Variability in Measured Deflections and Backcalculated Moduli for the Strategic Highway Research Program Southern Region

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It is well known that excessive variability in subgrade characteristics, layer thicknesses, material characteristics, and other such construction variables are major causes of distress and loss of performance in pavements. As the use of deflection measurements to characterize pavement structural capacity and to determine the elastic moduli of the separate layers increases, variability in the deflection measurements and the resulting estimates of the elastic moduli become more important. One study reported was intended as a preliminary evaluation of the amount of variability in deflections that may be expected in relatively short test sections (500 ft for the Strategic Highway Research Program test sections studies), and to learn what characteristics of pavements contribute to this variability. The relative causes of the variability were studied using correlations of variations in deflections with various characteristics of the pavements, such as layer thicknesses, layer stiffnesses, and asphalt viscosity. These studies indicate that the typical coefficients of variation for deflections range between 4 and 18 percent of the mean deflections, but some coefficients of variation for specific test sections will run over 40 percent of the mean deflections. A second study identified variations in backcalculated moduli for four test sections. This limited set of backcalculated moduli indicates that variability in backcalculated moduli for base layers is much higher than that for the asphalt concrete (AC) layers and subgrade and that the coefficients of variation for backcalculated AC moduli appear to be proportional to those for measured deflections. Some causes of the variability appear to have been identified, but variability in deflection measurements were found to result from a multitude of pavement characteristics, each resulting in minor effects to create the whole.

The design of pavement structures typically assumes that a pavement structure will be constructed of materials having certain assumed or expected properties or characteristics. This pavement structure is selected after study of any existing materials in place, new materials that may be specified, expected traffic, and the environment in which the pavement is to exist and function. Variability from these expectations in the field is a major cause of distress and loss of performance in pavements.

Because the material sampling for the Strategic Highway Research Program (SHRP) Long-Term Pavement Performance (LTPP) studies has been conducted at only two general locations (both close to but outside the test section), the only within-section measure of variability available will be from falling weight deflectometer (FWD) deflection measurements at close intervals throughout the test sections. The variations in measured deflections result from variability in layer thicknesses and in material properties, as well as from discontinuities, such as cracks, that usually begin at the bottom of bound layers and propagate toward the surface. Therefore, the variability in measured deflections is important, even though it will be difficult to differentiate among potential causes.

The LTPP data base for the SHRP Southern Region includes Dynatest FWD measurements at close intervals for over 260 general pavement studies (GPS) test sections 500 ft in length. Analysis of the variability in deflections for these test sections offers an opportunity for characterizing typical variability for various types of pavements and exploring apparent variations in moduli within test sections and between similar test sections.

All FWD measurements used in this study were made with the load 6 ft from the outer edge of the pavement. For flexible pavements, measurements were made every 25 ft. For jointed concrete pavements, tests were made at midpanel, except when a transverse crack occurred near that point. In that case, the measurement was made midway between the crack and a joint, within the largest "subpanel" between the crack and a joint. For continuously reinforced concrete pavements, tests were made approximately every 25 ft and midway between cracks.

Deflection data from the SHRP Southern Region Information Management System (RIMS) were extracted, and test section means, standard deviations, and coefficients of variation were calculated for the measured deflections for all seven sensors. After studying the distributions of the coefficients of variation, it was decided to continue studies for Sensor 1 directly under the load and Sensor 6 located 36 in. from the load. Plots were developed to show distributions of coefficients of variability separately for Sensor 1 and for Sensor 6 and for flexible and rigid pavements. Plots were also developed for deflections and backcalculated moduli along typical flexible pavement test sections to indicate how these quantities vary within test sections. Other plots showed coefficient of variation versus various pavement properties for 77 flexible pavements for which a "practice data base" had been developed. A correlation study was also conducted with the deflection data for the 77 flexible pavements and the practice data base to indicate levels of correlation between

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coefficients of variation of deflections and various other pavement characteristics.

The results from these studies have been evaluated and the conclusions reported about typical levels of variation of deflections and what pavement parameters may influence levels of variability.

DISTRIBUTIONS OF VARIABILITY FOR PAVEMENTS IN THE SHRP SOUTHERN REGION

The coefficients of variation (CV) have been calculated individually for Sensors 1 and 6 for 132 flexible pavement test sections and 88 rigid pavement test sections. Coefficients of variation are called CV1 for Sensor 1 and CV6 for Sensor 6. Histograms were developed to indicate distributions of levels of variation and appear as follows:

1. Figures 1 and 2: distributions of CV1 and CV6, respectively, for 132 flexible pavements from Experiments GPS-1, Asphalt Concrete with Granular Base; GPS-2, Asphalt Concrete with Bound Base; and GPS-6, AC Overlay of AC Pavement; and
2. Figures 3 and 4: distributions of CV1 and CV6, respectively, for 88 rigid pavements from Experiments GPS-3, Jointed

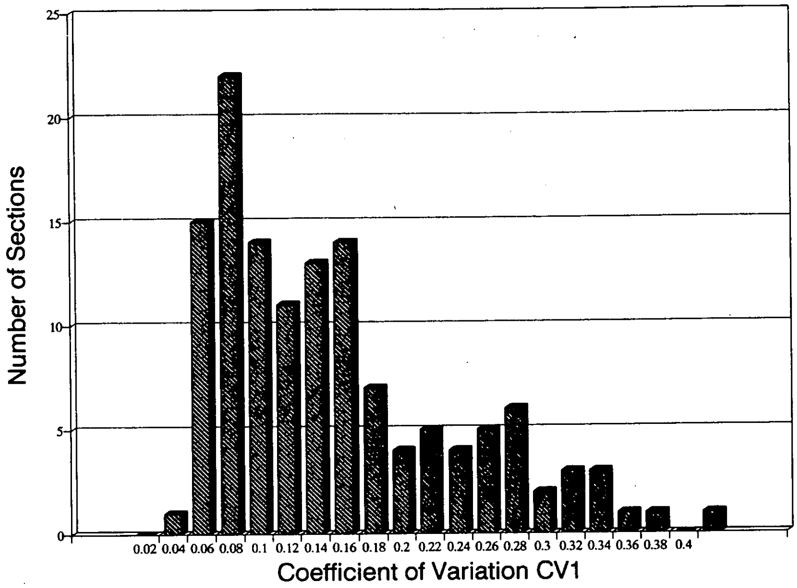

FIGURE 1 Distribution of Sensor 1 coefficients of variation for 132 flexible pavement test sections in the SHRP southern region, Experiments GPS-1, 2, and 6.

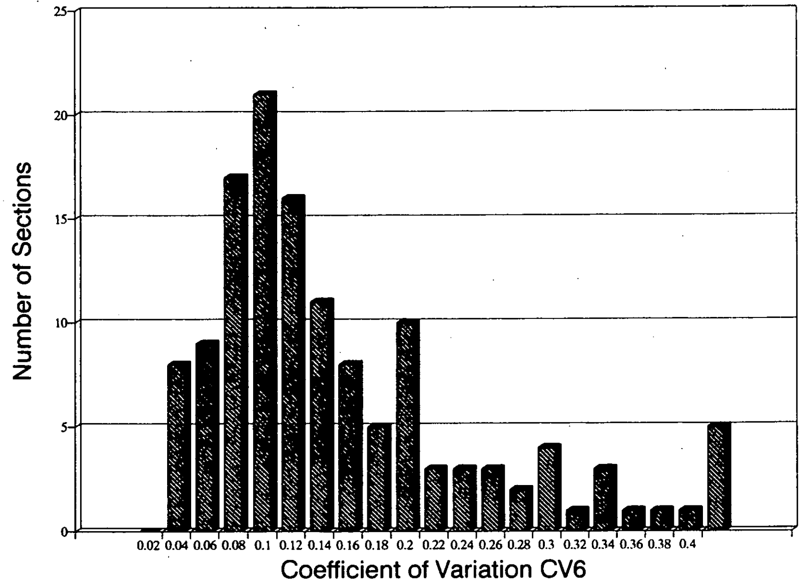

FIGURE 2 Distribution of Sensor 6 coefficients of variation for 132 flexible pavement test sections in the SHRP southern region, Experiments GPS-1, 2, and 6.

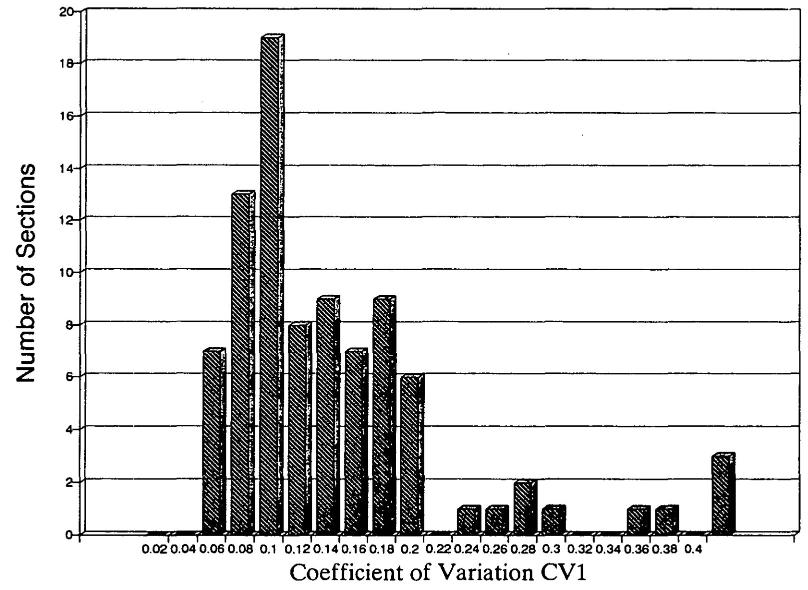

FIGURE 3 Distribution of Sensor 1 coefficients of variation for 88 rigid pavement test sections in the SHRP southern region, Experiments GPS-3, 4, and 5.

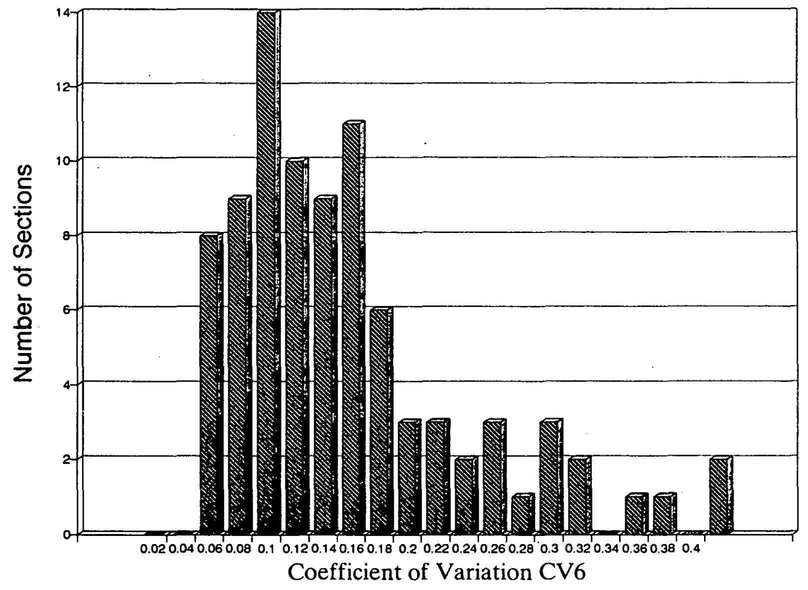

FIGURE 4 Distribution of Sensor 6 coefficients of variation for 88 rigid pavement test sections in the SHRP southern region, Experiments GPS-3, 4, and 5.

Plain Concrete Pavements; GPS-4, Jointed Reinforced Concrete Pavements; and GPS-5, Continuously Reinforced Concrete Pavements.

Because the coefficients of variation are simply the ratios of standard deviations from the means to the means, the intervals shown on Figures 1 through 4 represent intervals of standard deviation expressed as fractions of the means. All of the distributions are skewed. The evaluation of the deflections for the majority of the test sections resulted in standard deviations between 4 and 18 percent of the mean deflections for the test sections. However, there were for all pavements and sensors a lesser number of standard deviations ranging from 18 to over 40 percent of the mean deflections. The incidence of standard deviations above 20 percent of the mean deflections for Sensor 1 (below the load) was much greater for flexible than for rigid pavements; this difference for Sensor 6 was negligible.

DISTRIBUTIONS OF DEFLECTIONS WITHIN TEST SECTIONS

Four flexible pavements from Experiment GPS-1 (AC over granular base) were selected to include (a) two test sections with relatively heavy structures, one on coarse-grained and one on fine-grained soils, and (b) two sections with moderate structures, one on coarse-grained and one on fine-grained soils.

The measured deflections were not reviewed before selection of the test sections, so the selections were random with relation to measured deflection variability.

Plots of midlane deflections at 25-ft intervals for Drop Height 2 (approximately 9,000 lb normalized to mils/1,000 lb of load) appear in

1. Figure 5 (*top*) for SHRP ID 014126—13.0 in. of HMAC, 18.4 in. of coarse soil aggregate base, and subgrade of clayey sand, located in Alabama;
2. Figure 6 (*top*) for SHRP ID 471023—5.4 in. of HMAC and 6.1 in. of ATB (asphalt-treated base), 6.0 in. of crushed stone base, and a sandy clay subgrade, located in Tennessee;
3. Figure 7 (*top*) for SHRP ID 481065—8.6 in. of HMAC, 4.8 in. of crushed stone, and a sandy clay subgrade, located in Texas; and
4. Figure 8 (*top*) for SHRP ID 481076—4.7 to 6.1 in. of HMAC, 8.4 in. of crushed stone base, and a sand subgrade, located in Texas. (For backcalculations, two different structures were used and will be explained subsequently.)

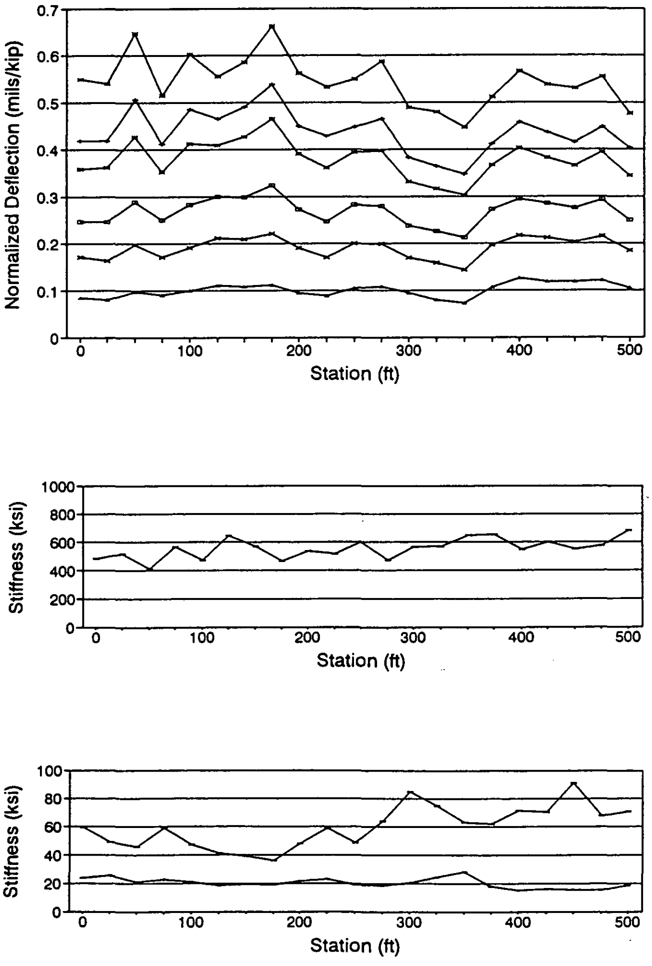

FIGURE 5 Measured midlane deflections (in mils per 1,000 lb) and backcalculated moduli, GPS Test Section 014126: *top*, deflections across test section, sensor spacings of 0, 8, 12, 24, 36, and 60 in. from center of load; *middle*, moduli for AC; and *bottom*, moduli for base and subgrade.

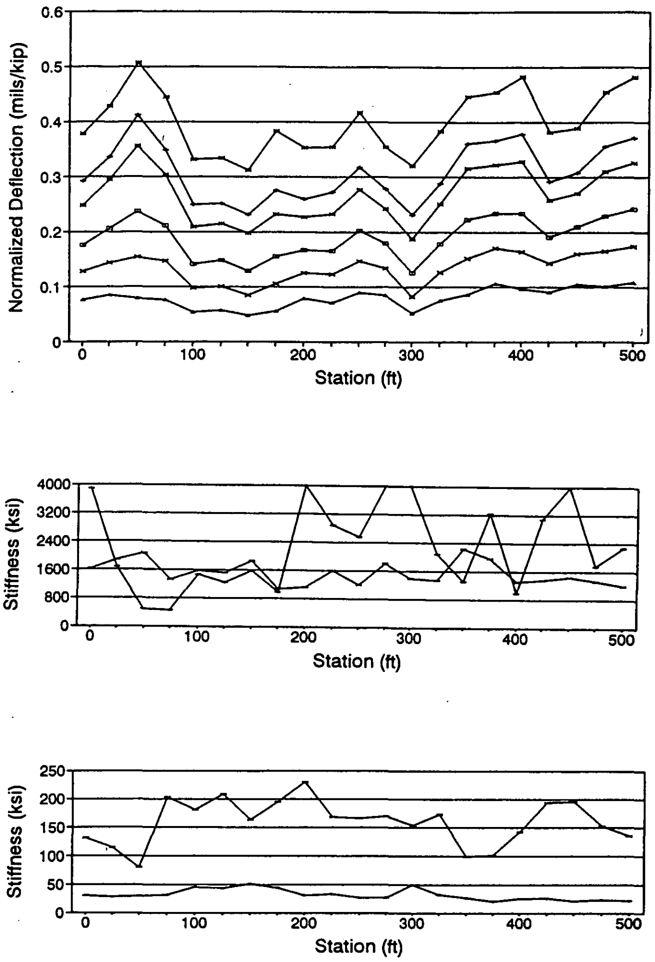

FIGURE 6 Measured midlane deflections (in mils per 1,000 lb) and backcalculated moduli, GPS Test Section 471023: *top*, deflections across test section, sensor spacings of 0, 8, 12, 24, 36, and 60 in. from center of load; *middle*, moduli for AC and granular base; and *bottom*, moduli for asphalt-treated base and subgrade.

These plots show the average deflections (over four drops at Drop Height 2) per 1,000 lb of load. (Drop Height 2 yields loads of about 9,000 lb.) The deflection measurements were made with the seven standard SHRP sensor spacings. Because the software package allowed only six dependent variables within a plot, Sensor 4 measurements 18 in. from the center of load were omitted from the plots (but not from the backcalculations).

The coefficients of variation for these test sections are as follows:

SHRP ID	*Sensor 1*	*Sensor 6*
014126	0.104	0.108
471023	0.140	0.197
481065	0.248	0.106
481076	0.314	0.073

Variations for Sensors 1 and 6 in deflections throughout a test series can vary markedly.

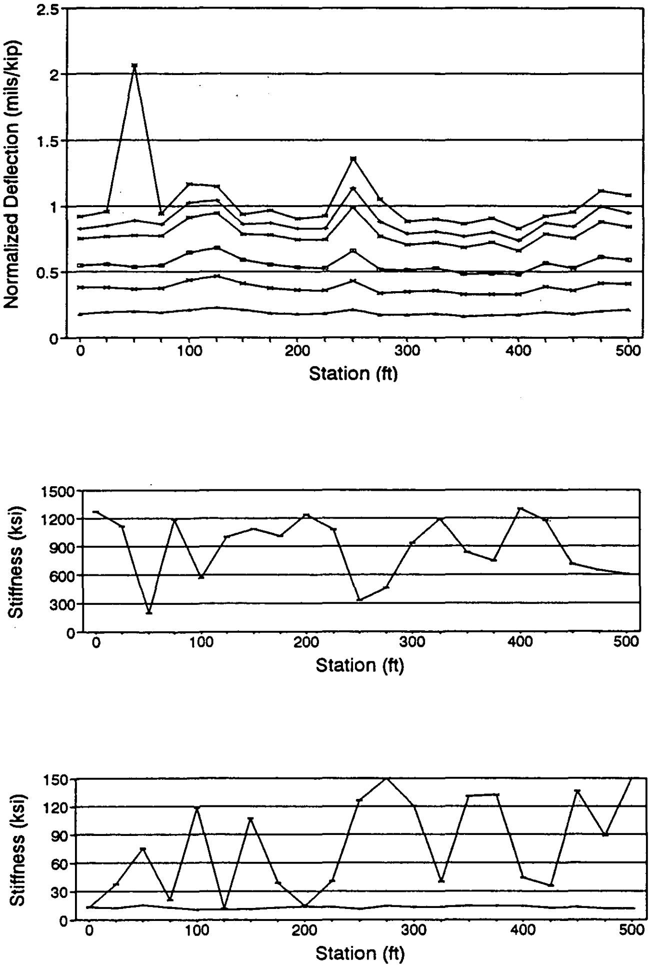

FIGURE 7 **Measured midlane deflections (in mils per 1,000 lb) and backcalculated moduli, GPS Test Section 481065:** ***top*****, deflections across test section, sensor spacings of 0, 8, 12, 24, 36, and 60 in. from center of load;** ***middle*****, moduli for AC; and** ***bottom*****, moduli for base and subgrade.**

Inspection of the plots indicates that the magnitudes of deflections for the separate sensors generally appear to follow the same trends from point to point along the test sections. Also, the measured deflections vary substantially, even in a short test section of 500 ft.

In Figure 7 (*top*) the deflections measured for Sensor 1 at Station 0 + 50 were relatively high and atypical for the trends reflected by the other sensors. It is likely that this sensor rested very near a crack or some other anomaly in the pavement.

It also may be noted in Figure 8 (*top*) that deflections measured between Stations 0 + 00 and 1 + 00 for Sensors 1 through 4 were substantially higher than those for the remainder of the test section. Review of the data from the material sampling indicated that the pavement structures differed between sampling points off the ends of the test section as follows:

Location	*AC Thickness (in.)*	*Base Thickness (in.)*
Approach	6.1	8.4
Leave	4.7	8.4

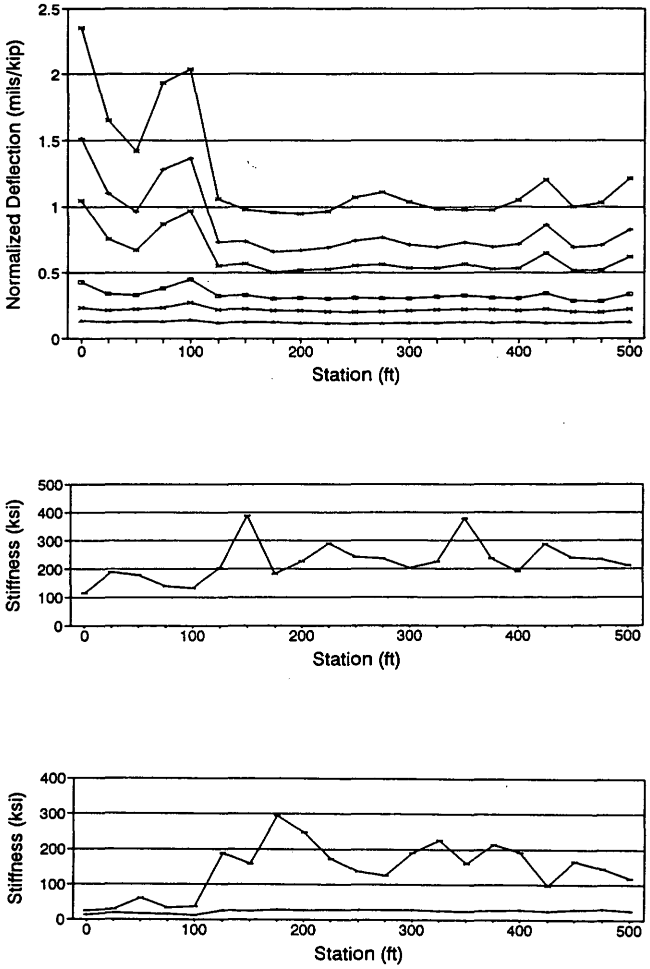

FIGURE 8 **Measured midlane deflections (in mils per 1,000 lb) and backcalculated moduli, GPS Test Section 481076:** ***top*****, deflections across test section, sensor spacings of 0, 8, 12, 24, 36, and 60 in. from center of load;** ***middle*****, moduli for AC; and** ***bottom*****, moduli for base and subgrade.**

The plots of deflections in Figure 8 (*top*) appear to indicate that the change in structure occurred between Stations 1 + 00 and 1 + 25, but the higher deflections occurred for the thicker structure. However, review of the laboratory test results indicated that the base material on the approach end was a clayey sand, whereas that on the leave end was a crushed gravel, and the silty clay subgrade on the approach end has 25.6 percent passing the No. 200 sieve compared with 9.8 percent passing the No. 200 sieve on the leave end. The substantial differences in deflections between the two subsections then result from several differences in pavement structure. Although the facts are indeterminate, it appears likely that the layer thicknesses also may have changed between Stations 1 + 00 and 1 + 25, so the backcalculations can be conducted separately for the subsections.

DISTRIBUTIONS OF BACKCALCULATED LAYER MODULI WITHIN TEST SECTIONS

Backcalculations have been conducted for the same test sections for which distributions of deflections were discussed earlier. These distributions for calculated moduli appear as Figures 5 through 8 (*middle*) for AC moduli and as Figures 5 through 8 (*bottom*) for base and subgrade moduli. MODULUS 4, developed by the Texas Transportation Institute for the NCHRP and the Texas State Department of Highways and Public Transportation, was used for the backcalculations. Because a 20-ft auger boring by each of the test sections indicated no rigid layer, the estimates for depths to effective stiff layers by MODULUS 4 were used, although other depths to effective stiff layers (including infinity) were tried. The errors in fit were less for three of the test sections when infinity was used, but the calculated moduli appeared illogical.

No reasonable moduli were calculated for Test Section 471023 (Figure 6). Trials included three layers (HMAC and ATB combined) and four layers (HMAC and ATB as separate layers), with combinations of 300 in. (for a single point), infinity (for a single point), and the depths selected by MODULUS 4 to effective stiff layer. As seen from the results plotted in Figure 6 (*middle* and *bottom*), the backcalculated values were not logical. The calculated granular base moduli exceeded those for the AC surface and ATB layers, which is not sensible. The results plotted were for the four-layer structure with a depth to effective stiff layer from the pavement surface of 165 in. Such results indicate that the use of measured deflections to estimate layer moduli is not yet a technique that can be applied without careful examination and evaluation of the results.

Nick Coetzee conducted backcalculations on the same four deflection data sets (unpublished data), with no stiff layers in the subgrade (infinite depth). Table 1 shows approximate ranges of backcalculated moduli across the test sections from ELMOD by Coetzee and from MODULUS 4 by Jordahl. Although the values varied, the trends were generally similar. Coetzee also experienced difficulties with Section 471023, although the moduli for his three-layer solution were less illogical than those from the four-layer solution with MODULUS. In general, lower values for a layer derived from one computer program than from the other would be reflected in higher numbers for another layer. These results further emphasize the need for more development before backcalculation of layer moduli from measured deflections can be considered reliable.

Coetzee later ran the backcalculations on the same data sets but allowed ELMOD to select depths to effective stiff layers. In all cases, the result was a worse fit to the measured deflections than when using an infinite depth.

The mean values of backcalculated moduli, the absolute errors per sensor, and the coefficients of variation for the asphalt concrete, base, and subgrade layers for the four test sections discussed previously appear in Table 2. The ranges for the backcalculated layer moduli appear in Table 1. Judgments were required in selection of the results from the multiple runs, because the best fit (as indicated by a lower value of absolute errors per sensor) often occurred when the resulting calculated moduli were illogical.

The following conclusions were drawn from study of the graphs for backcalculated moduli and Tables 1 and 2:

1. The error checks for the moduli backcalculated with MODULUS 4 indicated good fits between measured deflections and those calculated with the backcalculated moduli when no effective stiff layer was included in the subgrade, but the resulting moduli did not appear to be logical. More reasonable values of moduli were derived using MODULUS 4 estimates of depth to an effective stiff layer, but the fits were not as good.
2. For this limited set of test sections, the variabilities in moduli calculated for base layers are substantially higher than those for asphalt concrete and subgrade layers.
3. The coefficients of variation for asphalt concrete moduli, for this limited sample, appear to be approximately proportional to the variations in Sensor 1 deflections reported previously.
4. The ranges in values for backcalculated moduli may be expected to be substantial, even when the coefficients of variation appear to be relatively small.

Although the lack of data on variability in layer thicknesses within the test sections cause assignment of all of the variability to the moduli, it is believed that variations from the layer

TABLE 1 Results of Backcalculations on Deflections, SHRP Test Sections 014126, 471023, 481065, and 481076

Test Section	Computer Program	Ranges of Backcalculated Moduli in KSI		
		AC	Granular Base	Subgrade
014126	ELMOD	500 to 800	20 to 65	32 to 50
	MODULUS	410 to 683	36 to 91	15 to 29
471023	ELMOD	700 to 900	90 to 570	44 to 93
	MODULUS	1000 to 2300 (ATB) 80 to 210 (AC)	446 to 4000	21 to 52
481065	ELMOD	80 to 1900	8 to 70	15 to 22
	MODULUS	330 to 1298	11 to 150^+	11 to 15
481076	ELMOD	50 to 1900	30 to 160	20 to 39
	MODULUS	116 to 388	24 to 294	13 to 29

TABLE 2 Approximate Ranges for Backcalculated Layer Moduli from Programs ELMOD and MODULUS 4

SHRP ID	Average Pavement Temp. (°F)	Absolute[1] Error/Sensor (Percent)	Mean Values of Moduli (KSI)			Coefficients of Variation (Percent)			Average Depth to Stiff Layers (Inches)
			AC	Base	Subgrade	AC	Base	Subgrade	
014126	61	2.21	555	60	20	13	25	18	103
471023	95	1.94	1537 (ATB) 160 (AC)	2284	32	21 24	54	30	147
481065[2]	70	3.80	890	78	13	32	67	9 10	139
481076[3] 0-100	76	2.40	150	37	15	21	40	18	60
125-500		9.3[4]	248	177	26	24	29	6	153

Notes:

[1] = Average over seven sensors of the absolute value of percent error in deflections.

[2] = The one very high deflection data point for Sensor 1 at Station 0+50 was omitted from statistical calculations (see Figure 7).

[3] = Different structures were used for Stations 0+00 to 1+00 and 1+25 to 5+00 (see discussions in "Distributions of Deflections Within Test Sections").

[4] = Sensor 7 was fit very poorly in this case.

thicknesses measured at the ends and outside of the test sections cause a substantial amount of the variability. The results of one study on the effects on calculated moduli from errors in layer thicknesses have been published previously (*1*). Two possibilities for improvement exist for future backcalculations using layer thickness data specific to measurement stations:

1. Some experiments in Texas with calibrating radar output to the known layer thicknesses at each end of four SHRP GPS test sections appear to have resulted in measured layer thicknesses within the test section to reasonable accuracy. Holes were bored in an adjacent lane to check the point-to-point radar estimates. This success has led to a broader experiment funded by SHRP. If successful, radar measurement of all SHRP GPS test sections is probable. [Very accurate layer thickness measurements are being made for some overlays in GPS and all specific pavement studies (SPS) test sections.]
2. As GPS test sections reach a point requiring overlay, cores of the surface material and bound layers could be taken within the test sections before overlay in the existing pavements. Similarly, base material could be augered to establish its thickness. The deflection data will still be available, so new backcalculations could be conducted.

GPS-1 PRACTICE DATA BASE

A "practice data base" has been developed by the authors for use in conducting practice sensitivity analyses to develop procedures to be used for SHRP Contract P-020, LTPP Data Analysis. This practice data base includes inventory data now available in the southern RIMS for experiment GPS-1, rough measurements of distress by SHRP regional contractor personnel when first visiting the test sections, rough estimates of cumulated ESALs [based on original estimates of ESALs per year by state highway agencies (SHAs)], estimated environmental data from isobar climatic maps, and realistic estimates where data were missing. The estimated values primarily supplemented materials data not furnished (generally not available) by the SHAs, such as estimations for dry densities based on other data available and plasticity indexes based on AASHTO soils classifications. All layer moduli other than those for the subgrade were estimated on the basis of other data available and experience with previous measurements. Moduli for subgrades were obtained from Sensor 6 deflection measurements using the equation for estimating subgrade moduli in the AASHTO Design Guide, with rough reductions reflecting a modification to reflect stress sensitivity imbedded in Program FWDCHECK. All asphaltic layers were combined and all granular base and subbase layers were combined to result in three-layer structures. On the basis of combined results of significance ratings by experts, data were not sought for the many missing data items that were not expected to be significant for predicting pavement performance.

Although the estimated data elements in this data base limit its accuracy in predicting performance, the data base was considered to be adequate for correlation studies to obtain preliminary information on what variables were correlated with variability in measured deflections. The results of these studies are described subsequently. A similar but broader study should be conducted when the actual data become available in the National Pavement Data Base.

CORRELATION STUDIES

Data from the GPS-1 practice data base described above were used to relate the coefficients of variation CV1 and CV6 in deflections measured by Sensors 1 and 6 (S1 and S6) to a number of other variables. The Statistical Analysis System (SAS) software was used to conduct a correlation analysis and determine Pearson correlation coefficients between CV1 and CV2 and other variables in the data base. The results from this study appear in Table 3.

A positive magnitude for coefficient of correlation indicates that increases in that variable tend to cause increased variability in measured deflections, and vice versa for negative magnitudes. The absolute magnitude of the coefficient indicated the degree of the variable's effect on variability in mesured deflections. The absolute magnitudes for the correlation coefficients ranged from zero to 0.35, except for one at 0.59. To assign some different levels for the effects of variable increases in magnitude on the variability in measured deflections, an arbitrary system was established as follows (this system was also used for each variable in Table 3):

Range of Correlation Coefficients	*Level of Effect*
$CV_i > 0.20$	Significant (S)
$0.10 < CV_i \le 0.20$	Moderate (M)
$0 < CV_i \le 0.10$	Nominal (N)

The greatest correlation appears to be between CV1 and the SHRP ID numbers of the test sections. Once the skepticism stage runs its course and logic returns, it can be noticed that the first two digits of the ID numbers are the state codes, with the highest in the southern region being 48 for Texas, which has 38 of the 77 GPS-1 test sections. Considering that clay subgrades are relatively common in Texas and that CV1 appears to increase with plasticity index of the subgrade soil and the amount of the subgrade soil passing the No. 200 sieve, the correlation between CV1 and SHRP ID number seems more reasonable. Also, the state code for Tennessee is 47, and considerable variability in layer thicknesses was noted between approach and leave ends during material sampling.

If the magnitudes of the correlation coefficients indicate trends, although their accuracy is limited by the limitations of the practice data base, the following tendencies may be noted for effects rated as significant.

1. The higher the amount and plasticity of the clay fractions in subgrades, the higher CV1 is likely to be.
2. The higher the annual precipitation, the lower CV1 is likely to be.
3. High levels of traffic (ESALs) in pavements tend to reduce CV1 (this is probably because of the thicker structures that are designed for pavements expected to experience heavy traffic).
4. CV1 and CV6 appear to decrease for rutted pavements (possibly related to properties of materials that rut, or related to high traffic levels discussed above).
5. The occurrence of low-severity transverse cracking appears to increase CV1, but moderate or high-severity cracking does not. (This is probably a consequence of very limited occurrence of transverse cracking in the southern region, of which the great majority was of low severity.)
6. Increasing air temperatures when testing appears to increase CV1.
7. AADT appears to decrease CV1 (consistent with Item 3).
8. Increasing asphalt concrete thickness tends to decrease both CV1 and CV6.
9. Increasing asphalt viscosity in HMAC appears to decrease variability for Sensor 1 deflections (affects stiffness of the AC layer).
10. Increasing subgrade stiffness tends to decrease CV1 and increase CV6 (note that the effect is greater for Sensor 6, which primarily reflects subgrade characteristics).
11. Increased moisture content in the subgrade tends to increase both CV1 and CV6 (this does not appear to be consistent with Item 2).

Because the correlations between CV1 and CV6 and other variables were not generally strong, it appeared appropriate to conduct regressions to see how much of the variations could be explained with different combinations of the variables. Consequently, 15 variables were selected from the results of the correlation studies and SAS PROC REG, Option RSQUARE, was used to obtain the values of r^2, the proportion of variance in CV1 or CV6 explained by various combinations of variables. The SHRP ID number was omitted from this study.

Models for predicting CV1 with only one independent variable each resulted in values of r^2 equal to the square of the associated correlation coefficients, as would be expected. Using PROC REG, option STEPWISE, the values of r^2 increased moderately as more variables were included in the models, until four variables were included. The r^2 for the best model with four variables was 0.32, whereas the r^2 for the best model with 13 variables was only 0.39. The variables in the best four-variable model were thickness of the AC layer, Thornthwaite index, annual precipitation, and air temperature at time of testing. The software advised that no other variables were significant at the default value of the "*F* statistic for entry" of 0.15. Note on Table 1 that three of the individual correlation coefficients are negative and one is positive. Two of the four were rated to have significant effect and the other two moderate. The equation is

$$\begin{aligned} \text{CV1} = {} & 0.29479 - 0.00691\ (\text{AC thickness}) \\ & + 0.00211\ (\text{Thornthwaite index}) \\ & - 0.00533\ (\text{annual precipitation}) \\ & + 0.00106\ (\text{air temperature at testing}). \end{aligned}$$

The best five-variable model for CV6 had an r^2 of 0.29; the inclusion of nine additional variables increased the r^2 only to 0.34. The variables included were thickness of the AC layer, subgrade stiffness, subgrade soil passing the No. 200 sieve, Thornthwaite index, and annual precipitation. Three of the five also appeared in the equation for CV1, but only one was rated as having a substantial effect on CV6. The equation for

TABLE 3 Correlation Coefficients for Coefficients of Variation for Sensors 1 (S1) and 6 (S6) Deflections and Various Variables

Variable	Correlation Coefficients		Effects on Variability of Increases in Magnitude of Variable			
	S1 Deflections	S6 Deflections	S1		S6	
			Effect	Level	Effect	Level
Subgrade Plasticity Index	0.25	0.04	Increases	S	Increases	N
Subgrade, Passing #200	0.21	0.11	Increases	S	Increases	M
Thornthwaite Index	- 0.15	0.15	Decreases	M	Increases	M
Annual Precipitation	- 0.35	0.04	Decreases	S	Increases	N
Days Temp. > 90F	0.04	- 0.05	Increases	N	Decreases	N
Days Temp. < 32F	0.20	0.01	Increases	M	Increases	N
Cumulative ESAL's	- 0.12	- 0.07	Decreases	M	Decreases	N
Annual ESAL's (Rate)	- 0.21	- 0.15	Decreases	S	Decreases	M
Alligator Cracking						
Low Severity	0.19	0.06	Increases	M	Increases	N
Medium Severity	- 0.12	0.02	Decreases	M	Increases	N
High Severity	- 0.09	- 0.04	Decreases	N	Decreases	N
Rut Depth	- 0.30	- 0.22	Decreases	S	Decreases	S
Transverse Cracking						
Low Severity	0.34	- 0.10	Increases	S	Decreases	N
Medium Severity	- 0.08	0.00	Decreases	N	---	O
High Severity	0.00	- 0.07	---	O	Decreases	N
Air Temp. When Testing	0.30	- 0.07	Increases	S	Decreases	N
AADT	- 0.28	- 0.14	Decreases	S	Decreases	M
Percent Trucks	- 0.13	- 0.20	Decreases	M	Decreases	M
Asphalt Concrete Thickness	- 0.16	- 0.32	Decreases	M	Decreases	S
Asphalt Concrete Stiffness	- 0.14	0.07	Decreases	M	Increases	N
Base Thickness	- 0.15	- 0.12	Decreases	M	Decreases	M
Base Stiffness	0.03	0.17	Increases	N	Increases	M
Percent Voids in A.C.	- 0.12	- 0.06	Decreases	M	Decreases	N
Asphalt Viscosity (140F)	- 0.26	- 0.06	Decreases	S	Decreases	N
Asphalt Content	0.11	- 0.10	Increases	M	Decreases	N
Subgrade Stiffness	- 0.14	0.21	Decreases	M	Increases	S
Functional Class	- 0.18	- 0.23	Decreases	M	Decreases	S
Subgrade Moisture Content	0.23	- 0.21	Increases	S	Decreases	S
SHRP I.D. Number	0.59	0.29	Increases	S	Increases	S

Legend:

S1 = Sensor 1 Deflection
S6 = Sensor 6 Deflection
S = Substantial Effect = $CV_i > 0.20$
M = Moderate Effect = $0.10 < CV_i \leq 0.20$
N = Nominal Effect = $0 < CV_i \leq 0.10$

Note: Assignments of "levels of effect" are arbitrary.

CV6 is

$$\begin{aligned} \text{CV6} = {} & 0.2832 - 0.01249\ (\text{AC thickness}) \\ & + 0.00093\ (\text{subgrade stiffness}) \\ & + 0.00062\ (\text{passing No. 200 sieve}) \\ & + 0.00024\ (\text{Thornthwaite index}) \\ & - 0.00374\ (\text{annual precipitation}) \end{aligned}$$

Although the fractions of the variance of CV1 and CV6 explained by these equations (as indicated by the values for r^2) are quite low, this is partially a consequence of using a very simple linear equation form in the regressions. If the objective had been to develop predictive equations, variables could have been transformed to produce more realistic equation forms. Improvements in r^2 might have resulted from including interaction terms between the independent variables. Substantial unexplained error might still have existed because of such factors as limitations of the practice data base, testing error, and use of specific layer thicknesses for all locations within a test section when they are really variable.

To continue the search for identities of variables that affected magnitudes of CV1 and CV6, the independent variables in the equations were individually plotted for each test section against CV1 and CV6, respectively. Simple linear models were regressed from the data, using procedures in the spread sheet software, and plotted to give some insight as to the overall effects of the data represented by the very scattered points on the plots. These plots appear in Figure 9 for CV1 and Figure 10 for CV6.

None of the plots offer much in the way of a definite relationship, so it appears that the levels of variability for the measured deflections are not heavily influenced by any of the variables studied but appear to result from small effects from a number of sources, probably including some that were omitted from this study. Although these plots did not produce any strong candidate as a major cause of variability in deflections, it is comforting to note that the senses and magnitudes of the slopes for the simple linear relationships plotted are consistent with results from the correlation studies displayed in Table 3.

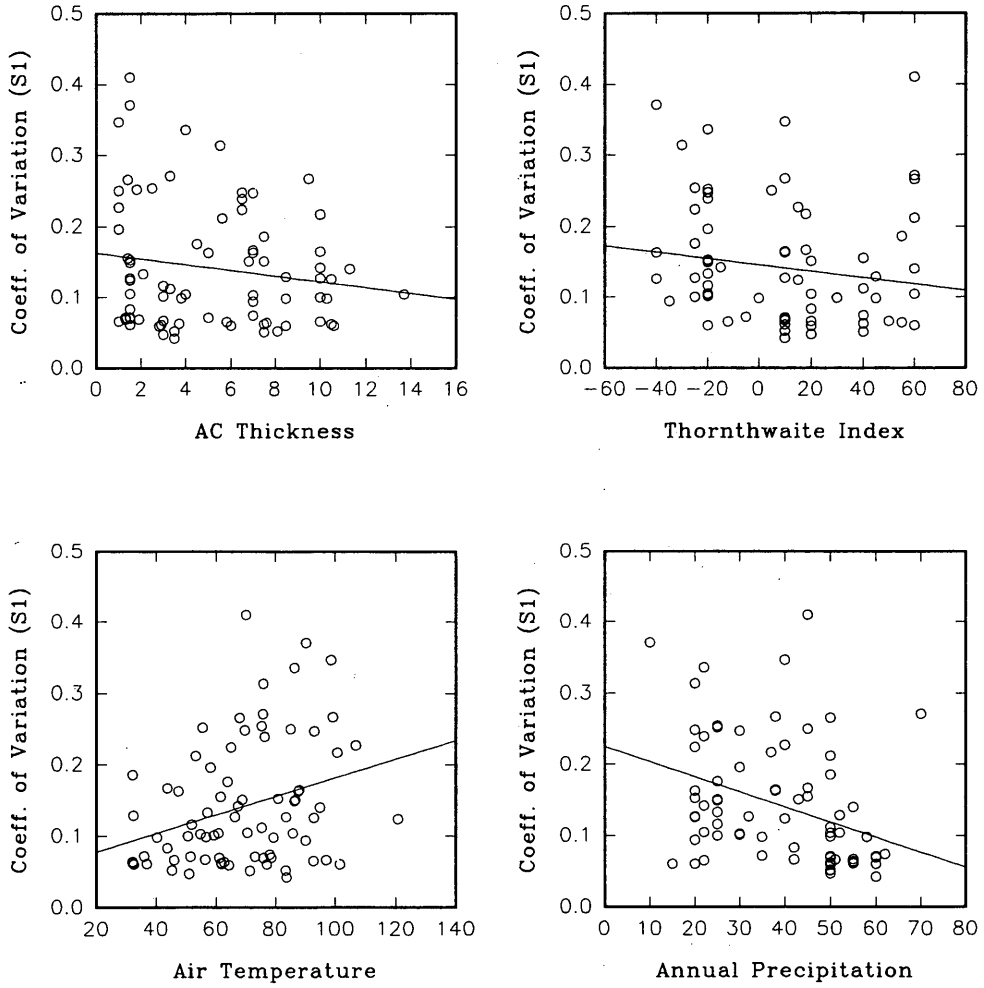

FIGURE 9 Plots of coefficients of variation CV1 of deflections measured by Sensor 1 (directly below the load) to other variables found to significantly affect the variations: *top left*, CV1 versus AC thickness; *top right*, CV1 versus Thornthwaite index; *lower left*, CV1 versus air temperature at testing; and *lower right*, CV1 versus annual precipitation.

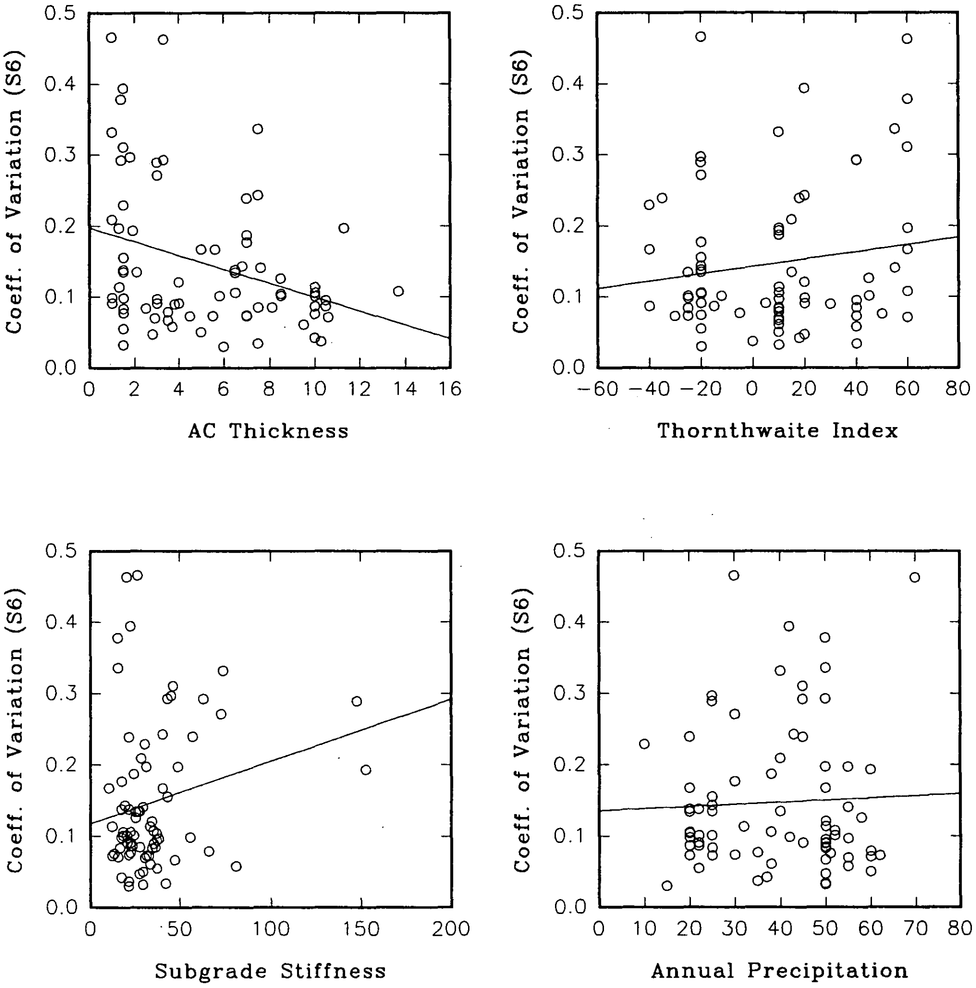

FIGURE 10 Plots of coefficients of variation CV1 of deflections measured by Sensor 6 (36 in. from the center of loading) to other variables found to significantly affect the variations: *top left*, CV6 versus AC thickness; *top right*, CV6 versus Thornthwaite index; *lower left*, CV6 versus subgrade stiffness; and *lower right*, CV6 versus annual precipitation.

CONCLUSIONS

These limited preliminary studies resulted in the following conclusions:

1. The distributions of coefficients of variation in measured deflections for 132 flexible and 88 rigid pavements indicate that the majority of the test sections reflected coefficients of variation from 4 percent to 18 percent of the mean deflections. However, a number of the coefficients of variation ranged from 18 percent to over 40 percent.
2. For the limited set of four test sections, the variations in backcalculated base moduli were much higher than those for asphalt concrete layers and the subgrade.
3. The coefficients of variation for asphalt concrete appear to be approximately proportional to the variations in Sensor 1 deflections.
4. Even when the coefficients of variability appear to be relatively small, the ranges in backcalculated moduli may be expected to be relatively large.
5. Increases in moisture content, clay fraction, and plasticity index for subgrade soils appear to result in increased variability in deflection measurements.
6. Increased annual precipitation appears to reduce variability in deflection measurements.
7. Increased asphalt concrete thickness, as well as overall structure, appears to reduce variability in measured deflections.
8. Variability in measured deflections appears to increase as the air temperature during testing increases (probably caused by reduced stiffness of the asphalt concrete).
9. The presence of transverse cracking in the pavement appears to increase variability in measured deflections.
10. Increasing viscosity in HMAC appears to reduce variability in Sensor 1 deflections (increases stiffness of AC layer).
11. Increased subgrade stiffness tends to decrease variability in measured deflections.
12. On the basis of the various analyses, the variables that most significantly contribute to the magnitudes of variability are (a) pavement structure (layer thicknesses and stiffnesses and amount and plasticity of clay in subgrade), (b) air temper-

ature during testing, (c) Thornthwaite index, and (d) annual precipitation.

13. When conducting backcalculations, the best fit between calculated and measured deflections does not imply that the most accurate set of layer moduli has been selected. In fact, such a set often includes modulus values that appear to be totally illogical.

It is important to remember that variations in layer thicknesses along a highway are common and can have major effects when moduli are backcalculated using average layer thicknesses throughout a test section. If the actual structure can be determined for a set of deflections at a point, much more accurate estimates of layer moduli can be backcalculated.

Because this is a limited study based on limited data, it will be possible in the future to learn much more about causes for variability in measured deflections, and thus perhaps for the sources of variability in the pavement itself. The ultimate objective is, of course, to be able to characterize the many variabilities in pavement structure and materials that lead to distress and loss of performance.

ACKNOWLEDGMENTS

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Nick Coetzee with Dynatest Consulting, Inc., provided backcalculated moduli developed from the same data, but using Program ELMOD. This allowed comparisons of backcalculated moduli.

The correlation study and the multiple regressions were conducted using SAS, a software system for data analysis leased from the SAS Institute, Inc., SAS Circle, Box 8000, Cary, N.C. 27512-8000.

REFERENCES

1. R. Briggs, T. Scullion, and K. Maser. Asphalt Thickness on Texas SHRP Sections and Effect on Backcalculated Moduli. Presented at a Symposium on Nondestructive Deflection Testing and Backcalculation for Pavements, Nashville, Tenn. Aug. 1991.