Asphalt Thickness Variation on Texas Strategic Highway Research Program Sections and Effect on Backcalculated Moduli

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Four Long Term Pavement Performance monitoring sites, part of the Strategic Highway Research Program (SHRP), were investigated in Texas with ground penetrating radar (GPR) to determine asphalt and base layer thicknesses as well as base moisture content. It was found that, with coring, the GPR could determine asphalt layer thicknesses to ± 0.11 in. This accuracy is reduced to ± 0.32 if the GPR results are not calibrated with cores. The base thicknesses could be determined to ± 0.99 in. The data obtained during this survey indicated that significant variations in layer thicknesses were present within the 500-ft SHRP sections. Practical limitations in the data collection process have forced SHRP personnel to treat pavement thicknesses as shown on plans, or obtained during the drilling and sampling process, as representative of the entire section, even though it is recognized that this may not be true. Deflection data currently are being gathered on the SHRP sites and will be used to backcalculate the material properties of the pavement layers. Values for material properties obtained through the backcalculation of deflection basins are extremely sensitive to pavement layer thickness. It was the intent of this study to quantify the errors introduced by variations in pavement layer thicknesses that are not accounted for in the backcalculation process. It was found that errors of up to 100 percent in pavement layer moduli were possible when comparing the moduli obtained using GPR measured thicknesses and moduli obtained using the SHRP data base thicknesses. It was also found that deflection basins alone are not a good indicator of layer thickness variations and that a good fit between measured and calculated deflection basins is not a good indicator of the correctness of the moduli values. The paper concludes by recommending that some method be investigated to quantify layer thickness variations on SHRP sites before using the deflections for backcalculation purposes.

The Strategic Highway Research Program (SHRP) as part of the Long Term Pavement Performance (LTPP) study, is currently performing deflection testing on over 1,000 in-service pavement sections located around the United States and Canada with falling weight deflectometers (FWDs). Measurements of pavement deflections under load are a generally accepted method of determining the material properties of the pavement layers and subsequent performance under traffic. Information obtained during this effort will be used to improve existing or formulate new equations for the design of pavements and overlays as well as pavement performance models for pavement management systems.

The SHRP staff has committed significant resources to ensuring that the deflection data obtained are complete, accurate, and meaningful before placement in the National Pavement Data Base. To achieve this end, numerous quality assurance practices have been developed. Manuals detailing the FWD data collection procedures on GPS rigid and flexible, as well as the SPS sections have been compiled and used to train FWD operators (*1*). Variables such as pavement surface temperature, as well as temperature gradients within the pavement structure, both of which heavily affect pavement deflections, are recorded by the FWD operator at the time of test. The FWD data collection program has been modified to include a subroutine that calculates the variance of multiple deflections taken at the same point and allows the operator to reject those deflections if the variance is too high. Programs such as FWDCHECK and FWDSCAN (*2*) have been written by SHRP contractors and distributed to the regional coordinating offices to identify FWD data files that are incomplete, contain questionable data, or contain deflections that indicate that the SHRP section is composed of variable pavement structure. An absolute calibration process has been developed by SHRP contractors and is scheduled to be implemented in four locations around the United States to ensure that the SHRP-owned FWDs have not drifted out of calibration and to certify state-owned FWDs for SHRP LTPP data collection. This calibration process is intended to ensure that the FWDs are measuring deflections at the accuracy published by their manufacturers (2 percent of the deflection $\pm 2\mu$). These quality assurance practices are considered vital in determining accurate moduli of the pavement layers.

There is a variable within the structural evaluation process in SHRP (a) that cannot be controlled in the design of the experiment, (b) can be quantified only in an indirect sense, (c) whose variance or standard deviation cannot be measured at all, and (d) that has a tremendous impact on the accuracy of the backcalculated material properties of the constituent pavement layers. This variable is pavement layer thickness.

SHRP pavement layer thickness data is obtained from two sources: (a) plan sheets and (b) measurements taken during the LTPP material sampling activities at the test pit locations on either end of the SHRP section. Obvious disadvantages

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are inherent in both sources. Plan sheets do not always reflect what was actually constructed, particularly when field changes have not been recorded on the plans. Normal variations in layer thicknesses as a result of construction activities are not reflected in the plans. Although layer thicknesses can be measured directly during the material sampling activities at both ends of the test section, there is no guarantee that these measurements are representative of the pavement structure located within the 500 ft between the test pits. To make matters worse, the plans often do not agree with the results obtained from the test pit. Layer thicknesses cannot be measured within the confines of the test section because drilling and trenching would disturb the structural integrity of the pavement and render the section useless for the study of pavement distress propagation. Thus, one is forced to assume that the pavement structure at either end of the SHRP section is representative of the entire section.

The Texas Department of Transportation (TxDOT) has faced this dilemma for years. Deflection testing equipment has been used for more than 20 years for design of new pavements and overlays. Recent acquisition of FWDs has expanded the role of deflection testing to determination of load zoning requirements, pavement evaluation for superheavy permit loads, and network level deflection testing for pavement management. In every case, the engineer is forced to assume that the pavement structure found on the cross-section drawings of the plan sheets is representative of the entire section under test. Experience has shown that this is not always true, as many pavements have been overlaid multiple times, increasing significantly the thickness of the asphalt surfacing. Deviations from the plans often are necessary during construction and are not shown on the drawings. Variations in layer thicknesses are commonplace as a result of variations in the construction process.

To overcome this problem, TxDOT has sponsored several research projects with the Texas Transportation Institute with the objective of developing a swift, accurate, nondestructive method for measuring pavement layer thicknesses and their variations along the roadway. This test technique is intended to be used in conjunction with the FWD. Ground penetrating radar (GPR) is one of the technologies currently under study.

As a result of these studies, recent improvements in hardware and signal processing techniques have boosted GPR capabilities and accuracy. A report recently submitted to TxDOT indicates that GPR, as developed in this study, has the capability of measuring the thickness of asphaltic concrete with an accuracy of ± 0.1 in. and determining base thickness on asphaltic pavements to within ± 0.99 in. if cores are obtained to calibrate the radar (*3*). Without coring (using only radar), the accuracy drops to ± 0.32 in. for asphalt concrete.

GPR SURVEY OF SHRP SITES

During June 1990, a GPR survey was performed on four SHRP LTPP sites near College Station, Tex. (*3*). These sites were Sections 481178, 483559, 481109, and 481050. The purpose of the survey was to determine how closely the GPR apparatus could predict asphalt and base thicknesses as well as determine moisture content of the base material. SHRP sites were selected as the pavement structure was reasonably well documented. Each test run consisted of 1,500 ft of pavement, 500 ft before the SHRP section, the SHRP section itself, and 500 ft after the test section. This provided 1,000 ft of pavement from which materials could be extracted for determination of dielectric constant. It also allowed the researchers to core the pavement and check the accuracy of the radar predictions. Four passes were made at each SHRP test section, one at 5 mph in the left wheel path, and one at 5, 15, and 40 mph over the right wheel path. Three types of destructive testing was performed to verify GPR results: (a) 4-in.-diameter wet cores were taken to verify asphalt concrete pavement (ACP) thickness; (b) 6-in.-diameter dry cores were obtained to verify base moisture content predictions; and (c) cone penetrometer tests were performed to measure GPR base thickness predictions. As a result of this study it was determined that GPR could predict asphalt thicknesses to within ± 0.11 in. with verification and calibration by coring, and to ± 0.32 in. without coring. Base thicknesses could be predicted within ± 0.99 in. and base moisture could be predicted within 2 percent by weight. Furthermore, the radar data indicated that significant variations in layer thicknesses were present on most of the SHRP sections tested.

Tables 1 through 4 compare the thicknesses measured with GPR on the four sites and that obtained from the SHRP data base, and Figure 1 illustrates this graphically. As can be seen

TABLE 1 Assumed Versus Measured Thicknesses, Section 481109

ASSUMED THICKNESSES: 7.0 in. HMAC, 6.0 in. Granular Base		
MEASURED THICKNESSES		
DISTANCE (ft.)	HMAC (in.)	BASE (in.)
0	6.5	5.2
50	6.0	5.3
100	6.4	4.9
150	6.6	5.0
200	6.6	5.0
250	6.5	4.8
300	6.3	5.8
350	6.5	5.5
400	6.5	6.1
450	6.5	5.4
500	7.0	5.5

TABLE 2 Assumed Versus Measured Thicknesses, Section 481050

ASSUMED THICKNESSES: 2.3 in. HMAC, 8.3 in. Granular Base		
MEASURED THICKNESSES		
DISTANCE (ft.)	HMAC (in.)	BASE (in.)
0	2.0	10.4
50	2.4	11.8
100	2.3	13.0
150	2.0	11.2
200	2.4	10.2
250	2.7	10.3
300	2.7	10.1
350	2.2	10.0
400	2.4	10.0
450	2.1	11.0
500	2.1	11.8

TABLE 3 Assumed Versus Measured Thicknesses, Section 481178

ASSUMED THICKNESSES: 8.8 in. HMAC, 10.2 in. Granular Base		
MEASURED THICKNESSES		
DISTANCE (ft.)	HMAC (in.)	BASE (in.)
0	8.6	10.3
50	8.4	9.7
100	8.1	10.5
150	8.0	10.5
200	8.0	10.8
250	8.2	8.9
300	8.3	10.4
350	8.6	10.0
400	8.4	8.7
450	8.3	8.2
500	8.5	9.6

TABLE 4 Assumed Versus Measured Thicknesses, Section 483559

ASSUMED THICKNESSES: 7.0 in. HMAC, 6.O in. Base		
MEASURED THICKNESSES		
DISTANCE (ft.)	HMAC (in.)	BASE (in.)
0	8.2	7.2
50	9.0	7.0
100	9.1	7.0
150	8.2	7.8
200	8.7	7.5
250	8.3	7.2
300	7.6	7.0
350	7.1	8.0
400	7.4	7.8
450	7.2	7.8
500	7.4	8.0

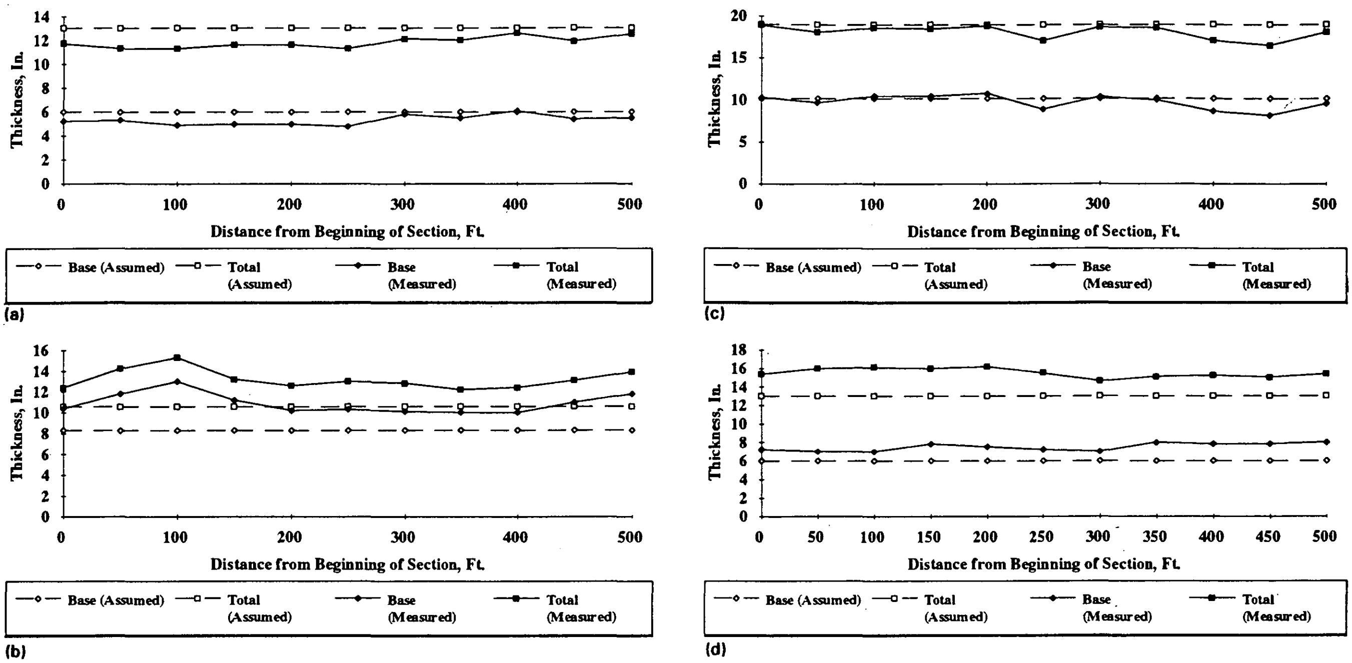

FIGURE 1 Assumed layer thicknesses for SHRP data base versus layer thicknesses obtained from GPR measurements: (*a*) Section 481109, (*b*) Section 481050, (*c*) Section 481178, and (*d*) Section 483559.

from the figure, the differences approached 2 in. on 481109, 481178, and 483559, whereas on 481050 a difference of up to 5 in. occurred at 100 ft from the beginning of the section. This led to the question of how these variations in pavement structure could possibly affect the backcalculated moduli of the paving materials if the pavement structure was assumed to be that which is stored in the SHRP data base. To quantify these variations, the FWD deflections were obtained from the data base. Pavement layer moduli were backcalculated using the SHRP layer thicknesses and the thicknesses obtained with GPR. The remainder of this report documents the results of this comparison.

DEFLECTION TESTS RESULTS

FWD deflection files were obtained for each of the SHRP sites: 481109, 481050, 481178, and 483559 from the Southeastern RCO. Only the midlane deflections were used in this comparison to avoid the effects of any distresses that may have been present in the wheel paths. Although deflections are obtained at 25-ft intervals on the test sections, the radar data were reported in 50-ft intervals; thus only deflections at 50-ft intervals were used in this analysis. A total of 16 deflection tests were performed at each test point, with four drops at four separate load levels. The 16 deflection basins at each point were normalized to 10,000 lb and then averaged for presentation in Tables 5 through 8, as well as graphically in Figure 2. However, for backcalculation purposes, the basins were neither normalized nor averaged.

No correlation was apparent between the variations in pavement thickness and the variations in deflections obtained along the section, as evidenced in a comparison of Figures 1 and 2, with the exception of the 100-ft position on 481050. Here, the deflections seemed to reduce as the base thickness increased. The deflections indicate that significant variation, either in

TABLE 5 Average Normalized Deflections, Section 481109

Distance	R=0"	R=8"	R=12"	R=18"	R=24"	R=36"	R=60"
0	11.18	10.06	9.25	7.86	6.58	4.57	2.43
50	8.46	7.53	6.86	5.84	4.93	3.48	1.96
100	8.92	7.81	7.02	5.80	4.72	3.07	1.35
150	8.08	7.09	6.36	5.29	4.32	2.81	1.15
200	7.12	6.13	5.47	4.56	3.74	2.51	1.18
250	8.77	7.80	7.10	5.97	4.97	3.46	1.87
300	10.18	8.98	8.19	6.94	5.79	4.03	2.05
350	11.22	9.96	9.06	7.62	6.32	4.26	2.01
400	8.34	7.14	6.42	5.36	4.42	3.00	1.42
450	7.64	6.61	5.93	4.93	4.03	2.67	1.17
500	5.96	5.11	4.51	3.60	2.83	1.73	0.69
Avg	8.71	7.66	6.92	5.80	4.79	3.24	1.57
Std	1.55	1.46	1.38	1.22	1.06	0.79	0.50

TABLE 6 Average Normalized Deflections, Section 481050

Distance	R=0"	R=8"	R=12"	R=18"	R=24"	R=36"	R=60"
0	20.65	13.51	8.95	6.03	4.47	2.91	1.63
50	27.46	17.73	11.68	7.40	5.01	3.01	1.93
100	15.96	10.59	7.31	5.26	4.21	3.09	1.84
150	14.89	9.72	7.04	5.26	4.18	3.12	1.91
200	21.34	12.29	7.98	5.41	3.98	2.73	1.69
250	17.87	11.93	8.38	5.82	4.20	2.75	1.61
300	25.70	16.32	10.90	7.43	5.36	3.57	1.93
350	25.68	16.20	10.47	7.07	5.14	3.37	1.99
400	23.09	14.75	9.85	6.64	4.84	3.22	1.94
450	17.93	11.35	7.92	5.56	4.13	2.79	1.71
500	20.97	13.59	8.78	5.84	4.26	2.89	1.70
Avg	21.05	13.45	9.02	6.16	4.52	3.04	1.81
Std	3.96	2.45	1.45	0.80	0.45	0.26	0.13

TABLE 7 Average Normalized Deflections, Section 481178

Distance	R=0"	R=8"	R=12"	R=18"	R=24"	R=36"	R=60"
0	7.97	6.99	6.28	5.42	4.49	3.06	1.74
50	5.73	4.73	4.16	3.61	3.11	2.47	1.65
100	6.70	5.53	4.90	4.32	3.75	3.04	2.00
150	6.76	5.72	5.08	4.49	3.90	3.18	2.08
200	5.77	4.63	4.07	3.60	3.17	2.62	1.83
250	5.92	4.84	4.25	3.73	3.25	2.69	1.84
300	5.07	4.12	3.61	3.16	2.77	2.29	1.56
350	7.40	6.10	5.28	4.48	3.74	2.83	1.77
400	4.57	3.79	3.36	3.02	2.71	2.29	1.59
450	5.36	4.48	3.96	3.49	3.05	2.47	1.70
500	6.17	4.96	4.34	3.81	3.31	2.66	1.80
Avg	6.13	5.08	4.48	3.92	3.39	2.69	1.78
Std	0.96	0.89	0.80	0.66	0.51	0.29	0.15

TABLE 8 Average Normalized Deflections, Section 483559

Distance	R=0"	R=8"	R=12"	R=18"	R=24"	R=36"	R=60"
0	6.22	5.51	5.07	4.25	3.66	2.69	1.33
50	5.60	5.06	4.68	4.10	3.54	2.57	1.28
100	5.73	5.10	4.50	4.20	3.75	2.62	1.37
150	5.24	4.64	4.20	3.56	3.02	1.98	0.85
200	3.90	3.47	3.14	2.58	2.08	1.30	0.50
250	4.76	4.24	3.66	3.17	2.41	1.55	0.53
300	5.31	4.58	4.07	3.29	2.57	1.50	0.49
350	6.07	5.40	4.81	3.86	3.03	1.73	0.50
400	5.32	4.59	4.04	3.35	2.56	1.51	0.43
450	5.74	5.04	4.34	3.45	2.63	1.48	0.42
500	5.72	4.92	4.37	3.54	2.74	1.66	0.51
Avg	5.42	4.78	4.26	3.58	2.91	1.87	0.75
Std	0.62	0.55	0.51	0.48	0.52	0.49	0.37

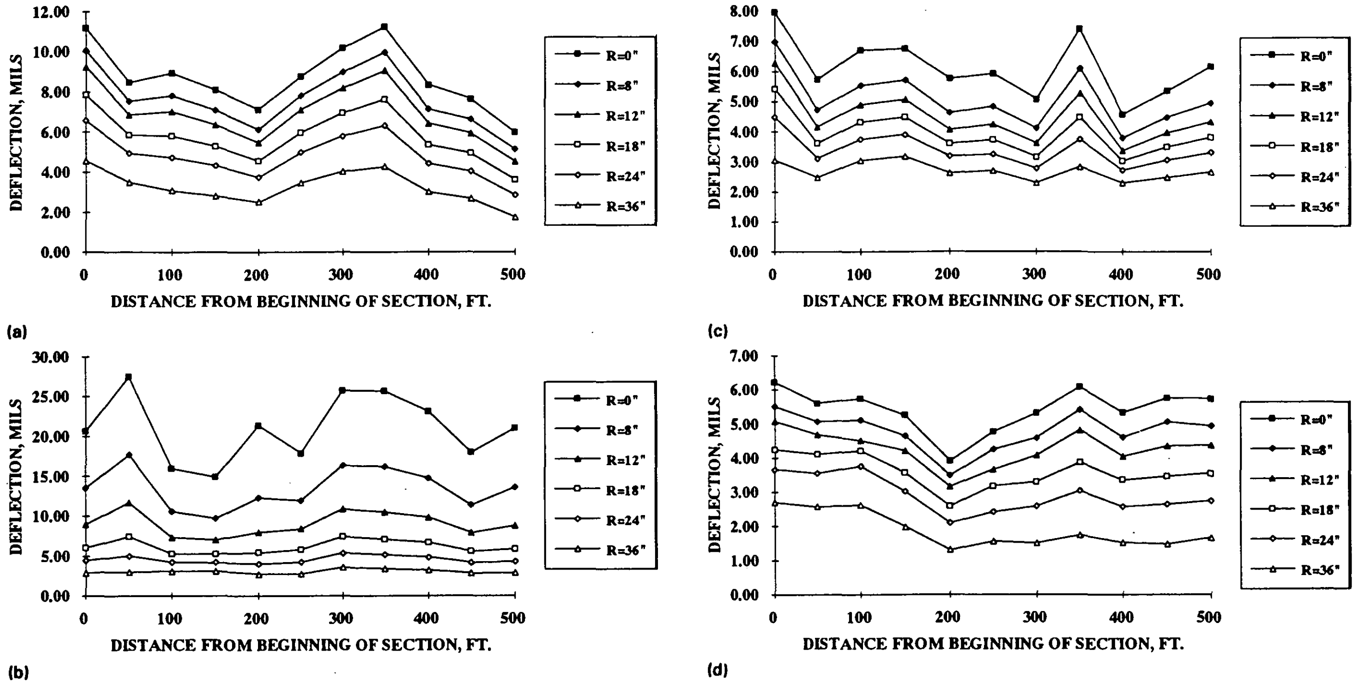

FIGURE 2 Average normalized deflections obtained on SHRP sites: (*a*) Section 481109, (*b*) Section 481050, (*c*) Section 481178, and (*d*) Section 483559.

strength or structure, can be found within each of these SHRP sites.

BACKCALCULATION OF MATERIAL PROPERTIES

The backcalculation effort for each section consisted of two runs. The first run was performed using thicknesses obtained from the SHRP data base. The second run was performed using thicknesses obtained from the GPR survey. The MODULUS program (*4*) was used for the backcalculation process. All other variables were held constant between the two runs, including the upper and lower ranges for the moduli. A rigid layer was assigned at 240 in. from the pavement surface. Poisson ratios were selected on the basis of commonly used values obtained from the literature.

For the MODULUS runs using the assumed layer thicknesses, the program was run iteratively with the goal of achieving an average error of 2 percent or less per geophone when comparing the backcalculated versus measured deflection basins while restricting the upper and lower ranges of moduli to reasonable limits.

Each test point consisted of 16 deflection basins, four drops at each of four load levels. The modulus program was run on each of the 16 deflection basins, and the average of the results is reported in the tables. The material types and associated thicknesses can be found in Tables 1 through 4.

RESULTS

In almost every case, using measured thicknesses in place of assumed thicknesses resulted in a better fit when comparing the measured versus backcalculated deflection basins. Figure 3 illustrates this clearly. In virtually every case, except for several points on Section 481178, the utilization of the GPR measured thicknesses improved the deflection basin fit; in the case of 481050 and 483559, it improved it dramatically. Note however, that on Section 481178, using the assumed thicknesses, the average error per sensor was already below the 3 percent range, and from Figure 1 we can observe that the measured versus assumed thicknesses were not significantly different compared with those in the other three sections. Thus, for this section, the introduction of GPR measured thicknesses did not improve by much the results of the analysis.

Tables 9 through 12 indicate that by introducing GPR-measured thickness in lieu of the SHRP data base thicknesses, the overall average error per sensor decreased from 1.41 to 1.01 on Section 481109, decreased from 6.38 to 2.94 for Section 481050, increased from 2.7 to 2.92 on Section 481178, and decreased from 3.96 to 1.73 on Section 483559. The standard deviation increased or decreased accordingly. It should be reiterated here that nothing was changed between the MODULUS runs using measured versus assumed layer thicknesses except the thicknesses themselves.

ACP Moduli

Tables 13 through 16 present the average backcalculated moduli for the ACP, base, and subgrade layers for all four SHRP sections, using both assumed and measured thicknesses. The modulus values are shown at 50-ft intervals beginning at the zero point on the section. Each cell on the table represents the average results for 16 deflection basins.

Tables 17 through 20 summarize the average percent difference between the backcalculated moduli using assumed

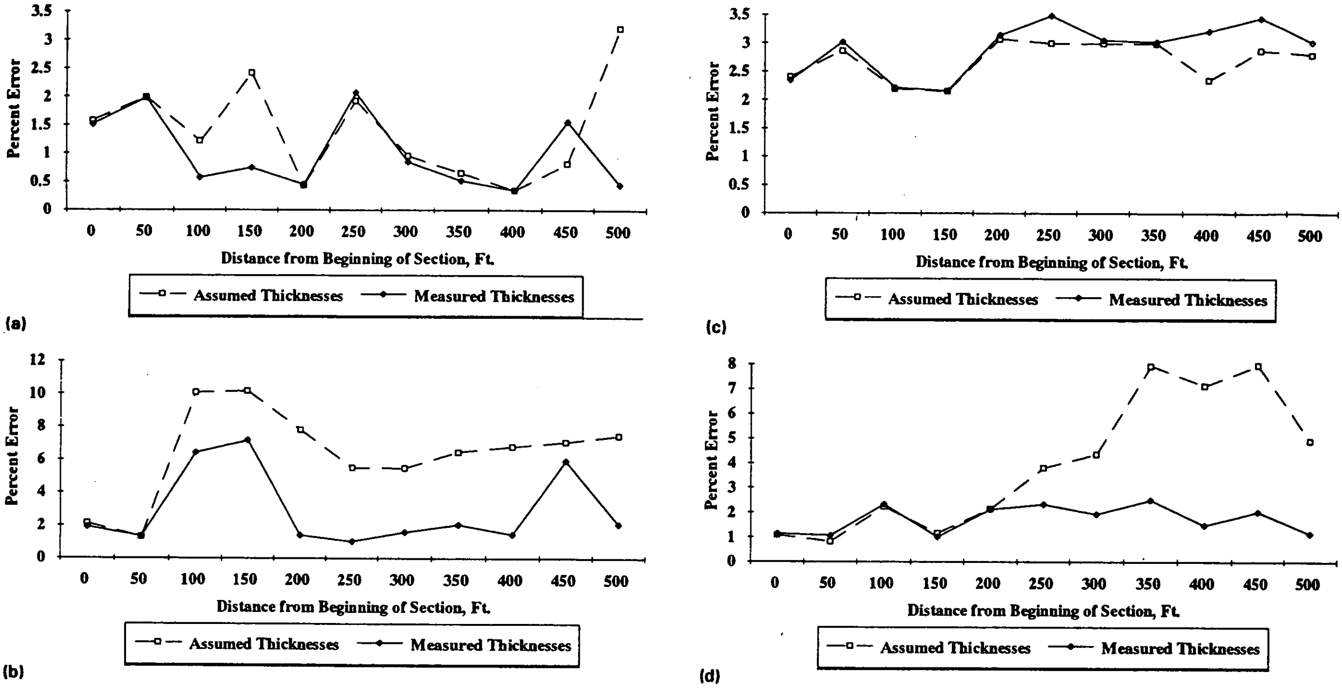

FIGURE 3 Average error per sensor for backcalculation using measured versus assumed layer thicknesses: (*a*) Section 481109, (*b*) Section 481050, (*c*) Section 481178, and (*d*) Section 483559.

TABLE 9 Average Error per Sensor, Section 481109

DISTANCE	ASSUMED THICKNESSES	MEASURED THICKNESSES
0	1.58	1.51
50	1.99	1.98
100	1.21	0.57
150	2.41	0.74
200	0.43	0.45
250	1.93	2.08
300	0.96	0.85
350	0.66	0.52
400	0.35	0.35
450	0.82	1.57
500	3.21	0.45
Avg	1.41	1.01
Std	0.94	0.65

TABLE 10 Average Error per Sensor, Section 481050

DISTANCE	ASSUMED THICKNESSES	MEASURED THICKNESSES
0	2.11	1.90
50	1.31	1.33
100	10.06	6.42
150	10.17	7.17
200	7.80	1.38
250	5.50	1.04
300	5.48	1.59
350	6.46	2.05
400	6.79	1.47
450	7.07	5.93
500	7.46	2.08
Avg	6.38	2.94
Std	2.71	2.27

TABLE 11 Average Error per Sensor, Section 481178

DISTANCE	ASSUMED THICKNESSES	MEASURED THICKNESSES
0	2.40	2.35
50	2.87	3.02
100	2.20	2.22
150	2.15	2.16
200	3.07	3.15
250	3.00	3.49
300	3.00	3.06
350	3.00	3.03
400	2.35	3.22
450	2.87	3.45
500	2.80	3.02
Avg	2.70	2.92
Std	0.41	0.51

TABLE 12 Average Error per Sensor, Section 483559

DISTANCE	ASSUMED THICKNESSES	MEASURED THICKNESSES
0	1.09	1.14
50	0.82	1.06
100	2.23	2.32
150	1.16	1.01
200	2.14	2.11
250	3.80	2.32
300	4.35	1.93
350	7.93	2.49
400	7.13	1.48
450	7.95	2.02
500	4.90	1.15
Avg	3.96	1.73
Std	3.19	0.83

TABLE 13 Average Backcalculated Moduli Values, Section 481109

DISTANCE	ASSUMED THICKNESSES			MEASURED THICKNESSES		
	ACP	BASE	SUBGR	ACP	BASE	SUBGR
0	1270861	33664	14124	1502636	44736	14151
50	1202360	142277	17825	1462478	250581	18052
100	1217483	22513	22511	1551991	27447	22202
150	1320798	24936	24933	1605450	31070	24155
200	1395401	60562	26715	1434563	111030	26503
250	1286523	79352	18388	1707190	88442	18712
300	1226050	46981	16237	1507749	67952	16190
350	1171804	16987	16120	1452957	16457	16154
400	1166171	62700	22207	1281846	82963	22046
450	1452738	27851	26153	1687505	43427	25592
500	1355823	38777	38772	1422720	38138	38134
Avg	1278728	50600	22180	1510644	72931	21990
Std	89538	34393	6672	117626	62714	6425

TABLE 14 Average Backcalculated Moduli Values, Section 481050

DISTANCE	ASSUMED THICKNESSES			MEASURED THICKNESSES		
	ACP	BASE	SUBGR	ACP	BASE	SUBGR
0	690852	38840	23374	1036038	37344	22922
50	692701	22517	19550	616998	21775	19486
100	320045	90470	23662	521148	64469	22657
150	502121	99999	23725	228976	93773	22897
200	214275	47506	25471	291054	39058	26469
250	609746	58961	22897	619669	43219	23755
300	315167	38452	18270	328046	29480	19024
350	307956	36833	19163	558852	29177	20026
400	354099	43090	20134	522756	32926	21108
450	285640	68302	24029	723510	50631	24137
500	440044	44734	22681	960286	33068	24013
Avg	430240	53609	22087	582485	43174	22409
Std	161801	22720	2265	243727	19467	2170

TABLE 15 Average Backcalculated Moduli Values, Section 481178

DISTANCE	ASSUMED THICKNESSES			MEASURED THICKNESSES		
	ACP	BASE	SUBGR	ACP	BASE	SUBGR
0	865565	41414	19925	892935	44140	19849
50	583858	328485	22116	581501	386996	22446
100	501303	316250	17800	511040	339547	17906
150	558158	291878	16907	577812	320001	17020
200	459003	597719	19922	461585	599727	20046
250	492775	467289	19809	467628	739099	20460
300	554894	565781	23353	555878	592894	23498
350	482413	155280	20348	486347	165743	20424
400	664908	817949	21823	763059	999997	23086
450	634126	432760	21238	600036	782441	22130
500	463280	396455	20396	455242	476503	20708
Avg	569117	401024	20331	577551	495190	20688
Std	114055	204306	1761	130768	269049	1936

TABLE 16 Average Backcalculated Moduli Values, Section 483559

DISTANCE	ASSUMED THICKNESSES			MEASURED THICKNESSES		
	ACP	BASE	SUBGR	ACP	BASE	SUBGR
0	2073723	116974	24749	1639274	46312	25452
50	3119528	70918	26140	1802766	22659	27467
100	2619711	183844	24385	1688967	51458	25258
150	2805006	16771	39117	1934697	15621	40157
200	3117260	18814	62457	1902148	18764	61693
250	2354590	16206	54012	1681229	15783	52440
300	1815968	15994	53306	1601528	15862	52561
350	1456681	15000	45964	1649556	15000	45502
400	1717293	16289	54288	1739869	16072	53568
450	1440741	15864	52876	1509539	16015	53377
500	1677222	15039	49402	1636301	15377	49642
Avg	2199793	45610	44245	1707807	22629	44283
Std	606908	53725	12943	122163	12599	12261

TABLE 17 Percentage Difference in Backcalculated Moduli, Section 481109

Distance	ACP	BASE	SUBGR
0	18.29	32.89	0.19
50	21.63	76.12	1.27
100	27.48	21.92	-1.37
150	21.55	24.60	-3.12
200	2.81	83.33	-0.80
250	32.70	11.46	1.76
300	22.98	44.64	-0.29
350	23.99	-3.12	0.22
400	9.92	32.32	-0.73
450	16.16	55.93	-2.14
500	4.93	-1.65	-1.65
Avg	18.14	44.13	-0.86

TABLE 18 Percentage Difference in Backcalculated Moduli, Section 481050

Distance	ACP	BASE	SUBGR
0	49.97	-3.85	-1.93
50	-10.93	-3.29	-0.33
100	62.84	-28.74	-4.25
150	-54.40	-6.23	-3.49
200	35.83	-17.78	3.92
250	1.63	-26.70	3.75
300	4.09	-23.33	4.13
350	81.47	-20.79	4.51
400	47.63	-23.59	4.84
450	153.29	-25.87	0.45
500	118.23	-26.08	5.87
Avg	35.39	-19.46	1.46

TABLE 19 Percentage Difference in Backcalculated Moduli, Section 481178

Distance	ACP	BASE	SUBGR
0	3.16	6.58	-0.38
50	-0.40	17.81	1.49
100	1.94	7.37	0.59
150	3.52	9.64	0.66
200	0.56	0.33	0.62
250	-5.10	58.17	3.29
300	0.18	4.79	0.62
350	0.82	6.74	0.37
400	14.76	22.26	5.79
450	-5.38	80.80	4.20
500	-1.73	20.19	1.53
Avg	1.48	23.48	1.76

TABLE 20 Percentage Difference in Backcalculated Moduli, Section 483559

Distance	ACP	BASE	SUBGR
0	-20.95	-60.41	2.84
50	-42.21	-68.05	5.08
100	-35.53	-72.01	3.58
150	-31.03	-6.86	2.66
200	-38.98	-0.27	-1.22
250	-28.60	-2.61	-2.91
300	-11.81	-0.82	-1.40
350	13.24	0.00	-1.00
400	1.31	-1.33	-1.33
450	4.78	0.96	0.95
500	-2.44	2.25	0.49
Avg	-22.37	-50.39	0.09

versus measured thicknesses for the 16 basins at each test point.

These tables indicate that the backcalculated moduli of the ACP layers, being highly sensitive to assumptions regarding the pavement structure, are adversely affected by normal layer thickness variations found on these SHRP sections. In the case of Section 481109, the average backcalculated modulus of the ACP increased from 1,278,728 lb/in.^{2} to 1,510,644 lb/in.^{2} when substituting the measured layer thicknesses for the SHRP data base thicknesses. Figure 4 illustrates this graphically. In each of these plots, the ACP moduli value obtained utilizing the assumed thicknesses is plotted against the x-axis, whereas the modulus value obtained utilizing the GPR measured thicknesses is plotted against the y-axis. The straight line on the graph represents the line of equality. Each point on the graph represents one deflection basin. From this graph, it is apparent that by using assumed thicknesses from the SHRP data base, one runs the risk of consistently over- or underpredicting the modulus of the ACP layer.

For Section 481050, the average ACP modulus increased from 430,240 lb/in.^{2} to 582,425 lb/in.^{2}, or 35 percent, when comparing assumed versus measured thicknesses. However, from Figure 4 it is apparent that the differences are far worse when considering individual deflection basins. Several deflection basins exhibited changes in backcalculated moduli of over 100 percent.

Section 481178, having less difference between the assumed versus the measured layer thicknesses, exhibited little change in ACP modulus. In fact, the average difference, as can be seen in Table 19, was only 1.48 percent, the largest change occurring at 400 ft from the beginning of the section and that being 14.76 percent. Furthermore, most of the points fell on the line of equality in Figure 4.

Section 483559 exhibited an interesting phenomenon near the beginning of the section, in which the ACP moduli reached the somewhat questionable value of 4,000,000 lb/in.^{2} while using the SHRP assumed thicknesses. Note that the average error per sensor between the measured and calculated de-

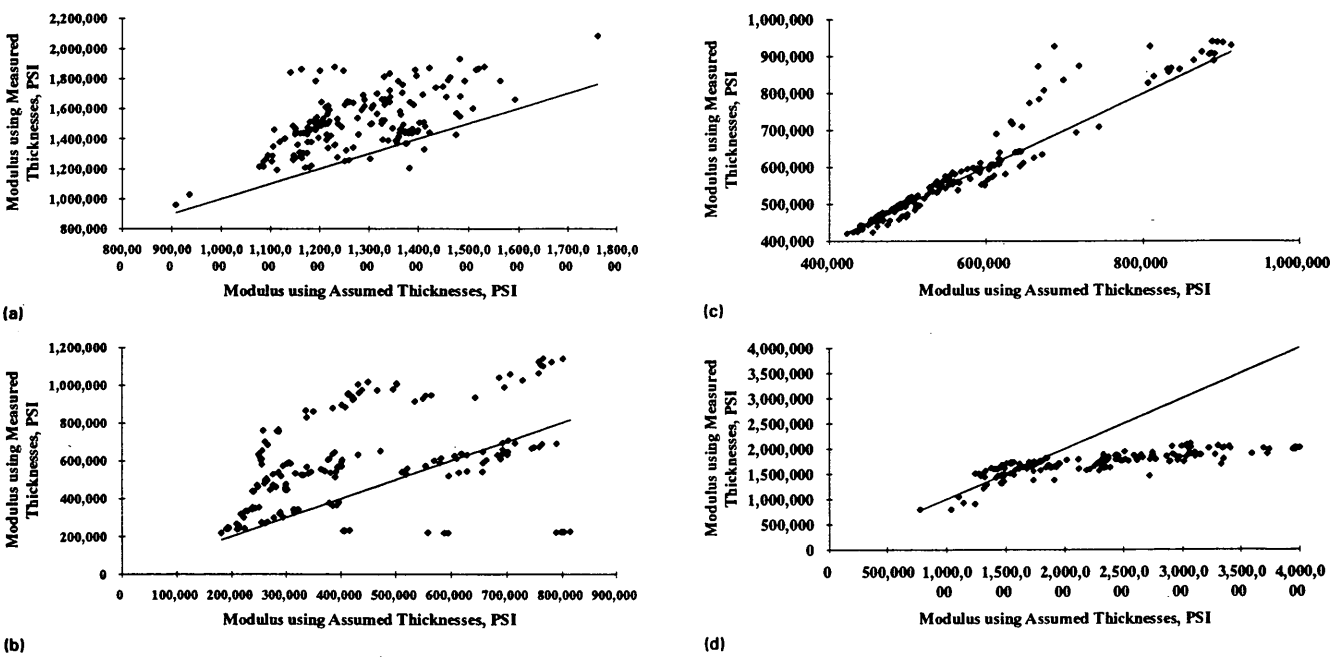

FIGURE 4 Backcalculated asphalt moduli using assumed versus measured layer thicknesses: (*a*) Section 481109, (*b*) Section 481050, (*c*) Section 481178, and (*d*) Section 483559.

flection basin was in most cases less than or near 2 percent. By using the GPR-measured thicknesses, the moduli were reduced to near 2,000,000 lb/in.^{2}, which is more consistent with values found elsewhere on the section, and the average error per sensor was similar to that obtained using the SHRP data base thicknesses. Table 4 provides insight into the cause of this apparent discrepancy. By examining Table 4 we find that between Test Points 0 and 300, substantial differences exist between the assumed and the measured ACP thicknesses. Differences of up to 2 in. were found at points 50 and 100. By taking this discrepancy into account, the backcalculated moduli on these points were not only more realistic, but the standard deviation of the moduli values over the section were reduced from 606,908 lb/in.^{2} to 122,163 lb/in.^{2}, as can be seen in Table 16. This illustrates that the error between the measured and calculated basin in the backcalculation process is not always a good indicator of the accuracy of the layer moduli obtained during the process.

The standard deviations of the ACP moduli increased for Sections 481109, 481050, and 481178 when substituting GPR measured thicknesses with those from the SHRP data base. In two instances, for Sections 481178 and 481109, the increase is considered by the authors to be negligible. However, for Section 481050 a dramatic increase from 161,801 to 243,727 can be seen. The ACP thicknesses, both measured and assumed, are less than 3 in. The FWD is relatively insensitive to variations in ACP modulus when the layer is this thin. That is, the deflections obtained do not vary significantly with changes in ACP modulus at this level of thickness. Thus when performing the backcalculation, one may expect a wide variation in the predicted ACP modulus when attempting to fit the basins. For instance, by varying the difference between the measured and calculated deflection basin by only a few tenths of a mil, wide variations in ACP modulus will result. It is standard practice in Texas to fix the ACP modulus to some temperature corrected value during the backcalculation process. For these reasons, the increase in standard deviation of the ACP modulus values for Section 481050 cannot be considered significant.

The ACP moduli values seem high for Sections 481109 and 483559. This can be explained as the result of combining the thin ACP surface layer with the underlying asphalt stabilized base layer that was present on both sections.

Base Course Moduli

The base course moduli were affected by the changes in thicknesses as well. Figure 5 illustrates the affect of including the GPR measured thicknesses in the analysis. Generally, by using assumed layer thicknesses, one underpredicts the base course modulus on Sections 481109 and 481178. On Section 481050 the reverse is true. From Tables 17 through 20 it is apparent that, on average, the modulus is underpredicted by 44.13 and 23.48 percent on 481109 and 481178, respectively. For Sections 481050 and 483559, it is overpredicted by 19.46 and 50.39 percent, respectively.

Another interesting finding was that the base course modulus for Section 483559 was substantially less than the subgrade modulus (22,629 versus 44,283 lb/in.^{2}), suggesting the presence of nonlinearity in the subgrade or the presence of a rigid layer. This trend was evident regardless of whether the assumed layer thicknesses or the GPR-measured thicknesses were used in the backcalculation procedure.

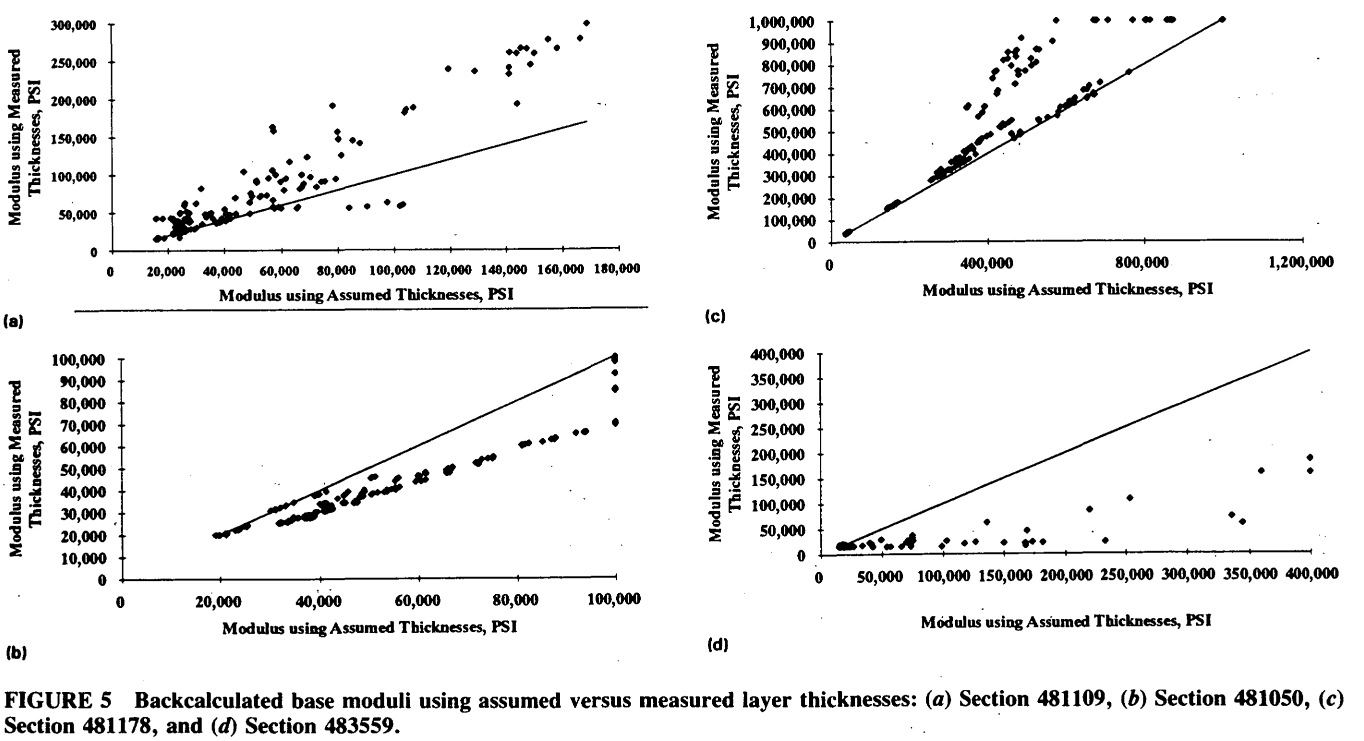

FIGURE 5 Backcalculated base moduli using assumed versus measured layer thicknesses: (*a*) Section 481109, (*b*) Section 481050, (*c*) Section 481178, and (*d*) Section 483559.

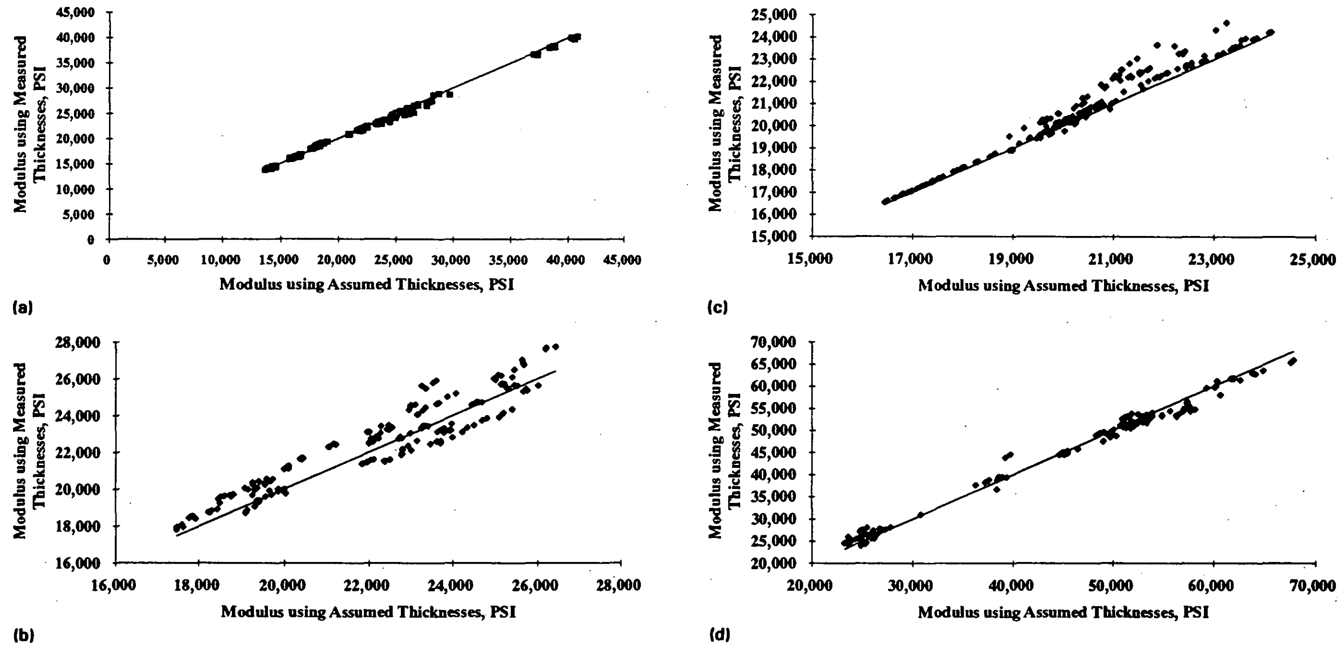

FIGURE 6 Backcalculated subgrade moduli using assumed versus measured layer thicknesses: (*a*) Section 481109, (*b*) Section 481050, (*c*) Section 481178, and (*d*) Section 483559.

Subgrade Modulus

As can be seen in Figure 6, the subgrade modulus value was affected very little by the variation in pavement thicknesses. Tables 17 through 20 show that the differences were less than 2 percent. Because this result was expected before the analysis, and because it is consistent with backcalculation theory, no further discussion is deemed necessary.

DISCUSSION OF RESULTS

Since at this time no laboratory testing of the materials obtained from the test pits on the sections has been performed by the SHRP contractors, it is difficult to determine the accuracy of the moduli, whether obtained using assumed thicknesses or GPR measured thicknesses. However, it is safe to say that if variations in layer thicknesses exist on SHRP sections, and the results of the GPR survey indicate that they do, and these variations are ignored in the backcalculation process, one can expect erroneous backcalculation results. Regardless of the complexity of the backcalculation scheme, the quality of the deflection data, or the thoroughness and care expended in the process, the magnitude of the errors probably will be along the lines of those found here.

With regard to backcalculation errors, they may not be significant with respect to the overlay design process. In certain cases, there may be compensating effects between layers. A 20 to 30 percent error in the backcalculation process may not have a great effect on overlay requirement, since the "error" is compensated for by thickness, that is, the total stiffness of both systems is essentially the same. The effect of the error is, of course, dependent on the design procedure being used. Any design procedure that uses tensile strain at the bottom of the ACP layer would be sensitive to these errors in the backcalculation process.

CONCLUSIONS

The results of this study indicate that

1. Variations found in layer thicknesses on SHRP sites in Texas are large enough to cause up to 100 percent error in the backcalculated modulus of the surface layer of the pavement, if not taken into account.
2. These variations also resulted in up to 80 percent error in the base materials.
3. These variations did not appreciably affect the backcalculated modulus of the subgrade.
4. Deflection basins alone cannot be used to identify or quantify changes in pavement layer thicknesses, which are severe enough to adversely affect the accuracy of the backcalculated moduli.
5. If reliable backcalculated moduli values are to be obtained on SHRP sites, or for that matter any pavement section, some method of identifying and quantifying layer thickness variations must be used before the backcalculation process.
6. The success with which a calculated deflection basin is "matched" with a measured basin is not a good indicator of the accuracy of the backcalculated moduli. It is possible to obtain small error terms with inaccurate moduli values.

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