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TITLE: Development of 3-D Finite Element Model to Quantify Bond Level of Thin Concrete Overlay

T. Nishiyama, M. A. Bhatti, H. D. Lee

Taizo Nishiyama
Graduate Research Assistant
Public Policy Center
Department of Civil and Environmental Engineering
4105 Seamans Center
University of Iowa
Iowa City, IA 52242-1527
Tel: 319-335-5647
Fax: 319-335-5660
E-mail: tnishiya@blue.weeg.uiowa.edu

M. Asghar Bhatti
Associate Professor
Public Policy Center
Department of Civil and Environmental Engineering
4116 Seamans Center
Iowa City, Iowa 52242-1527
Tel: 319-335-5656
Fax: 319-335-5660
E-mail: mabhatti@uiowa.edu

Hosin David Lee
Associate Professor
Public Policy Center
Department of Civil and Environmental Engineering
4117 Seamans Center
Iowa City, IA 52242-1527
Tel: 319-384-0831
Fax: 319-335-5660
E-mail: hlee@engr.uiowa.edu

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ABSTRACT

3-D finite element analysis (FEA) of pavement overlay model is developed to analyze the bonding level at the interface between the overlay and the lower pavement layer. The main objective of this research is to develop a correlation between the strains at the layer interface and the different bond levels. To model various bonding conditions, the FEA model consists of two individual layers that are connected by spring elements. By changing the stiffness of the spring elements, we were able to accurately model full-bonded, semi-bonded, and un-bonded conditions between the two layers. To validate our 3-D FEA model, we compared our computed results against the actual strain data reported in the literature. By carrying out an extensive simulation with varying values of interface spring constant, a selection matrix is developed that can be used to choose the most appropriate spring constant for a given bonding level. Our 3-D FEA model along with a parametric analysis matrix will help pavement engineers model various bonded concrete overlay designs. In the future, this research will lead to a breakthrough in modeling both short-and long-term performance of a thin concrete overlay on the existing pavement under various construction and deterioration conditions.

INTRODUCTION

Most of the national highway systems, constructed during the 1960s, have passed the end of their original design life. The rehabilitation of this system poses a significant economic and technical problem to the public agencies in the nation. During the 1970's, California used 7-9 inches of concrete overlay on several sections of existing asphalt highways. In 1993, 189 ultra-thin whitetopping (UTW) sections have been built, primarily on low-volume roadways. In Iowa over 400 miles of county roadways have been overlaid with concrete. The vast majority of these have been intersections and other locations where starting and stopping traffic has deteriorated the existing asphalt [1]

Traditional concrete pavements are designed to absorb energy by bending, and thus are made thick enough to resist stresses induced by bending. Conventional concrete overlays have been used in heavy truck corridors to combat asphalt rutting. These concrete overlays generally have a minimum thickness of 5 inches and are designed with the assumption that no bonding occurs between the existing pavement and the concrete overlay [2]. With bonding, however, the neutral axis in the concrete shifts from the middle of the concrete down toward the bottom of the concrete. This shifting lowers the stresses at the bottom of the concrete overlay. The concrete overlay and the underlying asphalt act as a composite section rather than two independent layers. This composite action significantly reduces the load-induced stresses in the concrete overlay. Therefore, the concrete overlay can be thinner for the same loading as compared to a concrete overlay with no bond with the underlying asphalt pavements. The following four factors differentiate thin concrete overlay from conventional concrete overlays [3]:

- very thin concrete overlay thickness (2 to 4 inches instead of 4 to 7 inches)
- bonding between concrete overlay and existing asphalt pavement
- short joint spacing compared to normal (2 to 6 ft instead of 12 to 18 ft)
- sufficiently thick existing asphalt pavement

The first 2-inch UTW experiment, conducted in Kentucky in 1991, showed that the corner cracking was the most predominant pavement distress and joint spacing had a significant effect on the rate of corner cracking. Joint spacing of 2 ft showed considerably less cracking than 6 ft joint spacing. The short joint spacing is expected to reduce the moment arm of the applied load, and thus minimizes the stresses due to bending. The short joint spacing also minimizes stresses due to curling and warping by decreasing the size of slab that can curl and warp. ACPA recommends that maximum joint spacing for UTW is 12 - 15 times the slab thickness. For example, for a 3-inch thick UTW, joints should be cut into concrete at 3 ft to 4.1 ft [1].

A clean surface is required for a proper bond between pavement layers. The milling creates a rough surface to develop a mechanical bond to an overlay. Synthetic fibers are often added to increase the post-crack integrity of the UTW. Maximum tensile stress developed in UTW is reported to be in the range of 180 psi and is dependent on the existing asphalt stiffness [4]. Dry surface would produce higher bond strength at the interface than wet surface [5]. The minimum asphalt thickness after milling should be at least 3 inches for UTW application [3].

In 2000, Obayashi Road Company conducted strain measurement on a thin concrete overlay model [6]. The strains at the surface, interface and the bottom of layers were measured.

They reported that the center of the pavement was well bonded; however the pavement edges were not well bonded. Another experiment of a simple thin concrete beam was conducted to measure the strain at the interface [7].

Although the perfect bonding condition could be achieved at a new construction of a thin concrete overlay, the bonding would also deteriorate over time. Currently, no study has been conducted to qualify pavement response under various deteriorated conditions. To model various levels of bonding between the concrete overlay and the existing pavement layer (or bridge deck), a 3-D FEA model was created using ANSYS software [8]. By using this model, a parametric study of various levels of bonding: full-bonded, semi-bonded and un-bonded, is performed.

FEA MODEL FOR FULLY BONDED CONCRETE OVERLAY

First, the perfect-bonded 3-D FEA model is created, which consists of three layers: the concrete overlay, the middle layer representing the existing asphalt pavement, and the lowest layer representing elastic foundation. This model does not have any sliding interface in the entire model and, thus, this model does not have any spring element to represent a bonding level.

FIGURE 1 shows the pavement cross section, where the thickness of the concrete overlay is varied from 2.5, 5, 7.5, to 10 [cm] while the thickness of asphalt layer is fixed at 15 [cm]. Young's modulus of new concrete is assumed as 3,430,000 [N/cm^2], and that of lower asphalt layer is 490,000 [N/cm^2]. The thickness of subgrade is assumed as 150 [cm] with a stiffness of 5,884 [N/cm^2]. Taking advantage of symmetry, one-fourth of concrete slab 45×45 [cm] is used to calculate the strains at the center of the pavement directly under the load. A load of 49 [kN] is applied at the center of concrete overlay and displacement constraints are applied to the edges due to the symmetry.

FIGURE 2 shows a strain distribution along the depth at the center of this FEA pavement model (▲) in 7.5 [cm] overlay. As expected, there is no difference in strain values at the layer boundary. The perfect-bonded FEA model confirms that when two layers are completely bonded, their strain values should be very close. Obayashi [6] measured strains at the interface of a thin concrete overlay with 49 kN loading. The bonding condition of the thin concrete test section showed a very good bonding condition at the center of the concrete overlay, and their measured strain values are plotted in FIGURE 2 [6]. The circle (●) and triangle (▲) symbols FIGURE 2 indicate concrete age of 7 days and 30 days, respectively. Because concrete may not have developed a good bonding in 7 days, there is a significant difference in strain values developed at the interface between the upper layer and bottom layer [6]. However, due to the increased curing condition, the concrete overlay at the age 90 days (■) produced nearly identical strain distribution.

FEA MODEL FOR THIN COCNERETE OVERLAY

We created a more general FEA model, which includes spring elements at the sliding interface between upper and lower layers. The interface between the two layers is modeled as two separate surfaces although they are geometrically located at the same coordinates. In this FEA model, spring elements are used to connect the bottom surface of the concrete overlay to the top surface of the lower layer. All other parameters such as material properties, model dimensions, mesh size, boundary condition, applied load, were kept same as the previous fully bonded FEA model. Since the general FEA model has spring elements between the two layers, these two layers can be allowed to slide. Spring constants are used to model various levels of sliding condition caused by a loss of bonding. FIGURE 3 shows a descretized FEA model including spring elements at the interface, where spring elements are connected to adjacent node at the interface.

By simulating various levels of strain in an overlay, the FEA model can be used to model the actual bonding condition between a concrete overlay and a lower pavement (or bridge deck). Spring elements are applied to the surface between the concrete overlay and lower layer in such a way that they are placed in the both longitudinal and transverse directions. Due to the longer dimension in its longitudinal direction, the strain developed in the longitudinal direction would become the most significant factor. Each spring element is connected to the adjacent nodes where one node is located on the concrete overlay, and the other node on the lower layer. It should be noted that there are two nodes at the exactly same coordinate on the surface so that those two layers can be calculated individually. The stiffness of spring element then controls whether the concrete overlay and the lower layer act as one unit (bonded) or semi-bonded, or two independent units (unbonded). Thus, the general FEA model can be used for analyzing these three different layer interface conditions.

As discussed earlier, it is very important to establish a relationship between strains at the interface and bond level because different bonding condition directly affects strain values at the interface. Therefore, we developed the following relationship, which can represent various bond levels.

Let $\Delta\varepsilon_{K=1}$ be the difference in the strain values at the bottom of the concrete overlay and at the top of the lower layer with a given spring stiffness K = 1.0 [N/cm].

$$\Delta\varepsilon_{K=1} = \left\| \varepsilon_{u,K=1} - \varepsilon_{l,K=1} \right\| \quad [1]$$

where, $\varepsilon_{u,K=1}$ is the strain at the bottom of the concrete overlay with spring stiffness K = 1 [N/cm], and $\varepsilon_{l,K=1}$ is the strain at the top of lower layer.

Then, the bond level derived from the different spring stiffnesses can be shown as follows.

$$Bond\ Level\,[\%] = \left(1 - \frac{\left\| \varepsilon_u - \varepsilon_l \right\|}{\Delta\varepsilon_{K=1}} \right) \times 100 \quad [2]$$

where, ε_u is the actual strain at the bottom of the concrete overlay, and ε_l is the actual strain at the top of lower layer.

Using the above relationship, for an unbonded overlay, the bond level is close to 0 [%]. For a full-bonded overlay, the bond level would become 100 [%]. Additionally, different bonding levels can be assigned for various levels of semi-bonded overlays.

FEM ANALYSIS RESULTS

Strains at the interface of the center of the pavement are critical in defining the bond condition whether layers are well bonded or not. Strains at the bottom of the concrete overlay and lower layer are used to determine the bond level. Fully-bonded model has essentially the same strain values at the bottom of the overlay and at the top of lower layer because two layers behave as a single layer. On the other hand, un-bonded layers have significantly different strain values because two layers are deformed independently.

FIGURE 4 shows strains at the top of the concrete overlay, bottom of the concrete overlay, top of the lower layer, and bottom of the lower layer for various spring stiffnesses [N/cm]. The critical strains representing the bond level in this figure are strains at the interface between the bottom of overlay (■) and at the top of lower layer (▲). The strain at the bottom of an overlay becomes a large positive value (tension) when spring stiffness is low. As spring stiffness increases, the strain at the bottom of an overlay would decrease. The strain at the top of lower layer, however, becomes a large negative value (compression) when the spring stiffness is low. The strain at the top of the existing pavement would increase as spring stiffness increases. The strain at the top of the existing pavement becomes the same value as the strain at the bottom of the concrete overlay as the spring stiffness becomes very high. Thus, when strains at the interface are almost same, the bond level can be considered full-bonded. When strains at the interface are significantly different, the bond level is unbonded or semi-bonded.

FIGURE 5 shows strain distribution of four locations within the 7.5 [cm] overlay: 1) the top of the concrete overlay, 2) bottom of the concrete overlay, 3) top of the lower layer, and 4) bottom of the lower layer, measured at the center of the pavement with varying spring stiffnesses. The difference between strain values at the interface is gradually increased due to the debonding between the layers. As expected, with high spring stiffness, strains at the interface are nearly identical, whereas, with low spring stiffness, strains at the interface are significantly different.

Another method is developed for modeling various levels of the semi-bonding cases using spring stiffnesses. FIGURE 6 plots the bond levels calculated using the equation (2) against the increasing levels of the spring stiffnesses for a given 7.5 [cm] thick overlay. Using this plot, the bond level can be modeled easily by changing the spring stiffness. The spring stiffness was tried from a very low value (K = 1) to a very high value ($K=10^6$). If the strain at the interface of the thin concrete overlay is known, for a given overlay design, the corresponding bond level can be obtained. As expected, the bond level increased as the spring stiffness increases. At a very high spring stiffness (say, K > 5.0E+5), however, the bond level becomes almost identical to the bond level of the perfect-bonded model. Through a parametric analysis, various bond levels (20%, 40%, 60%, and 80%) can be determined by varying spring stiffnesses (K = 1.5E+4, 2.5E+4, 5.5E+4, and 1.5E+5, respectively).

Another variable is a concrete overlay thickness which could affect strain values. FIGURE 7 shows the bond level for four different concrete overlay thickness given each spring stiffness. For a given spring stiffness, it can be observed that the thicker concrete overlay has slightly lower bond level whereas the thinner concrete overlay has slightly higher bond level. To determine the most appropriate spring stiffness for given overlay thickness and bonding level, first, a spring stiffness value was assumed for the FEM model to obtain strain values at the interface. Then, using equation (2), the bond level was calculated for given strain value and a reference strain value for a reference spring stiffness (K = 1). The same procedure is repeated a number of times for different spring stiffness values and different thicknesses to compute the bond levels. By interpolating the computed bond levels, the most appropriate spring stiffness values were estimated for four different bond levels and four different overlay thicknesses. TABLE 2 shows a set of spring stiffness values, which can be used to model different bond level for different overlay thicknesses.

Bond Level for Experimental Data

We then applied our mathematical bonding model to the experimental strain data measured by Obayashi [6]. The measured strain values at the center, the edge, and the joint of the pavement are given in TABLE 1. By using these measured strain data, the bond level was calculated assuming that $\Delta\varepsilon_{K=1}$ is the same number as the one obtained by our FEA model. Using our model, the calculated bond levels at the center, the edge, and the joint of the pavement are found as 98%, 71%, and 71%, respectively. These values are considered quite reasonable because the bond condition at the center of the pavement should be close to the full-bonded condition and the bond levels at the edge and joint of the pavement should be considered semi-bonded.

CONCLUSIONS

When overlaying a thin concrete layer on top of the deteriorated asphalt pavement, the bonding condition between the concrete overlay and the existing pavement is a very critical factor in determining its future performance. Various bond levels of a concrete overlay can be quantified from the strains developed at the bottom of the concrete overlay and the top of lower layer. Strains at the bottom of the concrete overlay and the top of lower layer become nearly identical when layers are well-bonded. In this research, a 3-D FEA model was developed to compute strain values for different bond level using spring stiffnesses between two layers, which can represent various bond levels. As spring stiffness increases, both strains at the bottom of the concrete overlay and the top the lower layer decrease.

We modeled various bond levels by using different strain values developed at the bottom of the concrete overlay and the top of the existing pavement layer (or concrete deck). By changing the spring stiffness, the general 3-D FEA model was used to simulate different levels of bonding condition such as bonded, semi-bonded, and unbonded. This paper presents a complete strain analysis of the concrete overlay placed over the asphalt pavement. Strain distribution of the well-bonded UTW is considered linear whereas strain distribution of the un-bonded or semi-bonded is bilinear.

Using our general FEA model and bonding formula, a spring stiffness matrix is developed for different bond levels and different overlay thicknesses. Then, we used our matrix to determine the bond levels where strains were measured at the interface. Our computed bond levels can be considered reasonable for the center and edges of the test slab. This marix can be used to help pavement engineers select the most appropriate spring stiffnesses for a given bonding condition and overlay thickness. Our 3-D FEA model along with the bond level matrix will lead to a breakthrough in modeling both short-and long-term performance of a thin concrete overlay on the existing pavement under different construction and deterioration conditions.

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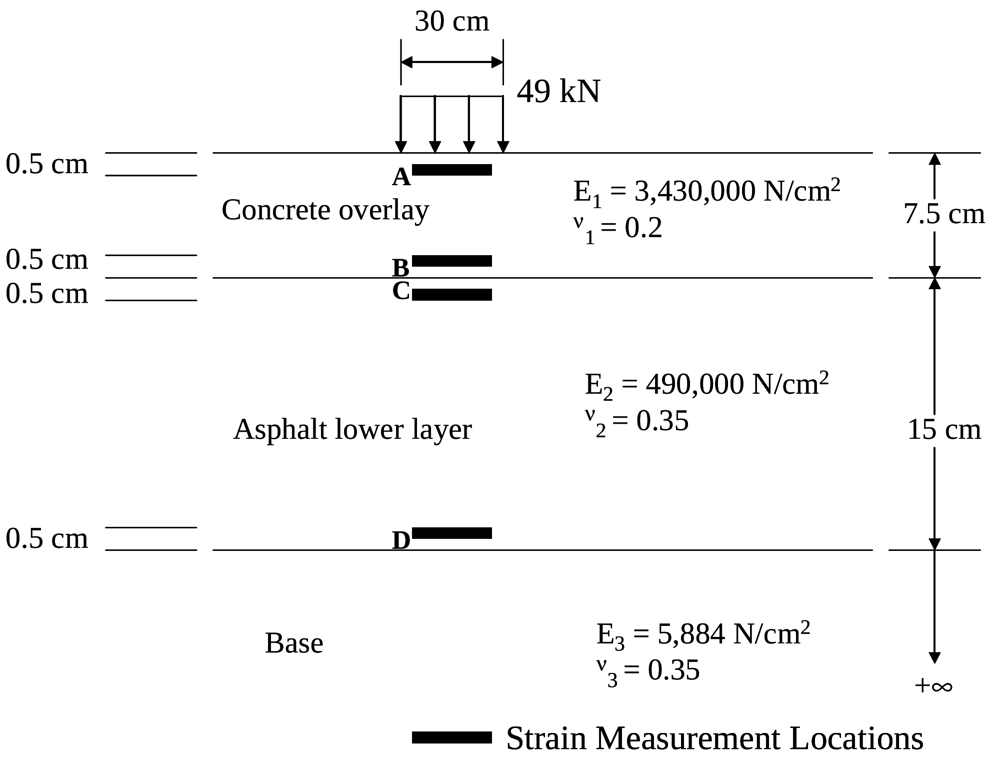

FIGURE 1 Cross section of the concrete overlay.

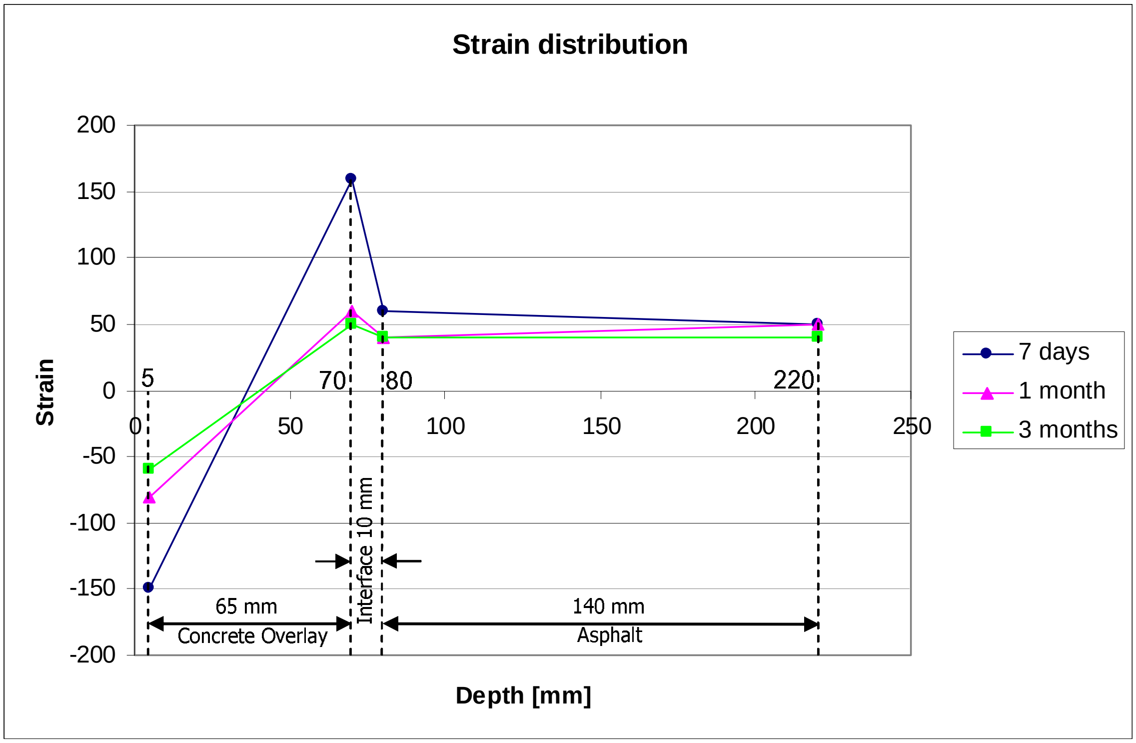

FIGURE 2 Stress distribution measured by Obayashi Road Company [6].

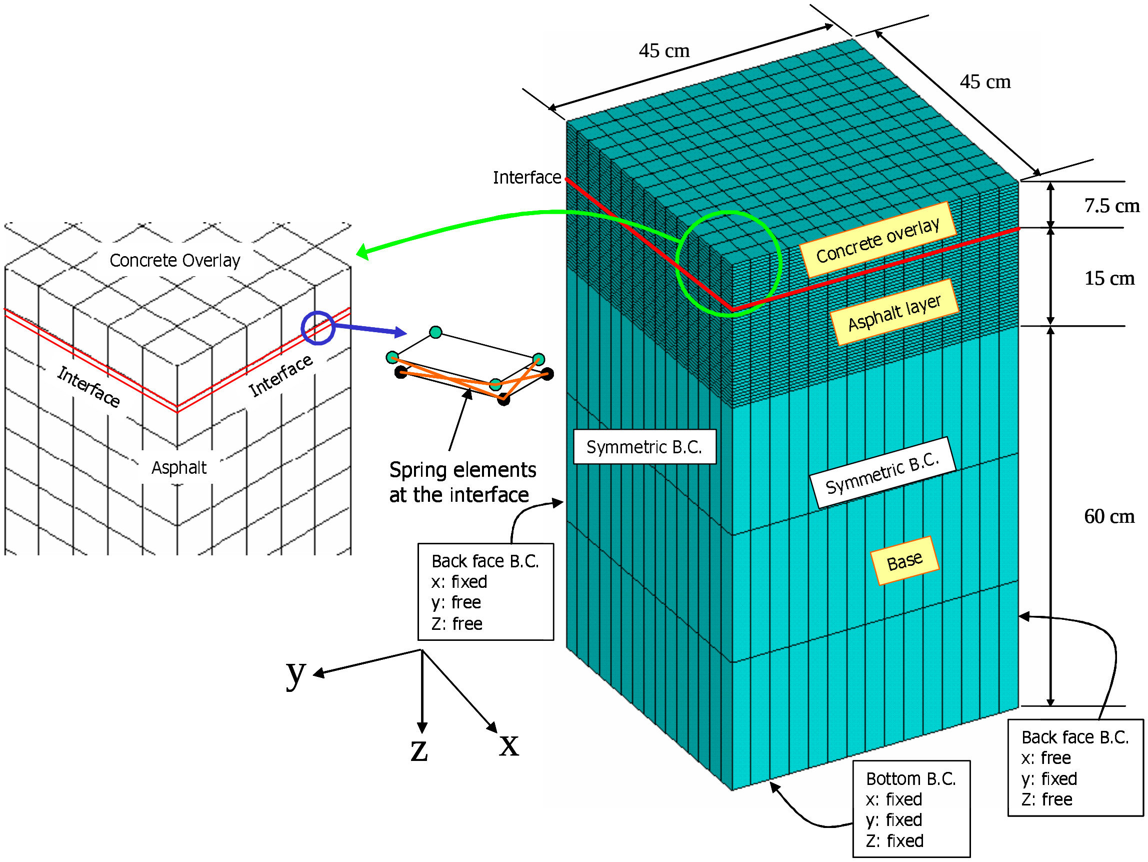

FIGURE 3 3-D FEA model of concrete overlay on asphalt pavement.

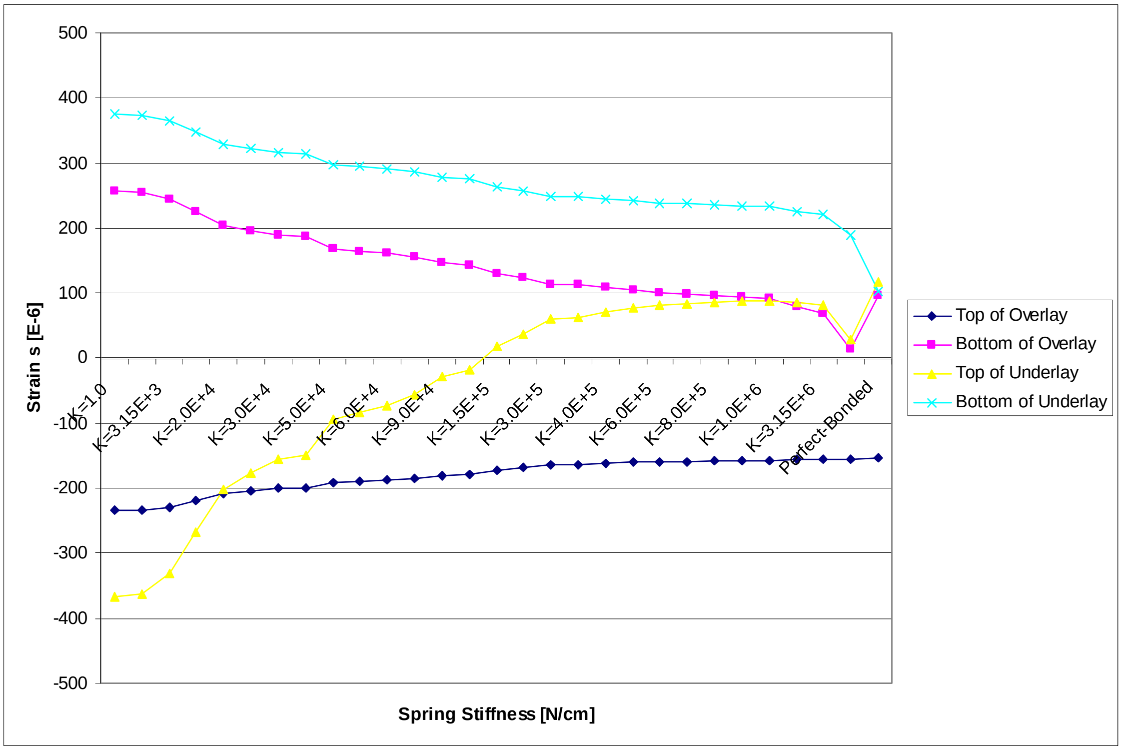

FIGURE 4 Plot of computed strains against the spring stiffnesses for 7.5 cm overlay.

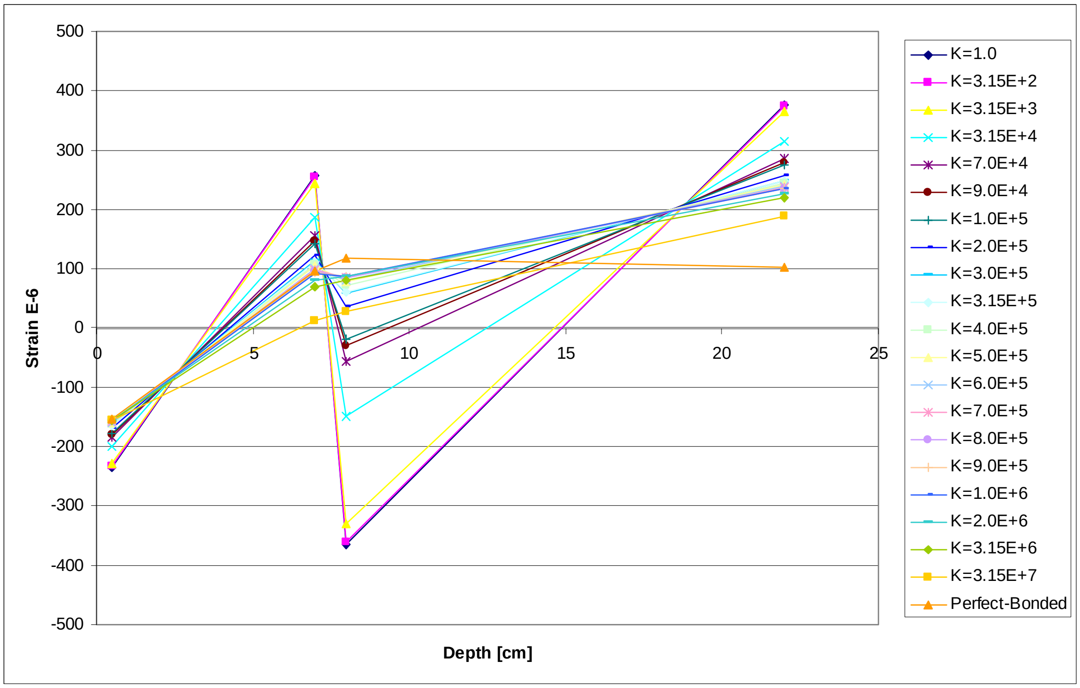

FIGURE 5 Strain distribution along the depth with different spring stiffness for 7.5 cm overlay.

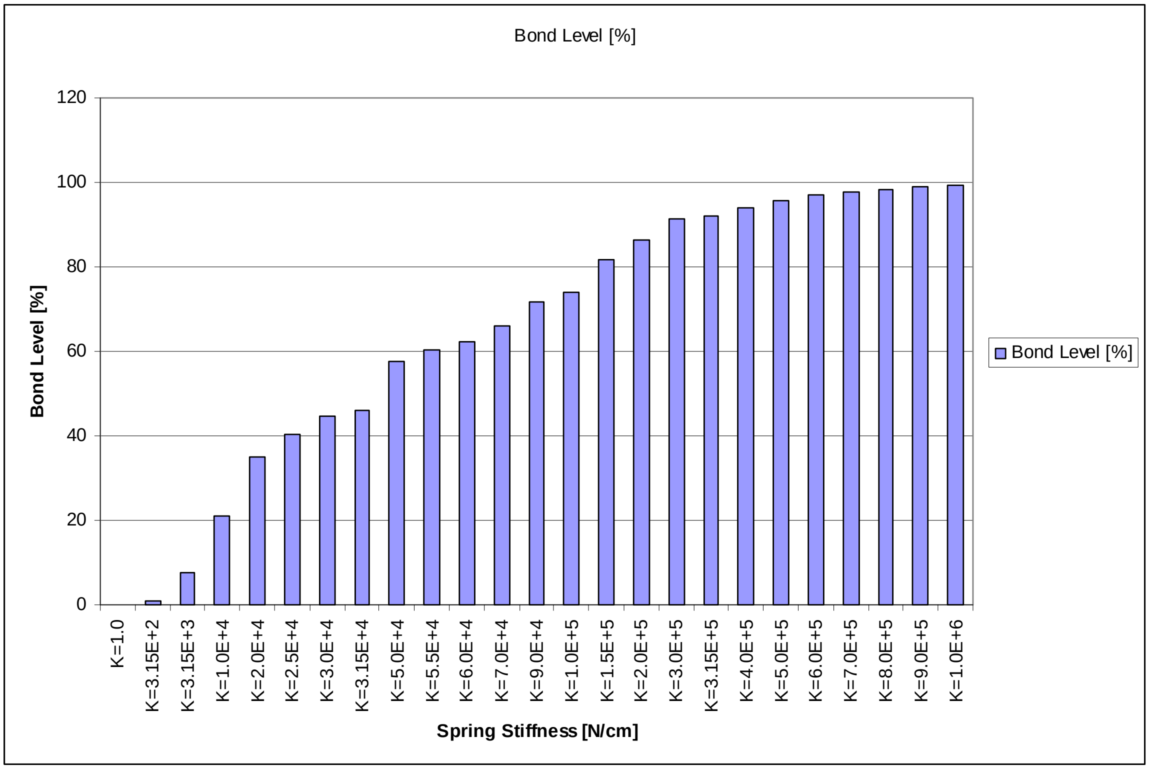

FIGURE 6 Plot of computed bond levels against spring stiffnesses for 7.5 cm overlay.

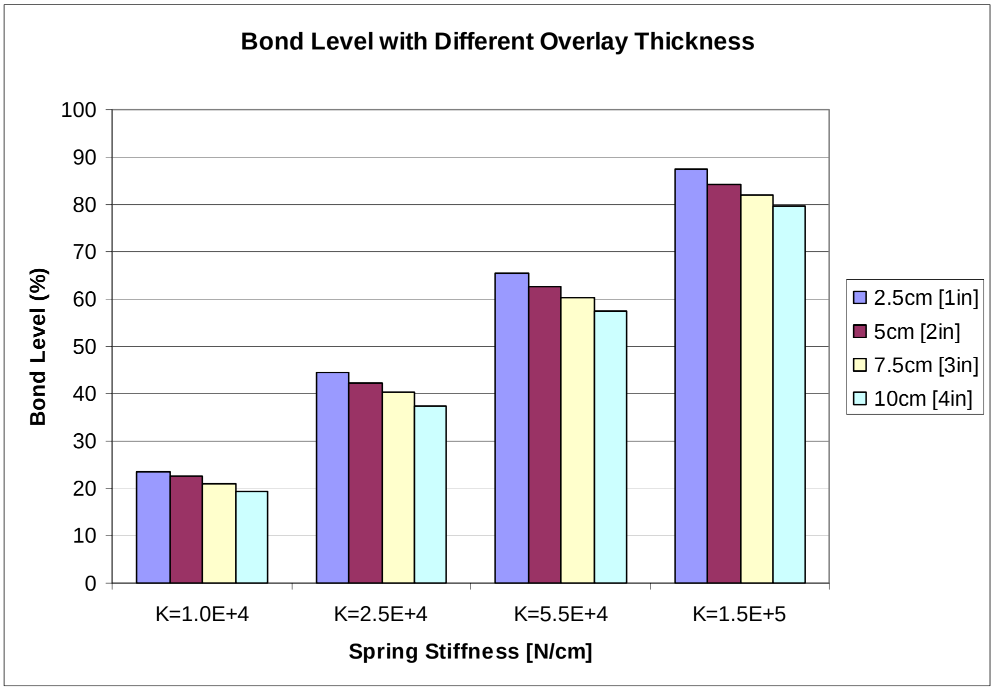

FIGURE 7 Plot of bond levels against spring stiffnesses and overlay thicknesses.

TABLE 1 Experimentally Measured Strains

Location	Center	Edge	Joint
Top of overlay	-50 E-6	-100 E-6	-160 E-6
Bottom of overlay	50 E-6	200 E-6	180 E-6
Top of lower layer	40 E-6	20 E-6	0
Bottom of lower layer	40 E-6	80 E-6	40 E-6

TABLE 2 Spring Stiffness Matrix for Different Bond Levels and Overlay Thicknesses

	20 %	40 %	60 %	80 %
10 cm	1.05E+4	2.79 E+4	6.12 E+4	1.54 E+5
7.5 cm	9.38 E+3	2.48 E+4	5.37 E+4	1.38 E+5
5 cm	8.62 E+4	2.28 E+4	4.95 E+4	1.23 E+5
2.5 cm	8.11 E+3	2.11 E+4	4.42 E+4	1.03 E+5