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16. Abstract

This report discusses the analyses of deflection data collected on thick and thin asphaltic concrete pavement sections instrumented with Multidepth Deflectometers (MDD's). Surface and depth deflection data were collected under both FWD and truck loadings. Linear elastic analysis was performed to compare layer moduli backcalculation from

- FWD surface deflections only, and
- FWD surface and MDD depth deflections combined,

Researchers compared backcalculated moduli values with the laboratory results. The moduli calculated from FWD loads were also used to predict pavement response under known truck loads. These predictions were compared to the actual measured response. In general it was found that the FWD characterization slightly overestimates the strength of the subgrade and underpredicts the vertical compressive subgrade strains induced by truck loads by between 14 and 18%.

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Comparing Pavement Responses Under FWD and Truck Loads

by

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TTI Report 1184-2 Vol. 1
Interim Report

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Texas Transportation Institute
The Texas A&M University System
College Station, Texas

July 1993

METRIC (SI*) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

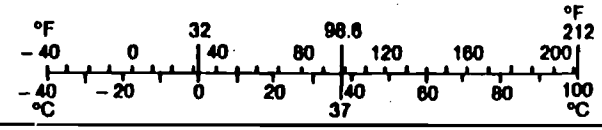
Symbol	When You Know	Multiply By	To Find	Symbol
	LENGTH			
in	inches	2.54	centimetres	cm
ft	feet	0.3048	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km
	AREA			
in^2	square inches	645.2	centimetres squared	cm^2
ft^2	square feet	0.0929	metres squared	m^2
yd^2	square yards	0.836	metres squared	m^2
mi^2	square miles	2.59	kilometres squared	km^2
ac	acres	0.395	hectares	ha
	MASS (weight)			
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
	VOLUME			
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft^3	cubic feet	0.0326	metres cubed	m^3
yd^3	cubic yards	0.0765	metres cubed	m^3

NOTE: Volumes greater than 1000 L shall be shown in m^3.

	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
	LENGTH			
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi
	AREA			
mm^2	millimetres squared	0.0016	square inches	in^2
m^2	metres squared	10.764	square feet	ft^2
km^2	kilometres squared	0.39	square miles	mi^2
ha	hectores (10 000 m^2)	2.53	acres	ac
	MASS (weight)			
g	grams	0.0353	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams (1 000 kg)	1.103	short tons	T
	VOLUME			
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m^3	metres cubed	35.315	cubic feet	ft^3
m^3	metres cubed	1.308	cubic yards	yd^3
	TEMPERATURE (exact)			
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



These factors conform to the requirement of FHWA Order 5190.1A.

* SI is the symbol for the International System of Measurements

IMPLEMENTATION STATEMENT

This work provides an important step in the implementation of the Department's mechanistic pavement design procedure. As described the FWD characterization of strengths can be used to make reasonable predictions of strains induced by known vehicle loads. These calculated strains can therefore be used with some confidence to predict pavement life.

DISCLAIMER

This report is not intended to constitute a standard, specification or regulation and does not necessarily represent the views or policies of the FHWA or the Texas Department of Transportation. Additionally, this report is not intended for construction, bidding, or permit purposes.

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SUMMARY

Nondestructive testing using Falling Weight Deflectometers is commonly performed to determine in-situ pavement layer strengths. These strength values are then used in pavement design to predict the stresses and strains that will be induced in the pavement by standard design loads. This report addresses the issue of "Given a set of moduli value obtained from FWD testing how accurate are they in predicting what a truck load will do to the pavement?". Testing was performed on instrumented pavements with both FWD and known truck loads.

In summary it was found that the FWD moduli values slightly underpredict strains induced by known truck loads by between 14 and 18%. Correction factors of this magnitude should be considered for mechanistic design procedures.

CHAPTER 1
INTRODUCTION

Study 1184 was initiated to evaluate the damaging effects of wide based super singles on highways. As a part of that study researchers instrumented two in-service pavements with multi-depth deflectometers (MDD's). This report describes work performed on these pavements to compare the response under Falling Weight Deflectometer (FWD's) and truck loads. FWD's are used extensively around the world to evaluate the structural strength of pavements. Backcalculation procedures provide the means by which the FWD deflection bowls are converted into pavement layer moduli. These moduli are then used to predict the stress and strains in the pavement by the design truck loads. These responses are used to design the layer thicknesses to accommodate all the truck loads in the pavements design life. One important aspect of this procedure that has not received much attention, but which this report addresses, is how reliable are the FWD moduli when used to predict pavement responses under truck loads. The basic question is, "given my E values from FWD backcalculation, how well can the subgrade strains be predicted for a known truck load.?"

The analysis has been limited to linear elastic solutions. The backcalculation scheme used is the MODULUS procedure developed by Uzan et al., 1988. This chapter describes the test section layouts together with the field data collection procedure.

1.1 Layout and Cross-Section of Test Pavement Sections

This study was conducted on test sites located on Farm to Market Road 2818 (Section I [Thin]) near Bryan, Texas and State Highway 21 (Section II [Thick]) between Bryan and Caldwell, Texas. MDDs with four Linear Variable Differential Transformers (LVDT) modules were installed at each site. To determine the transverse position of the truck tires relative to the MDD location, a grid was painted on the pavement surface next to the MDD hole. As the test vehicle passed over the MDD, a video camera recorded the transverse (or lateral) position of the outer tires relative to the MDD position. Figure 1 shows the cross-sections of the test pavements showing the locations of MDD sensors.

1.2 Overview of Field Testing and Data Analyses

Field testing included FWD testing, with simultaneous recording of both surface and MDD depth deflections. Depth deflections were also measured in the pavement structure under controlled truck loadings. The truck testing was completed immediately after FWD testing. A 3S2 water tanker, shown in Figure 2, was used for the testing.

Figures 3a shows typical MDD responses from Section II (Thick) under the test vehicle loading. From the information shown in this figure, it is possible to compute the average vertical compressive strains within the pavement layers. Average vertical compressive strains at the top of the subgrade layer are calculated as the deflection measured by MDD 2 minus MDD 3 divided by the separation distance for Section I (Thin), and MDD 3 minus MDD 4 divided by the separation distance for Section II (Thick). Figure 3b shows a typical multidepth strain profile computed for truck loading on Section II (Thick).

1.3 Outline of Report

In the analysis phase attempts were made to match both surface and depth deflections using linear elastic models. The results of moduli backcalculated from different deflection data sets were compared with those from laboratory testing. In further analysis the moduli backcalculated from FWD loads were used to characterize the pavement structure. These were then used to predict the vertical compressive strains at the top of the subgrade layer that should be induced by a known dual tire load. The predicted subgrade strains were compared with those measured under the actual truck loads. Chapter 5 of this report shows these comparisons.

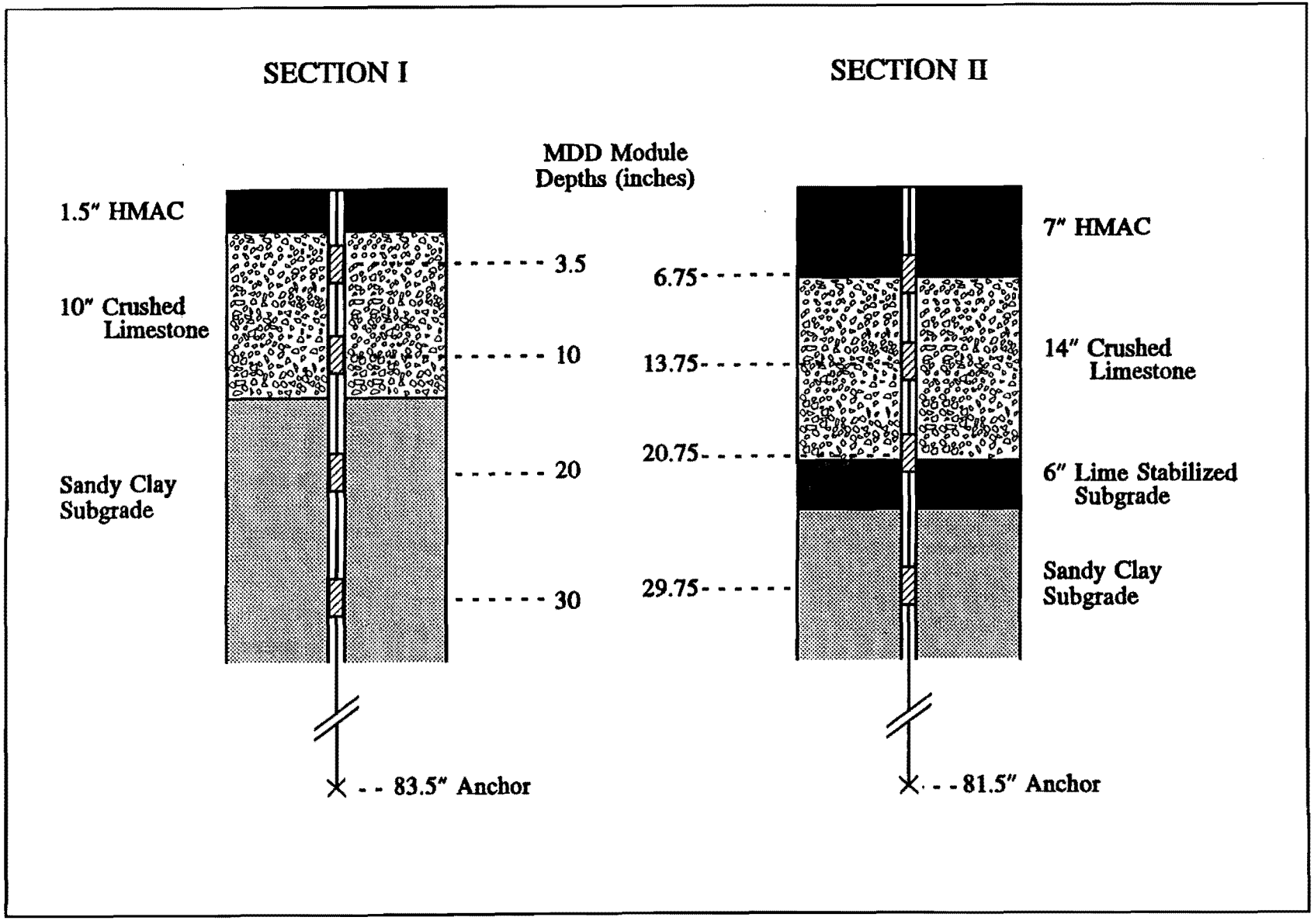

FIG. 1. MDD Locations in Test Pavements

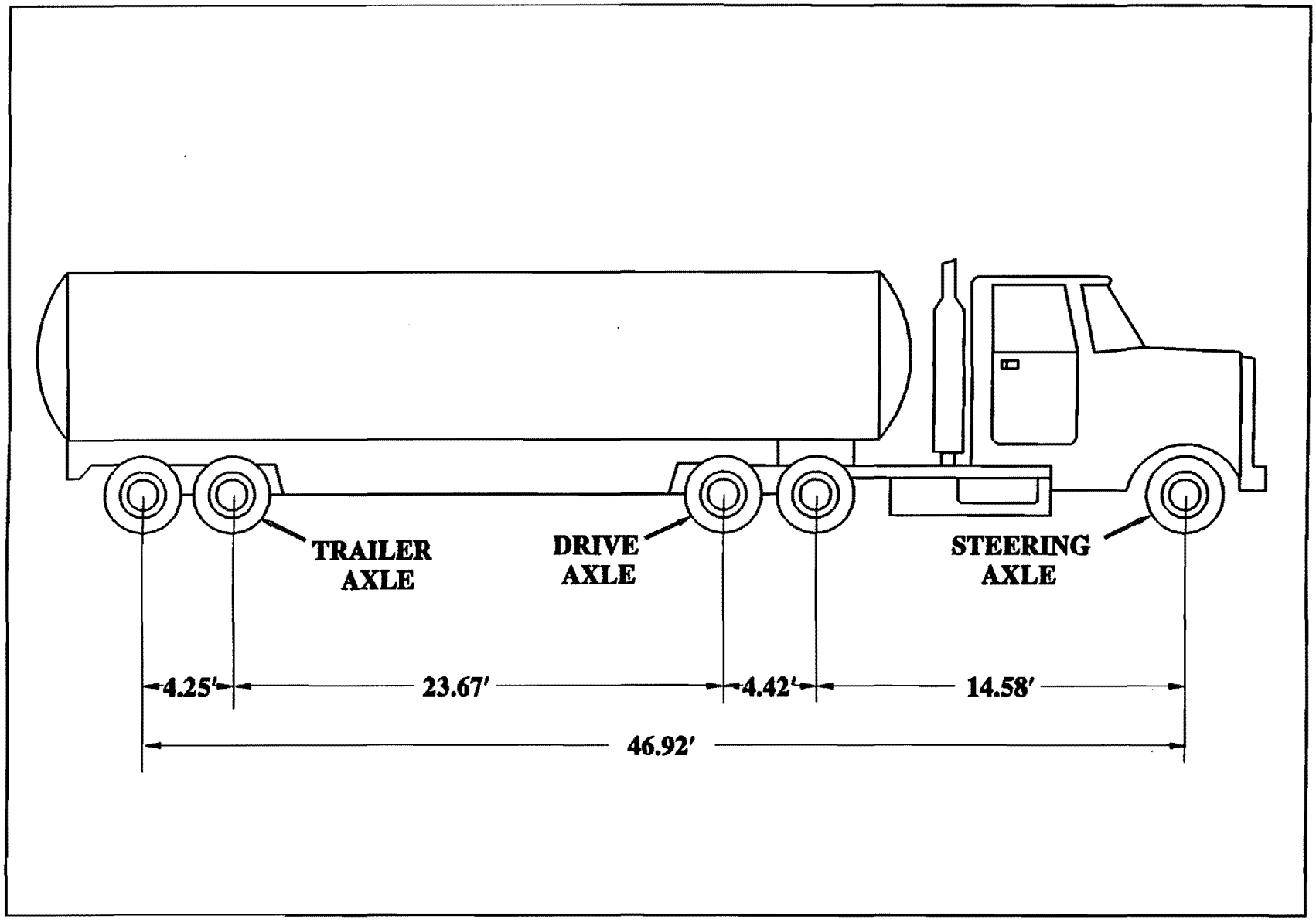

FIG. 2. 3S2 Water Tanker Used for Testing

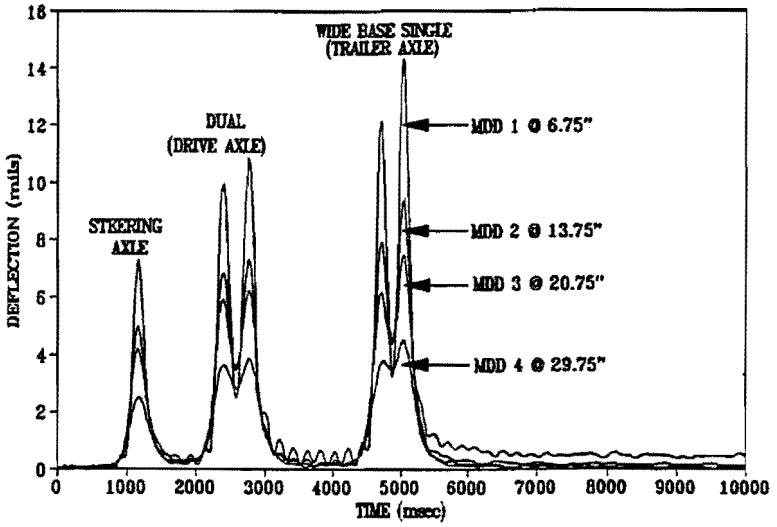

FIG. 3a. Typical Depth Deflections Profile Measured by MDD on Section II (Thick) Under the Test Vehicle (5 Axle) Loading

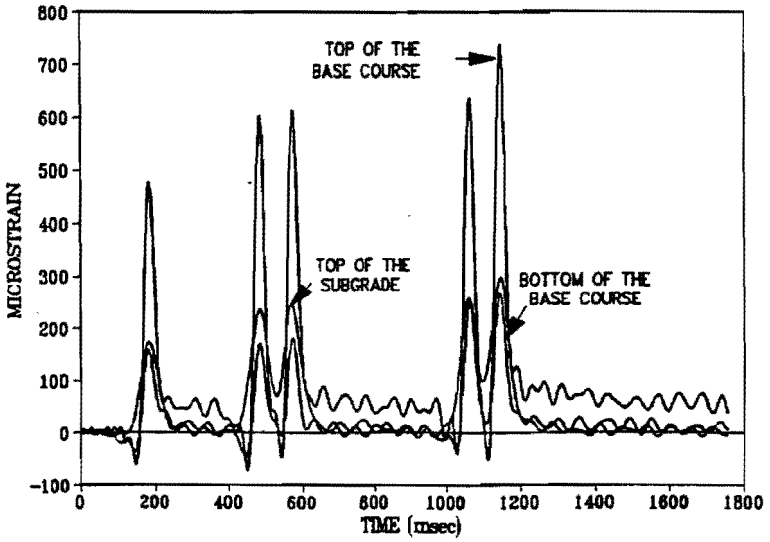

FIG. 3b. Typical Multidepth Strain Profile Measured by MDD on Section II (Thick) Under the Test Vehicle (5 Axle) Loading

CHAPTER 2
ANALYSIS OF DEFLECTION DATA UNDER FWD LOADING

2.1 Analysis of Surface Deflections

On both instrumented test sections, FWD deflection measurements were recorded using two different load levels with 4 replicate drops. Peak loads and peak surface deflections were used in the analysis. Using the layered elastic backcalculation program MODULUS 4.0, researchers analyzed the deflection data and backcalculated the layer moduli values.

The Analysis of Section I (Thin)

In the surface deflection analysis for the thin section the 1.5 inches thick asphalt concrete surface layer modulus was fixed at 293 ksi, based on the asphalt concrete layer temperature at the time of FWD deflection testing.

The summary results of surface deflection analysis for the thin section, at different load levels are shown in Table 1. The average base modulus value at the higher load level was computed to be greater than at the 8,000 lbs load level. The subgrade modulus decreased slightly with the increase in load.

The Analysis of Section II (Thick)

The pavement was modelled as a three layer system. Based on cone penetration test results, the lime stabilized layer was considered as part of the subgrade layer. A summary of the backcalculation results for different load levels along with average moduli values, and absolute error per sensor are given in Table 2. The granular base layer moduli values increased with the increase in load level. The subgrade modulus did not change significantly under different load levels.

Table 1. Summary Results of the Surface Deflection Analysis at Different Load Levels for Section I (Thin)

TTI MODULUS ANALYSIS SYSTEM (SUMMARY REPORT) (Version 4.0)

District: 1
County: 1
Highway/Road: 2818

	Thickness(in)	MODULI RANGE(psi) Minimum	Maximum
Pavement:	1.50	292,971	293,029
Base:	10.00	10,000	150,000
Subbase:	0.00	0	0
Subgrade:	288.50	10,000	

Station	Load (lbs)	Measured Deflection (mils): R1	R2	R3	R4	R5	R6	R7	Calculated Moduli values (ksi): SURF(E1)	BASE(E2)	SUBB(E3)	SUBG(E4)	Absolute ERROR/Sens.	Depth to Bedrock
1.000	8,383	34.12	20.15	9.61	5.88	4.16	2.94	2.41	293.	31.7	0.0	8.9	4.71	292.66
1.000	8,343	33.57	19.81	9.53	5.84	3.99	3.10	2.41	293.	32.4	0.0	8.9	5.11	293.83
1.000	8,375	34.04	20.15	9.65	5.96	4.12	3.06	2.41	293.	32.2	0.0	8.8	4.20	300.00
1.000	8,295	34.28	20.36	9.74	6.04	4.16	3.22	2.45	293.	31.9	0.0	8.6	4.97	300.00
Mean:		34.00	20.12	9.63	5.93	4.11	3.08	2.42	293.	32.0	0.0	8.8	4.75	300.00
Std. Dev:		0.31	0.23	0.09	0.09	0.08	0.12	0.02	0.	0.3	0.0	0.2	0.40	16.03
Var Coeff(%):		0.90	1.13	0.91	1.50	1.96	3.75	0.83	0.	1.0	0.0	1.7	8.40	5.34
1.000	14,703	55.05	33.99	17.38	10.86	7.37	5.43	4.30	293.	41.7	0.0	8.2	5.61	274.24
1.000	14,071	55.21	34.20	17.51	10.78	7.41	5.39	4.34	293.	39.3	0.0	7.8	5.64	300.00
1.000	14,758	55.29	34.33	17.59	10.42	7.45	5.55	4.38	293.	41.2	0.0	8.2	6.61	208.82
Mean:		55.18	34.17	17.49	10.69	7.41	5.46	4.34	293.	40.7	0.0	8.1	5.95	260.48
Std. Dev:		0.12	0.17	0.11	0.23	0.04	0.08	0.04	0.	1.3	0.0	0.2	0.57	48.17
Var Coeff(%):		0.22	0.50	0.61	2.19	0.54	1.53	0.92	0.	3.1	0.0	2.7	9.53	18.49

Table 2. Summary Results of the Surface Deflection Analysis (Second Model) at Different Load Levels for Section II (Thick)

TTI MODULUS ANALYSIS SYSTEM (SUMMARY REPORT) (Version 4.0)

District: 1
County: 1
Highway/Road: 21

	Thickness(in)	MODULI RANGE(psi) Minimum	Maximum
Pavement:	7.00	100,000	400,000
Base:	14.00	10,000	100,000
Subbase:	0.00	0	0
Subgrade:	83.40	16,900	

Station	Load (lbs)	Measured Deflection (mils): R1	R2	R3	R4	R5	R6	R7	Calculated Moduli values (ksi): SURF(E1)	BASE(E2)	SUBB(E3)	SUBG(E4)	Absolute ERROR/Sens.	Depth to Bedrock
1.000	8,839	13.23	7.32	3.35	2.09	1.54	1.25	1.05	169.	38.3	0.0	17.3	4.69	111.75
1.000	8,863	13.12	7.28	3.31	2.05	1.50	1.25	1.05	174.	37.8	0.0	17.7	4.69	106.42
1.000	8,839	13.04	7.28	3.35	2.05	1.50	1.25	1.05	181.	36.9	0.0	17.6	4.30	100.17
1.000	8,783	13.04	7.32	3.35	2.05	1.46	1.25	1.05	181.	36.3	0.0	17.5	4.43	100.00
Mean:		13.11	7.30	3.34	2.06	1.50	1.25	1.05	176.	37.3	0.0	17.5	4.53	104.36
Std. Dev:		0.09	0.02	0.02	0.02	0.03	0.00	0.00	5.	0.9	0.0	0.2	0.20	4.78
Var Coeff(%):		0.69	0.32	0.60	0.97	2.18	0.00	0.00	3.	2.5	0.0	0.9	4.37	4.58
1.000	10,799	14.57	8.72	4.09	2.45	1.79	1.49	1.33	231.	37.5	0.0	17.3	4.26	90.39
1.000	10,791	15.51	8.80	4.13	2.57	1.87	1.57	1.37	181.	41.3	0.0	16.4	4.55	110.74
1.000	10,823	15.47	8.80	4.13	2.53	1.87	1.57	1.33	186.	40.1	0.0	16.7	4.31	101.22
Mean:		15.18	8.77	4.12	2.52	1.84	1.54	1.34	199.	39.7	0.0	16.8	4.37	100.09
Std. Dev:		0.53	0.05	0.02	0.06	0.05	0.05	0.02	27.	1.9	0.0	0.4	0.16	8.35
Var Coeff(%):		3.50	0.53	0.56	2.43	2.51	2.99	1.72	14.	4.9	0.0	2.6	3.64	8.34
1.000	15,783	20.77	12.02	5.89	3.63	2.66	2.21	1.93	218.	43.2	0.0	17.9	3.57	105.50
1.000	15,775	20.65	12.02	5.85	3.63	2.66	2.21	1.93	218.	43.5	0.0	17.9	3.85	109.31
1.000	15,751	20.69	12.02	5.89	3.63	2.66	2.21	1.93	219.	43.2	0.0	17.8	3.60	105.48
Mean:		20.70	12.02	5.88	3.63	2.66	2.21	1.93	218.	43.3	0.0	17.8	3.67	106.73
Std. Dev:		0.06	0.00	0.02	0.00	0.00	0.00	0.00	1.	0.2	0.0	0.0	0.15	1.78
Var Coeff(%):		0.30	0.00	0.39	0.00	0.00	0.00	0.00	0.	0.4	0.0	0.2	4.18	1.67

2.2 Analysis of Surface and Depth Deflections

On the two test sections, simultaneous surface and depth deflection measurements were obtained from FWD loadings at three different load levels and at three offsets from the MDD location. The detailed description, installation techniques, testing procedures, and measurement of anchor movements are described in detail elsewhere (Scullion et al. 1988). The measured peak loads, surface deflections, and depth deflections were used in the analysis phase of this study. The deflection results were analyzed using the linear elastic generalized backcalculation procedure developed by Uzan et al. (1988a). The analyses include simultaneously matching theoretically computed surface and depth deflections with those measured in the field.

The Analysis of Section I (Thin) Deflection Data

Three sets of surface and depth deflection data were collected at offsets of 2.25, 8.5 and 17.5 inches from the center of the FWD loading plate to the middle of the MDD hole. An offset distance of 2.25 inches from the center of the FWD load plate to the middle of the MDD hole was used to prevent the center geophone from sitting directly on the MDD top cap. The resulting surface deflections, depth deflections, and anchor movements were measured simultaneously. When the FWD plate was not over the MDD hole (offset of 8.5 and 17.5 inches), the movement of the anchor was monitored by measuring the movement on the center rod of the MDD system. This was achieved by placing one of the FWD outer geophones (the geophone at 60 inches) on top of a pedestal mounted on the center core.

Figure 4 shows the plot of the averaged measured surface and depth deflection data for Section I (Thin) normalized to 9,000 lbs load. It includes average FWD surface deflections for all offsets combined, and averages of MDD depth deflections for each of three offset. The depth deflections measured at the top and the bottom of the granular base layer by MDD 1 and MDD 2, at an offset of 8.5 and 17.5 inches from the load, were larger than those measured by the FWD surface sensors. These deflection values suggest that some dilation or extension takes place in the granular base layer.

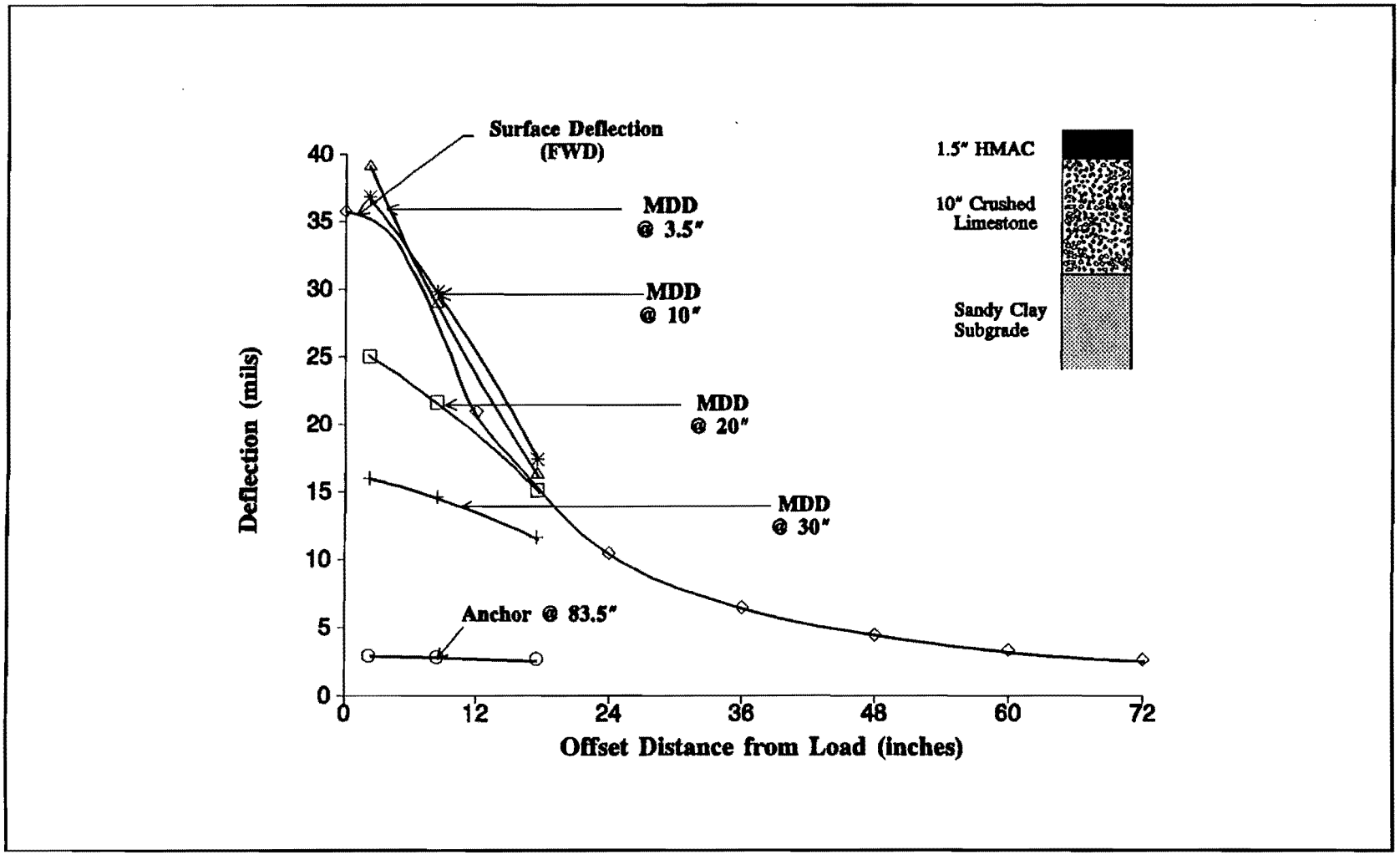

FIG. 4. Measured Surface and Depth Deflections Under FWD Loading on Section I (Thin)

For the purpose of linear analysis, Section I (Thin) was modelled as a three layer system. The thin asphalt layer modulus value was fixed at 293 ksi and the base and subgrade layer moduli were backcalculated. In the backcalculation analyses, researchers included the average of all FWD surface deflections measured at all three offsets (seven) and the average of the MDD depth deflections for individual offset (4 depths x 3 offsets from load). Table 3 lists the measured and calculated surface and depth deflections as well as the backcalculated moduli. The best match base modulus was 24.6 ksi with a subgrade modulus of 7.6 ksi. Figures 5a and 5b graphically illustrate the results of deflection analyses.

From studying the results for nineteen deflections (seven surface plus twelve depth), the best fit linear elastic model resulted in an average error of 10.5% per sensor. The error value is quite reasonable for the thin section with an assumption of linearity-elasticity, it is of the same magnitude as those presented by Uzan and Scullion (1990). The surface deflections, as shown in Figure 4a, match well for all sensors except the one directly under the loading plate, which is over predicted by about 28%. For depth deflections, the match proves good for MDD 1 (top of the base layer) and for MDD 4 (18.5 inches into the subgrade layer), as shown in Figure 5b. The largest error in this system (8-21% error) occurs at MDD 2 (bottom of the base) and at MDD 3 (8.5 inches into the subgrade). The deflections were under predicted for MDD 2 and MDD 3 for all offsets. This implies that the subgrade modulus appears to be slightly over predicted.

The Analyses of Section II (Thick) Deflection Data

The thick pavement was modelled as a three layer system and the lime stabilized layer was considered as part of the subgrade layer. Three FWD/MDD data sets were collected at offsets of 2.5, 8.75, and 14.5 inches from the center of the FWD loading plate to the middle of the MDD hole. The data collection procedure was identical to that used for Section I (Thin).

Figure 6 shows the measured data for Section II (Thick) normalized to 9,000 lbs. It shows that the depth deflection measured at the top of the granular base layer (MDD 1), at an offset of 14.5 inches from the load, is larger than that measured at the surface of the pavement.

Table 3. Results of the Surface and Depth Deflection Analysis for Section I (Thin) Under FWD Loadings

Surface Deflections							
Offset r (inches)	0.00	12.00	24.00	36.00	48.00	60.00	72.00
Measured Deflection (mil)	35.75	20.92	10.46	6.47	4.45	3.33	2.64
Predicted Deflection (mil)	45.78	21.51	11.91	7.44	5.02	3.58	2.67
Error (percent)	-25.06	-2.80	-13.87	-14.97	-12.75	-7.66	-1.16
Absolute Error (mil)	10.03	0.59	1.45	0.97	0.57	0.25	0.03
Backcalculated Moduli							
Asphalt Concrete (psi)	293,000						
Granular Layer (psi)	24,580						
Subgrade (psi)	7,588						

Table 3. Continued

MDD Deflections			
Offset from Load to MDD Hole (inches)	2.25	8.5	17.5
LVDT at a Depth of 3.5 inches (Top of the Base)			
Measured Deflection (mil)	39.10	28.87	16.27
Predicted Deflection (mil)	39.87	27.35	16.10
Error (percent)	-1.97	5.28	1.05
Absolute Error (mil)	0.77	-1.52	-0.17
LVDT at a Depth of 10 inches (Bottom of the Base)			
Measured Deflection (mil)	36.82	29.81	17.41
Predicted Deflection (mil)	30.72	24.72	15.81
Error (percent)	16.56	17.06	9.18
Absolute Error (mil)	-6.10	-5.09	-1.6
LVDT at a Depth of 20 inches (8.5 inches into the Subgrade)			
Measured Deflection (mil)	25.02	21.59	15.09
Predicted Deflection (mil)	19.83	18.01	13.85
Error (percent)	20.73	16.59	8.24
Absolute Error (mil)	-5.19	-3.58	-1.24
LVDT at a Depth of 30 inches (18.5 inches into the Subgrade)			
Measured Deflection (mil)	15.99	14.62	11.65
Predicted Deflection (mil)	14.20	13.47	11.45
Error (percent)	11.18	7.86	1.70
Absolute Error (mil)	-1.79	-1.15	-0.20

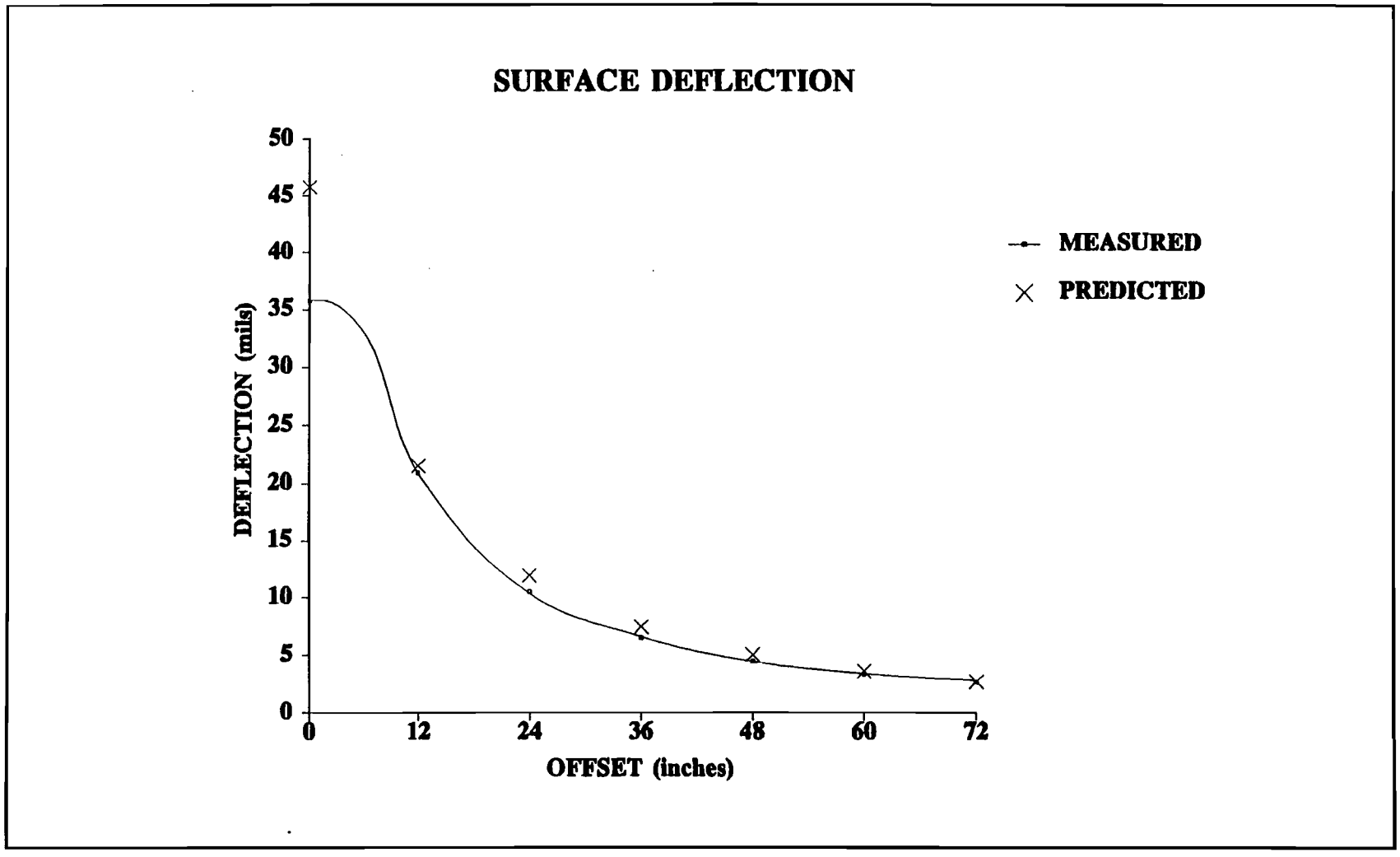

FIG. 5a. Measured and Predicted Surface Deflections Under FWD Loading on Section I (Thin)

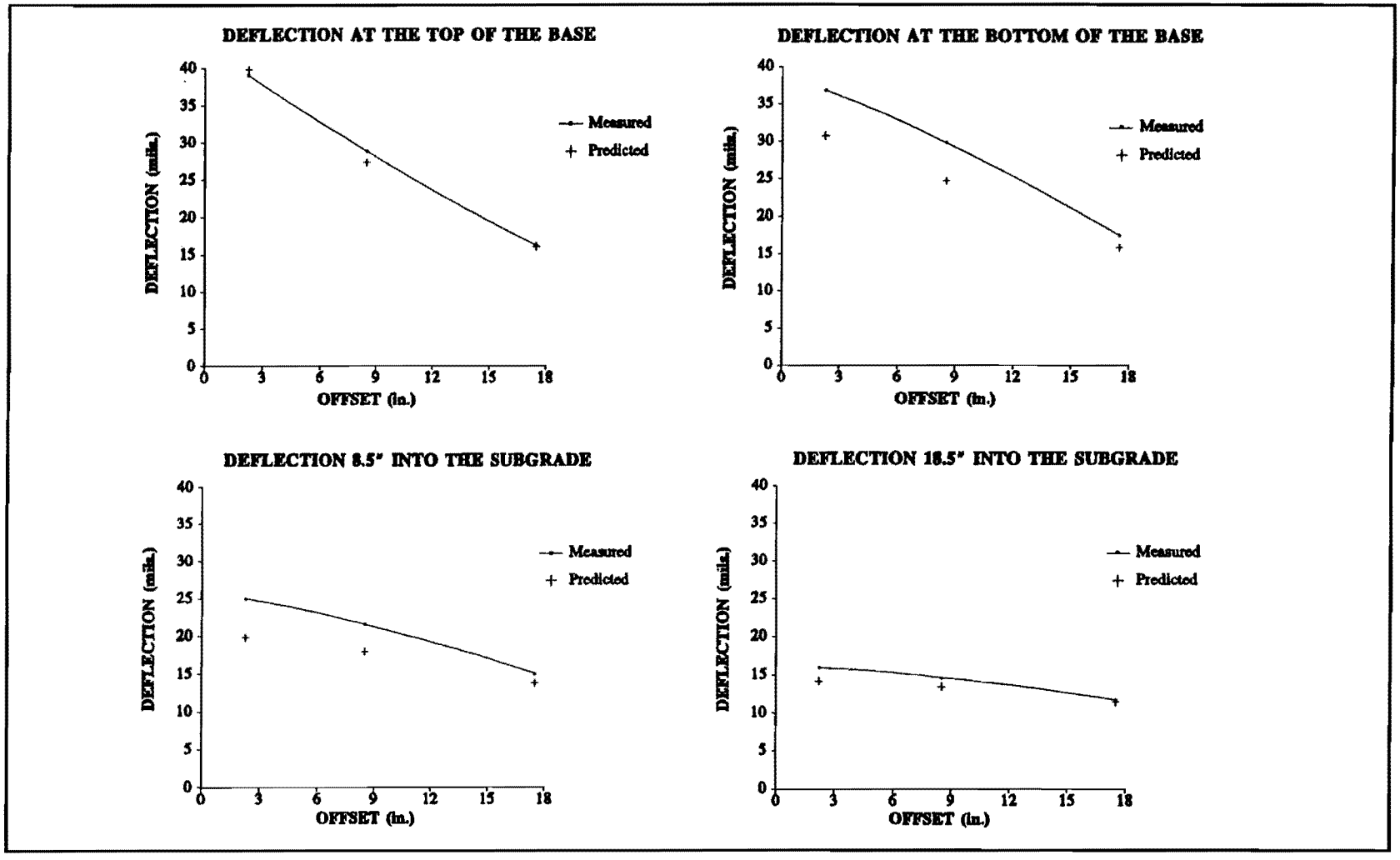

FIG. 5b. Measured and Predicted Depth Deflections Under FWD Loading on Section I (Thin)

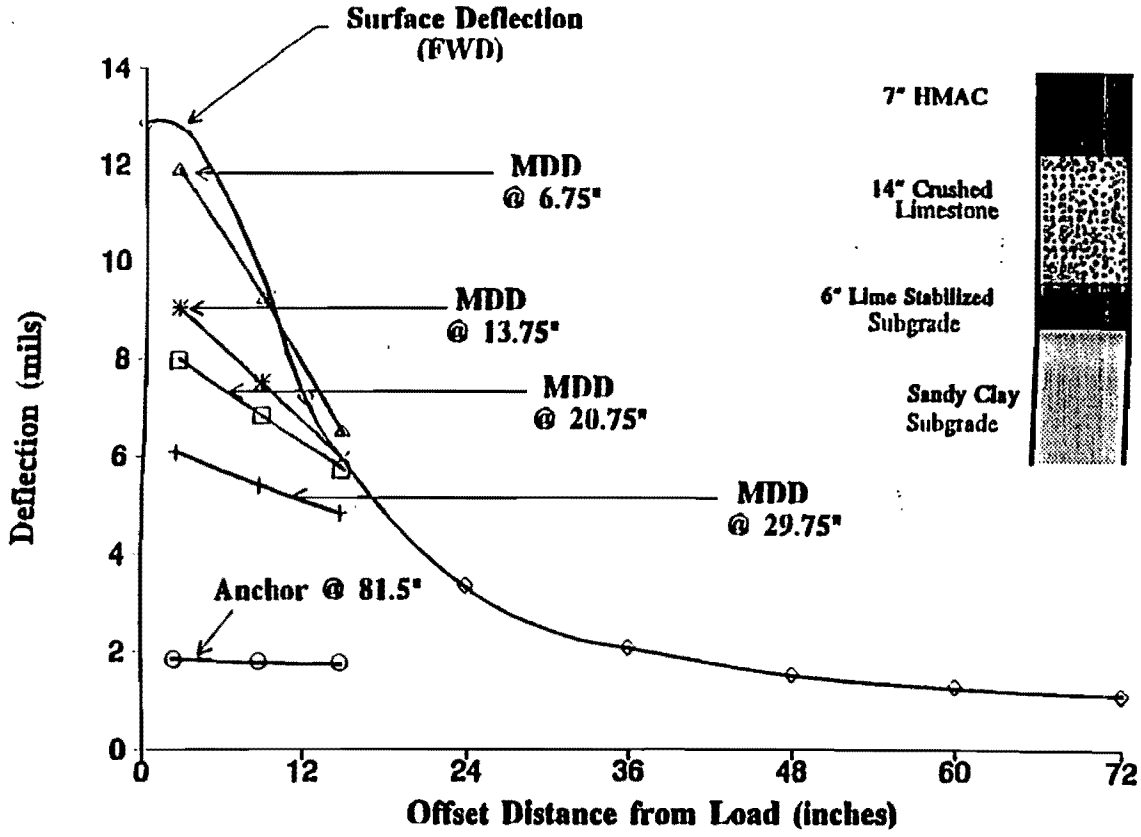

FIG. 6. Measured Surface and Depth Deflections Under FWD Loading on Section II (Thick)

Similar to Section I (Thin), these deflection values suggest that some dilation or extension takes place in the granular base layer.

Table 4 lists the measured and calculated surface and depth deflections, as well as their backcalculated moduli. Figures 7a and 7b graphically illustrate the results of the deflection analyses.

From studying the results, the linear elastic backcalculation model resulted in an average error of about 7% per sensor over sixteen deflection readings. This value of error is quite reasonable considering the non-linear behavior of the pavement analyzed and with an assumption of a three-layer linear system. The surface deflections, as shown in Figure 7a, match well for all the sensors taken into account. For depth deflections, the match was good at MDD 1 (top of the base layer) and MDD 2 (middle of the base layer), as shown in Figures 7b. The largest errors in this system (10-16% error) occur at MDD 3 (bottom of the base layer) and MDD 4 (8.75 inches into the subgrade). The deflections were under predicted at MDD 3 and MDD 4 for all offsets. The backcalculated subgrade modulus value appears to be a slight overestimate of the subgrade strength.

Table 4. Results of the Surface and Depth Deflection Analysis for Section II (Thick) Under FWD Loadings (Four Surface Plus Twelve Depth Sensors)

Surface Deflections				
Offset r (inch)	0.00	12.00	24.00	48.00
Measured Deflection (mil)	12.85	7.24	3.36	2.09
Predicted Deflection (mil)	14.55	7.30	4.00	2.32
Error (percent)	13.22	0.90	18.34	10.90
Absolute Error (mil)	1.70	0.06	0.64	0.23
Backcalculated Moduli				
Asphalt Concrete (psi)	135,737			
Granular Base (psi)	44,698			
Subgrade (psi)	15,199			
MDD Deflections				
Offset from Load to MDD Hole (inches)	2.5	8.75	14.5	
LVDT at a Depth of 6.75 inches (Top of the Base)				
Measured Deflection (mil)	11.88	9.21	6.50	
Predicted Deflection (mil)	11.97	8.92	6.45	
Error (percent)	0.80	-3.14	-0.75	
Absolute Error (mil)	0.09	-0.29	-0.05	
LVDT at a Depth of 13.75 inches (Middle of the Base)				
Measured Deflection (mil)	9.04	7.55	5.93	
Predicted Deflection (mil)	8.96	7.68	6.11	
Error (percent)	-0.85	1.74	3.04	
Absolute Error (mil)	-0.08	0.13	0.18	
LVDT at a Depth of 20.75 inches (Bottom of the Base)				
Measured Deflection (mil)	7.97	6.85	5.72	
Predicted Deflection (mil)	7.26	6.52	5.46	
Error (percent)	-8.88	-4.81	-4.46	
Absolute Error (mil)	-0.71	-0.33	-0.26	
LVDT at a Depth of 29.75 inches (8.75 inches into the Subgrade)				
Measured Deflection (mil)	6.09	5.42	4.83	
Predicted Deflection (mil)	5.11	4.78	4.25	
Error (percent)	-16.15	-11.87	-12.10	
Absolute Error (mil)	-0.98	-0.64	-0.58	

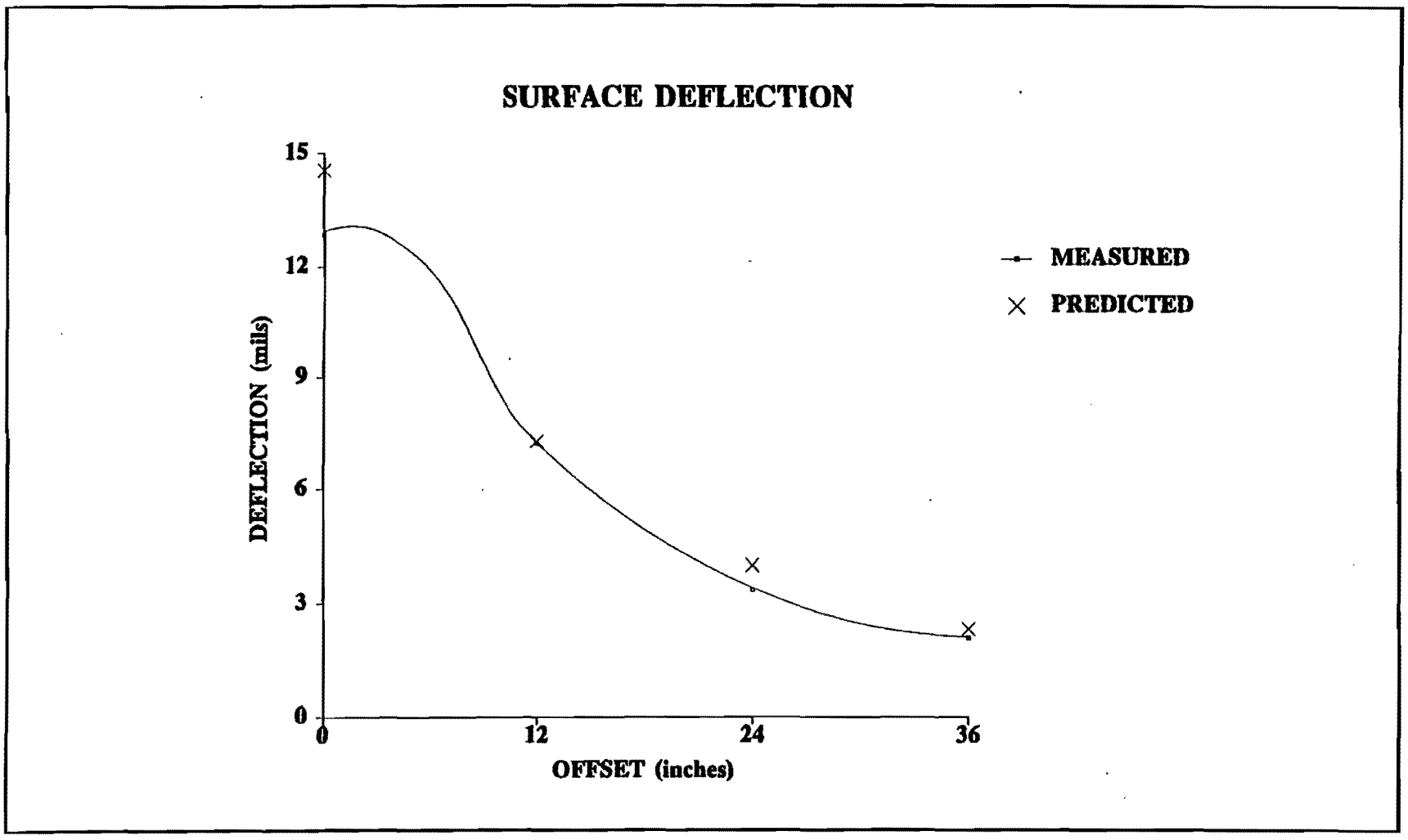

FIG. 7a. Measured and Predicted Surface Deflections (First Backcalculation Model for Four FWD Surface Sensors) Under FWD Loading on Section II (Thick)

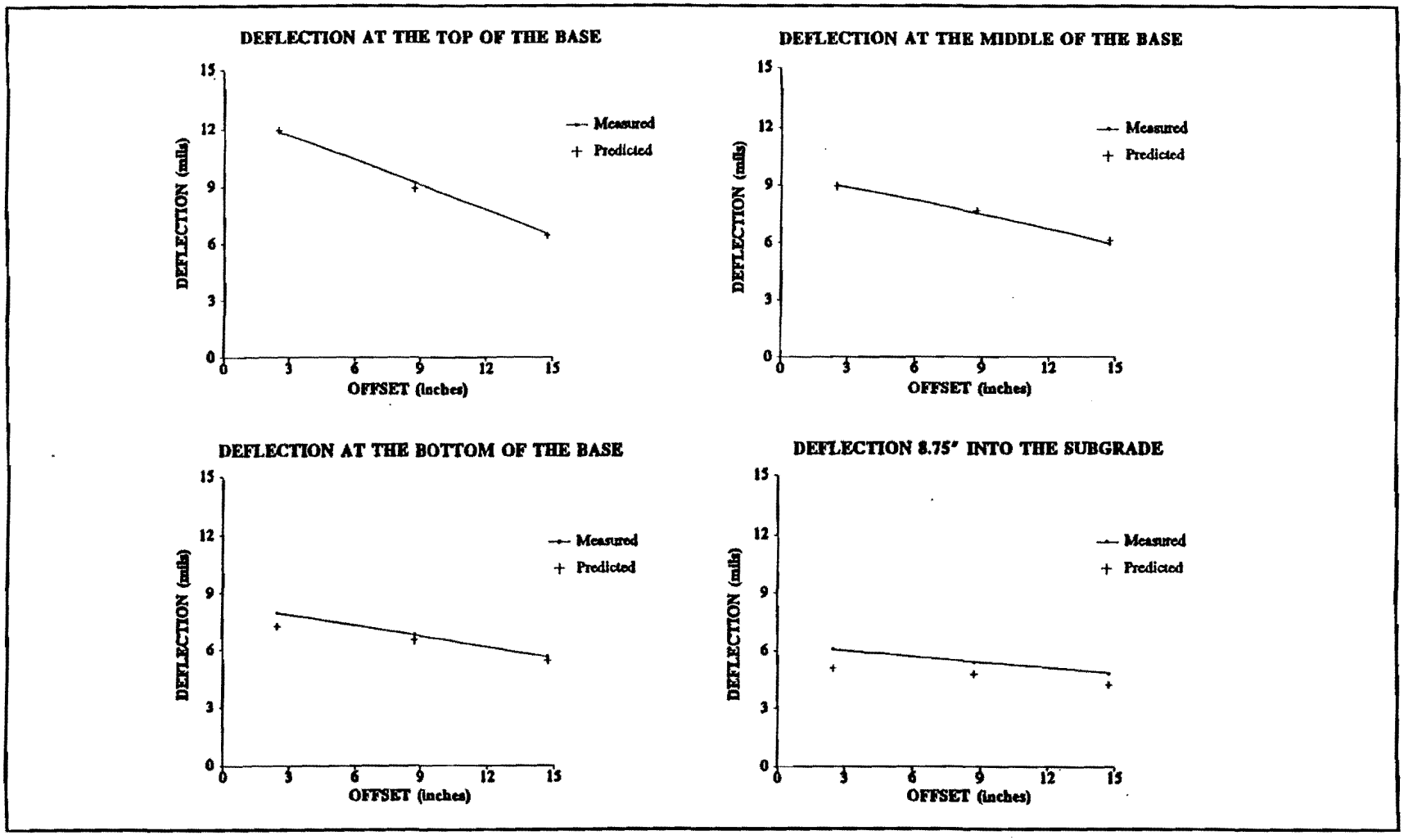

FIG. 7b. Measured and Predicted Depth Deflections Under FWD Loading (First Backcalculation Model for Twelve MDD Depth Deflections) on Section II (Thick)

CHAPTER 3
COMPARISON OF BACKCALCULATION RESULTS TO THE LABORATORY DATA

Table 5 summarizes the layer moduli backcalculated for the different sets of deflection data using the linear elastic backcalculation procedure. The backcalculated results were further evaluated by comparing them with the laboratory data. The laboratory testing consisted of indirect tension tests on asphalt concrete cores and resilient modulus tests on remolded samples of the base and subgrade materials, performed at 0.4, 5, and 10 Hz loading frequencies. Figures 8a and 8b compare the measured laboratory and backcalculated moduli.

When comparing laboratory and backcalculated moduli, perfect agreement should not be expected. The laboratory tests are performed under simulated field stress conditions. The material samples are disturbed by the extraction process, and the granular base materials are remolded. The results from the backcalculation, on the other hand, are model dependent properties rather than true material properties (Rohde 1990). By using the linear elastostatic approach, a single layer stiffness is obtained for each layer. This is only an average apparent stiffness for the whole layer. Actually, the stiffness of each pavement layer changes vertically and horizontally due to material variability and stress sensitivity. As a result, the backcalculated moduli do not match perfectly with the laboratory results.

Asphaltic Concrete

In Table 6, the laboratory results from the indirect tension test are tabulated for various temperatures and loading frequencies.

On Section II (Thick), Table 5 tabulates the backcalculated surface moduli from both of the backcalculation procedures. The backcalculated asphalt concrete moduli were considerably less than the laboratory results. The asphalt temperature at the time of conducting the FWD survey was approximately 85°F. The lab results indicate that the modulus should be considerably higher than the 135 → 176 ksi backcalculated. The only major factor not included in the analysis is surface cracking. Wheelpath cracking was apparent close to the test area. It is proposed that the surface cracking was the main cause of the poor correlation between laboratory and backcalculated moduli.

Table 5. Backcalculated Layer Moduli Under FWD Loadings By Using Different Deflection Data Set on Section I (Thin) and Section II (Thick)

Backcalculation Procedure	Backcalculated Moduli (psi)	
	Section I (Thin)	Section II (Thick)
Surface Deflections (FWD)	293,000*	176,000*
	32,000$	37,300$
	8,800**	17,500**
Surface and Depth Deflections (FWD)	293,000	135,000
	24,580	44,698
	7,588	15,199

*Asphalt Concrete $Granular Base **Subgrade

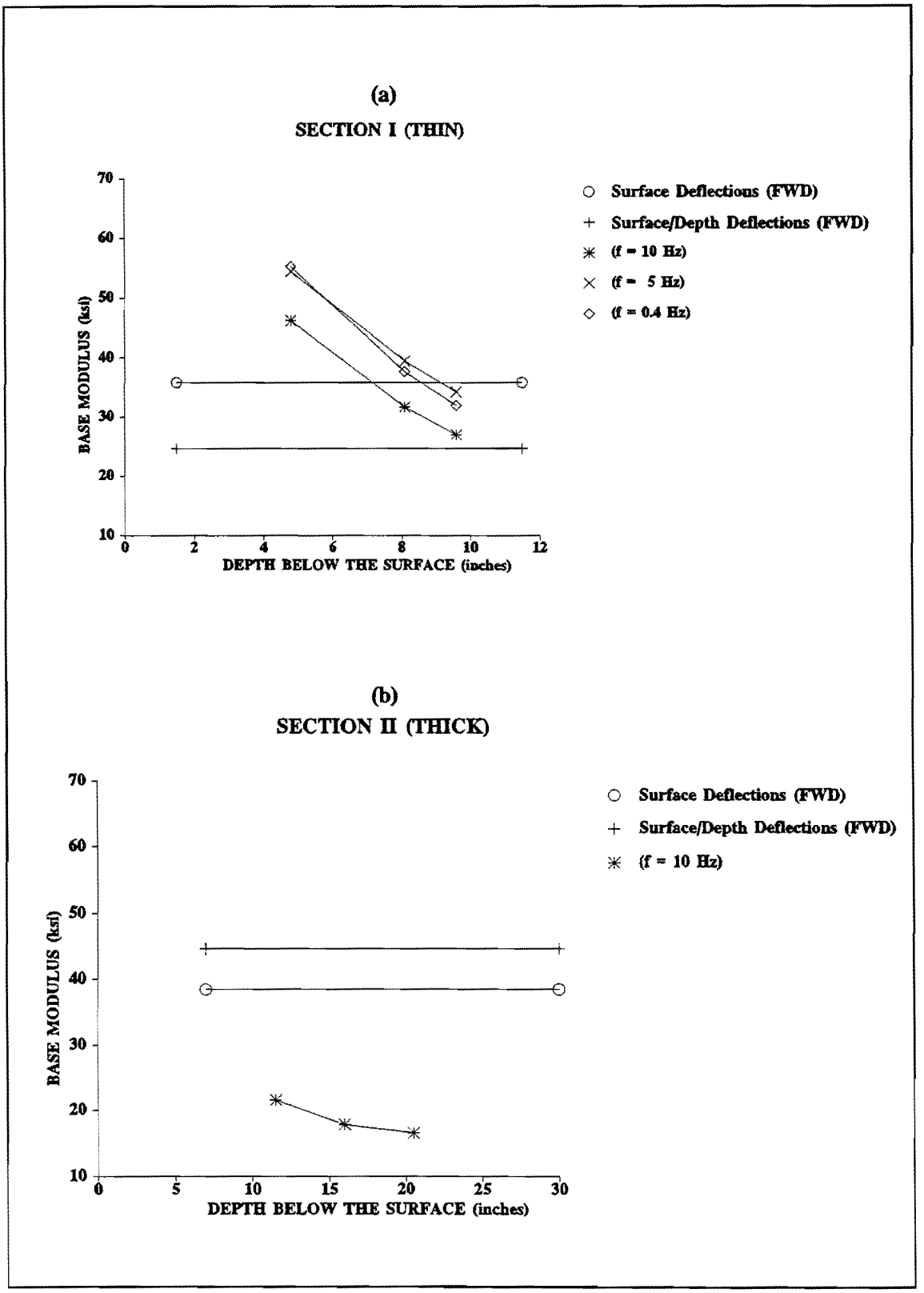

FIG. 8a. Comparison Between Backcaluated and Laboratory Results for the Base of Section I (Thin) and Section II (Thick)

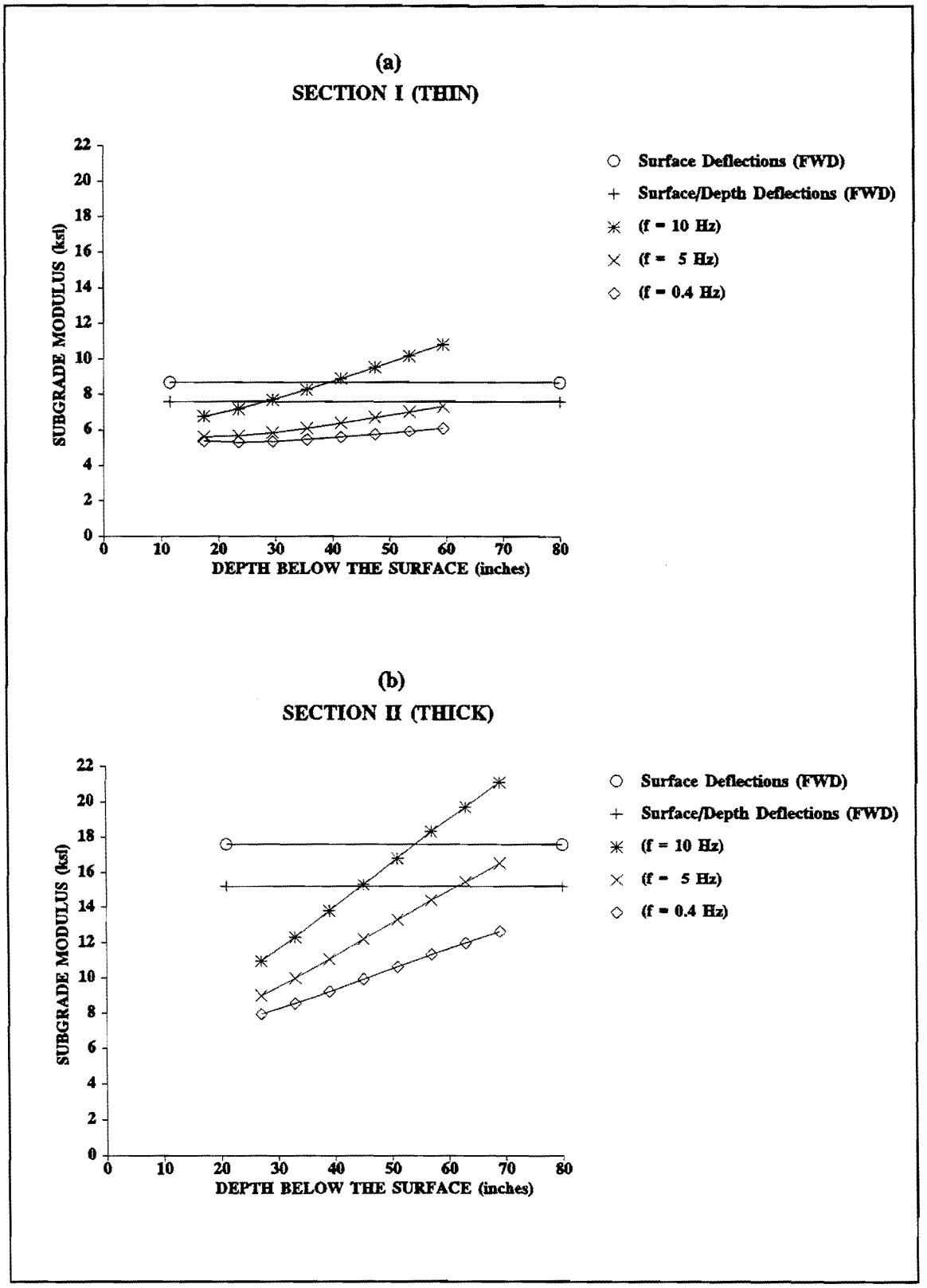

FIG. 8b. Comparison Between Backcaluated and Laboratory Results for the Subgrade of Section I (Thin) and Section II (Thick)

Table 6. The Laboratory Results for Asphalt Concrete Layer Samples at Different Temperatures and Loading Frequencies

Test Section	Temperature (oF)	Frequency (Hz)	Modulus (ksi)
I (Thin)	77	10	743
		5	547
		0.4	310
	104	10	325
		5	210
		0.4	162
II (Thick)	77	10	591
		5	253
		0.4	149
	104	10	347
		5	84
		0.4	55

Base Course

Table 7 tabulates the backcalculated base course moduli on Section I (Thin). Standard triaxial tests were performed on both base and subgrade materials according to the AASHTO procedure. In these tests the samples are subjected to a range of stress conditions. The resulting moduli are related by regression analysis to the prevailing stress conditions. The stress conditions in the pavement are then computed, and the corresponding appropriate field layer moduli calculated. As shown in Figure 8a, no significant trend was observed in loading frequency in the laboratory data. However, as the resulting lab values are stress sensitive, the laboratory results predicted a decreasing trend in the base course modulus with depth. In the linear elastic backcalculation a single number is generated to represent the average value of the entire base course, Figure 8 shows this as horizontal lines. However, the stress conditions vary from the top to the bottom of the base, therefore, a range of moduli are computed from the lab data. The agreement between the laboratory and the backcalculated results in the lower half of the base layer proved reasonably good. As shown in Fig. 8a, the laboratory results over predicted the modulus value for the upper half of the base layer in Section I (Thin). The granular material on Section II (Thick) was tested for only one loading frequency. The laboratory results show a decreasing trend in the modulus value with depth; however, compared to Section I (Thin), it is a relatively small change. Compared with the backcalculated base moduli, the laboratory results under predicted the backcalculated base modulus.

The major problem with laboratory testing is its inability to adequately represent materials and loading conditions experience in the field under either FWD or truck loadings. The pavement elements which come directly under the wheel or FWD load are subjected to axial and lateral stresses, and the elements away from the load are subjected to shear stress as well. As shown in Figs. 4, 6, 8a, and 8b, away from the load, researchers observed dilation/extension in the granular layers on both sections. Uzan and Scullion (1990) have also reported similar effects in the granular base layer on thin asphalt concrete sections.

Table 7. Comparison Between the Vertical Compressive Subgrade Strain Values Measured Under Truck Loadings and Those Predicted by the Linear Elastic Program BISAR for Dual Tires on Tandem Axles for Section I (Thin) and Section II (Thick)

Backcalculation Procedure	Test Section	Backcalculated Moduli (psi)	Subgrade Strain (μstrain)		Error (percent)
			Measured	BISAR	
Surface Deflections (FWD)	I	293,000* 32,000$ 8,800**	1047	857	-18
Surface and Depth Deflections (FWD)	I	293,000 24,580 7,588	1047	1030	-2
Surface Deflections (FWD)	II	176,000 37,300 17,500	242	209	-14
Surface and Depth Deflections (FWD)	II	135,000 44,698 15,199	242	228	-6

*Asphalt Concrete $Granular Base **Subgrade

Subgrade

The laboratory results clearly indicate the subgrade modulus on both the test sections to be frequency and stress dependent. The laboratory modulus increased with an increase in loading frequency and confining pressure.

On Section I (Thin), the agreement between the laboratory data and the backcalculated moduli over a range of frequencies looks reasonable. The agreement between the subgrade moduli backcalculated from surface deflections under FWD and from combined surface and depth deflections under FWD is reasonably good with laboratory results at high frequency (10 Hz). The laboratory results at low frequencies (0.4 and 5 Hz) match well with the subgrade moduli backcalculated from depth deflections under FWD and truck loadings. On Section II (Thick), it was found that the backcalculated subgrade modulus was between 15 and 17.5 ksi (depending on sensors used). This corresponds to a stiffness at a depth of between 40 and 50 inches below the surface (from laboratory data, high frequency and computed stress conditions).

CHAPTER 4
COMPARISON OF FWD AND TRUCK LOADING CONDITIONS

The FWD applies approximately a haversine shaped impulse with a duration of about 28 msec. Moving wheel deflection durations reported by Bohn et al. (1972), Hoffman et al. (1981), and Wiman et al. (1990) are much longer than FWD deflection durations. These researchers found the durations caused by moving trucks to measure three to five times longer than those caused by FWD loadings.

The deflection pulse times were measured under a moving truck and FWD loadings at MDD sensor locations on both the thin and thick sections. Figures 9a and 9b illustrates the measured pulse times at different depths under FWD, truck steering (single) axle, and truck drive (tandem) axle loadings for truck speeds of 5 and 55 mph. Figure 9 shows only limited data, however; from the entire data set it was found that the FWD deflection pulse duration remained constant with depth on both test sections (24 msec to 27 msec). These results are similar to the findings of Bohn et al. (1972) and Wiman et al. (1990).

From the truck deflection profiles, the single steering axles produced narrower pulses than the tandem axles. The measured pulse duration ratios for FWD, truck single, and tandem axle loadings (normalized to a FWD pulse width of 1 at a speed of 55 mph) are, respectively, 1 : 2.60 : 5.85 on Section I (Thin), and 1 : 3.25 : 6.75 on Section II (Thick). As the speed increased from 5 to 55 mph, the measured pulse duration at the bottom MDD sensor under tandem drive axle loading decreased by about 80% (800 msec to 158 msec) on Section I (Thin) and by about 81% (850 msec to 162 msec) on Section II (Thick). Similarly, under the single steering axle, the pulse duration decreased by about 78% (325 msec to 70 msec) on Section I (Thin) and by about 83% (446 msec to 78 msec) on Section II (Thick) for an increase in speed from 5 to 55 mph. At a speed of 55 mph on Section I (Thin), the pulse time at the bottom MDD sensor under the tandem drive axle equalled about 6 times the FWD pulse time and equalled about 3 times the FWD pulse time under the single axle loading. Under similar conditions on Section II (Thick), the pulse time under single and dual axles was 3 and 7 times longer respectively at the bottom MDD than those measured under the FWD load.

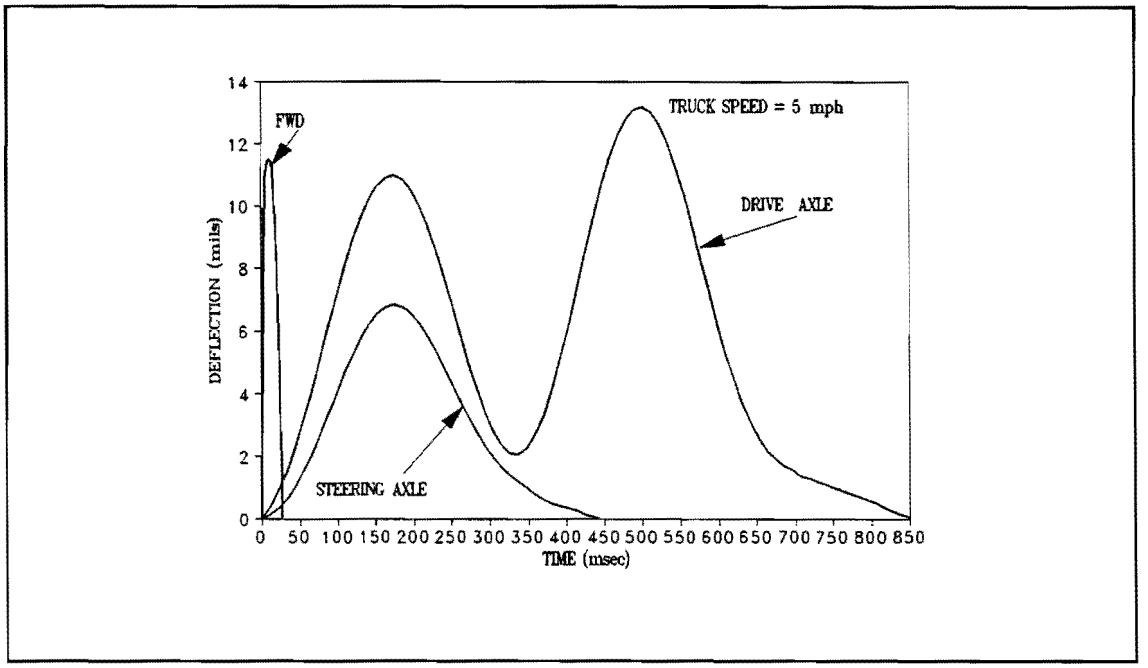

FIG. 9a. Deflection Pulse Duration Measured by MDD Sensor at a Depth of 29.75 inches Under Moving Truck (5 mph) and FWD Loading on Section II (Thick)

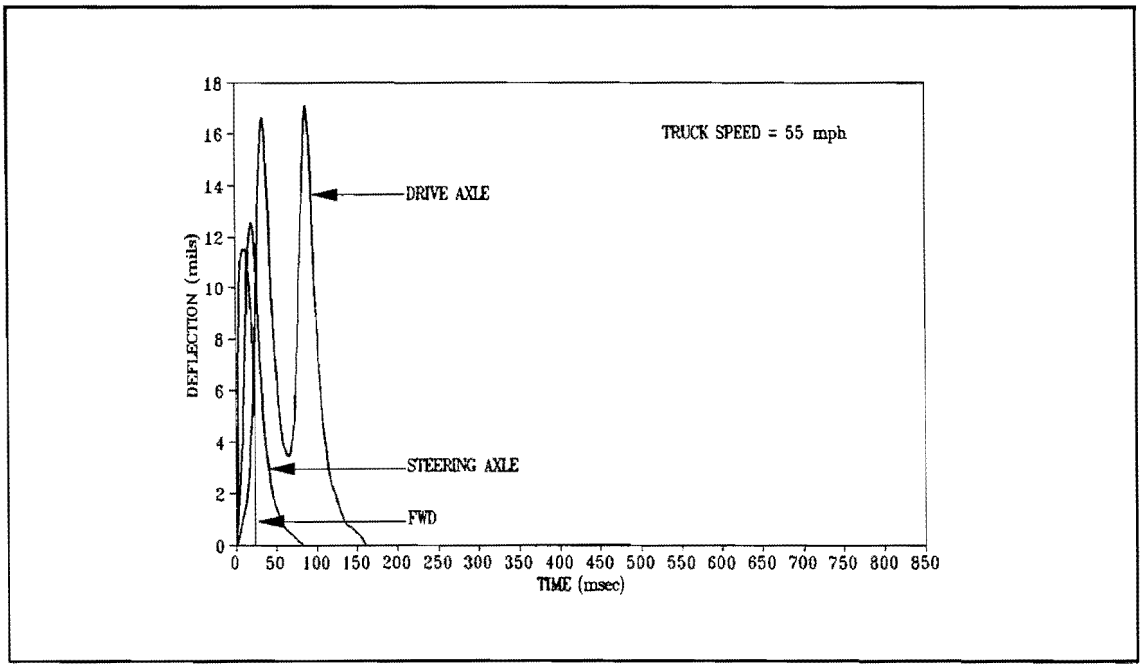

FIG. 9b. Deflection Pulse Duration Measured by MDD Sensor at a Depth of 29.75 inches Under Moving Truck (55 mph) and FWD Loading on Section II (Thick)

Figures 10a and 10b illustrate the manner in which the granular layer performed under the moving vehicular loading. They show dilation/extension in the granular layer. It appears that the moving wheel compresses the granular material directly under it and pushes (extending) the material ahead of it. This phenomenon is not observed under FWD loading.

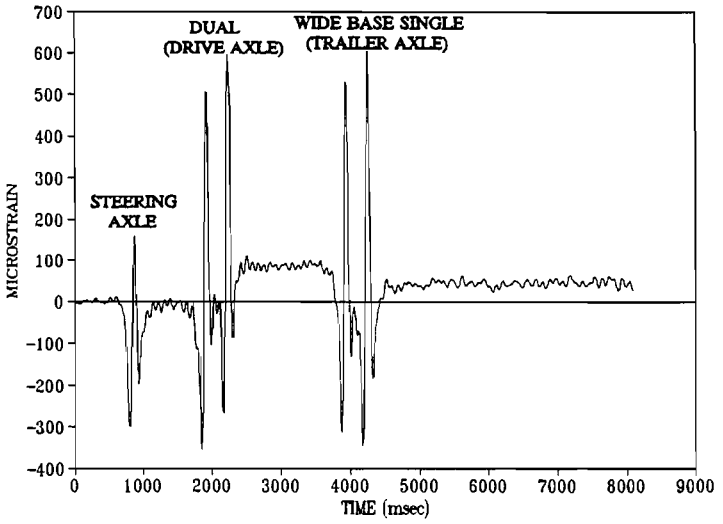

FIG. 10a. Vertical Strain Profile for Granular Base Layer in Section I (Thin) Showing Material Dilation at a Speed of 10 mph

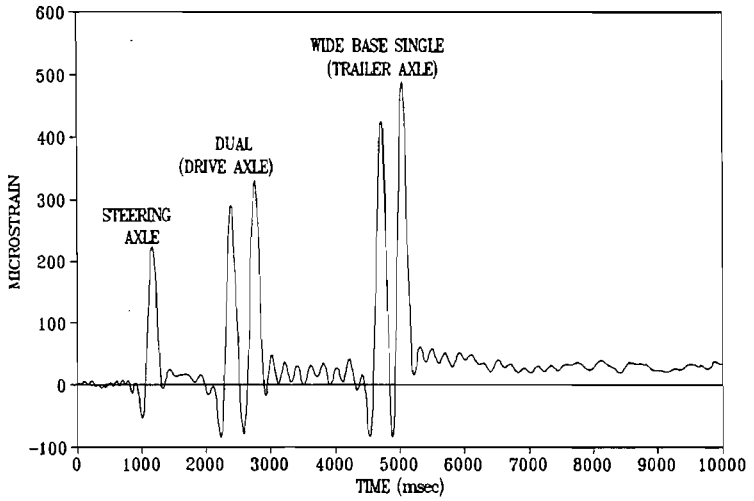

FIG. 10b. Vertical Strain Profile for Granular Base Layer in Section II (Thick) Showing Material Dilation at a Speed of 35 mph

CHAPTER 5
COMPARISON OF MEASURED AND PREDICTED SUBGRADE STRAINS UNDER TRUCK LOADINGS

The main purpose of backcalculation is to determine layer moduli that can be used in a forward calculation model to predict strains within the pavement. Researchers made the theoretical predictions of strains induced by a known truck load using the computer program BISAR (1978) with the backcalculated layer moduli from Table 5. The calculated vertical compressive subgrade strains were compared with those measured under the test truck loads. Table 7 tabulates the comparison for Section I (Thin) and Section II (Thick) along with the resulting percentage errors. The measured strains were computed by subtracting adjacent MDD depth deflections and dividing by the gauge separation distance, as described previously. The computed strains were predicted at the midpoint of the two MDD's.

On Section I (Thin), under dual tires, the errors between the measured subgrade strain and the subgrade strain predicted by the theoretical model, using moduli backcalculated from surface deflections under FWD loadings, proved relatively high (18%). However, the strains predicted by using the backcalculated moduli from both surface and depth deflections under FWD loadings matched very well with the measured strain values. As shown in Table 7, the lowest percentage difference of 2% was obtained when researchers used moduli values backcalculated using both surface and depth deflections under FWD loading to make theoretical strain predictions. This shows that even on a thin pavement section, despite all the material non-linearities, subgrade strain predictions made using a linear layered elastic model are reasonably accurate. However, using moduli obtained solely from the FWD surface deflections, the strains predicted in the subgrade under estimate by 18% the actual strains induced under dual tire loads.

On Section II (Thick), under dual tires, the errors between the measured and predicted strains were found to be between 6% and 14%. From Table 7 it is clear that the moduli values backcalculated by matching both surface and depth deflections under FWD loading on both thin and thick pavement sections, produced the best prediction of the strains induced by truck loads.

CHAPTER 6
CONCLUSIONS

Researchers collected both surface and multidepth deflection data under FWD and truck loadings on both a thick and thin pavement section. Using a linear, elastostatic backcalculation technique, the layer moduli were backcalculated from the different sets of deflection data and these are summarized in Table 5.

These trends were evident from the backcalculated layer moduli:

- on Section I (Thin), using the FWD surface deflections, researchers found a reasonably low mean square error of 4.75 percent per sensor, the base and subgrade modului values exhibited a non-linear behavior with an increase in load;
- on Section II (Thick), the surface deflection analyses resulted in an average mean square error of 4.53 percent per sensor, similar to Section I (Thin), the base and subgrade modului values demonstrated a non-linear behavior with an increase in load;

The comparsion of the pulse durations between the FWD and truck loadings showed that the FWD pulse duration stayed almost constant with depth, whereas the deflection pulse under truck loading changed with speed and depth. The pulse duration measured at the bottom MDD sensor under dual axles moving at a speed of 55 mph was about 6 to 7 times longer than the FWD pulse duration. The pulse duration under a single tire moving at 55 mph was 3 times longer than the FWD pulse duration. For an increase of speed from 5 to 55 mph, the deflection pulse duration under the single and dual tires decreased by about 80%.

As expected, the backcalculated moduli did not match well with the laboratory data. Researchers conducted the laboratory tests on remolded samples under simulated stress conditions. Laboratory data showed higher moduli with an increase in the loading frequency for subgrade materials, which indicated that the loading frequency affects deeper pavement layers. Similar findings were reported by Wiman et al. (1990). The backcalculated asphalt concrete stiffnesses at lower temperature and frequency compared reasonably well with those found in the laboratory. The comparsion of backcalculated and measured moduli was generally better for the thin section than for the thick section.

As shown in Table 7, by using the different combinations of deflection measurement (surface and/or depth), it is possible to backcalculate layer moduli. However, the main purpose of backcalculation is to determine the layer moduli that can be used in a forward calculation mode to predict strains within the pavement. The set of moduli values backcalculated by matching both surface and depth deflections under FWD loading (on both thin and thick pavement sections) produced the best estimate of truck induced vertical compressive strains. Using moduli obtained using only surface deflections resulted in an apparent overprediction of subgrade modulus and an underestimation of the truck induced subgrade vertical compressive strains by 15 to 18%.

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