Technical Paper

ISSN 1997-1400 Int. J. Pavement Res. Technol. 5(4):257-266

Simulation of Flexible Pavement Response to FWD Loads: A Mechanistic Approach

Hao Yin[1+]

Abstract: Pavement deflection data coupled with backcalculation analysis are widely used to estimate the layer moduli of pavement structures for rehabilitation design and for pavement asset management. This paper presents a mechanistic approach to simulate full-depth flexible pavement responses when subjected to falling weight deflectometer (FWD) loads. The FWD testing is conducted at pavement locations instrumented with strain gauges, pressure cells, and thermocouples. For the selected full-depth asphalt concrete (AC) pavement structure, layer moduli are first backcalculated from FWD data, assuming that the AC and subbase materials are linear elastic, and that the subgrade can be treated as a nonlinear elastic material. The backcalculated AC moduli are compared to laboratory values, adjusted for load duration and temperature. The adjusted laboratory values for the surface layers are consistently lower, averaging about 70 percent of the backcalculated values. The adjusted laboratory values for the bituminous concrete base course (BCBC) are about 10 percent higher than the backcalculated values. The backcalculated layer moduli are then employed to predict horizontal strains in bound materials and vertical stresses in unbound materials through three-dimensional (3-D) finite element simulations. Finally, simulated responses and pavement responses from embedded instrumentation devices during the FWD loading are compared. An average prediction error of 30 percent was found through comparison of the simulated and measured pavement responses, with the predicted responses exceeding the measured responses in every case.

***Key words**: Backcalculation; Finite element method; Flexible pavement; FWD; Instrumentation; Pavement response.*

Introduction

Mechanistic-empirical design procedures for flexible pavements utilize mechanistic models to predict pavement responses, such as stresses and strains. One of the most important parameters required by the response models is the modulus of each pavement layer. Two basic means of obtaining layer material properties are laboratory and in situ testing. Typical laboratory tests for asphalt concrete (AC) materials include the complex modulus (E*) test, the indirect tensile test (IDT), and tests related to the shear stiffness (G*) measured using the simple shear tester (SST) at low, intermediate, and high test temperatures. The resilient modulus test is performed to determine the moduli of granular materials (e.g., base, subbase, and subgrade). For decades, pavement engineers have worked with both laboratory and in situ data, often using the laboratory results for new design and new layers, and the in situ results from nondestructive testing for rehabilitation and pavement management.

The use of in situ layer moduli has become an integral part of structural evaluation and rehabilitation design for pavements. It provides valuable information on the behavior or response of pavement structures subjected to traffic loads and the interaction between pavement layers. The in situ layer moduli are typically obtained by falling weight deflectometer (FWD) testing and backcalculation analysis. Most of the backcalculation analyses in use today are based upon the layered elastic theory to calculate the modulus of elasticity for each pavement layer, such that the difference between the measured and predicted deflection basins is minimal. Some backcalculation programs also account for the viscoelastic and/or nonlinear material behavior. Backcalculated layer moduli from FWD deflection data can be used to determine the resilient modulus of different pavement layers. There are some uncertainties related to the backcalculation, as only one single modulus value per pavement layer can be obtained with no sufficient discrimination of the near-surface AC moduli [1-2]. Furthermore, various studies reported that backcalculated moduli usually differ significantly from those obtained through laboratory testing [3-9]; no consensus exists as to which procedure provides the most appropriate moduli values for pavement design.

The goal of this research is to integrate in situ tests, laboratory material characterization, backcalculation, and finite element analysis (FEA) in a rational manner so that flexible pavements' response to FWD loads can be numerically simulated. At this stage, only one instrumented full-depth AC pavement was studied, and the laboratory characterization focused on the bituminous layers. To achieve the research goal, a three-phase mechanistic approach was taken, as illustrated in Fig.1. In phase 1, the research focus was placed on field and laboratory data collection. The main products from this phase are the load and deflection time history data from the FWD testing, and dynamic modulus data from the complex modulus test. Phase 2 began with backcalculations of linear and nonlinear elastic moduli of individual pavement layers. Backcalculated AC moduli were then compared to adjusted laboratory-determined values. The last phase of this research was targeted at using three-dimensional (3-D) FEA to simulate pavement responses under the FWD load, as measured by embedded instrumentation devices.

It is noted that the material nonlinearities are attributed by load magnitude/rate, the temperature, location of the underneath firm

[1] Airport Pavement Research, Gemini Technologies, Inc., Egg Harbor Twp, NJ 08234, USA.
[+] Corresponding Author: E-mail hao.yin@gemitek.com
Note: Submitted October 22, 2011; Revised February 17, 2012; Accepted February 21, 2012.

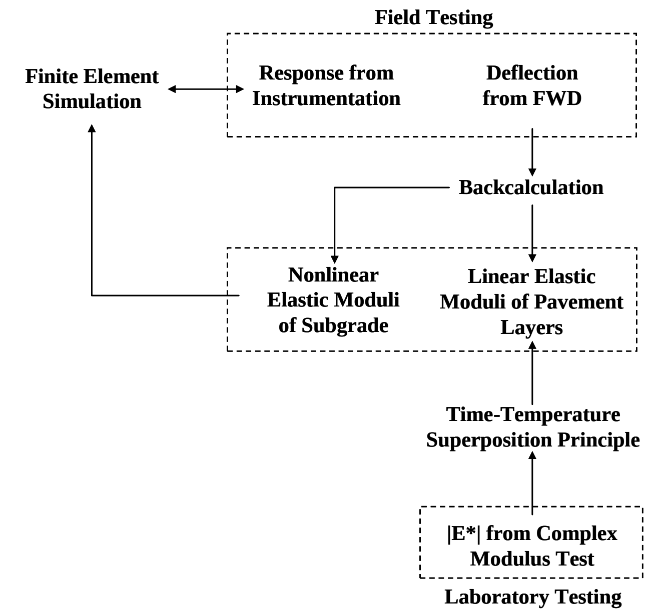


Fig. 1. Research Approach.

Table 1. Pavement Structure.

Layer	Thickness mm (in)	Binder PG Grade	Nominal Maximum Aggregate Size (NMAS) mm (in)
Wearing	54 (2.1)	64-22	12.5 (0.5)
Binder	47 (1.9)	64-22	19.0 (0.8)
BCBC	162 (6.4)	64-22	25.0 (1.0)
Subbase	200 (7.9)	Not Applicable	37.5 (1.5)

(a) Pressure Cell

(b) Strain Gauge

Fig. 2. Dynamic Sensors.

layer and/or the bedrock, and depth of the water table. These factors should be taken into account while trying to determine the layer moduli of the pavement [10-12]. Due to limited data available, however, this paper suggests a general approach to use the FWD data.

Pavement Structure and Instrumentation

The pavement section selected for this study was a full-depth AC pavement section on the southbound lane of U.S. SR 1001 in Blair County, Pennsylvania. The construction of this section was completed in the fall of 2003. The pavement consisted of a granular 2A subbase and three Superpave-designed hot-mix asphalt (HMA) layers: a bituminous concrete base course (BCBC), a binder course, and a wearing course. Table 1 provides a summary of the pavement structure. Details of pavement construction are provided in the project construction report [13].

Instrumentation of the pavement layers was performed at the time of construction. To capture the pavement response under traffic loading, the dynamic (load-associated) sensors were installed in different layers in the travel lane. These sensors included pressure cells and strain gauges in the unbound and AC layers (Fig. 2). Respectively, these gauges were installed to measure vertical stresses and horizontal strains. The dynamic sensors were placed either in or immediately adjacent to the right wheel path. Temperatures in the pavement layers were captured using thermocouples installed at various depths. Details of the instrumentation are reported elsewhere [14].

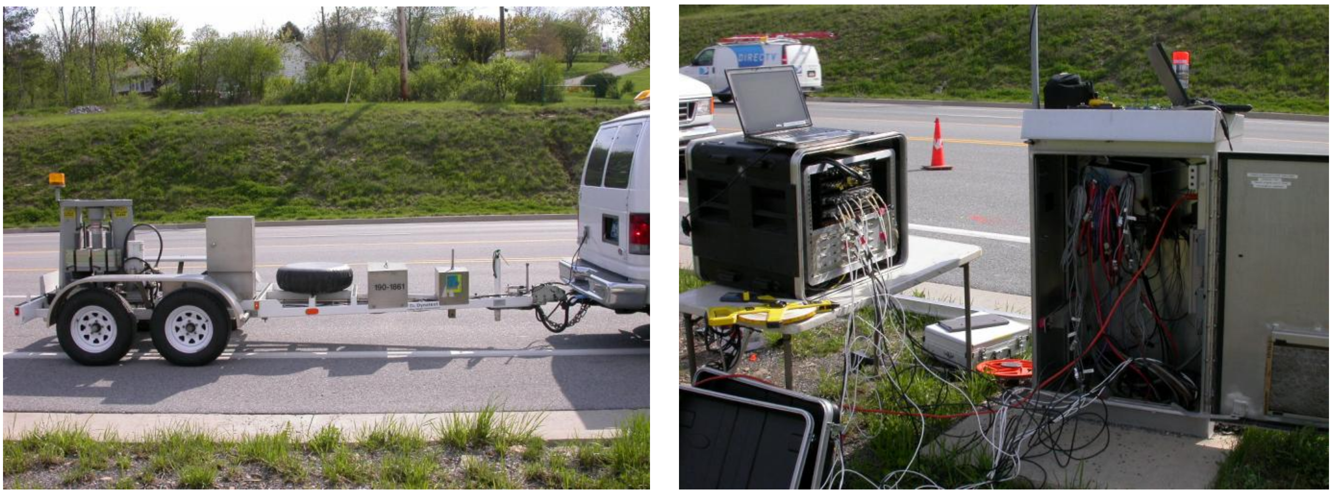
Testing Program

Field Data Collection

All FWD testing was performed by the Pennsylvania Department of Transportation (PennDOT) with their Dynatest FWD (Fig. 3a). The Dynatest FWD, as utilized, was configured with a 150-mm (5.91-in) radius load plate, with sensors spaced at 305-mm (12-in) intervals from the center of the load. One sensor was behind the load, one centered under the load plate, and the remaining sensors were in front of the load. FWD testing was performed at four load levels (LLs): 2 drops at 33.36 kN (7500 lb), 2 drops at 46.71 kN (10500 lb), 2 drops at 64.50 kN (14500 lb), and 2 drops at 84.52 kN (19000 lb). A special Data Acquisition System (DAQ) was used to collect and process pavement responses during FWD testing (Fig. 3b). A total of three instrumentation locations were included in this study. At each instrumentation location, FWD testing was repeated three times to ensure data quality.

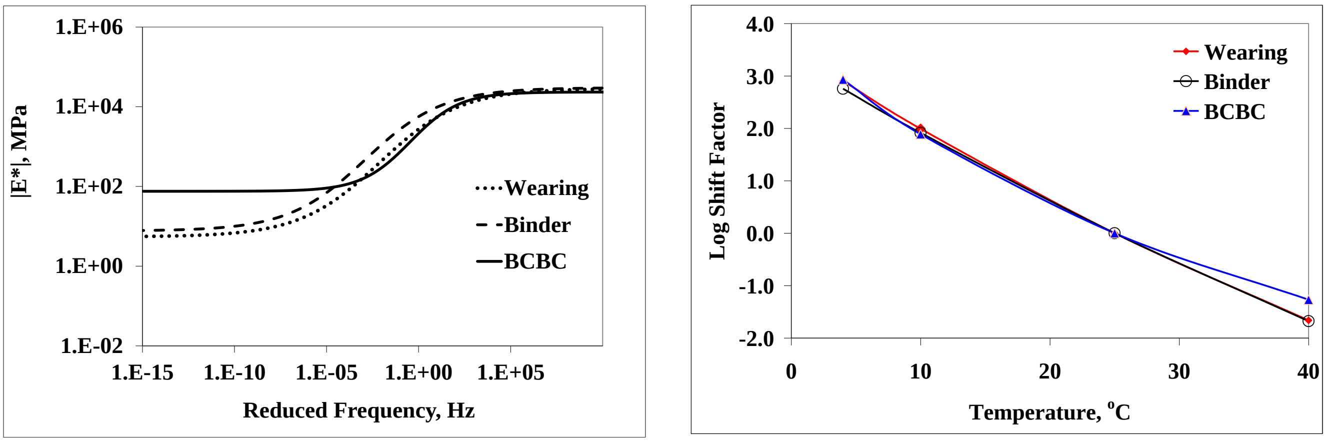
Laboratory Data Collection

The dynamic modulus (|E*|) of AC materials is typically obtained from an |E*| master curve that represents the relationship between the elastic modulus and “reduced” frequency. The complex modulus test was conducted according to AASHTO TP62 to determine the |E*| of the AC materials from the individual pavement layers. Specimens 150 mm in diameter and 180 mm in height were



(a) Dynatest FWD (b) Data Acquisition System for Response Data

Fig. 3. Field Data Collection.



(a) |E*| Master Curves (b) Log Shift Factor vs. Temperature

Fig. 4. |E*| Data from Complex Modulus Test.

compacted using a Superpave gyratory compactor. Specimens used for uniaxial testing were cut and cored to 100-mm diameter and 150-mm height. The amplitude of the applied uniaxial haversine load was selected based on the material stiffness, temperature (4℃, 10℃, 25℃, and 40℃), and frequency (0.1, 0.5, 1, 5, 10, and 25Hz), to ensure that the strain response remained within 70 to 100 microstrain.

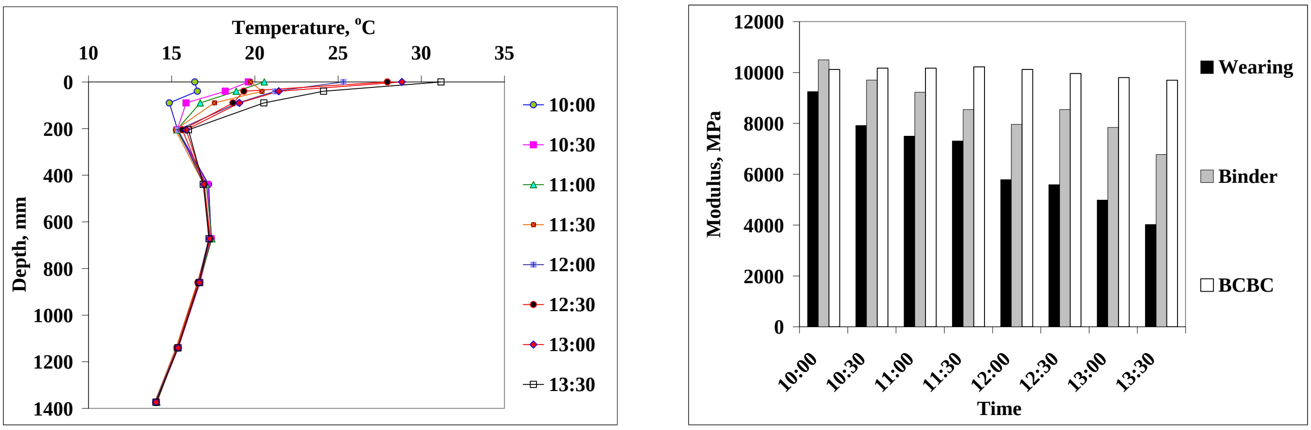
For AC materials, the effect of time can be translated to the effect of temperature and vice versa. For example, the strain response of an AC mixture subjected to a stress for a certain time (frequency) at a high temperature would be the same as the strain response when the mixture is subjected to a stress of the same magnitude for a much longer time (lower frequency) when loaded at low temperatures. Materials that exhibit such a phenomenon of time-temperature superposition are termed thermorheologically simple (TRS) materials. Thus, if the effect of temperature is being translated into frequency (time), a new entity called "reduced frequency" ("reduced time") at a reference temperature is utilized. In the case of |E*|, the effect of temperature is incorporated into "reduced frequency."

To construct a master curve, |E*| values measured at different temperatures are "shifted" relative to the reference temperature (25℃) using the sigmoidal function so that the various curves can be assembled to form a single curve. The master curve as a function of time formed in this manner describes the time dependency of the AC materials. The amount of shifting at each temperature required to form the master curve reflects the temperature dependency of the AC materials. Thus, both the master curve (Fig. 4a) and the shift factors (Fig. 4b) are needed for a complete description of the rate of loading and temperature effects.

Determination of Layer Moduli

AC Moduli from |E*| Data

The temperature and time dependency of viscoelastic materials were captured in two steps. First, a haversine function [15] was adopted to approximate the intensity of FWD loads. A load time of 0.03 sec, which equals the duration of the FWD load pulse, was used. Second, with the time-temperature superposition, for a specific temperature in the field at the time of FWD testing (e.g., 10:43), the elastic modulus was obtained from the dynamic modulus master curve. Fig. 5a indicates that temperatures measured from thermocouples in the upper layers vary significantly from the underlying layers during



(a) Temperature Profile (b) Dynamic Moduli

Fig. 5. Variation of Laboratory-determined Layer Moduli at Temperatures of FWD Testing.

Table 2. Summary of Adjusted Laboratory-Determined Layer Moduli.

Pavement Layer	Time	Mid-depth Layer Temperature (℃)	Modulus (MPa)
Wearing	10:00	16.5	9253
	10:30	18.9	7916
	11:00	19.7	7498
	11:30	20.1	7311
	12:00	23.3	5786
	12:30	23.7	5587
	13:00	25.1	4982
	13:30	27.7	4021
Binder	10:00	15.7	10499
	10:30	17	9703
	11:00	17.8	9226
	11:30	19	8544
	12:00	20.1	7963
	12:30	19	8544
	13:00	20.3	7841
	13:30	22.3	6775
BCBC	10:00	15.4	10118
	10:30	15.3	10171
	11:00	15.3	10171
	11:30	15.2	10223
	12:00	15.4	10118
	12:30	15.7	9959
	13:00	15.9	9801
	13:30	16	9696

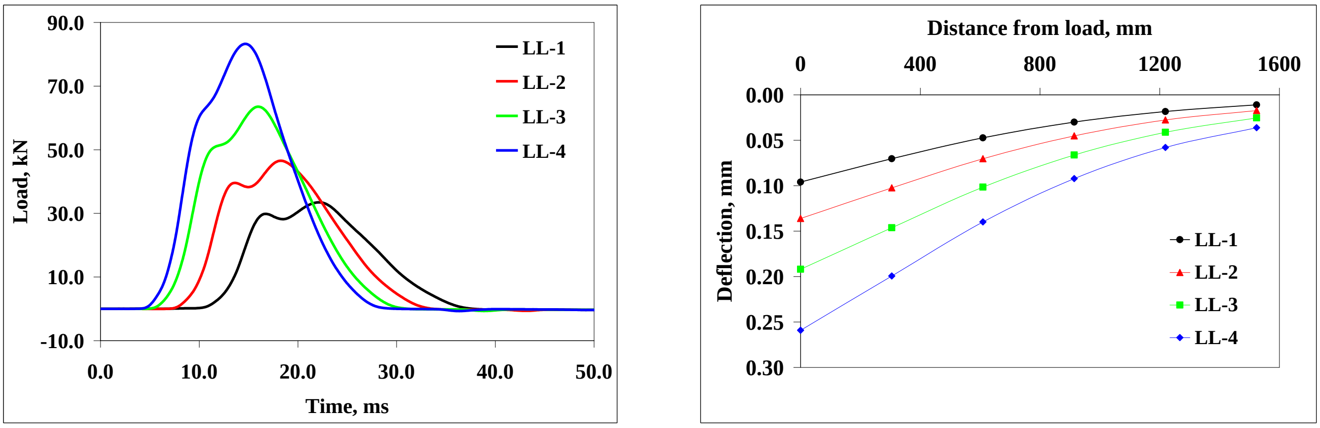
FWD testing (10:30-13:00). The maximum fluctuation, 6℃, occurred in the wearing layer. The 1993 AASHTO guide provides standards and guidelines that are mainly used in the design and restoration of flexible, rigid, and composite pavements. AASHTO recommends, as a minimum, determining the temperature at the top, middle, and bottom of the AC layer and using the average of these temperatures to represent the temperature of the AC layer. Since the thermocouples were installed at or near the top and the bottom of the AC layers, mid-depth temperatures of each AC layer were linearly interpolated from top and bottom temperatures. Fig. 5b shows how laboratory-determined layer moduli vary with the pavement temperature. As expected, the AC layer moduli are significantly affected by the pavement temperature, particularly the top layers. A complete set of layer elastic moduli from |E*| master curves is given in Table 2.

Layer Moduli from Backcalculations

FWD analysis requires extensive user input and judgment. Batch processing of FWD data may be suitable for pavement management purposes, but as discovered during the Long-Term Pavement Performance (LTPP) efforts, it is typically not adequate for research usage. The analysis steps conducted in this study have been similar to those utilized for the LTPP data analysis. Backcalculations were performed with the MODCOMP5 computer program because of its features, which include nonlinear analysis [2].

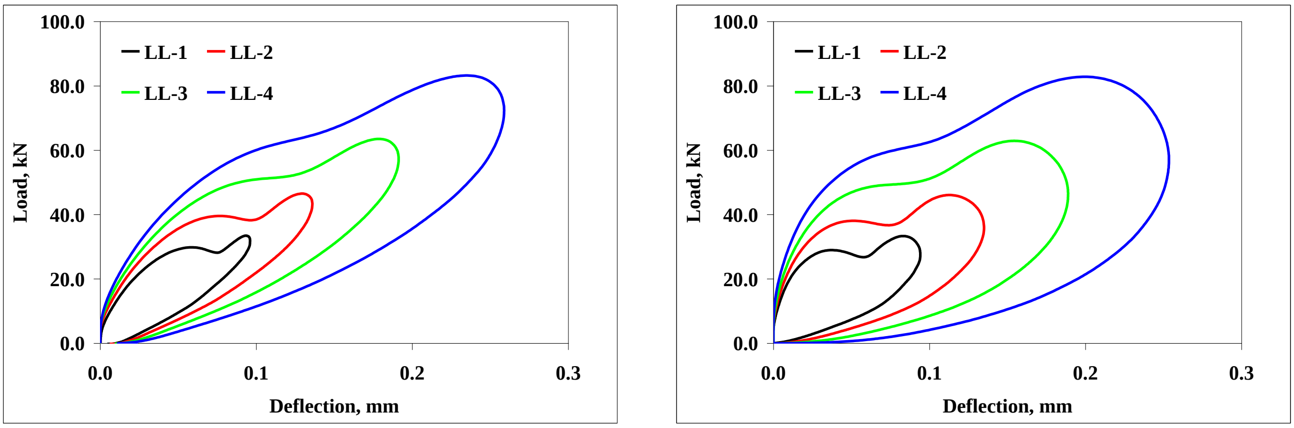
The deflections are first normalized to the approximate (rounded) mean load for each load level. The mean and standard deviation of deflection for each sensor is computed, and any outliers noted and removed from averaging. The normalized deflections for each specific drop height at each test point location are averaged. For a test location, this results in two basins being averaged. This method assists in minimizing the effect of random measurement error. This is especially important for thick, stiff pavement sections, where the magnitude of deflections is small, and the impact of measurement error is therefore larger. The normalized deflection basins are examined for shape. Deflections basins with a significant decrease in measured deflections between two adjacent sensors are noted, but included in the analysis. An example of FWD load and deflection data is given in Fig. 6.

Viscoelastic materials, such as asphalt concrete (AC), have elements of both of elastic and viscous material behaviors and exhibit time-dependent strain when subjected to a stress. This strain occurs such that a part of the strain (elastic part) appears instantaneously, and the remaining part of the strain (viscous part) increases with time at a decreasing rate. Given that FWD testing is a relatively high frequency (short loading time, such as .03 sec) test, the backcalculation will be largely simplified if AC layers can be modeled as elastic materials. Fig. 7a and 7b plot the load-deflection history (hysteresis loop) for sensor 1. For both low and high temperatures, most or all of the induced deflections are recovered



(a) Loads (b) Deflections

Fig. 6. Example of Load and Deflection Data from FWD Testing.



(a) Low Temperature, 10:30, Location 1 (b) High Temperature, 13:00, Location 2

Fig. 7. Hysteresis Loops of FWD Data from Sensor 1.

immediately after the FWD load pulse returns to zero. Therefore, characterizing AC layers of the selected pavement structure as elastic materials will not greatly influence the effectiveness of backcalculated layer moduli, as the viscoelastic properties are insignificant in relation to the total measured deflection. In addition, the subbase layer was also treated as linear elastic.

Subgrade materials often exhibit nonlinear, stress-dependent elastic moduli. The modulus of a stress-dependent material changes as the overburden pressure changes with depth, and as the load stress changes with radial distance from the load. Therefore, the use of nonlinear models is primarily a means of taking into consideration the horizontal effect of the load stress variation in a layer. The nonlinear model used for subgrade layer modulus, E, is expressed as:

$$E = K_1 S^{K_2} \tag{1}$$

in which S is the vertical stress that is always compressive, and K_1 and K_2 are model constants. When the stress is zero, then $E = K_1$, and thus K_1 is equal to the initial tangent modulus.

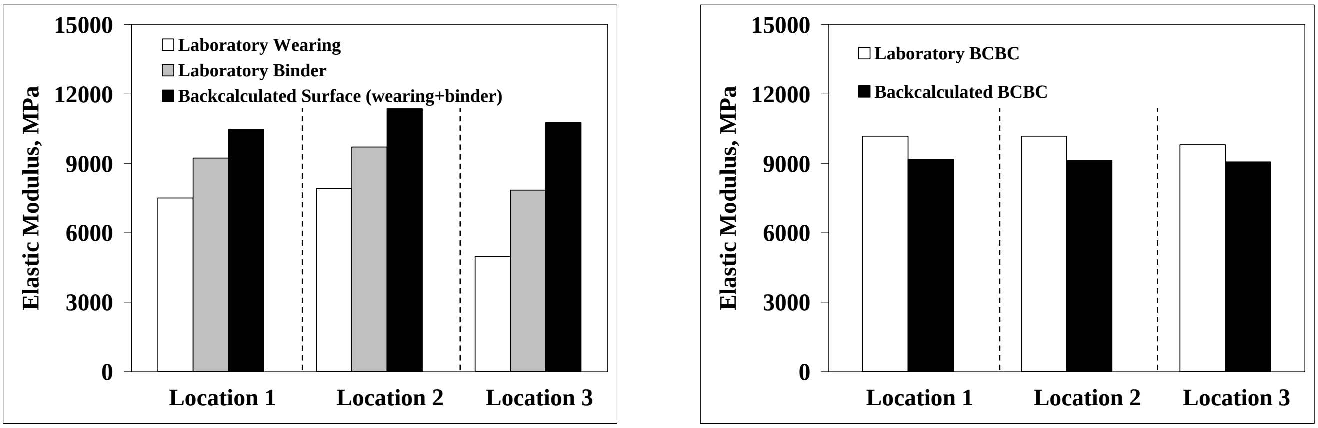
MODCOMP was executed, and strategies revised until a root mean square (RMS) error less than one percent was achieved. The RMS error is a measure of the "goodness of fit" of the deflection basin. The backcalculated layer moduli are used in MODCOMP to compute a set of deflections at the same distance from FWD load where the deflections were measured. The difference is calculated as a percent error at each sensor. The RMS error is a composite value that is derived from the set of individual errors. MODCOMP also checks the modulus rate of change, to help ensure that a wide range of moduli would not produce the same RMS error, and that a stable solution has been achieved; one percent was also used for this convergence criterion.

The selected pavement is a traditional flexible pavement structure. It was modeled for backcalculation as a combined AC surface (wearing and binder), BCBC, and granular 2A subbase. A rigid deep layer was introduced at approximately 2,000 mm below the surface. The rigid layer was modeled as an unknown layer so that the layer modulus would not remain fixed. The reason for introducing a variable rigid layer was to account for varying depth to bedrock [16]. The exact depth to bedrock is hard to estimate, as it is very likely to fluctuate in a hilly terrain like that found in Blair.

The backcalculated AC, subbase and subgrade moduli are fairly consistent, as summarized in Table 3. The subbase moduli appear very low, but are consistent. FWD testing at three load levels, with a KUAB FWD, and without time histories being recorded, was performed on five different dates in different seasons since construction. Linear elastic backcalculations on all of those data sets also indicated very low subbase moduli.

Table 3. Summary of Layer Moduli from Backcalculation.

Location	Repetition	Time	Surface Modulus (MPa)	BCBC Modulus (MPa)	Subbase Modulus (MPa)	Subgrade K_1 (MPa)	Subgrade K_2	Stiff Layer Modulus (MPa)	RMS (%)
1	1	10:43	10534	9241	34	415	-0.572	428	0.95
1	2	10:44	10457	9103	36	426	-0.597	435	0.92
1	3	10:46	10390	9172	37	441	-0.541	461	0.71
1	Mean		10460	9172	36	427	-0.57	442	0.86
1	Standard Deviation		72	69	2	13	0.028	18	0.13
2	1	10:21	11341	9172	36	452	-0.535	439	0.83
2	2	10:24	11310	9034	40	415	-0.516	444	0.98
2	3	10:27	11417	9172	42	428	-0.509	490	0.91
2	Mean		11356	9126	39	432	-0.52	458	0.91
2	Standard Deviation		55	80	3	19	0.013	28	0.08
3	1	12:58	10828	8966	35	414	-0.531	406	0.51
3	2	13:00	10672	9093	31	444	-0.555	415	0.63
3	3	13:03	10783	9124	34	408	-0.506	451	0.75
3	Mean		10761	9061	33	422	-0.531	424	0.63
3	Standard Deviation		80	84	2	20	0.025	24	0.12



(a) Wearing and Binder Combined Layer (b) BCBC Layer

Fig. 8. Comparison of Layer Elastic Moduli.

Laboratory versus Field AC Moduli

Fig. 8a and 8b give a comparison of elastic moduli obtained from these two sources for upper and lower AC layers, respectively. The backcalculated moduli are always higher than the laboratory-determined values. The observation is in general agreement with the suggestion by the 1993 AASHTO design guide [3] that the FWD backcalculated moduli are typically higher than the laboratory determined moduli. The maximum divergence between these two moduli, 4,349 MPa, occurs when FWD testing was performed at testing location 3. Compared to the other two testing locations, pavement temperature is significantly higher at 13:00. In addition, the layer moduli obtained from backcalculations do not decrease as significantly as pavement temperature increases (i.e., from testing location 2 to location 3). The differences between layer moduli obtained from backcalculations and laboratory complex modulus can be explained in at least three parts. First, laboratory-determined moduli represent intact, and for the most part, homogeneous materials, while the backcalculated moduli represent a kind of effective moduli. All material orientations due to laboratory compaction, thickness variations, confinement, interfaces, and micro- and macro-cracks make the effective moduli backcalculated from in situ FWD deflections a field characteristic of the entire pavement structure. Second, the uniaxial compression loading mode used in the complex modulus test does not reflect the stress state or load pulse in the field. For example, fatigue cracking usually initiates from the bottom of the AC layer due to bending-induced tension; FWD testing also induces a downward deflection or bending. Third, the laboratory specimens were tested at a constant and uniform temperature; whereas the backcalculated moduli represent a composite modulus which has a built-in temperature gradient from the top to the bottom of each AC layer. In addition, the linear interpolation of mid-depth layer temperature may introduce errors in extracting modulus values from |E*| master curves. Finally, other factors, not contemplated here, may also contribute.

Comparison of Measured and Simulated Responses

The general purpose finite element software ABAQUS was used to

Table 4. Summary of Measured and Predicted Horizontal Strains.

Gage Location, Bottom of Layer	Testing Location	Measurement Repetition	LL-1[a] M[b] (E-6)	LL-1[a] P[c] (E-6)	LL-2 M (E-6)	LL-2 P (E-6)	LL-3 M (E-6)	LL-3 P (E-6)	LL-4 M (E-6)	LL-4 P (E-6)
Wearing	1	1	6.8	10.1	8.8	12.5	11.9	17.9	15.4	23.9
Wearing	1	2	7.2	10.2	9.3	12.5	11.6	17.8	15.8	23.8
Wearing	1	3	7.5	10.1	8.9	12.4	11.9	17.6	15.6	23.5
Wearing	2	1	7.2	10.7	8.1	12.9	11.5	18.2	15.2	24.2
Wearing	2	2	6.8	10.2	8.6	12.3	12.1	17.6	15.7	23.6
Wearing	2	3	6.8	10	8.7	12.2	12.2	17.3	16.4	23.3
Wearing	3	1	6.9	10.3	8.9	12.7	11.5	18.1	14.7	24.2
Wearing	3	2	6	10.7	8.4	13	11.2	18.5	16	24.6
Wearing	3	3	7.4	10	9.4	12.4	11.7	17.7	15.4	23.8
Binder	1	1	3	3.9	4.4	5.2	6.5	7.7	9.2	10.9
Binder	1	2	2.9	3.8	4.2	5.1	6.2	7.4	8.6	10.6
Binder	1	3	2.9	3.7	4.6	5	7	7.3	8.9	10.3
Binder	2	1	3	3.8	4.3	5	6.7	7.3	8.8	10.4
Binder	2	2	3	3.9	4.4	5.1	6.5	7.4	9.2	10.6
Binder	2	3	2.8	3.8	4.6	5	6.4	7.2	9.6	10.3
Binder	3	1	3	3.9	4.1	5.2	6.6	7.6	9.5	10.9
Binder	3	2	3	3.9	3.8	5.2	6.2	7.5	9.8	10.8
Binder	3	3	3	3.9	4.3	5.2	6.4	7.7	8.9	10.9
BCBC	1	1	1.4	1.7	2.2	2.7	3.6	4.3	5.4	7
BCBC	1	2	1.3	1.7	2.2	2.6	3.7	4.3	5	6.9
BCBC	1	3	1.3	1.6	2.1	2.6	3.7	4.2	5.7	6.8
BCBC	2	1	1.4	1.7	2.2	2.6	3.4	4.3	5.3	6.9
BCBC	2	2	1.3	1.7	2.1	2.6	3.6	4.3	5.9	6.9
BCBC	2	3	1.3	1.6	2.3	2.6	3.5	4.2	5.3	6.8
BCBC	3	1	1.3	1.7	2.4	2.7	3.6	4.4	5.8	7
BCBC	3	2	1.4	1.7	2.3	2.7	3.8	4.3	4.7	7
BCBC	3	3	1.2	1.7	2.1	2.7	3.6	4.3	5.3	7

[a] FWD load level; [b] Measured horizontal strain; [c] Predicted horizontal strain.

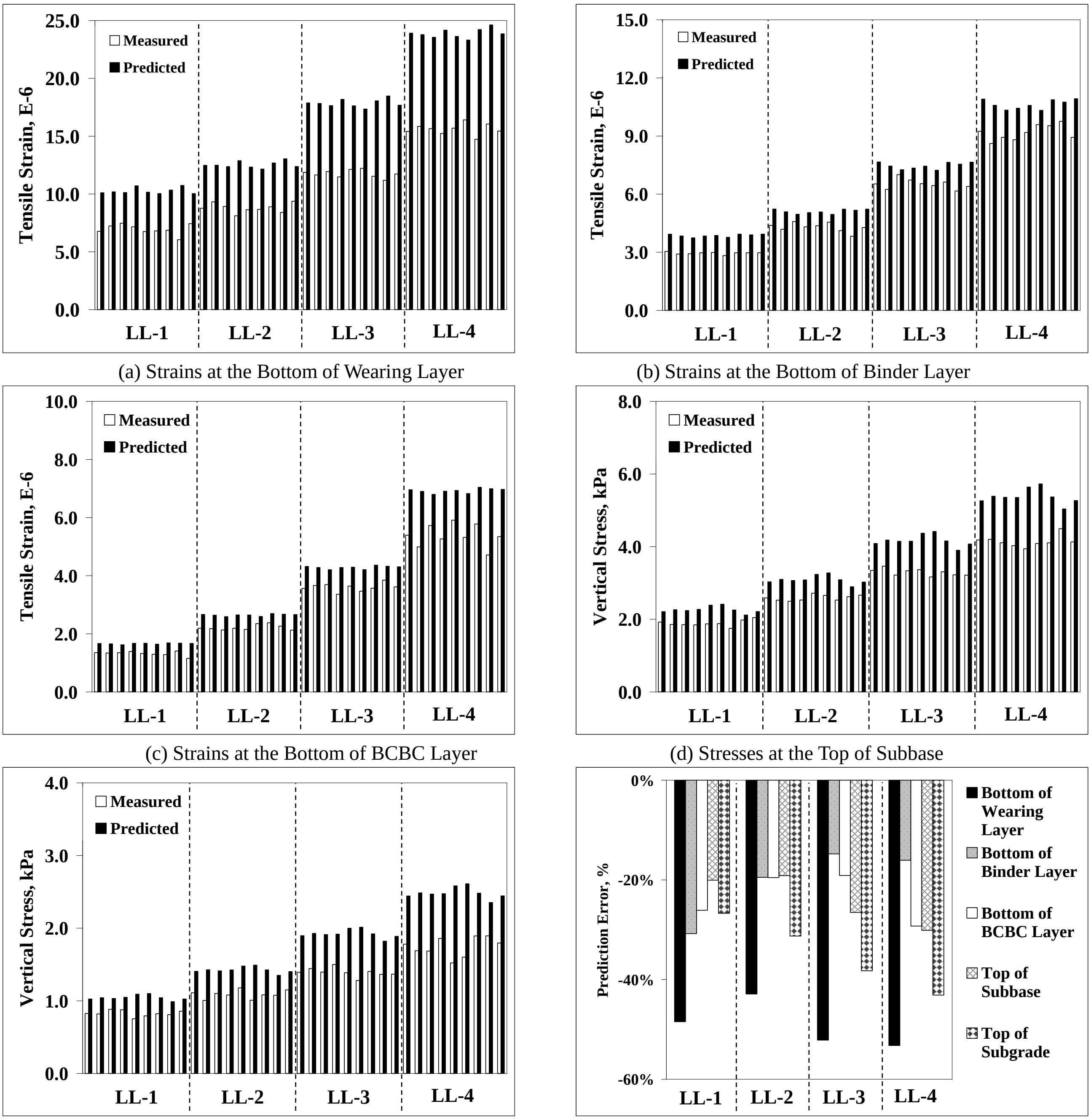
Table 5. Summary of Measured and Predicted Vertical Stresses.

Gage Location, Top of Layer	Testing Location	Measurement Repetition	LL-1[a] M[b] (kPa)	LL-1[a] P[c] (kPa)	LL-2 M (kPa)	LL-2 P (kPa)	LL-3 M (kPa)	LL-3 P (kPa)	LL-4 M (kPa)	LL-4 P (kPa)
Subbase	1	1	1.9	2.2	2.6	3	3.3	4.1	4.2	5.3
Subbase	1	2	1.9	2.3	2.5	3.1	3.5	4.2	4.2	5.4
Subbase	1	3	1.9	2.2	2.5	3.1	3.2	4.1	4.1	5.4
Subbase	2	1	1.8	2.3	2.5	3.1	3.3	4.1	4	5.4
Subbase	2	2	1.9	2.4	2.7	3.2	3.4	4.4	3.9	5.6
Subbase	2	3	1.9	2.4	2.7	3.3	3.2	4.4	4.1	5.7
Subbase	3	1	1.8	2.3	2.5	3.1	3.3	4.2	4.1	5.4
Subbase	3	2	2	2.1	2.6	2.9	3.2	3.9	4.5	5
Subbase	3	3	2	2.2	2.7	3	3.2	4.1	4.1	5.3
Subgrade	1	1	0.8	1	1.1	1.4	1.4	1.9	1.8	2.4
Subgrade	1	2	0.8	1	1	1.4	1.4	1.9	1.7	2.5
Subgrade	1	3	0.9	1	1.1	1.4	1.4	1.9	1.7	2.5
Subgrade	2	1	0.9	1	1.1	1.4	1.5	1.9	1.9	2.5
Subgrade	2	2	0.8	1.1	1.2	1.5	1.4	2	1.5	2.6
Subgrade	2	3	0.8	1.1	1	1.5	1.3	2	1.6	2.6
Subgrade	3	1	0.8	1	1.1	1.4	1.4	1.9	1.9	2.5
Subgrade	3	2	0.8	1	1.1	1.4	1.4	1.8	1.9	2.4
Subgrade	3	3	0.9	1	1.1	1.4	1.4	1.9	1.8	2.4

[a] FWD load level; [b] Measured vertical stress; [c] Predicted vertical stress.

Table 6. Summary of Prediction Errors.

Location	LL-1 Prediction Error (%)	LL-2 Prediction Error (%)	LL-3 Prediction Error (%)	LL-4 Prediction Error (%)	Average Prediction Error (%)
Bottom of Wearing	-48.5	-42.9	-52.2	-53.2	-49.2
Bottom of Binder	-30.8	-19.5	-14.8	-16.1	-20.3
Bottom of BCBC	-26.1	-19.5	-19.1	-29.3	-23.5
Top of Subbase	-20.1	-19.2	-26.5	-30.1	-24
Top of Subgrade	-26.7	-31.3	-38.2	-43.1	-34.8
Average	-30.4	-26.5	-30.2	-34.4	-30.4



(a) Strains at the Bottom of Wearing Layer

(b) Strains at the Bottom of Binder Layer

(c) Strains at the Bottom of BCBC Layer

(d) Stresses at the Top of Subbase

(e) Stresses at the Top of Subgrade

(f) Prediction Errors

Fig. 9. Comparison of Measured and Predicted Pavement Responses.

compute horizontal strains in the AC layers and vertical stresses in the subbase and subgrade. The same pavement structure used in backcalculation was utilized. Key considerations of 3-D FE modeling, such as boundary conditions, analysis procedures, and element selection are detailed elsewhere [17], as the FE model was developed for other analyses of the pavement section. Because the FWD testing was conducted directly above instrumentation locations, layer moduli from backcalculations were used in the FE model for this study.

Measured and simulated pavement responses to FWD loads are tabulated in Table 4. The effectiveness of developed FE models in simulating pavement response is evaluated in terms of the prediction error at each load level, *e*:

$$e = (\frac{\varepsilon_M - \varepsilon_S}{\varepsilon_M}) * 100 \quad (2)$$

where S is the simulated response from FEA, and M is the measured response. A positive value of *e* indicates an underprediction from FE simulations, while a negative value of *e* suggests an overprediction. Prediction errors at all FWD load levels are summarized in Tables 4 and 5 for horizontal strains and vertical stresses, respectively. Graphical presentations of these tables are also given in Fig. 9a through 9e.

As seen from Table 6 (Fig. 9f), the FE model generally overpredicts measured both strain and stress responses in all pavement layers. The magnitude of the prediction error is independent of FWD load levels. The FE model results in the largest prediction error (about 50 percent) at the bottom of the wearing layer. One possible explanation would be the combination of wearing and binder layers in the FE model. First of all, although both mixtures have the same binder PG grade (PG 64-22), different nominal maximum aggregate size (9.5 mm vs. 19.0 mm) could result in a large variation in mixture stiffness at low temperatures. Also, during the FWD testing, the temperature in the wearing layer was considerably higher than the binder layer (Fig. 5a). The use of one single modulus value backcalculated from FWD deflections may not be appropriate for a thin surface layer, as seen in the selected Blair pavement structure, if responses in that thin layer are to be predicted. In addition, the over prediction from the FE model might be due to weak support from base. Further laboratory tests are needed so that the base layer moduli can be calibrated.

Conclusions

This paper presents a mechanistic approach to simulate full-depth flexible pavement responses when subjected to FWD loads. This general purpose approach has a low computational cost and great merits for highway pavement applications.

FWD testing was conducted at pavement locations instrumented with strain gauges, pressure cells, and thermocouples. Layer moduli were backcalculated from the FWD load and deflection data. In the backcalculation, the AC layers and subbase were modeled as linear elastic materials, while nonlinear elastic behavior was assumed for the subgrade. The backcalculated AC moduli were compared to laboratory values, which were adjusted for load duration and temperature. The adjusted laboratory values for the surface layers were consistently lower, averaging about 70 percent of the backcalculated values. The adjusted laboratory values for the BCBC were about 10 percent higher than the backcalculated values.

Three-dimensional FE simulations, using a previously developed model for the pavement section, were then conducted using the backcalculated layer moduli. The FE model was used to predict horizontal strains in AC layers and vertical stresses in subbase and subgrade, at the locations of the instrumentation. An average prediction error of 30 percent was found through comparison of the simulated and measured pavement responses, with the predicted responses exceeding the measured responses in every case.

Future research plans include the extension of this work to other instrumented pavement sections, laboratory characterization of the remaining pavement layers, and the further consideration of causes of differences between the laboratory and backcalculated values, and between the measured and predicted pavement responses under the FWD load.

References

1. Stolle, D., and Hein, D. (1989). Parameter estimates of pavement structure layers and uniqueness of the solution. In Nondestructive testing of pavements and backcalculation of moduli. *Special Technical Publication (STP) 1026*, ASTM, Philadelphia, PA, USA, pp. 313-322.
2. Irwin, L. H. (2000). MODCOMP. Cornell Local Roads Program, Ithaca, NY, USA.
3. American Association of State Highway and Transportation Officials (AASHTO) (1993). Guide for design of pavement structures, Vol. II. Joint Task Force on Pavements, Highway Subcommittee on Design, Washington, DC, USA.
4. Beer, M., Johnson, G., Van Deusen, D. (1997). Performance of MnRoad Load Response and Environmental Instrumentation. Presented at 76th Transportation Research Board Annual Meeting, Washington, DC, USA.
5. Quintus, H. V. and Killingsworth, B. (1998). Analysis Relating Pavement Material Characterizations and Their Effects on Pavement Performance. Report No. *FHWA-RD-97-085*, Federal Highway Administration, McLean, VA, USA.
6. Daleiden, J. F., Killingsworth, B. M., Simpson, A. L., and Zamora, R. A. (1994). Analysis of Procedures for Establishing In Situ Subgrade Moduli. *Transportation Research Record*, No. 1462, pp. 102-107.
7. Akram, T., Scullion, T., and Smith, R. E. (1994). Comparing Laboratory and Backcalculated Layer Moduli on Instrumented Pavement Sections. *Special Technical Publication (STP) 1298*, ASTM, Philadelphia, PA., pp. 170-202.
8. Zhou, H. (2000). Comparison of Backcalculated and Laboratory Measured Moduli on AC and Granular Base Layer Materials. Nondestructive Testing of Pavements and Backcalculation of Moduli: Third Volume, *ASTM STP 1375*, West Conshohochen, PA, USA, pp. 161-173.
9. Mikhail, M. Y., Seeds, S. B., Alavi, S. H., and Ott, W. C. (1999). Evaluation of laboratory and backcalculated resilient moduli from the WesTrack experiment. *Transportation Research Record*, No. 1687, pp. 55-65.
10. Chang, D.W., J.M. Roesset and K.H. Stokoe, II, (1992). Nonlinear Effects in Falling Weight Deflectometer Tests, *Transportation Research Record*, No. 1355, pp. 1-7.
11. Chang, D.W., V.Y. Kang, J.M. Roesset and K.H. Stokoe II,

(1992). Effects of Depth to Bedrock on Deflection Basins Obtained with Dynaflect and FWD Test, *Transportation Research Record*, No. 1355, pp. 8-16.
12. Chang, D.W. and C.L. Chang, (1998). Dynamic Interpretation for Impulsive Deflection Test on Flexible Pavements, *The Chinese Journal of Mechanics*, 14(2), Series A, pp. 91-100.
13. Solaimanian, M., Hunter, D., and Stoffels, S. M. (2006). Design and Construction Report for Superpave In-Situ Stress-Strain Instrumentation Sites, State Route 1001, Blair County, Pennsylvania. Final Report. Pennsylvania Transportation Institute, University Park, PA, USA.
14. Anderson, D.A., Solaimanian, M., Hunter, D. and Soltani, A. (2003). Superpave Validation Studies: SISSI Instrumentation, Operating Instructions and Baseline Measurements. Final Report. Pennsylvania Transportation Institute, University Park, PA, USA.
15. Huang, Y. (1993). *Pavement Analysis and Design*, Prentice Hall, Upper Saddle River, NJ, USA.
16. Stoffels, S. M., Solaimanian M., and Morian, D. (2006). Seasonal Variations for Superpave In-Situ Stress/Strain Investigation. Final Report, Pennsylvania Transportation Institute, University Park, PA, USA.
17. Yin, H. (2007). Integrating Instrumentation Data in Probabilistic Performance Prediction of Flexible Pavements. Ph.D. Dissertation. The Pennsylvania State University, University Park, PA, USA.