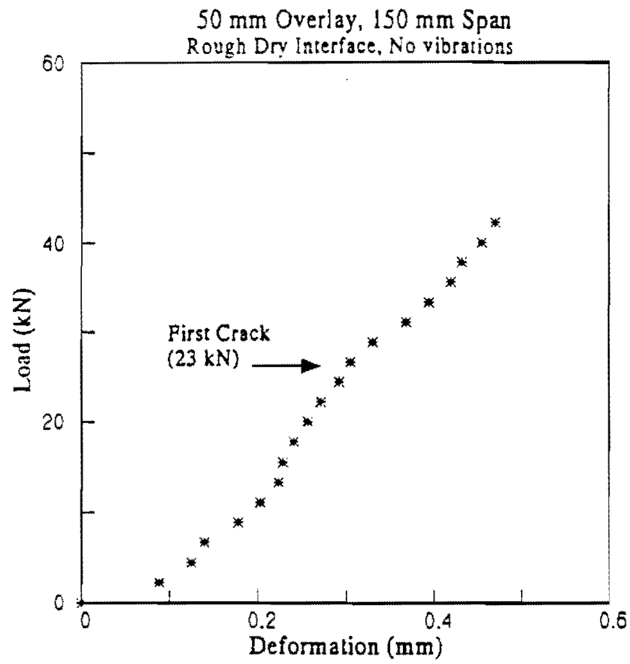
REFERENCES

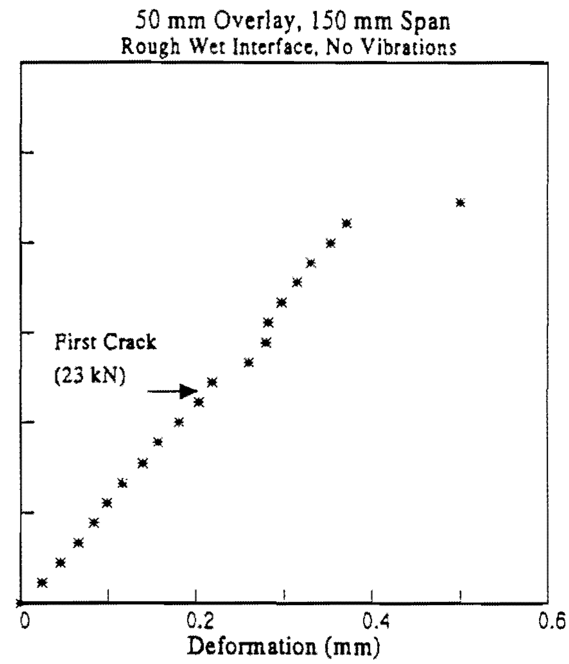
1. Makahaube, J., Nazarian S., and Rozendal D. (1993), "Investigation of Parameters Affecting the Interface Bonding of Thin Concrete Overlays due to Vehicular Vibration," Research Report 1920-2, Center for Geotechnical and Highway Materials Research, The University of Texas at El Paso.

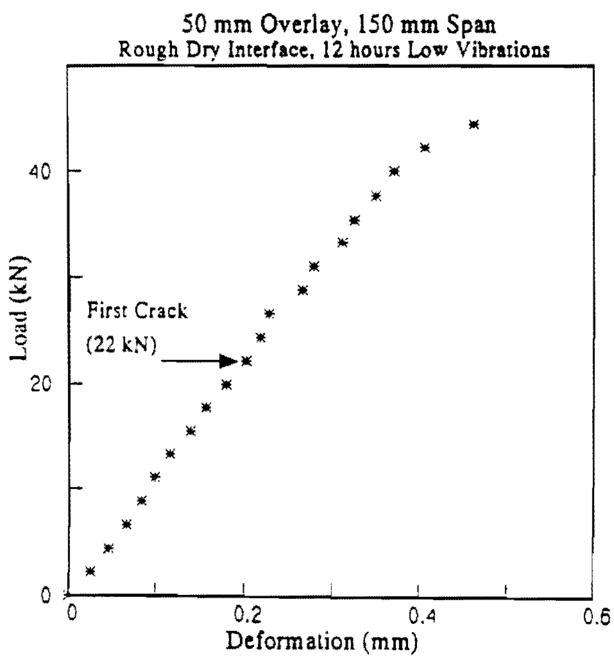
2. Rodriguez-Gomez, J. and Nazarian S. (1992), "Laboratory Investigation of Delamination and Debonding of Thin-Bonded Overlays due to Vehicular Vibration," Research Report 1920-1, Center for Geotechnical and Highway Materials Research, The University of Texas at El Paso.

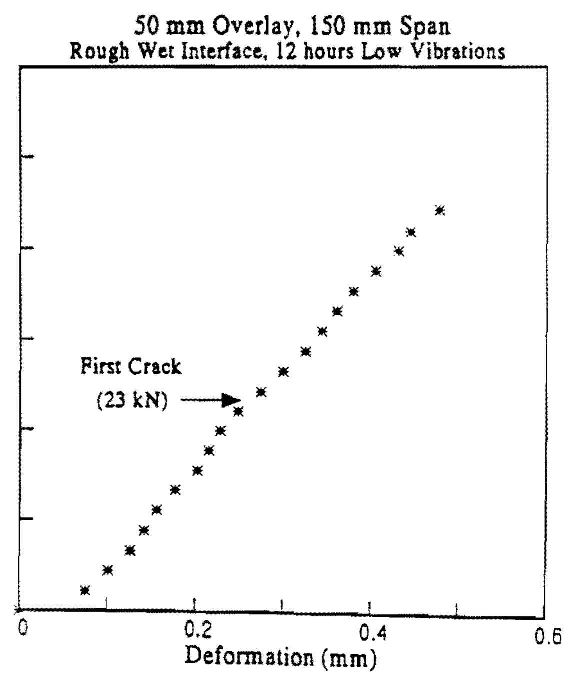
APPENDIX A

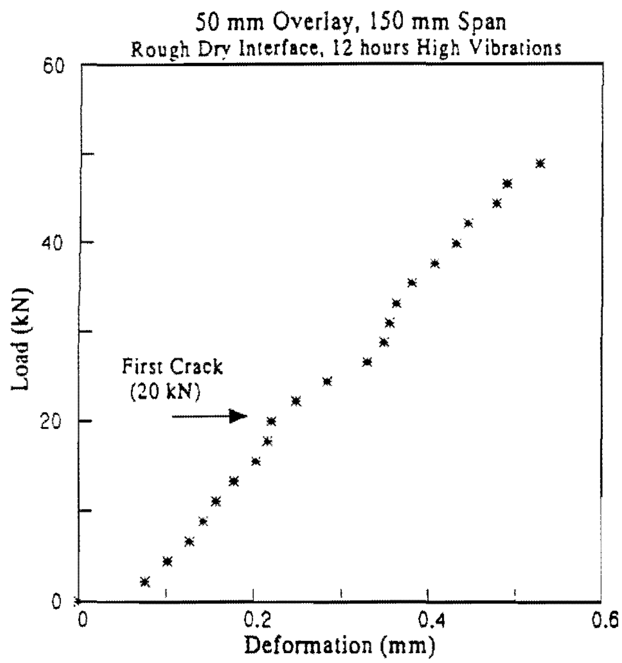
LOAD-DEFORMATION CURVES

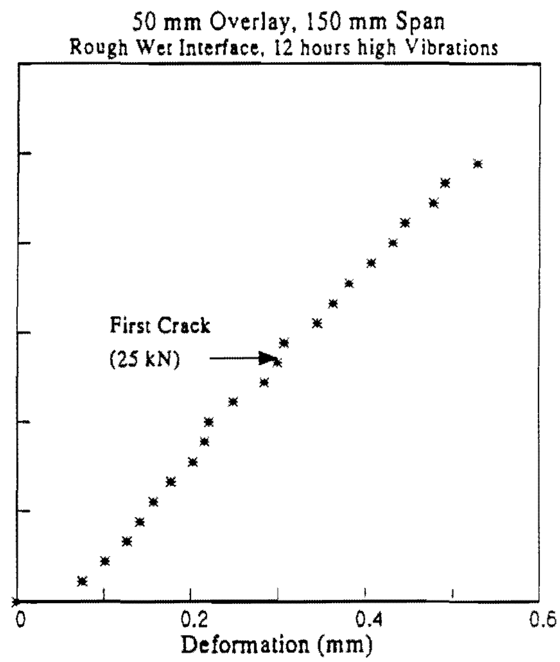

50 mm Overlay, 150 mm Span
Rough Dry Interface, No vibrations
Load (kN)
First Crack
(23 kN)
Deformation (mm)
0
20
40
60
0.2
0.4
0.6

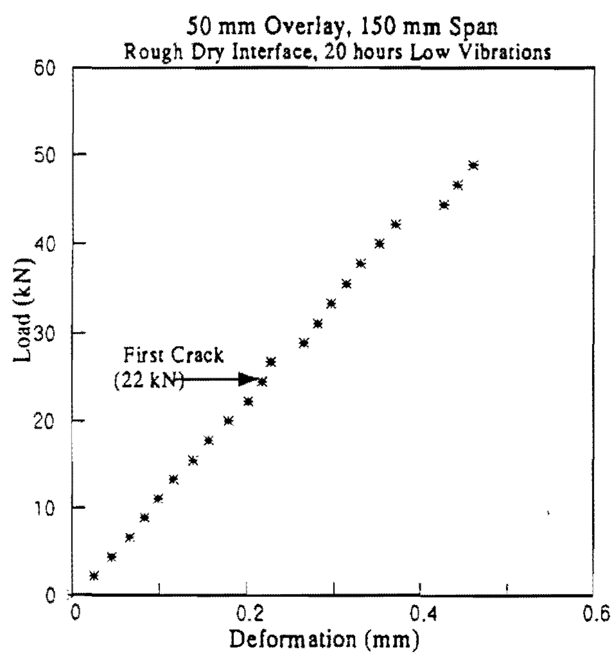

50 mm Overlay, 150 mm Span
Rough Wet Interface, No Vibrations
First Crack
(23 kN)
Deformation (mm)
0
0.2
0.4
0.6

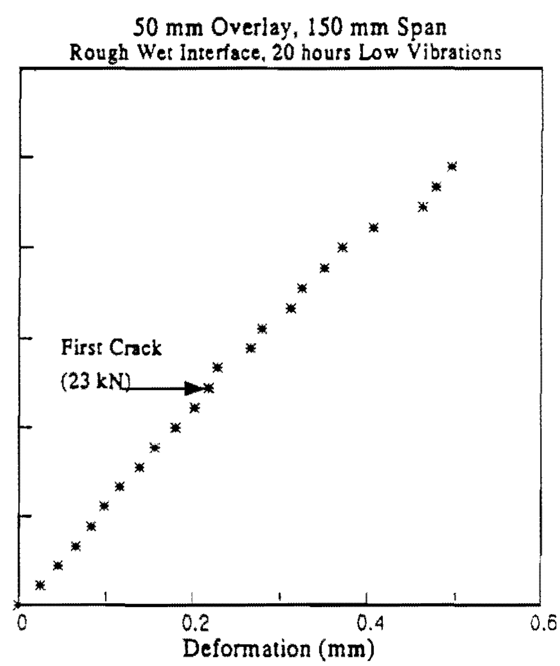

50 mm Overlay, 150 mm Span
Rough Dry Interface, 12 hours Low Vibrations
Load (kN)
First Crack
(22 kN)
Deformation (mm)
0
20
40
0.2
0.4
0.6

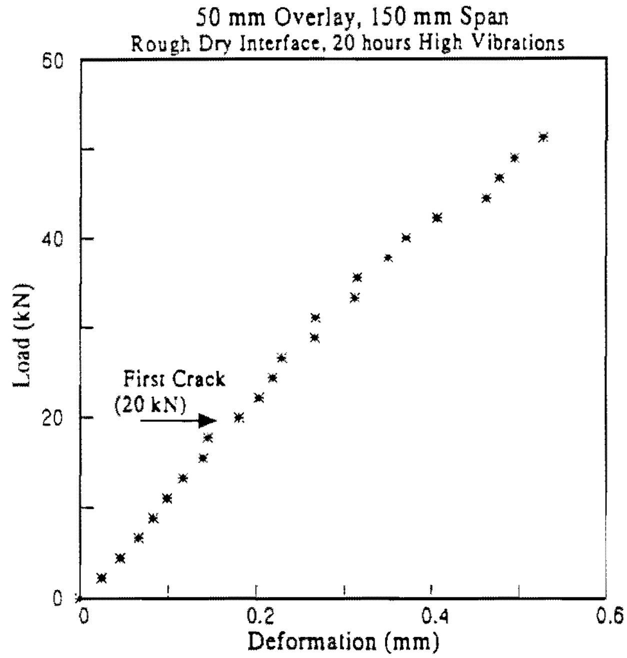

50 mm Overlay, 150 mm Span
Rough Wet Interface, 12 hours Low Vibrations
First Crack
(23 kN)
Deformation (mm)
0
0.2
0.4
0.6

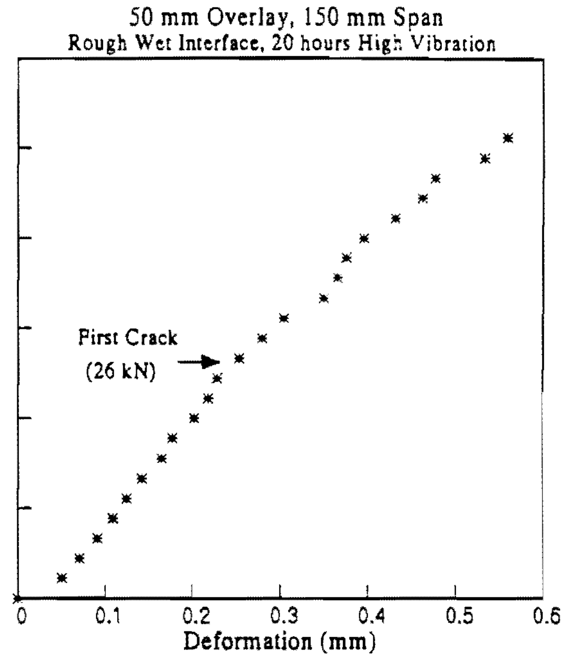

50 mm Overlay, 150 mm Span
Rough Dry Interface, 12 hours High Vibrations
Load (kN)
Deformation (mm)
First Crack
(20 kN)

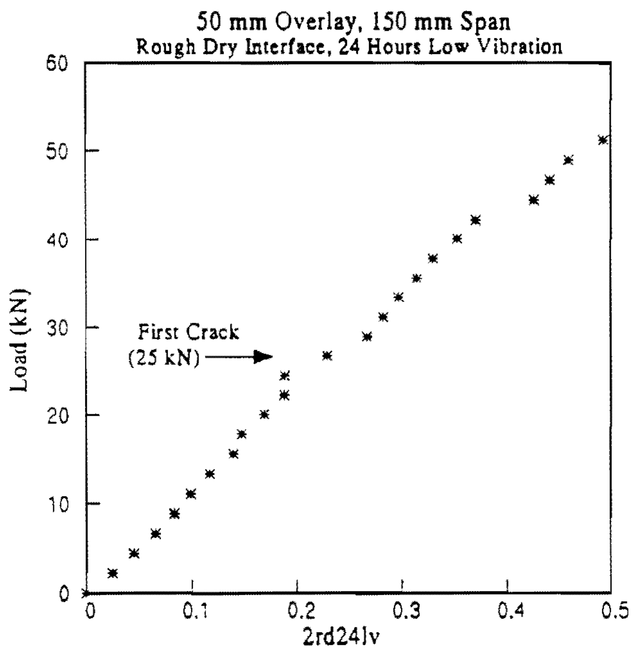

50 mm Overlay, 150 mm Span
Rough Wet Interface, 12 hours high Vibrations
Deformation (mm)
First Crack
(25 kN)

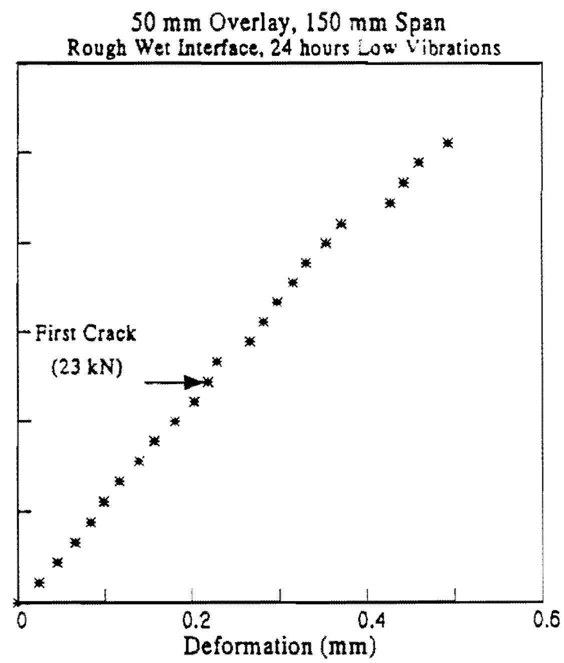

50 mm Overlay, 150 mm Span
Rough Dry Interface, 20 hours Low Vibrations
Load (kN)
Deformation (mm)
First Crack
(22 kN)

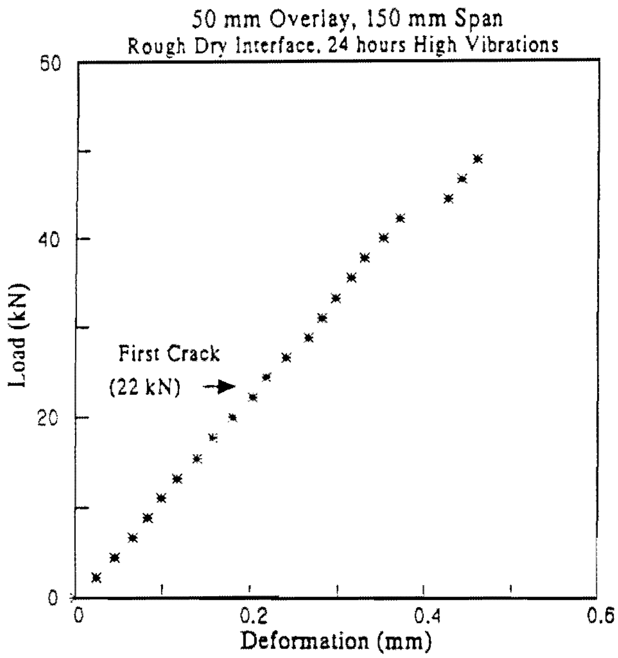

50 mm Overlay, 150 mm Span
Rough Wet Interface, 20 hours Low Vibrations
Deformation (mm)
First Crack
(23 kN)

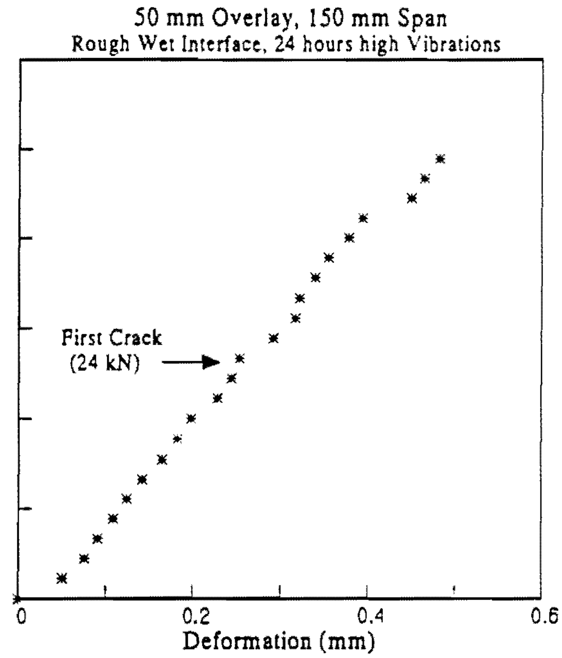

50 mm Overlay, 150 mm Span
Rough Dry Interface, 20 hours High Vibrations
Load (kN)
Deformation (mm)
First Crack
(20 kN)
0
20
40
60
0.2
0.4
0.6

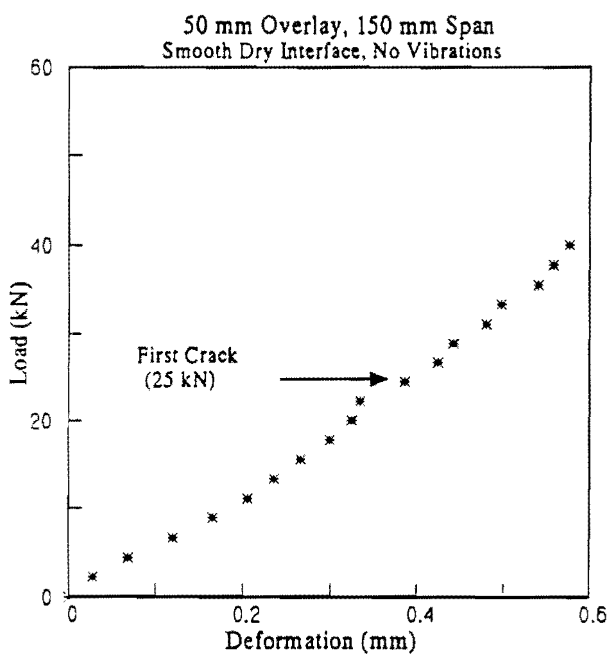

50 mm Overlay, 150 mm Span
Rough Wet Interface, 20 hours High Vibration
Deformation (mm)
First Crack
(26 kN)
0
0.1
0.2
0.3
0.4
0.5
0.6

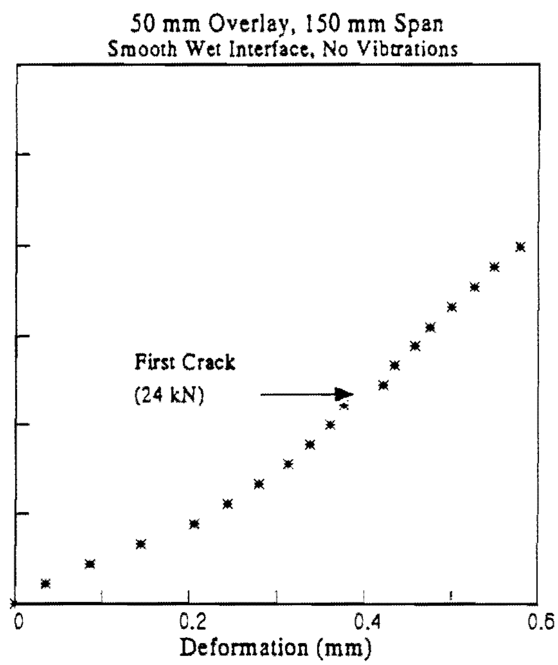

50 mm Overlay, 150 mm Span
Rough Dry Interface, 24 Hours Low Vibration
Load (kN)
2rd24lv
First Crack
(25 kN)
0
10
20
30
40
50
60
0.1
0.2
0.3
0.4
0.5

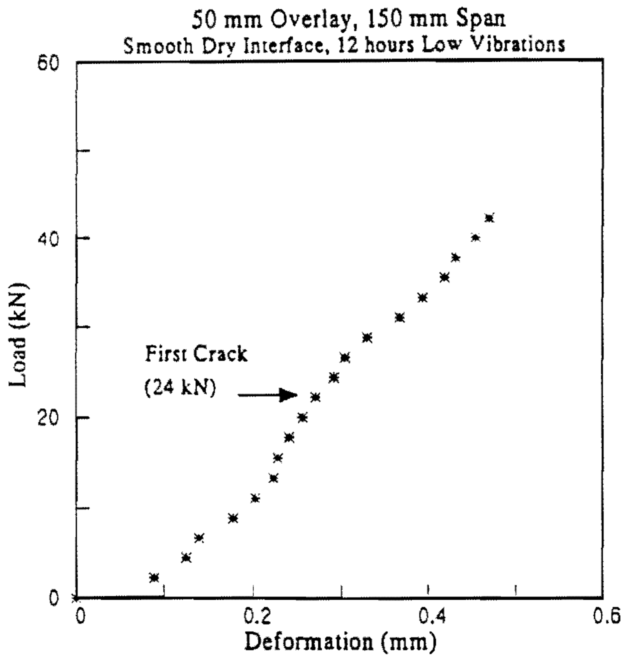

50 mm Overlay, 150 mm Span
Rough Wet Interface, 24 hours Low Vibrations
Deformation (mm)
First Crack
(23 kN)
0
0.2
0.4
0.6

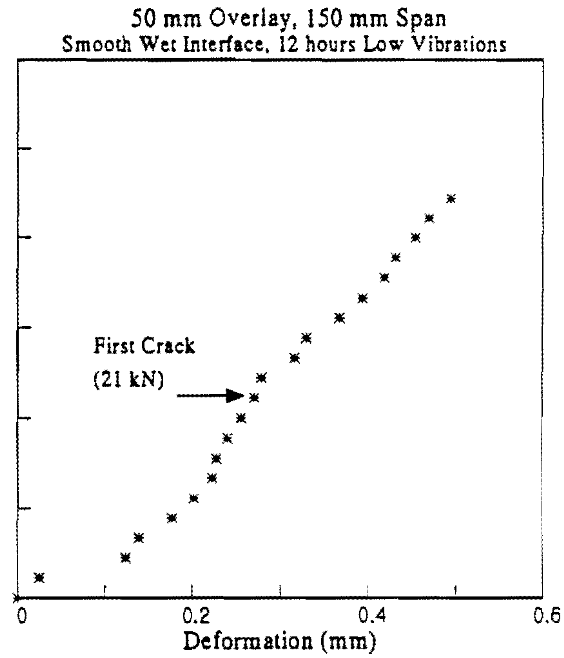

50 mm Overlay, 150 mm Span
Rough Dry Interface, 24 hours High Vibrations
Load (kN)
Deformation (mm)
First Crack
(22 kN)
0
20
40
60
0.2
0.4
0.6

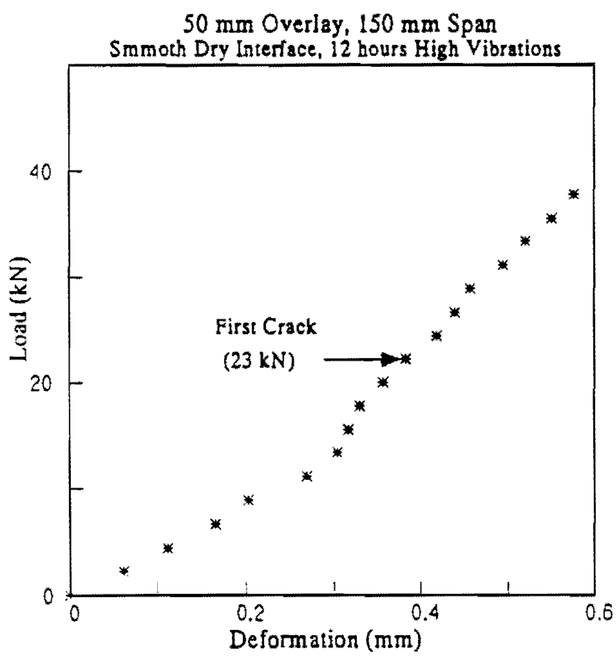

50 mm Overlay, 150 mm Span
Rough Wet Interface, 24 hours high Vibrations
Deformation (mm)
First Crack
(24 kN)
0
0.2
0.4
0.6

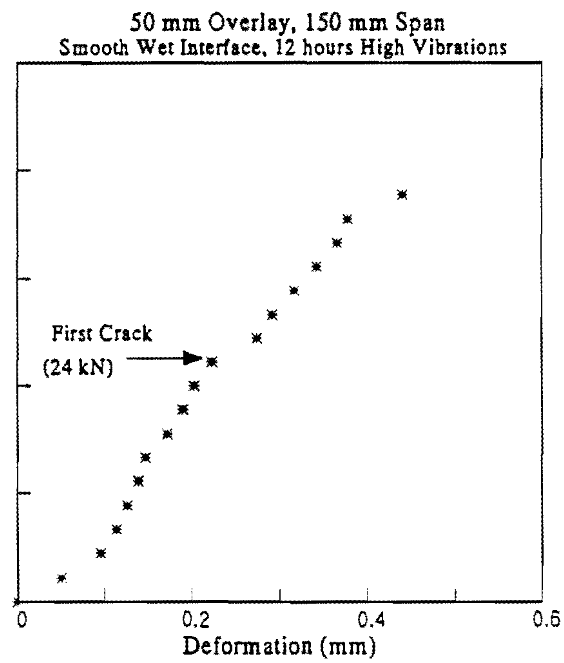

50 mm Overlay, 150 mm Span
Smooth Dry Interface, No Vibrations
Load (kN)
Deformation (mm)
First Crack
(25 kN)
0
20
40
60
0.2
0.4
0.6

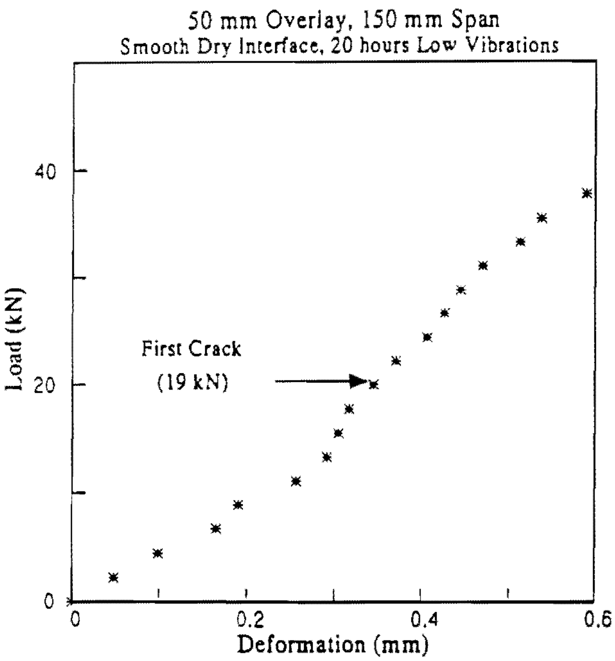

50 mm Overlay, 150 mm Span
Smooth Wet Interface, No Vibtrations
Deformation (mm)
First Crack
(24 kN)
0
0.2
0.4
0.6


50 mm Overlay, 150 mm Span
Smooth Dry Interface, 12 hours Low Vibrations
Load (kN)
Deformation (mm)
First Crack
(24 kN)
0
20
40
60
0
0.2
0.4
0.6

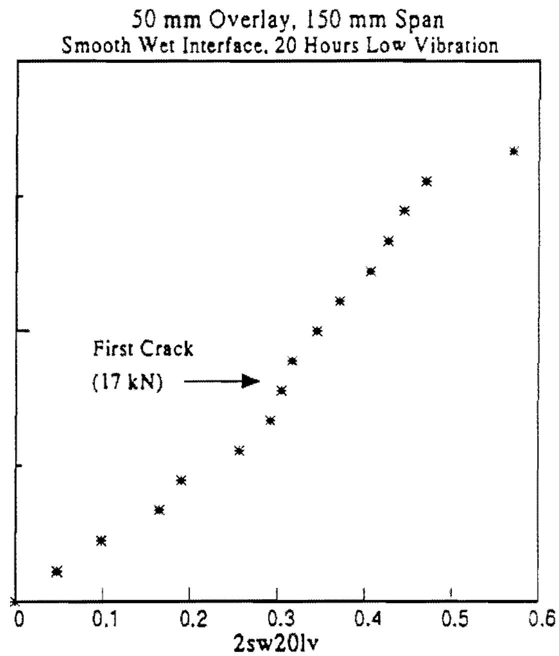

50 mm Overlay, 150 mm Span
Smooth Wet Interface, 12 hours Low Vibrations
Deformation (mm)
First Crack
(21 kN)
0
0.2
0.4
0.6


50 mm Overlay, 150 mm Span
Smmoth Dry Interface, 12 hours High Vibrations
Load (kN)
Deformation (mm)
First Crack
(23 kN)
0
20
40
0
0.2
0.4
0.6

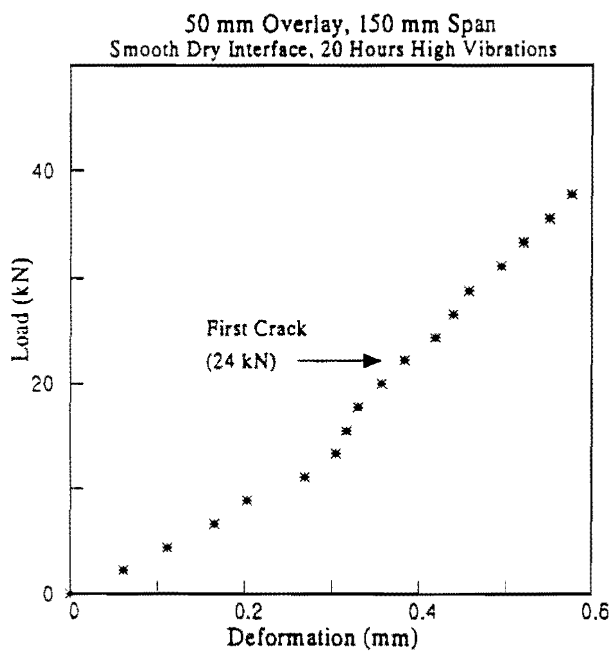

50 mm Overlay, 150 mm Span
Smooth Wet Interface, 12 hours High Vibrations
Deformation (mm)
First Crack
(24 kN)
0
0.2
0.4
0.6



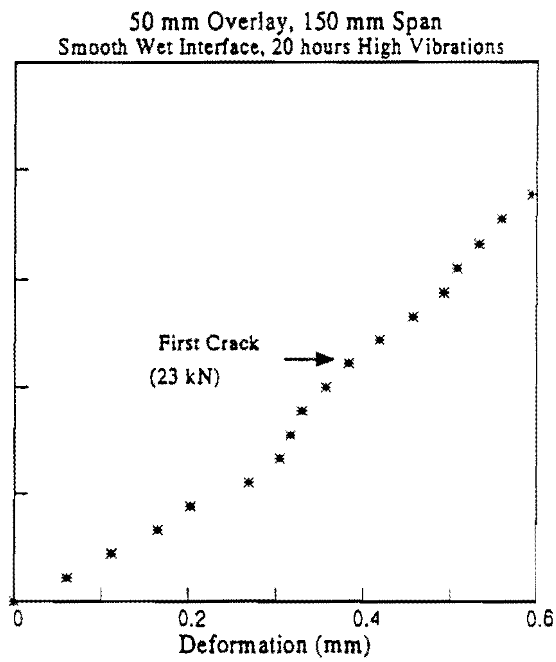
50 mm Overlay, 150 mm Span
Smooth Dry Interface, 20 hours Low Vibrations
Load (kN)
Deformation (mm)
First Crack
(19 kN)
0
20
40
0.2
0.4
0.6



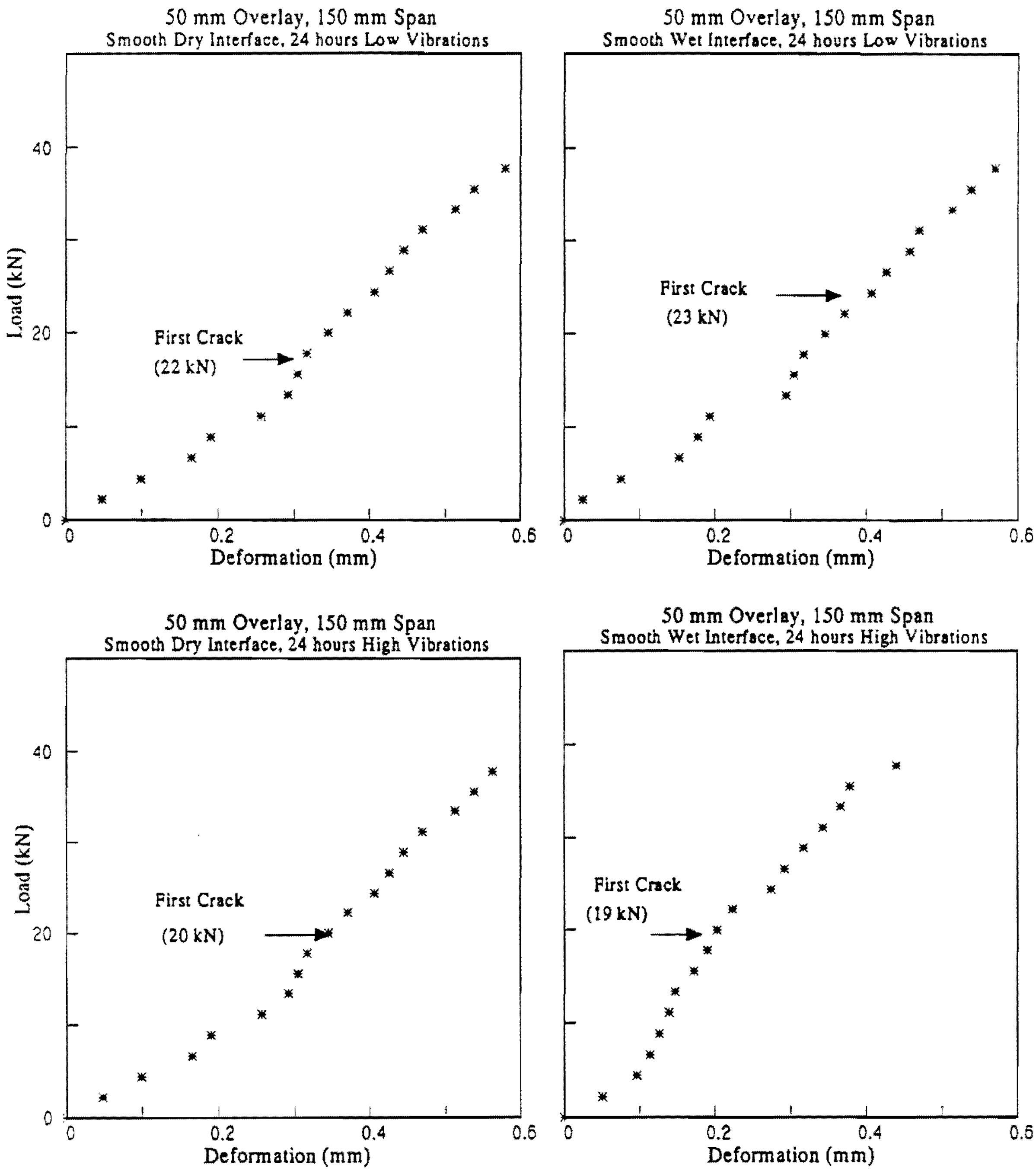
50 mm Overlay, 150 mm Span
Smooth Wet Interface, 20 Hours Low Vibration
2sw20lv
First Crack
(17 kN)
0
0.1
0.2
0.3
0.4
0.5
0.6

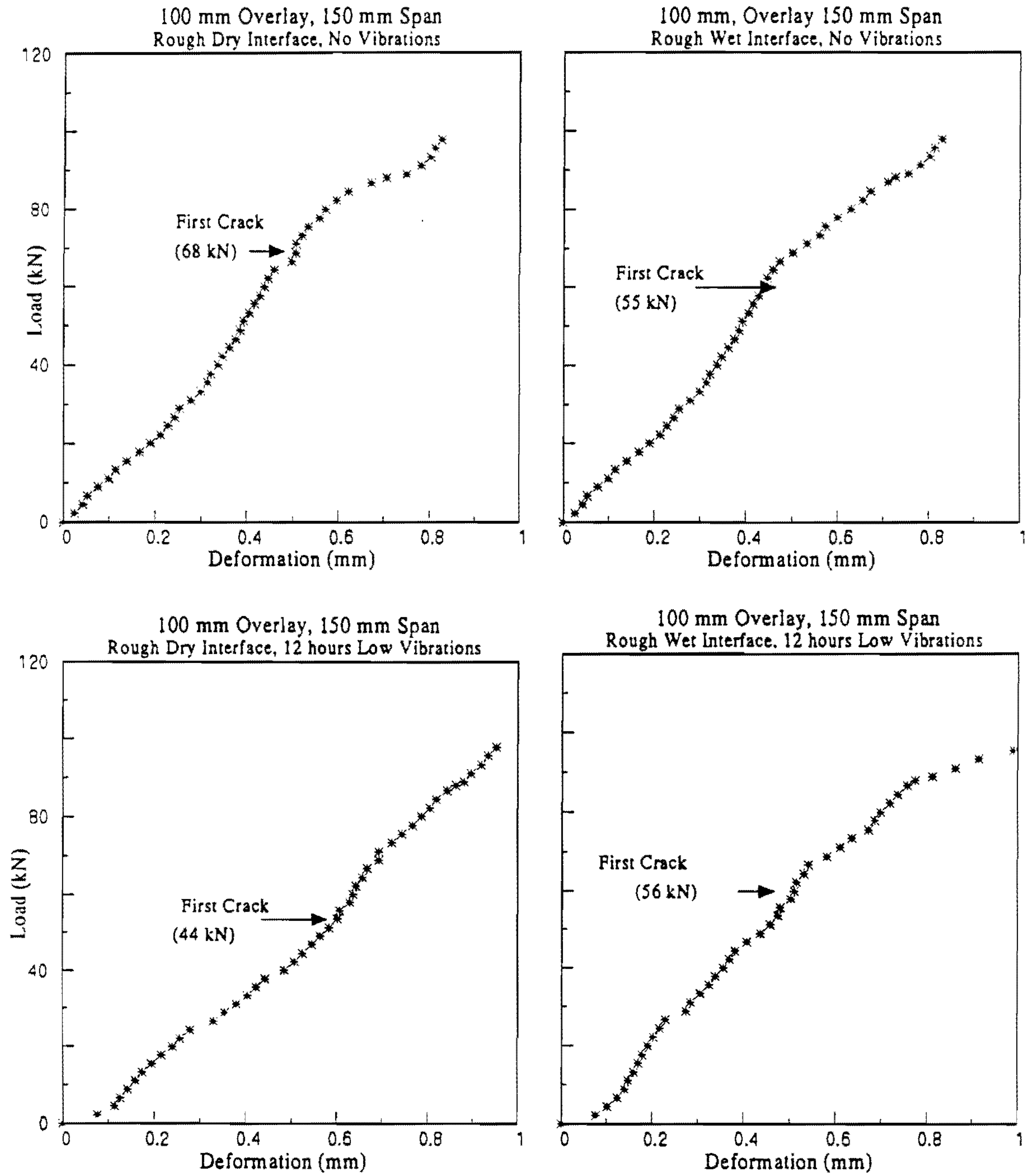


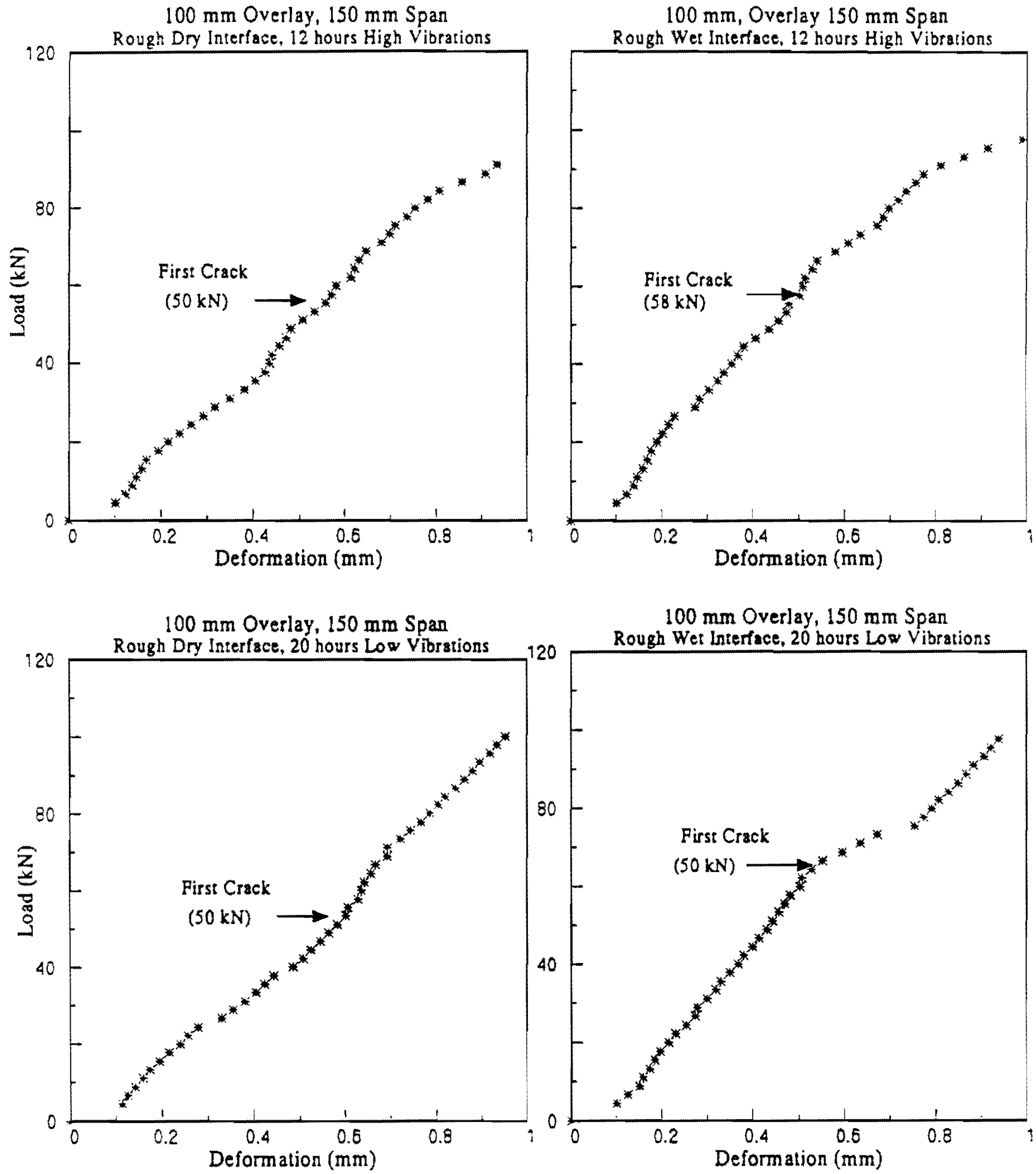
50 mm Overlay, 150 mm Span
Smooth Dry Interface, 20 Hours High Vibrations
Load (kN)
Deformation (mm)
First Crack
(24 kN)
0
20
40
0.2
0.4
0.6

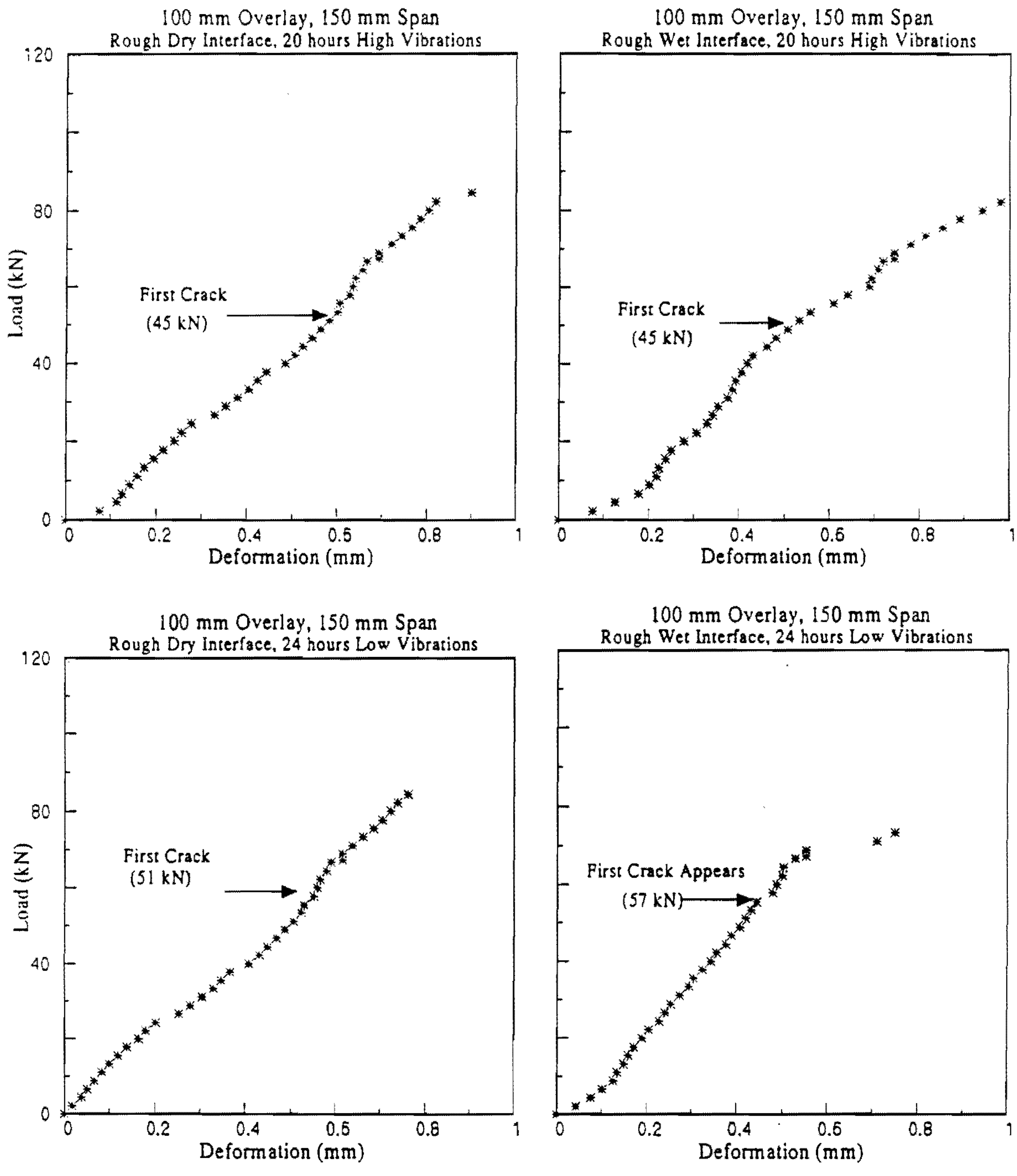


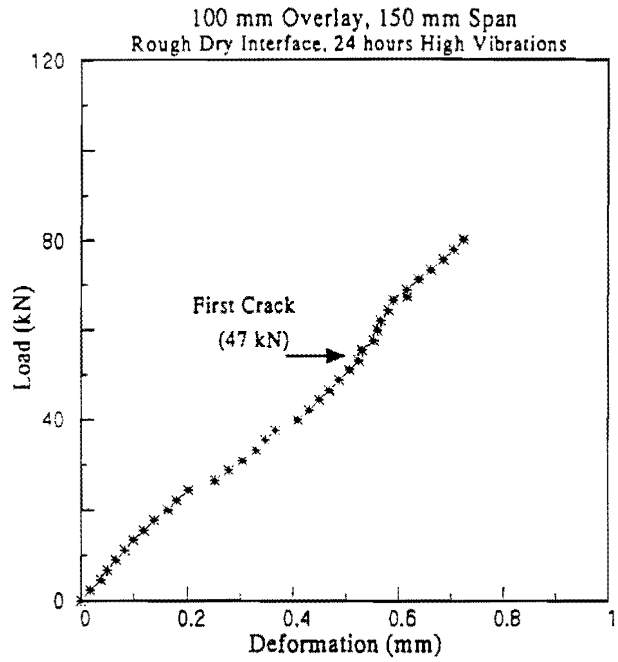
50 mm Overlay, 150 mm Span
Smooth Wet Interface, 20 hours High Vibrations
Deformation (mm)
First Crack
(23 kN)
0
0.2
0.4
0.6

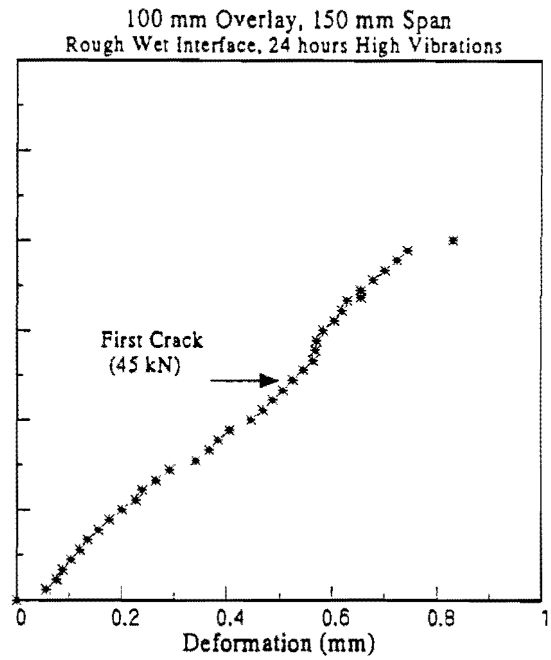

50 mm Overlay, 150 mm Span
Smooth Dry Interface, 24 hours Low Vibrations
First Crack
(22 kN)
50 mm Overlay, 150 mm Span
Smooth Wet Interface, 24 hours Low Vibrations
First Crack
(23 kN)
50 mm Overlay, 150 mm Span
Smooth Dry Interface, 24 hours High Vibrations
First Crack
(20 kN)
50 mm Overlay, 150 mm Span
Smooth Wet Interface, 24 hours High Vibrations
First Crack
(19 kN)
Load (kN)
Deformation (mm)
0
20
40
0.2
0.4
0.6

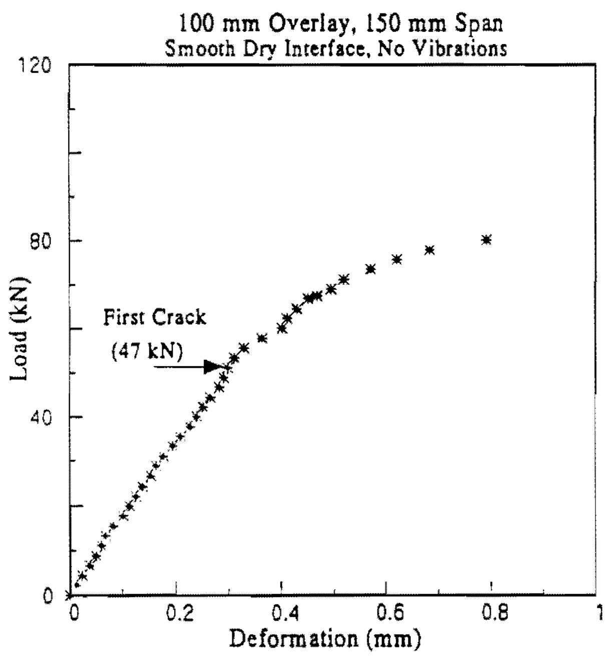

100 mm Overlay, 150 mm Span
Rough Dry Interface, No Vibrations
First Crack
(68 kN)
Load (kN)
Deformation (mm)
0
40
80
120
0.2
0.4
0.6
0.8
1
100 mm, Overlay 150 mm Span
Rough Wet Interface, No Vibrations
First Crack
(55 kN)
Deformation (mm)
100 mm Overlay, 150 mm Span
Rough Dry Interface, 12 hours Low Vibrations
First Crack
(44 kN)
Load (kN)
Deformation (mm)
100 mm Overlay, 150 mm Span
Rough Wet Interface, 12 hours Low Vibrations
First Crack
(56 kN)
Deformation (mm)

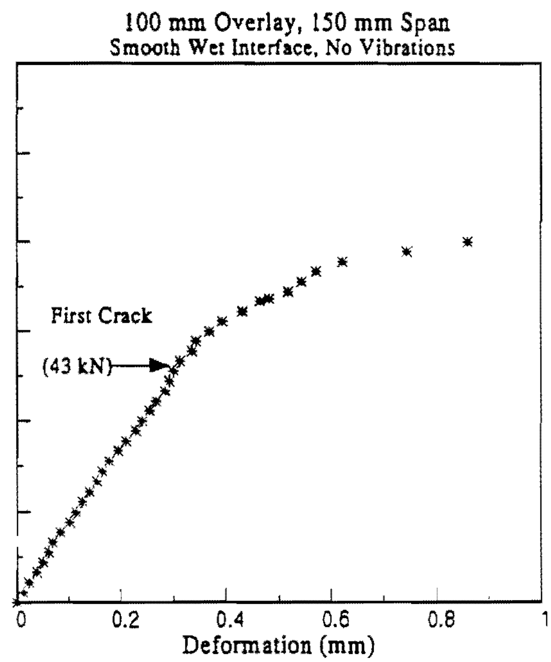

100 mm Overlay, 150 mm Span
Rough Dry Interface, 12 hours High Vibrations
First Crack
(50 kN)
100 mm, Overlay 150 mm Span
Rough Wet Interface, 12 hours High Vibrations
First Crack
(58 kN)
100 mm Overlay, 150 mm Span
Rough Dry Interface, 20 hours Low Vibrations
First Crack
(50 kN)
100 mm Overlay, 150 mm Span
Rough Wet Interface, 20 hours Low Vibrations
First Crack
(50 kN)
Load (kN)
Deformation (mm)
0
40
80
120
0
0.2
0.4
0.6
0.8
1

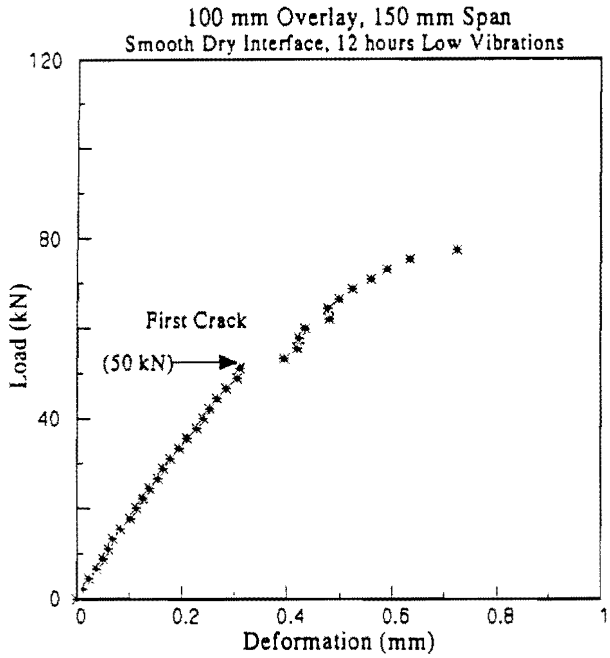

100 mm Overlay, 150 mm Span
Rough Dry Interface, 20 hours High Vibrations
Load (kN)
Deformation (mm)
First Crack
(45 kN)
120
80
40
0
0
0.2
0.4
0.6
0.8
1
100 mm Overlay, 150 mm Span
Rough Wet Interface, 20 hours High Vibrations
First Crack
(45 kN)
Deformation (mm)
100 mm Overlay, 150 mm Span
Rough Dry Interface, 24 hours Low Vibrations
Load (kN)
First Crack
(51 kN)
Deformation (mm)
100 mm Overlay, 150 mm Span
Rough Wet Interface, 24 hours Low Vibrations
First Crack Appears
(57 kN)
Deformation (mm)

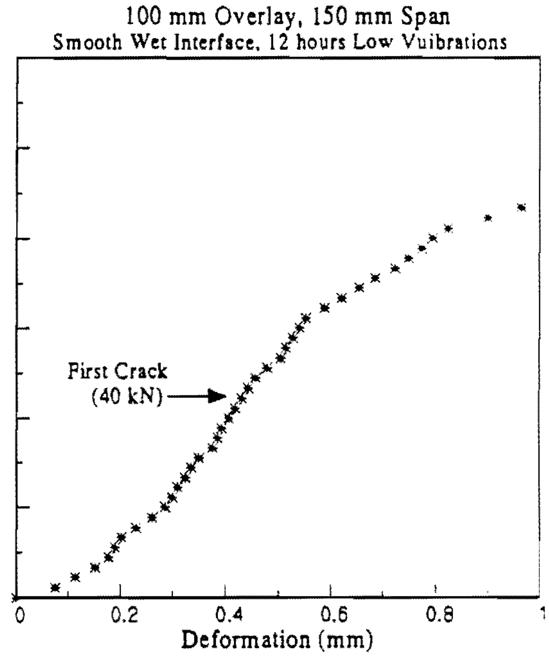

100 mm Overlay, 150 mm Span
Rough Dry Interface, 24 hours High Vibrations
Load (kN)
Deformation (mm)
First Crack
(47 kN)
0
40
80
120
0
0.2
0.4
0.6
0.8
1

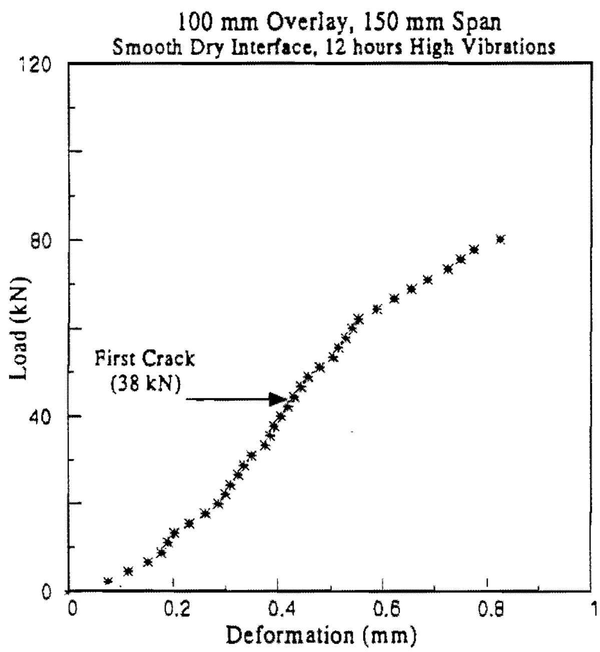

100 mm Overlay, 150 mm Span
Rough Wet Interface, 24 hours High Vibrations
Deformation (mm)
First Crack
(45 kN)
0
0.2
0.4
0.6
0.8
1

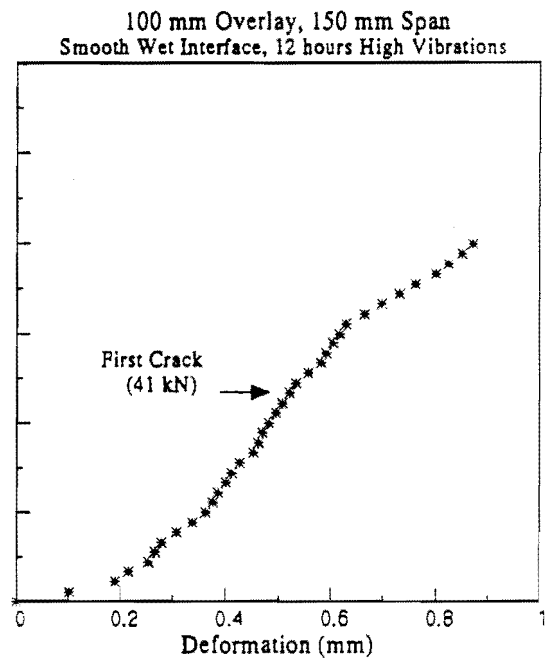

100 mm Overlay, 150 mm Span
Smooth Dry Interface, No Vibrations
Load (kN)
Deformation (mm)
First Crack
(47 kN)
0
40
80
120
0
0.2
0.4
0.6
0.8
1

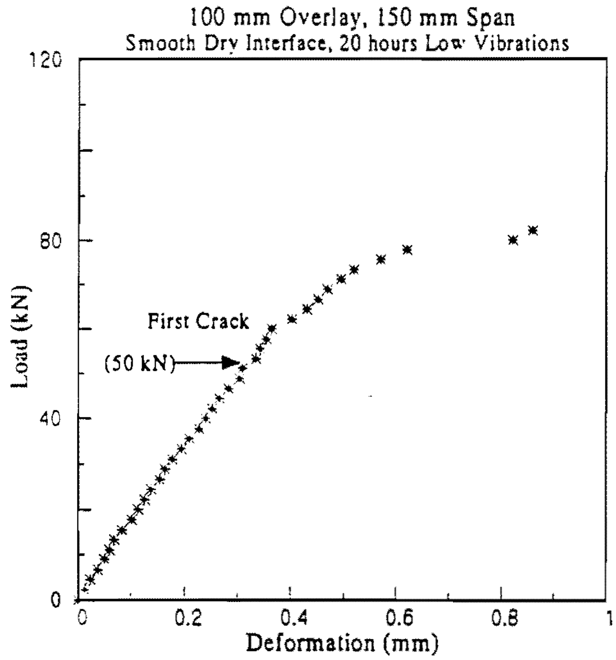

100 mm Overlay, 150 mm Span
Smooth Wet Interface, No Vibrations
Deformation (mm)
First Crack
(43 kN)
0
0.2
0.4
0.6
0.8
1

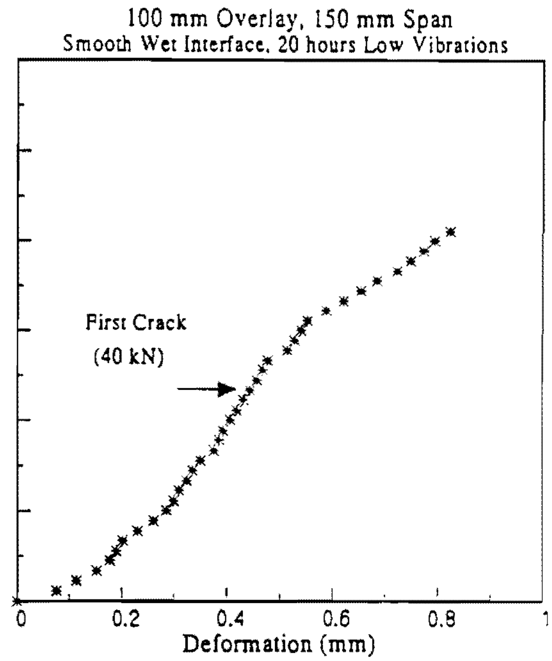

100 mm Overlay, 150 mm Span
Smooth Dry Interface, 12 hours Low Vibrations
Load (kN)
Deformation (mm)
First Crack
(50 kN)
120
80
40
0
0
0.2
0.4
0.6
0.8
1

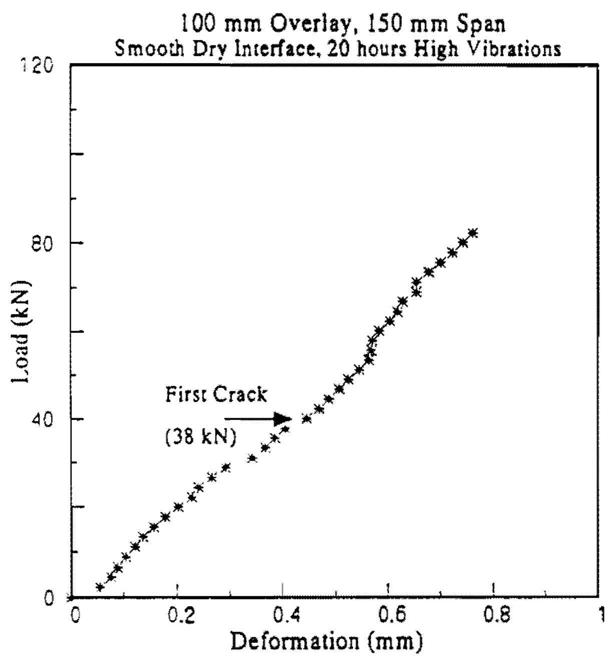

100 mm Overlay, 150 mm Span
Smooth Wet Interface, 12 hours Low Vuibrations
Deformation (mm)
First Crack
(40 kN)
0
0.2
0.4
0.6
0.8
1

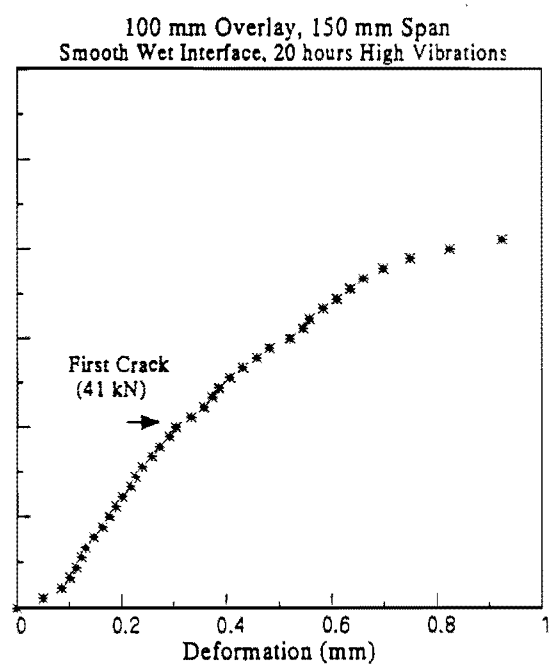

100 mm Overlay, 150 mm Span
Smooth Dry Interface, 12 hours High Vibrations
Load (kN)
Deformation (mm)
First Crack
(38 kN)
120
80
40
0
0
0.2
0.4
0.6
0.8
1

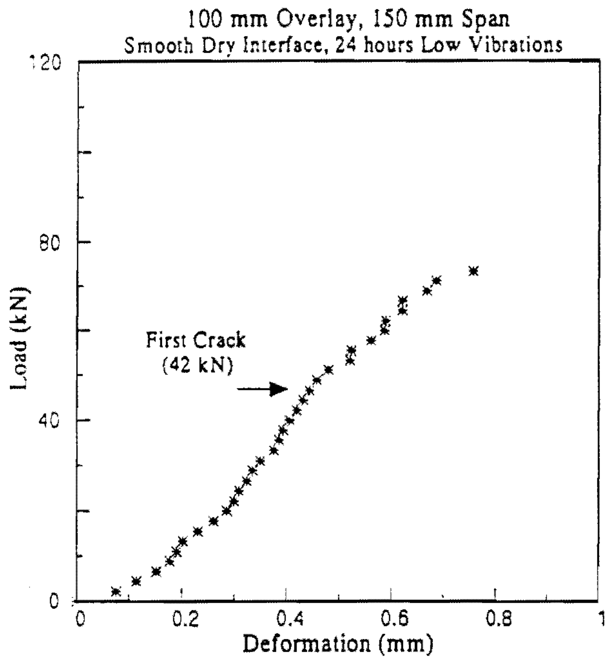

100 mm Overlay, 150 mm Span
Smooth Wet Interface, 12 hours High Vibrations
Deformation (mm)
First Crack
(41 kN)
0
0.2
0.4
0.6
0.8
1

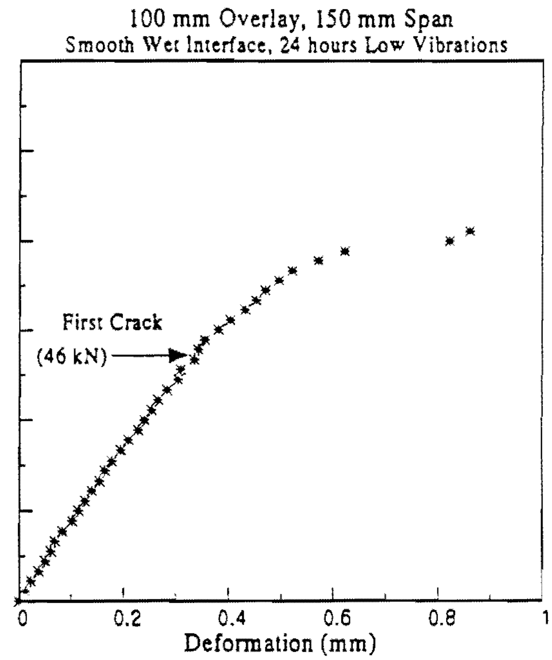

100 mm Overlay, 150 mm Span
Smooth Dry Interface, 20 hours Low Vibrations
Load (kN)
Deformation (mm)
First Crack
(50 kN)
120
80
40
0
0
0.2
0.4
0.6
0.8
1

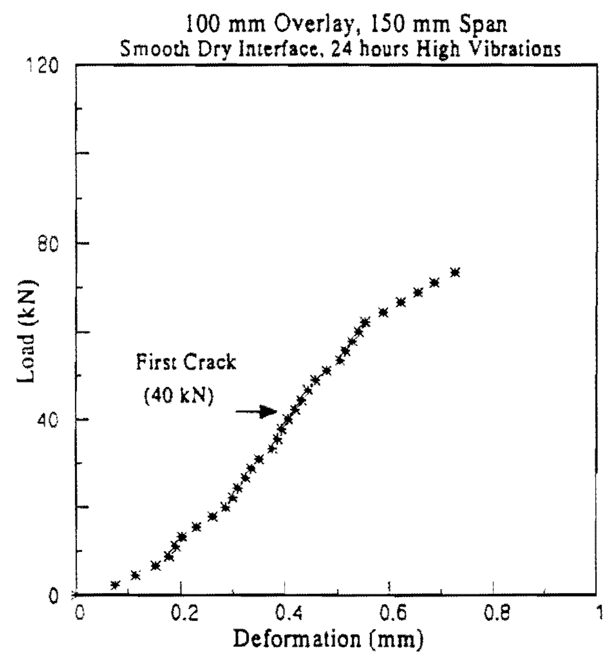

100 mm Overlay, 150 mm Span
Smooth Wet Interface, 20 hours Low Vibrations
Deformation (mm)
First Crack
(40 kN)
0
0.2
0.4
0.6
0.8
1

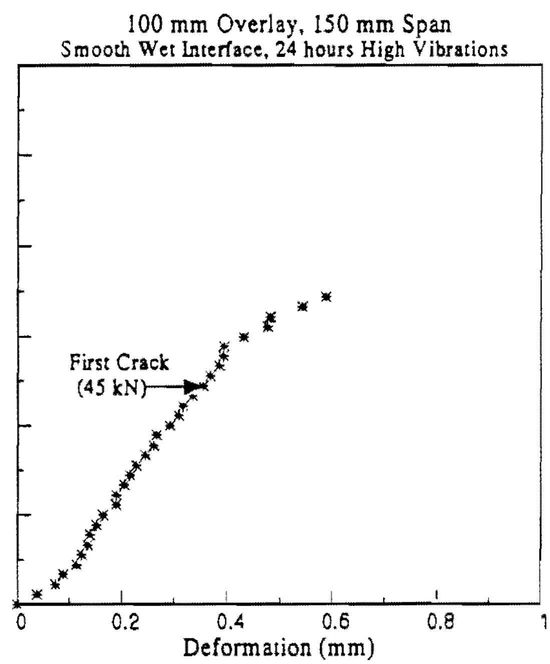

100 mm Overlay, 150 mm Span
Smooth Dry Interface, 20 hours High Vibrations
Load (kN)
Deformation (mm)
First Crack
(38 kN)
120
80
40
0
0
0.2
0.4
0.6
0.8
1


100 mm Overlay, 150 mm Span
Smooth Wet Interface, 20 hours High Vibrations
Deformation (mm)
First Crack
(41 kN)
0
0.2
0.4
0.6
0.8
1


100 mm Overlay, 150 mm Span
Smooth Dry Interface, 24 hours Low Vibrations
Load (kN)
Deformation (mm)
First Crack
(42 kN)
0
40
80
120
0.2
0.4
0.6
0.8
1


100 mm Overlay, 150 mm Span
Smooth Wet Interface, 24 hours Low Vibrations
Deformation (mm)
First Crack
(46 kN)
0
0.2
0.4
0.6
0.8
1


100 mm Overlay, 150 mm Span
Smooth Dry Interface, 24 hours High Vibrations
Load (kN)
Deformation (mm)
First Crack
(40 kN)
0
40
80
120
0.2
0.4
0.6
0.8
1


100 mm Overlay, 150 mm Span
Smooth Wet Interface, 24 hours High Vibrations
Deformation (mm)
First Crack
(45 kN)
0
0.2
0.4
0.6
0.8
1

APPENDIX B

BOND STRENGTHS

Table B.1 Bond Strengths and Tensile Strengths for 5-cm-Thick Overlays after 0-hrs of Pre-vibration Cure Time (Smooth Surface)

a) Wet Interface

Span (cm)	Vibration Level	Bond Strength, kPa		Tensile Strength, kPa	
		First Crack	Ultimate	First crack	Ultimate
75	None	344	413	10413	12493
	Low	334	420	8326	10261
	High	379	550	11453	16638
30	None	733	858	8901	10435
	Low	875	936	10632	11375
	High	848	961	10298	11680
15	None	1447	1770	8762	10720
	Low	1449	2108	8774	12768
	High	1174	1853	7107	11225

b) Dry Interface

Span (cm)	Vibration Level	Bond Strength, kPa		Tensile Strength, kPa	
		First Crack	Ultimate	First Crack	Ultimate
75	None	334	398	10111	12031
	Low	334	439	10413	11328
	High	372	462	11258	13988
30	None	781	904	9488	10992
	Low	902	1205	10969	13820
	High	689	834	8373	10138
15	None	1577	1898	9556	11497
	Low	902	1560	7328	11429
	High	1296	1738	7843	10527

Table B.2 Bond Strengths and Tensile Strengths for 5-cm-Thick Overlays after 0-hrs of Pre-vibration Cure Time (Rough Surface)

a) Wet Interface

Span (cm)	Vibration Level	Bond Strength, kPa		Tensile Strength, kPa	
		First Crack	Ultimate	First Crack	Ultimate
75	None	360	480	10890	15252
	Low	275	418	10960	12645
	High	379	407	8678	12320
30	None	903	1326	8326	15220
	Low	845	955	10269	13820
	High	1034	1168	8762	11608
15	None	1434	1991	11453	12058
	Low	1447	2120	12560	12844
	High	1473	2146	8915	13012

b) Dry Interface

Span (cm)	Vibration Level	Bond Strength, kPa		Tensile Strength, kPa	
		First Crack	Ultimate	First Crack	Ultimate
75	None	355	436	10752	13201
	Low	344	462	10413	13988
	High	296	384	8954	11612
30	None	1001	1370	12168	12046
	Low	903	1250	8878	10475
	High	1379	1428	8373	17359
15	None	1484	2157	8985	13065
	Low	1585	2256	9597	13666
	High	1379	2038	8345	12342

Table B.3 Bond Strengths and Tensile Strengths for 5-cm-Thick Overlays after 4-hrs of Pre-vibration Cure Time (Smooth Surface)

b) Wet Interface

Span (cm)	Vibration Level	Bond Strength, kPa		Tensile Strength, kPa	
		First Crack	Ultimate	First Crack	Ultimate
75	None	334	413	10413	12493
	Low	369	491	11157	14854
	High	434	460	13114	14854
30	None	733	858	8884	10435
	Low	731	951	11721	11558
	High	1083	1181	13155	14360
15	None	1447	1770	8762	10720
	Low	1105	1785	6689	10814
	High	1427	2101	8636	12742

b) Dry Interface

Span (cm)	Vibration Level	Bond Strength, kPa		Tensile Strength, kPa	
		First Crack	Ultimate	First Crack	Ultimate
75	None	334	398	10110	12031
	Low	500	750	9366	13432
	High	365	442	10413	13381
30	None	781	904	9488	10992
	Low	827	946	10045	11535
	High	965	1185	11721	14360
15	None	1577	1898	9556	11497
	Low	1208	2004	7315	12138
	High	1447	2101	8762	12805

Table B.4 Bond Strengths and Tensile Strengths for 5-cm-Thick Overlays after 4-hrs of Pre-vibration Cure Time (Rough Surface)

a) Wet Interface

Span (cm)	Vibration Level	Bond Strength, kPa		Tensile Strength, kPa	
		First Crack	Ultimate	First Crack	Ultimate
75	None	360	480	10890	15252
	Low	410	585	6246	17700
	High	450	502	10413	15201
30	None	903	1326	9869	15220
	Low	1013	1150	12307	13983
	High	1123	1398	13646	16998
15	None	1434	1991	8678	12058
	Low	1450	2123	8775	12860
	High	1620	2056	9850	12452

b) Dry Interface

Span (cm)	Vibration Level	Bond Strength, kPa		Tensile Strength, kPa	
		First Crack	Ultimate	First Crack	Ultimate
75	None	355	436	10752	13201
	Low	374	450	11323	12117
	High	310	413	9366	12493
30	None	1001	1326	12168	12046
	Low	1034	1149	12560	13971
	High	758	1309	9209	15908
15	None	1484	2157	8985	13065
	Low	1397	2123	8455	13256
	High	1259	1936	7622	11730

Table B.5 Bond Strengths and Tensile Strengths for 5-cm-Thick Overlays after 12-hrs of Pre-vibration Cure Time (Smooth Surface)

a) Wet Interface

Span (cm)	Vibration Level	Bond Strength, kPa		Tensile Strength, kPa	
		First Crack	Ultimate	First Crack	Ultimate
75	None	344	413	10413	12493
	Low	413	482	12493	14573
	High	310	502	9366	15201
30	None	733	858	8901	10435
	Low	731	895	8884	10885
	High	634	826	7702	10045
15	None	1447	1770	8762	10720
	Low	1307	1866	7913	11306
	High	1516	2071	9179	12547

b) Dry Interface

Span (cm)	Vibration Level	Bond Strength, kPa		Tensile Strength, kPa	
		First Crack	Ulitmate	First Crack	Ultimate
75	None	334	398	10110	12031
	Low	386	620	11662	18470
	High	344	413	10413	12493
30	None	781	904	9488	10992
	Low	758	826	9209	10045
	High	965	1235	11825	11721
15	None	1577	1898	9556	11497
	Low	1498	1819	9069	11019
	High	1434	1873	8678	11346

Table B.6 Bond Strengths and Tensile Strengths for 5-cm-Thick Overlays after 12-hrs of Pre-vibration Cure Time (Rough Surface)

a) Wet Interface

Span (cm)	Vibration Level	Bond Strength, kpa		Tensile Strength, kPa	
		First Crack	Ultimate	First Crack	Ultimate
75	None	360	480	10890	15252
	Low	257	613	8326	18530
	High	310	551	9366	16660
30	None	903	1326	10969	15220
	Low	758	1446	9209	17583
	High	731	1136	8884	13814
15	None	1434	1991	8678	12058
	Low	1415	2089	8567	12656
	High	1213	2008	7343	12165

b) Dry Interface

Span (cm)	Vibration Level	Bond Strength, kPa		Tensile Strength, kPa	
		First Crack	Ultimate	First Crack	Ultimate
75	None	355	436	10752	13201
	Low	275	558	8326	16869
	High	344	551	10413	16660
30	None	1001	1326	12168	12046
	Low	689	1033	8373	10885
	High	620	1135	7534	12560
15	None	1484	2157	8985	13065
	Low	1379	1936	8345	11730
	High	1309	1869	7927	11319

Table B.7 Bond Strengths and Tensile Strengths for 10-cm-Thick Overlays after 0-hrs of Pre-vibration Cure Time (Smooth Surface)

a) Wet Interface

Span (in)	Vibration Level	Bond Strength, kPa		Tensile Strength, kPa	
		First Crack	Ultimate	First Crack	Ultimate
75	None	414	657	8011	13231
	Low	483	709	9360	16360
	High	572	633	9614	12285
30	None	635	888	4914	6890
	Low	1071	1446	7128	11217
	High	849	1240	8290	9615
15	None	1842	2527	7478	9799
	Low	1933	2465	6569	8433
	High	1919	2224	7426	8621

b) Dry Interface

Span (cm)	Vibration Level	Bond Strength, kPa		Tensile Strength, kPa	
		First Crack	Ultimate	First Crack	Utimate
75	None	455	757	8812	14689
	Low	407	620	7879	12017
	High	441	551	8544	10683
30	None	850	1446	6569	11217
	Low	753	1171	5822	9080
	High	850	1157	6579	8974
15	None	1980	2237	7662	8674
	Low	1794	2175	6944	8433
	High	1670	1975	6464	7657

Table B.8 Bond Strengths and Tensile Strengths for 10-cm-Thick Overlays after 0-hrs of Pre-vibration Cure Time (Rough Surface)

a) Wet Interface

Span (cm)	Vibration Level	Bond Strength, kPa		Tensile Strength, kPa	
		First Crack	Ultimate	First Crack	Ultimate
75	None	717	1102	13887	21366
	Low	572	964	11083	18694
	High	497	675	8279	13086
30	None	1387	1860	10736	14422
	Low	1230	1612	9517	12499
	High	849	1378	7713	10683
15	None	2318	3080	8971	11940
	Low	1967	2728	7609	10576
	High	1919	2673	7396	10362

b) Dry Interface

Span (cm)	Vibration Level	Bond Stresses, kPa		Tensile Strength, kPa	
		First Crack	Ultimate	First Crack	Ultimate
75	None	697	1033	13487	20032
	Low	469	895	9080	17360
	High	414	620	8011	12017
30	None	1378	1722	10736	13354
	Low	1201	1446	7905	11217
	High	996	1412	7477	10950
15	None	2858	3011	11060	11673
	Low	2156	2769	8359	10737
	High	1998	2611	7745	10121

Table B.9 Bond Strengths and Tensile Strengths for 10-cm-Thick Overlays after 4-hrs of Pre-vibration Cure Time (Smooth Surface)

a) Wet Interface

Span (cm)	Vibration Level	Bond Strength, kpa		Tensile Strength, kPa	
		First Crack	Ultimate	First Crack	Ultimate
75	None	414	675	8011	13231
	Low	441	702	8544	13619
	High	414	716	8011	10683
30	None	635	888	4914	6890
	Low	828	1584	6409	9615
	High	883	1378	6837	10148
15	None	1842	2527	7128	9799
	Low	1849	2458	7156	9531
	High	1580	2265	6113	8781

b) Dry Interface

Span (cm)	Vibration Level	Bond Strength, kPa		Tensile Strength, kPa	
		First Crack	Ultimate	First Crack	Ultimate
75	None	455	757	8812	14689
	Low	393	695	7611	13487
	High	390	716	7611	13887
30	None	849	1446	6569	11217
	Low	1056	1584	8173	12286
	High	1021	1378	7905	10683
15	None	1980	2237	7662	8674
	Low	1842	2451	7128	9504
	High	2085	2151	8068	8339

Table B.10 Bond Strengths and Tensile Strengths for 10-cm-Thick Overlays after 4-hrs of Pre-vibration Cure Time (Rough Surface)

a) Wet Interface

Span (cm)	Vibration Level	Bond Strength, kPa		Tensile Strength, kPa	
		First Crack	Ultimate	First Crack	Ultimate
75	None	717	1102	13887	21366
	Low	500	1033	16692	20032
	High	400	675	7743	13086
30	None	1387	1860	10736	14422
	Low	1014	1419	7851	11004
	High	1353	1619	10469	12552
15	None	2318	3080	7662	11940
	Low	2256	3019	8731	11705
	High	1835	2521	7102	9773

b) Dry Interface

Span (cm)	Vibration Level	Bond Strength, kPa		Tensile Strength, kPa	
		First Crack	Ultimate	First Crack	Ultimate
75	None	697	1033	13487	20032
	Low	372	689	7210	13354
	High	421	861	8144	16692
30	None	1378	1722	10736	13354
	Low	1104	1378	8546	10683
	High	1001	1433	7745	11110
15	None	2858	3011	11060	11672
	Low	2111	2873	8170	11138
	High	1911	2596	7369	10067

Table B.11 Bond Strengths and Tensile Strengths for 10-cm-Thick Overlays after 12-hrs of Pre-vibration Cure Time (Smooth Surface)

a) Wet Interface

Span (cm)	Vibration Level	Bond Strength, kPa		Tensile Strength, kPa	
		First Crack	Ultimate	First Crack	Ultimate
75	None	414	675	8011	13231
	Low	552	1074	10683	20833
	High	469	730	9080	14155
30	None	635	888	4914	6890
	Low	828	1446	6409	11217
	High	1021	1357	7905	10522
15	None	1842	2527	7128	9799
	Low	1725	2258	6677	8756
	High	1746	2279	6757	8837

b) Dry Interface

Span (cm)	Vibration Level	Bond Strength, kPa		Tensile Strength, kPa	
		First Crack	Ultimate	First Crack	Ultimate
75	None	455	757	8812	14689
	Low	455	723	8812	14020
	High	372	620	7210	12017
30	None	849	1446	6569	11217
	Low	698	1446	5404	10148
	High	925	1357	7154	10522
15	None	1980	2237	7662	8674
	Low	2105	2258	8146	10523
	High	1635	2279	6326	9585

Table B.12 Bond Strengths and Tensile Strengths for 10-cm-Thick Overlays after 12-hrs of Pre-vibration Cure Time (Rough Surface)

a) Wet Interface

Span (cm)	Vibration Level	Bond Strength, kPa		Tensile Strength, kPa	
		First Crack	Ultimate	First Crack	Ultimate
75	None	717	1102	13887	21366
	Low	500	675	7210	13086
	High	600	730	7210	14155
30	None	1387	1860	10736	14422
	Low	1311	1584	10148	12286
	High	1315	1584	10148	12286
15	None	2318	3080	8971	11940
	Low	2409	2943	9320	11410
	High	1980	2742	7662	10629

b) Dry Interface

Span (cm)	Vibration Level	Bond Strength, kPa		Tensile Strength, kPa	
		First Crack	Ultimate	First Crack	Ultimate
75	None	697	1033	13487	20032
	Low	513	792	9932	15357
	High	503	668	9746	12951
30	None	1387	1722	10736	13354
	Low	1319	1584	10212	12552
	High	1277	1784	9881	12286
15	None	2858	3011	11060	11672
	Low	2022	2859	7823	11085
	High	2067	2604	8012	10094