Theoretical versus Measured Flexible Pavement Responses Under Dynamic Loading

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ABSTRACT: As mechanistic-empirical design of pavement structures advances toward full implementation, there is a need to evaluate the accuracy of theoretical load response models and backcalculation procedures employed in the design and analysis processes. To that end, a full-scale pavement structural study is underway at the National Center for Asphalt Technology (NCAT) Test Track to investigate the accuracy of the applicable models. Falling weight deflectometer (FWD) testing was conducted on eight different cross sections at the facility. The sections represented different pavement thicknesses, and use of modified and unmodified asphalt binders. FWD loads were dropped directly on top of and in close proximity to strain gauges and pressure cells embedded at different depths within the sections. This enabled the measurement of both surface deflections and in situ pavement responses under FWD loading. The surface deflections were used to backcalculate elastic layer properties within each test section. The properties were then used in forward calculation to compute stresses and strains at locations coinciding with embedded instrumentation. Direct comparisons were made between predicted pavement responses and measured responses to evaluate the effectiveness of both the backcalculation and forward calculation models. Better agreement was observed in the horizontal strain responses of the asphalt layer when compared to vertical pressures measured in the base and subgrade layers, respectively. However, it was generally found that layered elastic back- and forward-calculation was sufficiently accurate for the conditions at the NCAT Test Track and also served to validate the sensor installation procedures.

KEY WORDS: Backcalculation, FWD, Instrumentation, Stress, Strain

1.0 INTRODUCTION

Most mechanistic-empirical design procedures for flexible pavements, such as KENLAYER, VESYS and ILLI-PAVE, use a multilayer linear elastic model for the calculation of stress and strain in the pavement structure (Huang, 1993). However, the consideration of pavement layers as a continuum of isotropic linear elastic materials and the treatment of vehicle loads as static and uniformly distributed over circular areas are major simplifications (Mateos and Snyder, 2002). The inability of the multilayer linear elastic model to consider dynamic effects is a serious deficiency, as several experimental studies have shown significant increases in strain at the bottom of the HMA layer with decreasing vehicle speed (Mateos and Snyder, 2002).

In recent years, there have been several attempts at correlating actual viscoelastic, dynamic response from a live-loaded pavement structure to its calculated response through linear-elastic models. There has been limited success in providing a working correlation between measured and theoretical response. In 2002, Mateos and Snyder attempted a validation of linear-elastic flexible pavement structural response models with data from the Minnesota Road Research Project. It was met with limited success because it was not possible to calibrate or fit the model to observe longitudinal and transverse strains simultaneously because the pavement behaved more stiffly longitudinally than transversely (Mateos and Snyder, 2002). Mateos and Snyder also discovered that they could not match or fit longitudinal or transverse strain measurements simultaneously with moving loads.

Another attempt at correlating actual pavement response to a calculated pavement response was taken by Guzina and Osburn in 2002. They discovered in their analysis that there was a high percentage of error in predicting layer moduli due to the presence of a shallow rigid layer or a seasonal stiff layer. This high error percentage would not allow an accurate comparison between actual and calculated pavement response (Guzina and Osburn, 2002).

A different approach was taken by Xu et al. (2002) to correlate actual pavement response to calculated pavement response. They believed that reliable prediction of stresses and strains in a pavement structure could be made directly from falling weight deflectometer (FWD) deflections without backcalculation of layer moduli. Both regression and artificial neural network techniques, used in conjunction with nonlinear synthetic databases, were used in developing this prediction procedure. This research endeavor, which resulted from NCHRP 10-48, was somewhat successful in developing regression equations for predicting horizontal strain in the asphalt layer as well as vertical strain in the base and subgrade layers. The root mean square error between the actual strains in the pavement structure and the predicted strains from these regression equations, however, ranged from 13% to 21% (Xu et al., 2002).

One of the most recent attempts at correlating actual measured pavement response to calculated or predicted response is currently taking place in the NCAT Test Track 2003 Structural Experiment in Auburn, Alabama. This most recent attempt was needed to compare measured pavement response to calculated, linear-elastic modeled response without the presence of a seasonal stiff layer or shallow rigid layer. This study showed the effectiveness of linear-elastic pavement response prediction when these elements are not present in the pavement structure. The main difference between this most recent attempt and past attempts is that the 2003 Test Cycle’s Structural Experiment contains embedded instrumentation to directly measure distresses within the pavement structure when loads are applied. Within the 2003 Structural Experiment, there are eight instrumented test sections of varying thickness and material properties for the purpose of exhibiting differing performance and types of distress over the two-year trafficking cycle (Timm et al., 2004). The findings of this study are shown herein.

1.1 Objective

The objective of this study was to compare measured dynamic responses from FWD testing and compare them to calculated responses from computer-generated linear-elastic models of the eight experimental sections.

2.0 METHODOLOGY

As previously mentioned, the 2003 NCAT Test Track Structural Experiment contains eight instrumented pavement test sections. A layout of these eight test sections are shown in Figure 1. Each test section was built on a layer of improved subgrade fill on top of the existing subgrade. The same improved subgrade fill was used in all eight sections.

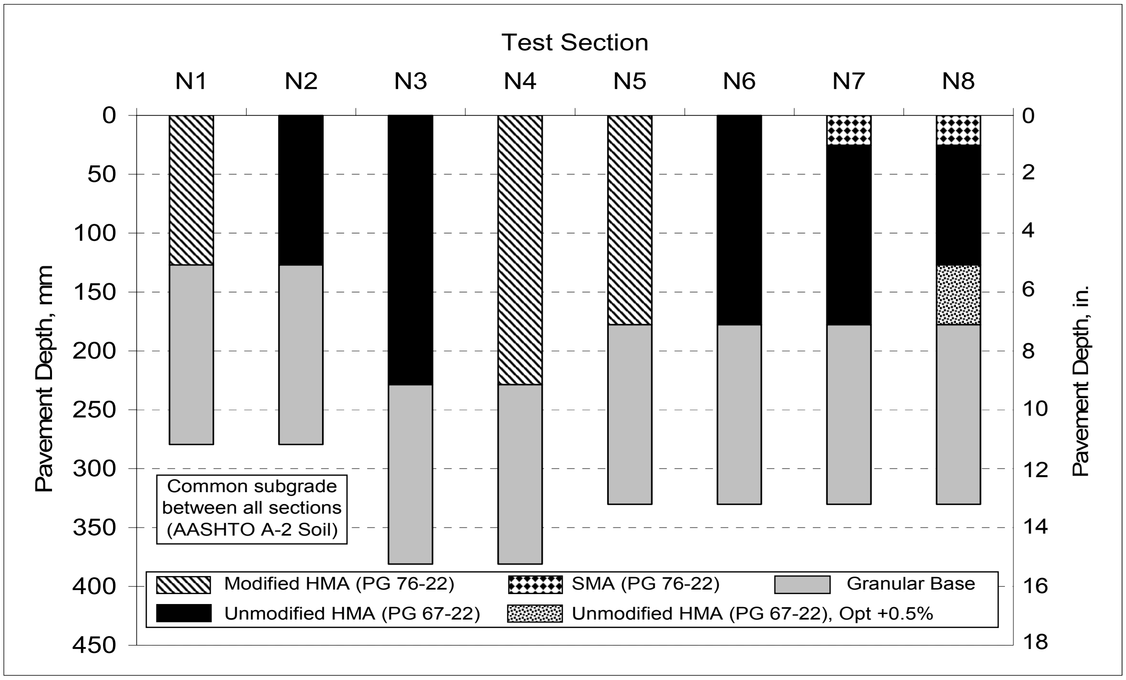

Figure 1: NCAT Test Track structural section layout.

Instrumentation in these test sections is comprised of asphalt strain gauges and earth pressure cells. The asphalt strain gauges measure strain at the bottom of the asphalt layer, while the earth pressure cells measure stress in the top of the base and subgrade layer. The typical layout of the instrumentation array consists of 12 asphalt strain gauges with four positioned to the left, four positioned to the right, and four positioned in the center of the outside wheelpath to record longitudinal and transverse strain. There are typically two pressure plates in each section positioned in the center of the wheelpath at the top of the base layer and at the top of the improved subgrade layer, respectively. The asphalt strain gauges and the earth pressure cells used in this experiment are shown in Figure 3a and 3b**.**

Figure 3a: Installation of asphalt strain gauge array.

Figure 3b: Installation of earth pressure cell.

2.1 Falling Weight Deflectometer (FWD) Testing

The major goal of this study was to compare measured pavement response against calculated pavement response. This was accomplished by controlled FWD testing, performed by the Alabama Department of Transportation (ALDOT), over the instrumentation arrays embedded in the eight structural sections as shown in Figure 4.

Figure 4: Dynatest FWD Model 9000 over instrumentation array.

This pavement response consisted of surface deflection, measured by the FWD, as well as strain in the bottom of the asphalt layer and stress in the base and subgrade layers, measured by the embedded instrumentation. The measured deflections were used to backcalculate the stiffness of the pavement structure. The stiffness values were used in conjunction with the known applied load to forward calculate corresponding strains and stresses from the FWD loading.

On April 28, 2004, FWD testing was performed directly over the instrumentation arrays in the structural sections. FWD loads were dropped directly over active asphalt strain gauges centered in the outside wheelpath. As the FWD loads were dropped directly over gauges in the center of the wheelpath, strain and stress measurements were recorded by the embedded instrumentation.

Once the deflection, strain, and stress data had been collected, the analysis of the data could begin. The first step in this analysis was to determine the stiffness of the pavement sections containing the instrumentation. The backcalculated stiffness, determined from EVERCALC 5.0, of each section from FWD testing over the instrumentation is shown in Figure 5. Each data point in Figure 5 represents average layer stiffness per section. The layer stiffness appears fairly consistent throughout each of the eight sections; however there is a slight decrease in stiffness in sections N1 and N2. The root mean square error (RMSE) of the stiffness predictions for N1 and N2 are high as well. This is most likely due to the presence of bottom-up fatigue cracking in N1 and N2 skewing the FWD deflection readings. It is also important to note in Figure 5 that the base stiffness is less than the subgrade stiffness. This was verified by resilient modulus laboratory testing performed by the Alabama Department of Transportation in accordance with AASHTO T 307-99 on material from the base and subgrade layer. Figure 5 also indicates that there is not a clear distinction between the polymer modified and unmodified test sections in terms of HMA stiffness.

In the ensuing analysis particular stiffness values over each gauge were used rather than averages per section. Figure 5 simply presents representative layer stiffness for each section.

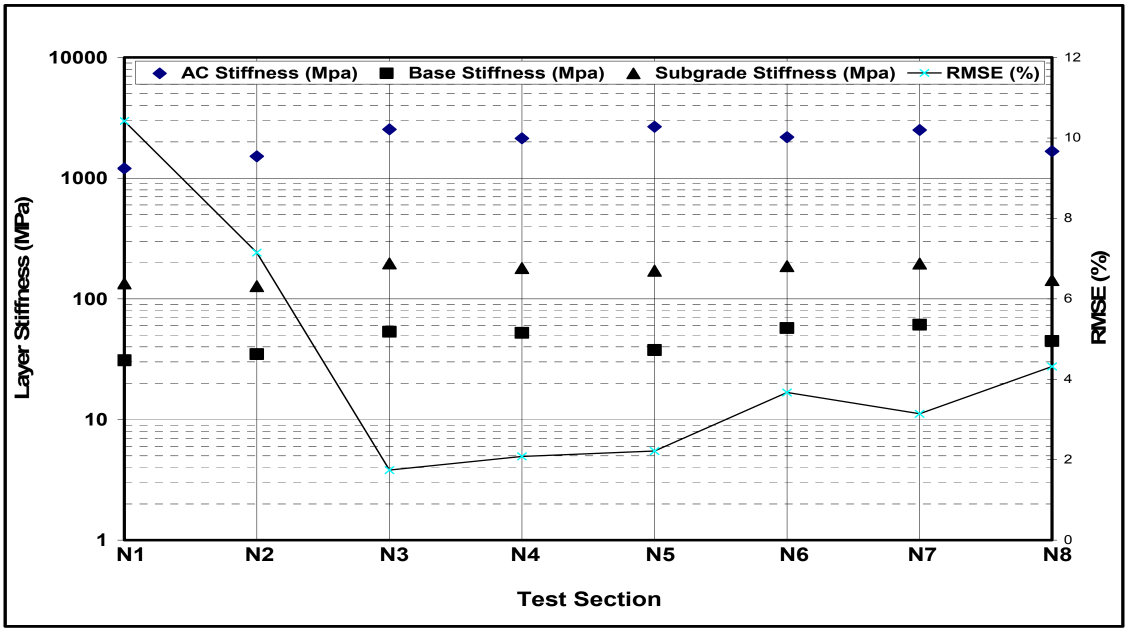

Figure 5: Average Backcalculated Layer Stiffness

2.2 Measured Data Acquisition

A high speed data acquisition system was used to collect pavement responses under the FWD load. Full documentation of this acquisition process as well as the installation and calibration of the embedded instrumentation is documented elsewhere (Timm and Priest, 2004). A typical strain trace recorded by the data acquisition system from an asphalt strain gauge FWD testing directly over an asphalt strain gauge is shown in Figure 6.

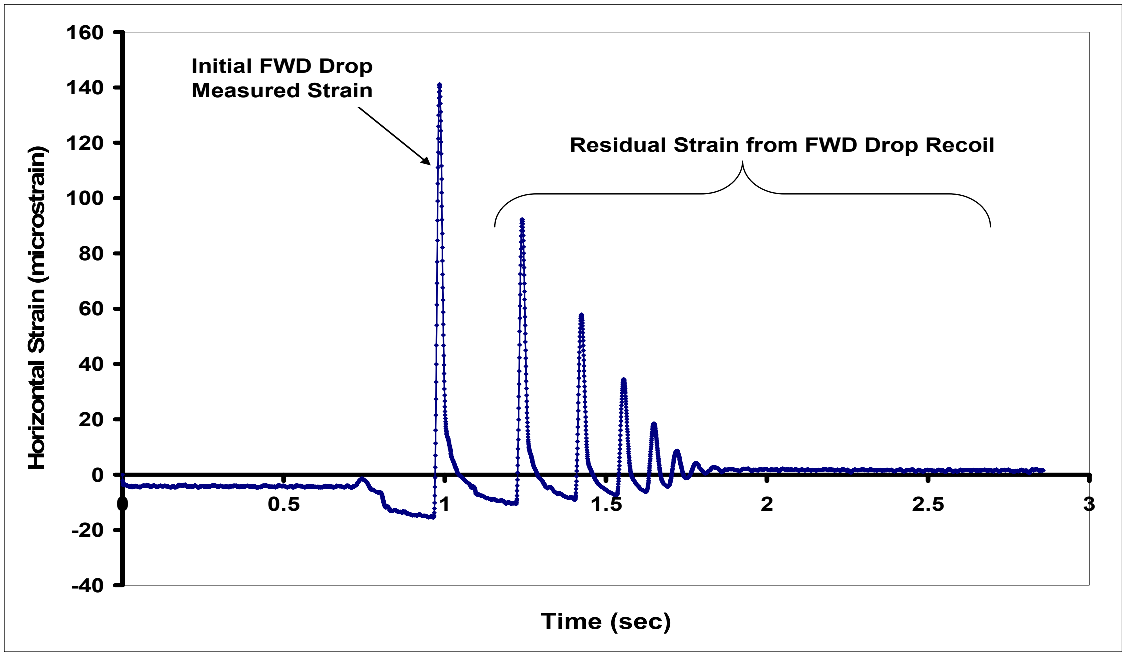

Figure 6: Strain trace from FWD load over asphalt strain gauge

The first strain spike, shown in Figure 6, is the initial reading from the FWD load drop. The remaining, lesser strain spikes are residual effects from the FWD load rebounding on the surface of the asphalt layer after the drop.

It is important to note that not every gauge or cell in the instrumentation array would produce a discernable voltage signal on each drop. This occurred because several of the gauges in each section were either offline or located outside of the area affected by the FWD load drop. The gauge and cell locations that did produce a discernable voltage signal were documented and listed as the critical points for evaluation in the linear-elastic model for determining theoretical stress and strain under the same loading conditions.

2.3 Linear-Elastic Stress and Strain Modeling

Linear-elastic analysis of these eight structural pavement test sections was performed by a program called WESLEA for Windows (Waterways Experiment Station Linear Elastic Analysis for Windows). WESLEA for Windows is a mechanistic analysis program that calculates pavement response to applied tire loads through user-input tire pressure and tire load and pavement layer properties.

In the analysis, backcalculated pavement layer moduli, in addition to the applied load and measured contact pressure, were used to compute stresses and strains corresponding to gauge locations in the actual pavement structure. The predicted pavement responses, derived from measured surface deflections and forward calculation were then compared against the measured pavement response under the dynamic FWD loading.

2.4 Results and Discussion

Once the measured data from the FWD load drops over the instrumentation arrays had been compiled along with the theoretical data from the linear-elastic models through the WESLEA program, a comparison could be made between theoretical linear-elastic response and measured response, as illustrated in Figure 7. It is important to note that the responses correspond to locations directly under the applied load in addition to gauges at known longitudinal or transverse offsets from the load center. Thus, locations directly under the load are in tension while points further away from the load center are in compression.

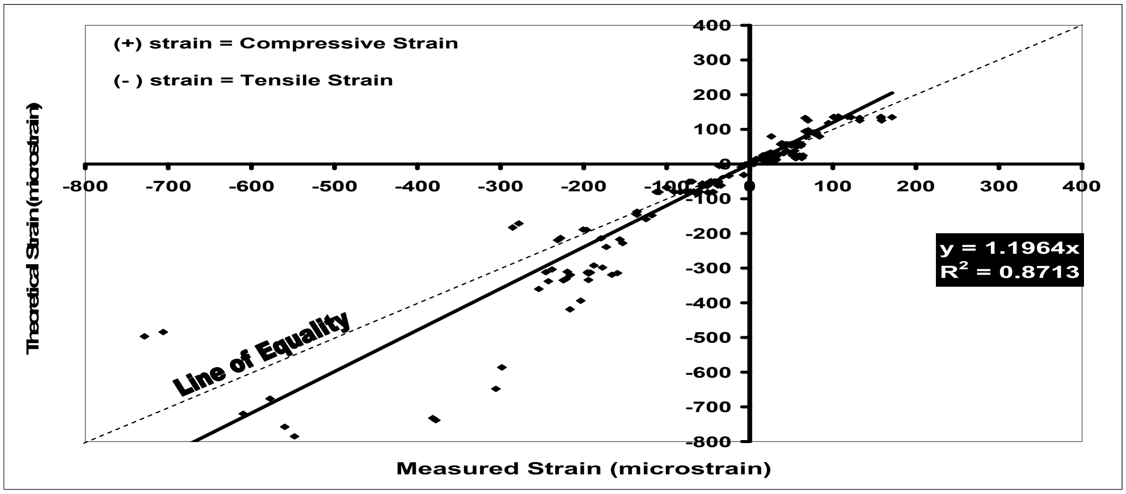

Figure 7: Measured vs. theoretical strain in the bottom of the asphalt layer.

While Figure 7 shows a strong correlation between theoretical and measured strain over the eight test sections, several outliers were present, especially at higher strain levels. A significant portion of these outliers were thought to be attributed to fatigue cracking in sections N1 and N2. Cracking is a clear violation of a linear elastic model which assumes the layers extend infinitely in the horizontal direction, so this result was somewhat expected. To investigate this, all N1 and N2 data points were removed from the analysis. Removing these data points from the comparison, the overall relationship between measured and theoretical strain becomes closer to unity as shown in Figure 8, while the R^2 value is comparable between the two data sets. Both figures also indicate that the match between theoretical and measured response is better at lower strain levels. This is logical since the material is more likely in the linear elastic range at lower strain levels.

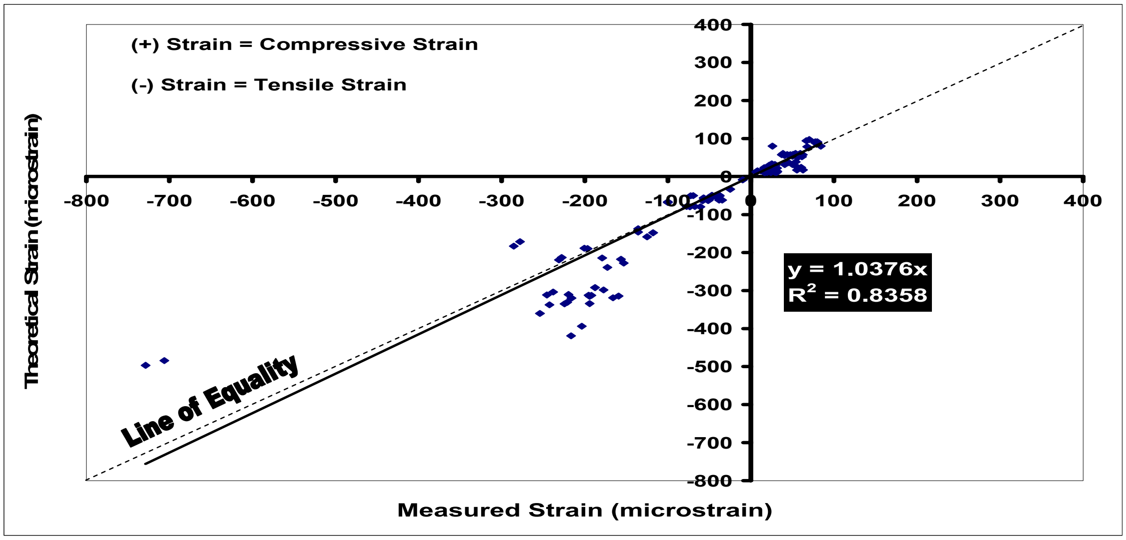

Figure 8: N1-N8 measured vs. theoretical asphalt strain (excluding sections N1 and N2).

The stress in the base layer and in the subgrade layer showed a strong correlation to the linear-elastic theoretical stress calculations at lower stresses. The comparison between theoretical and measured stresses is shown in Figure 9 excluding the fatigued sections, N1 and N2. As shown in Figure 9, a strong linear correlation could not be drawn between measured and theoretical subsurface stresses due to increasingly non-linear behavior of the subsurface layers at higher stresses. This is an important point since the theoretical model would underestimate the state of stress in the pavement.

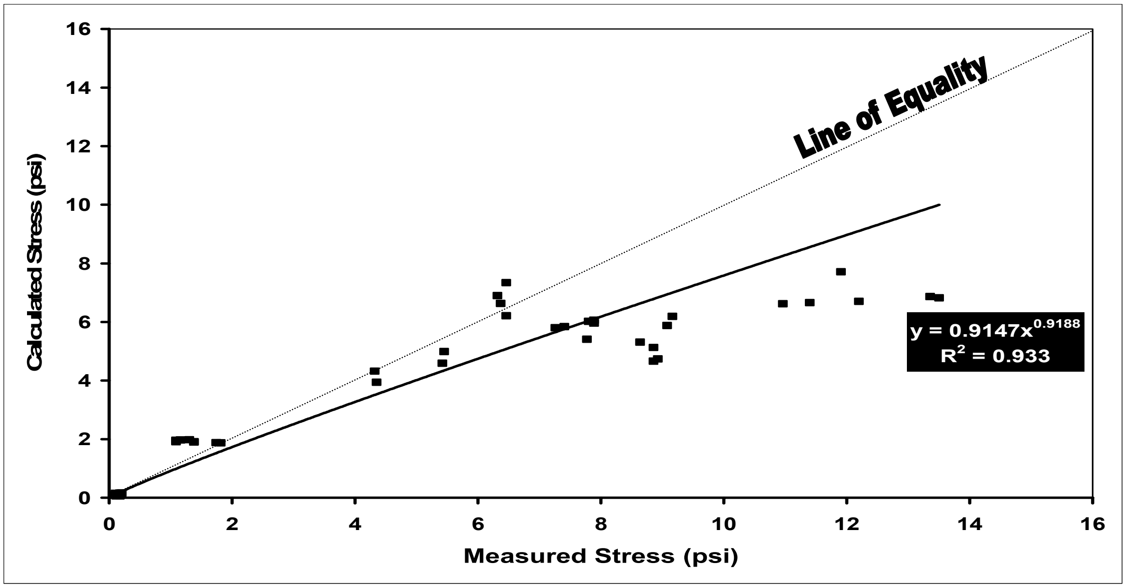

Figure 9: N1-N8 measured vs theoretical stress in base and improved subgrade layer.

The non-linear pattern observed in Figure 9 was most likely linked to the non-homogeneity of the subsurface layers as well as the non-linear behavior of the soil under applied loads. WESLEA assumes each layer to be an isotropic, homogenous continuum, thus a linear relationship may not be entirely applicable in the base and subgrade soil layers.

3.0 SUMMARY AND DISCUSSION

As previous research by Guzina and Osburn has shown, the presence of a shallow rigid layer may lead to systematic errors in the estimation of pavement moduli. This paper reemphasized their theory by showing that it is possible to simulate dynamic pavement response through linear-elastic models where this is not present. The results presented in this paper support the following conclusions:

- This research suggests that linear-elastic analysis can a reasonable approximation of pavement response to dynamic loading in low strain/stress conditions (i.e. ± 200 microstrain / < 7psi). Beyond these thresholds, non-linear behavior must be taken into account. It is important, however, to recall that this study focuses on FWD loads rather than actual traffic loads. Further studies are required to ascertain whether linear-elastic analysis can effectively model dynamic traffic loads.
- While the main objective of this study was to show the validity of linear-elastic analysis on a pavement structure, another objective was also reached. The strong correlation between linear-elastic and measured pavement response has served as a reference point for the validation of the installation and operation of the embedded instrumentation at the 2003 NCAT Test Track Structural Experiment.

4.0 REFERENCES

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