Estimation of Paving Materials Design Moduli from Falling Weight Deflectometer Measurements

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The emergence of mechanistic pavement thickness design procedures or semiempirical design procedures, as contained in the 1986 *AASHTO Guide for Design of Pavement Structures*, has created a need for methods of evaluating elastic moduli of paving materials and subgrade soils. A study was conducted to develop methods for using falling weight deflectometer (FWD) measurements to determine moduli of in situ pavement materials and to compare FWD-estimated moduli with laboratory-measured values in order to achieve consistent input to thickness design procedures. A three-layer pavement model was used to characterize typical Alabama flexible pavements. Simple procedures were developed to account for seasonal variations and to estimate average or effective moduli values for granular base-subbase and subgrade soils from limited FWD measurements. A procedure for adjusting asphalt-aggregate moduli to standard design temperature (70°F) was developed. Laboratory moduli for asphalt-aggregate mixtures measured with indirect tension tests (ASTM D4123) produce moduli that compare well with moduli backcalculated from FWD pavement deflection basin measurements. As expected, characterization of granular base-subbase was most difficult. There were large differences between FWD moduli and laboratory moduli from triaxial testing (AASHTO T274). Although some inconsistencies in input to thickness design procedures may result, FWD moduli are recommended for characterizing in situ granular base-subbase. In general, good agreement was demonstrated between FWD and laboratory (AASHTO T274) moduli for subgrade soils.

The emergence of mechanistic or semiempirical design procedures, as contained in the 1986 *AASHTO Guide for Design of Pavement Structures* (*1*), has created a need for methods of evaluating elastic moduli of paving materials. In addition, the emphasis on pavement rehabilitation and maintenance activities has increased the need for in situ evaluation. After years of utilization and evaluation of in situ testing devices, beginning with the static Benkelman beam and progressing through various vibratory loading devices, the falling weight deflectometer (FWD) has gained widespread acceptance.

The Alabama Highway Department, preparing for implementation of the 1986 *AASHTO Guide* and utilization of the FWD, funded a study of methods for evaluating elastic moduli of paving materials. Portions of that study are described, with emphasis on methodology for selection of moduli values for use in thickness design procedures. The study was limited to flexible (asphalt-aggregate surfaced) pavements with granular or asphalt base courses and granular subbase courses. No pavements with lime- or cement-treated base, subbase, or subgrade were considered.

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The moduli of paving materials backcalculated from FWD load–deflection basin measurements reflect pavement conditions at the time of measurement and stress conditions induced by the applied load. The moduli values must be modified to average or design conditions for use in pavement thickness design procedures. Some backcalculation programs can modify moduli on the basis of preset criteria. For example, ELMOD (*2*) can adjust asphalt-aggregate modulus for temperature and granular base and subgrade for seasonal variations.

For asphalt-aggregate mixtures, temperature dramatically affects modulus, and most design procedures require adjustment to a standard design temperature (usually around 70°F). The procedure considered for temperature adjustment follows that suggested in the 1986 *AASHTO Guide*. Rate of loading also influences asphalt-aggregate modulus. The procedure considered for adjusting FWD moduli to values for comparable laboratory testing load rates follows that suggested by Lee et al. (*3*).

Granular base-subbase is the most difficult paving material to characterize. The modulus is sensitive to the state of stress, and there may be seasonal variations. In Alabama, where there is no significant frost action, seasonal variations are caused primarily by moisture content variations. Procedures for estimating average moduli were considered. Comparisons were made with typical granular material constants (k_1 and k_2) contained in the 1986 *AASHTO Guide* for dry, damp, and wet conditions and with values presented by other researchers.

Subgrade moduli must be adjusted for seasonal variations. As with granular base-subbase, this variation is due primarily to moisture. The magnitude of the expected variation does not appear to warrant application of a procedure as complex as the one recommended in the 1986 *AASHTO Guide* for computing an effective roadbed soil resilient modulus. Because there is no significant frost action in Alabama, the relative damage factors are rather uniform, and the use of average moduli for design is considered adequate.

The sensitivity of moduli of all materials (asphalt-aggregate mixtures, granular base-subbase, and subgrade) to stress levels was considered. The magnitude of the FWD load was varied, and backcalculated moduli were compared.

STUDY PLAN

To develop procedures for estimating design moduli of paving materials from FWD measurements, a program of sampling and testing was conducted. Eight seasonal sites, Locations 1 through 8 in Figure 1, were selected. Beginning in fall 1985, FWD data were collected at approximately 2-month intervals for a period of about 3 years. In addition, four sites on the Interstate system, Locations A through D in Figure 1, were selected for limited testing.

Site Selection

Sites were selected to include as many variables as possible. The test sites were distributed geographically from north to south to cover the limited climatic variability within the state. They were located in three geologic regions: Appalachian Plateau, piedmont, and coastal plains. To ensure a range in pavement structure, sites were selected on the Interstate, primary, and secondary road systems. Pavement structures are described in Table 1.

FWD Testing

Deflection basins were measured with a Dynatest 8000 FWD by the Bureau of Materials and Tests of the Alabama Highway Department. Dynamic loads of 9, 12, and 15 kips were applied. Asphalt-aggregate temperature was measured periodically during FWD testing. All FWD testing was conducted in outside lanes.

At each seasonal site there were 10 test points spaced approximately 200 ft apart. Interstate sites consisted of 2.4- to 5-mi-long sections with test points spaced at approximately 400 ft.

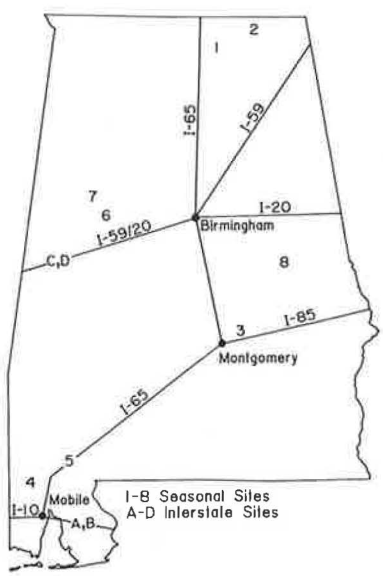

FIGURE 1 Locations of test sites.

TABLE 1 PAVEMENT STRUCTURES AT TEST SITES

Site	Structure	Model
	Seasonal Sites	
1	5.5" asphalt -aggregate 10" crushed aggregate base 14" select soil	t_1 = 5.5" t_2 = 24"
2	4" asphalt -aggregate 3" sand gravel base 12" select soil	t_1 = 4" t_2 = 15"
3	9" asphalt -aggregate 6" soil aggregate base 12" select soil	t_1 = 9" t_2 = 12"
4	3.5" asphalt -aggregate 8" granular soil base 12" select soil	t_1 = 3.5" t_2 = 20"
5	10" asphalt -aggregate 5" roadmix reef shell base 12" select soil subbase 12" improved roadbed	t_1 = 10" t_2 = 24"
6	4.8" asphalt -aggregate 4" soil aggregate base 6" soil aggregate subbase	t_1 = 4.8" t_2 = 10"
7	3.2" asphalt -aggregate 10" soil aggregate base and subbase 12" improved roadbed	t_1 = 3.2" t_2 = 22"
8	4.5" asphalt -aggregate 8" soil aggregate base	t_1 = 4.5" t_2 = 8"
	Interstate Sites	
A & B	7.6" asphalt -aggregate 5" soil aggregate (shell) base 6" select soil subbase 12" improved roadbed	t_1 = 7.6" t_2 = 23"
C	9.3" asphalt -aggregate 5" soil aggregate base 6" select soil subbase 12" improved roadbed	t_1 = 9.3" t_2 = 11"
D	8.8" asphalt -aggregate 5" soil aggregate base 12" select soil subbase 12" improved subgrade	t_1 = 8.8" t_2 = 17"

Improved roadbed included in pavement structure where indicated from available as constructed information, or where sampling indicated dramatic differences (density and/or water content) between top 12 inches and remainder of subgrade.

Backcalculation of Moduli

Moduli were backcalculated with the program ELMOD (*2*). The rigid subgrade boundary option of ELMOD, in which the depth to a rigid boundary is computed on the basis of an analysis of the outer deflections, was used.

Typical pavement structures consisted of asphalt-aggregate surface, granular base, granular subbase, and, usually, a processed subgrade layer. Within layers there were often additional layers creating a more complex layered system. For estimation of moduli from FWD data, such a complex system is neither practical (because of computation time required) nor necessary (in terms of characterization). Simplified models are normally used, but no generally accepted recommendations for the number of layers required to adequately model flexible pavements were found in a literature review. In the literature three layers were most often used, and four were used occasionally. When four were used, the moduli for the third and fourth (subgrade) layers were often quite close. Bush and Alexander (*4*) indicate that best results are obtained when not more than three layers with unknown moduli are used. Husain and George (*5*) recommend that pavements with four or more layers be reduced to three-layer models.

For this study pavement structures were modeled with three layers, not including the rigid boundary placed by the ELMOD program. Thicknesses for Layers 1 and 2 are given in Table 1.

Asphalt-aggregate layers included several different types of asphalt concrete, but some also included tack, flush, or seal coats, as well as chip seals. All asphalt-aggregate layers, including asphalt base course, were combined into Layer 1 of the model.

Base and subbase layers were composed of granular unbound soil-aggregate materials. They were combined into Layer 2 of the model.

Determining where to place the processed subgrade (upper portion of subgrade) in the model presents the most problems. Select material, with possibly stabilizing additives, is included in this layer to improve or modify its properties. The decision is whether the processed subgrade should be included in Layer 2 because it is more like the base-subbase or in Layer 3 because it is more like the subgrade. The location of the processed subgrade layer was based on in situ density and moisture content measurements, which in this study usually resulted in inclusion in Layer 2. A sensitivity analysis indicated that inclusion of the processed subgrade in Layer 2 or 3 of the model had little effect on E_1, some effect on E_3, and significant effect on E_2.

Sampling and Laboratory Testing

Cores of asphalt-aggregate layers and disturbed samples of unbound granular base-subbase layers and subgrade soils were obtained at six of the eight seasonal sites and the four Interstate sites. The asphalt-aggregate cores were sawed along layer interfaces, where possible, to produce specimens for indirect tension testing. The specimens were tested at 41°F, 77°F, and 104°F, in accordance with ASTM D4123. A weighted composite modulus was computed for the entire asphalt-aggregate layer from the moduli of individual layers.

Specimens (8 × 4 in.) for triaxial testing were recompacted from disturbed samples of base-subbase and subgrade soils. Specimens were compacted with a kneading compactor in accordance with AASHTO T190 to densities and moisture contents approximating those measured in situ. The recompacted specimens were tested for resilient modulus in accordance with AASHTO T274.

ANALYSIS OF TEST RESULTS

Data from the FWD and laboratory testing were analyzed to develop procedures for selecting design modulus. The effects of temperature and load rate on asphalt-aggregate modulus, the effects of seasonal variations on unbound granular base-subbase and subgrade modulus, and the effects of load or stress intensity on the modulus of all materials were examined.

Asphalt-Aggregate Modulus

To study the effects of temperature, plots were made of asphalt-aggregate moduli backcalculated from FWD measurements versus temperature. Figure 2 shows a plot for Site 1 with data for all three FWD load levels. Linear and power curves were fitted to the data using least squares criteria. The power curves more accurately modeled the variation in asphalt-aggregate moduli with temperature and were similar to relationships suggested by Lee et al. (*3*) and Witczak (*6*).

The data for all eight seasonal sites were combined and the following composite power curve was developed:

$$E_1 = 322{,}000/T^{1.591} \quad (1)$$

The composite curve is shown in Figure 3 with curves for the individual sites and in Figure 4 with relationships suggested by Lee et al. (*3*) and Witczak (*6*).

The wide range of moduli exhibited in Figure 3 reflects the wide range of asphalt-aggregate materials encountered. The asphalt-aggregate layer at Site 5 is composed of 10 in. of high-quality surface, binder, and base course hot mix, whereas Site 2 is composed of road mix, seal coats, and lower-quality hot mix. Comparison of the composite curve with the curves suggested by Lee et al. (*3*) and Witczak (*6*) indicates that, on the average, the asphalt-aggregate mixtures were less sensitive to temperature. At 70°F the composite curve also agrees with the curve suggested by Witczak (*6*).

To provide a way to adjust asphalt-aggregate modulus backcalculated with FWD data to standard design temperature,

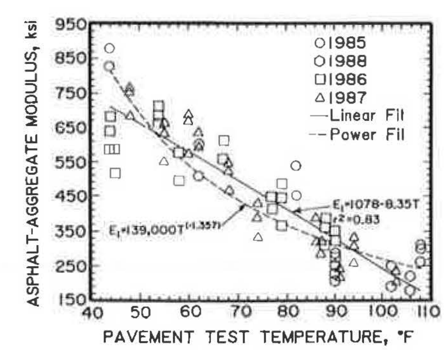

FIGURE 2 Asphalt-aggregate modulus versus temperature, Site 1.

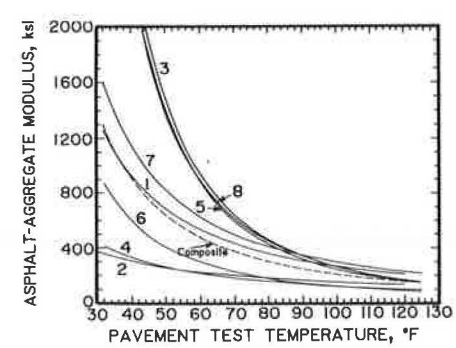

FIGURE 3 Composite and individual curves for eight seasonal sites.

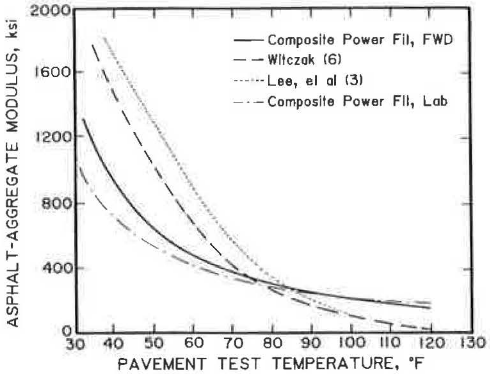

FIGURE 4 Relationships between asphalt-aggregate modulus and temperature.

the moduli-temperature relationships in Figure 3 were used. Moduli were computed using Equation 1 for various temperatures, and the ratios of those moduli to the moduli at 70°F were computed as

$$F_a = E_{1(70)}/E_{1(T)} \quad (2)$$

These ratios were used to develop the curve shown in Figure 5. Also shown in Figure 5 are the correction curve provided in the 1986 *AASHTO Guide* and modular ratios for the eight individual seasonal sites at 40°F and 100°F. Although there will be some inaccuracies for particular sites, the composite correction curve provides criteria for adjusting asphalt-aggregate moduli measured at temperatures between 30°F and 120°F to 70°F design temperature.

Figure 6 shows the variable influence of FWD load magnitude. At Site 1, modulus increased as FWD load increased. This trend was also observed at Sites 2, 4, 6, and 7. At Site 3, FWD load had virtually no effect on asphalt-aggregate

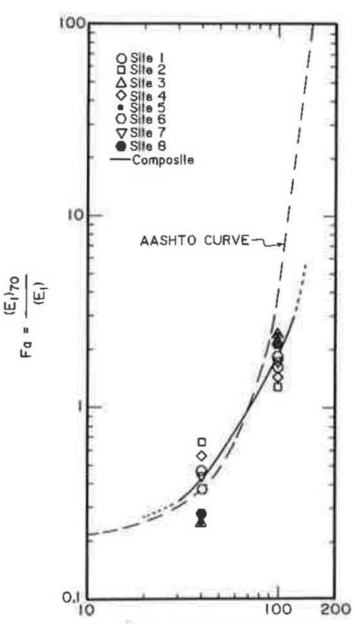

FIGURE 5 Asphalt-aggregate modulus temperature adjustment factor.

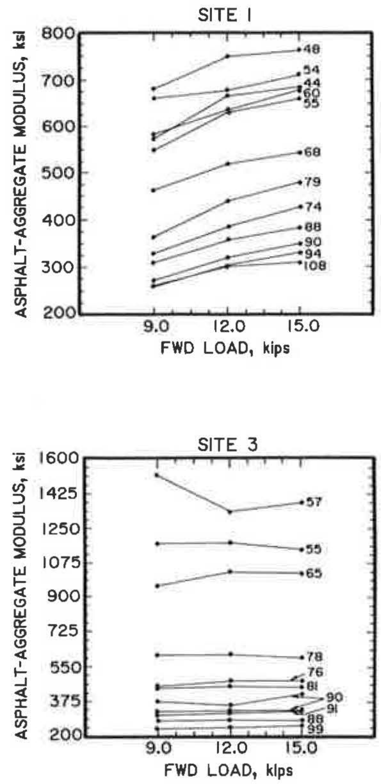

FIGURE 6 Effects of FWD load level on asphalt-aggregate modulus.

modulus. This trend was also observed at Sites 5 and 8. The reasons for the observed differences in response are not clear but are probably due to the stiffness of the asphalt-aggregate layers in relation to that of the overall pavement structure. As indicated in Figure 3, the asphalt-aggregate moduli at Sites 3, 5, and 8 are higher (at temperatures below about 80°F) than at the other seasonal sites. The asphalt-aggregate layers at Sites 3 and 5 are also the thickest.

The implication is that the overall state of stress induced in the asphalt-aggregate layer influences the modulus. However, the nature of the influence is unclear, and laboratory testing provided no clarification. Indirect tension testing was conducted on samples from six of the eight seasonal sites and the four Interstate sites. Three levels of indirect tension stress were applied, ranging from 5 to 30 percent of the indirect tensile strength at 77°F. Modulus increased for six of the sites and decreased for four sites as the stress intensity increased. There was no correlation between field and laboratory trends, although, as shown in Figure 4, there is good agreement between the composite FWD curve and a similar composite curve developed from laboratory data.

After considering plots similar to Figure 6 for all sites and the laboratory data, it was concluded that the stress (load) sensitivity would not be sufficient to alter the relationship between the average moduli at the various sites, as shown in Figure 3. However, load level apparently influences estimated asphalt concrete modulus and, therefore, justifies testing at multiple levels and using average values. Selection of loads for testing should be based on the anticipated operation of critical vehicles (trucks). A 9-kip FWD load may be representative of standard 18-kip axle loads, but larger loads should be considered to account for heavier trucks. For low-volume roads, FWD loads smaller than 9 kips might also be considered.

A correction for differences in the rate of loading was necessary to compare laboratory moduli with FWD moduli. The FWD rate of loading is faster than the laboratory rate and, therefore, FWD moduli will be inherently larger than laboratory moduli. The following adjustment factor suggested by Lee et al. (3) was used:

$$R = 0.791 + 0.00813T \quad (3)$$

where R is the ratio of FWD modulus to laboratory-determined resilient modulus and T is the temperature (°F). FWD and laboratory moduli at 77°F, the midrange temperature for laboratory testing, are shown in Table 2. As indicated by the means and standard deviations of the unadjusted and adjusted modular ratios, the adjustment for load rate improves the mean ratio from 1.36 to 0.96 and the standard deviation from 0.63 to 0.44.

Unbound Granular Base-Subbase Modulus

Figure 7 is a typical plot showing seasonal variations in base-subbase modulus. Average monthly temperature and rainfall, as percentages of maximum average monthly temperature and rainfall, are also shown. The correlation between base-subbase modulus and temperature and rainfall shown in Figure 7 was generally observed at all sites. Heavy rainfall provides a source of water and low temperatures prevent rapid evaporation, which results in low values in winter and spring and high values in summer and fall.

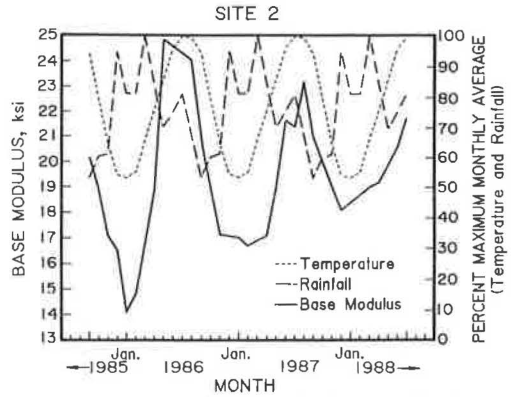

FIGURE 7 Typical variation in base moduli with temperature and rainfall.

To develop factors for adjusting base-subbase modulus for seasonal variations, average monthly moduli values and their ratios to the maximum monthly values were computed. Plots of these ratios, as shown in Figure 8a, were made for each site. Two groups (winter/spring and summer/fall) were apparent from the plots. The beginning and ending months for both groups varied from site to site, but an analysis of average ratios indicated that the most consistent were January to June and July to December. Yearly average ratios and average ratios by group are given in Table 3.

Ratios of minimum to maximum modulus (E_{min}/E_{max}) are another indicator of seasonal variability. They are shown in Table 3 and range from 0.58 to 0.85. These ratios and the average monthly to maximum moduli ratios do not indicate dramatic seasonal variations.

TABLE 2 COMPARISON OF LABORATORY AND FWD MODULI FOR ASPHALT-AGGREGATE AT 77°F

Site	FWD Moduli, E (ksi)	Unadjusted Laboratory Moduli M_R (ksi)	Laboratory Moduli, M_R, Adjusted for Load Duration (ksi)	Unadjusted E/M_R[1]	Adjusted E/M_R[2]
1	380	397	563	0.96	0.67
3	500	329	466	1.52	1.07
5	470	336	476	1.40	0.99
6	190	181	256	1.05	0.74
7	440	162	230	2.72	1.91
8	490	319	452	1.54	1.08
A	530	257	364	2.06	1.46
B	600	481	682	1.25	0.88
C	160	321	455	0.50	0.35
D	230	380	538	0.61	0.43

[1] E/M_R Mean = 1.36
Std Deviation = 0.63

[2] E/M_R Mean = 0.96
Std Deviation = 0.44

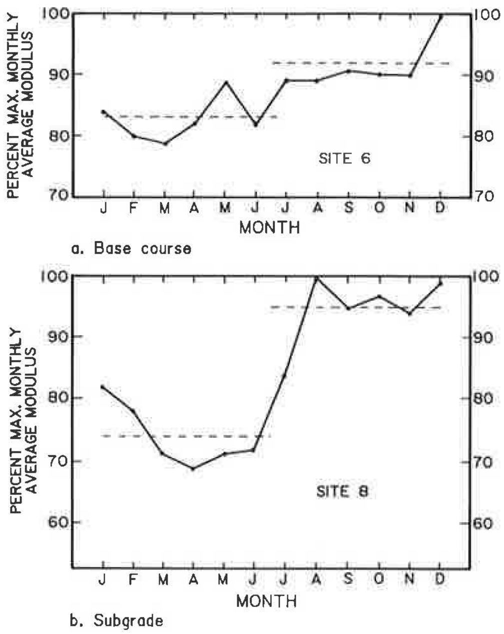

FIGURE 8 Typical variations in base and subgrade modulus.

The analysis of yearly modulus variability indicated that characterization with average values would be adequate for design and suggested a simple procedure for converting moduli backcalculated from particular FWD measurements to average values. The average of the modular ratios in Table 3 was 0.82 for January to December, 0.78 for January to June, and 0.86 for July to December. Correction factors were obtained by dividing the yearly average ratio by the average ratio for each group. To convert to average conditions, moduli backcalculated from FWD measurements made during January through June should be multiplied by 0.82/0.78 = 1.05, and those backcalculated from measurements made during July through December should be multiplied by 0.82/0.86 = 0.95.

Figures 9a, 9b, and 9c show the effects of FWD load on base-subbase modulus for Sites 5, 4, and 1, respectively. Load magnitude had essentially no effect for Sites 5 and 6 (see Figure 9a). Moduli increased with increasing load for Sites 3, 4, and 7 (see Figure 9b). Differences between 9- and 15-kip loads were 2 to 3 ksi (less than 10 percent) for Sites 4 and 7. Differences were 8 to 12 ksi (10 to 15 percent) for Site 3. Moduli decreased with increasing load for Sites 1, 2, and 8 (see Figure 9c). The effect of load magnitude was somewhat erratic for Site 1, and the differences between 9- and 15-kip loads were 4 to 8 ksi (about 10 percent). The differences were more uniform, only 2 to 4 ksi (less than 10 percent), for Sites 2 and 8.

As shown in Figure 9, load effects are smaller than seasonal effects and are not a major consideration. However, as with asphalt-aggregate, the variation that may occur at individual sites justifies testing at representative multiple FWD load levels and averaging the results.

To compare laboratory and FWD moduli, the effects of the state of stress must be considered. Using material coefficients (k_1 and k_2) in Table 4 and first stress invariant at midlayer for a 15-kip FWD load, base course laboratory moduli were calculated with the familiar equation

$$M_{R(BS)} = k_1\Theta^{k_2} \quad (4)$$

where Θ is the first stress invariant, $\sigma_1 + 2\sigma_3$ for triaxial test.

Moduli calculated with Equation 4 are compared with average FWD moduli in Table 5. The modular ratios in the last column of Table 5 range from 0.80 to 8.57 and indicate good to poor correlation between FWD and laboratory moduli. The mean value of the ratios is 3.03, which indicates that FWD moduli are consistently higher than laboratory moduli. The standard deviation is 1.99, which indicates considerable variability.

There are several possible causes of the poor correlation between FWD and laboratory moduli. Laboratory moduli were measured on specimens recompacted to densities and moisture contents as close as possible to those measured in the field. Field sampling operations, which involved wet sawing through asphalt-aggregate layers, may have increased water contents above actual in situ values. Disturbance during sampling surely destroyed any cementation or thixotropic strengthening that may have existed. Removal of 0.75-in. particles for 4-in. diameter laboratory specimen preparation would also have caused decreased moduli.

Finally, the characterization of the state of stress in the unbound granular base-subbase layers may not have been adequate. The first stress invariant (Θ) was calculated at midlayer directly beneath the center of the FWD load with an elastic layered model (ELSYMS5). It did not include the influence of overburden confinement or, probably more important, the influence of horizontal residual confining stresses developed during compaction and traffic application. The use of this single value for computing modulus from laboratory equations may not have been adequate and probably contributed to the poor correlations. This explanation is more appealing when values of material coefficients (k_1 and k_2) are compared with typical values recommended in the 1986 *AASHTO Guide*. The typical range for k_1 is 4 to 6 ksi and for k_2 is 0.5 to 0.7 for damp base course. The mean value for k_1 is 6.1 ksi (standard deviation = 3.3) and for k_2 is 0.43 (standard deviation = 0.14) for the data in Table 4. The mean values are on the high end of the typical range for k_1 and are low for k_2. The typical range for k_2 is 4 to 6 ksi and for k_2 is 0.4 to 0.6 for damp subbase course. The mean value for k_1 is 8.3 ksi (standard deviation = 3.1) and for k_2 is 0.38 (standard deviation = 0.18) for the data in Table 4. Again the mean values are higher than the typical range for k_1 and on the low end for k_2. However, natural soil aggregate type materials widely used in Alabama tend to have high cohesion (indicating high k_1) and low friction (indicating low k_2).

A second comparison strengthens the contention that the poor correlation between FWD and laboratory moduli is the result of the representation of the state of stress with a single value (Θ). Values of k_1 and k_2 and their relationship are compared with results reported by Rada and Witczak (*7*) in Figure 10. Rada and Witczak's results were for 271 granular materials and compare reasonably well with the 18 materials tested in this study.

TABLE 3 BASE-SUBBASE DATA FROM SEASONAL SITES

Site	Material Classification: Unified	Material Classification: AASHTO	Description	Avg. E	Avg. E/Emax: J-D	Avg. E/Emax: J-J	Avg. E/Emax: J-D	E_{min}/E_{max}
1	GW	A-1-a	10" Crushed Agg Base (w = 3%)	58 ksi	0.93	0.90	0.96	0.85
	SP-SC	A-2-6	14" Select Soil (w = 22%)					
2	–	–	3" Sand Gravel Base	20 ksi	0.82	0.79	0.85	0.68
	SW-SM	A-1-b	12" Select Soil (w = 21%)					
3	SP	A-1-b	6" Soil Aggregate Base (w = 9%)	80 ksi	0.76	0.77	0.76	0.70
4	–	–	8" Granular Soil Base	27 ksi	0.82	0.76	0.87	0.67
5	SP	A-3	5" Sandy Shell Base (w = 7%)	34 ksi	0.74	0.72	0.76	0.63
	SP	A-3	12" Select Soil (Sand Clay) Subbase (w = 11%)					
6	SP	A-1-a	4" Sandy Gravel Base (w = 6%)	31 ksi	0.87	0.83	0.92	0.80
	SP	A-1-b	6" Clayey Sand Subbase (w = 8%)					
7	GP	A-1-a	4" Soil Aggregate Base (w = 3%)	32 ksi	0.86	0.81	0.90	0.73
	SP	A-1-b	6" Soil Aggregate Subbase (w = 4%)					
8	SP-SC	A-2-4	8" Soil Aggregate Base (w = 11%)	60 ksi	0.77	0.65	0.90	0.58

1. Moisture contents as sampled.
2. Average modulus and modular ratio for 3 year period. Ten (10) locations, spaced at approximately 200', tested at approximately 2 month intervals.

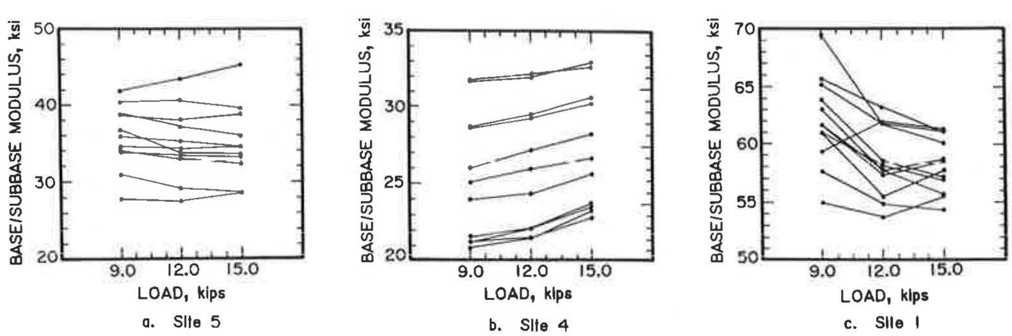

FIGURE 9 Effects of FWD load level on base-subbase modulus.

TABLE 4 MATERIAL COEFFICIENTS (k_1 AND k_2) FOR UNBOUND GRANULAR BASE-SUBBASE FROM TRIAXIAL TESTING

Site	Layer	k_1	k_2
1	Base	11.9	0.21
	Subbase	11.6	0.14
3	Base	3.0	0.58
5	Base	2.1	0.71
	Subbase	5.7	0.27
6	Base	6.7	0.29
	Subbase	4.5	0.46
7	Base	5.6	0.37
	Subbase	4.1	0.62
8	Base	1.0	0.57
A	Base	10.2	0.39
	Subbase	9.3	0.27
B	Base	6.4	0.47
	Subbase	3.7	0.55
C	Base	6.1	0.37
	Subbase	25.5	0.12
D	Base	8.0	0.33
	Subbase	2.3	0.64

Base: Average k_1 = 6.1 ksi, Average k_2 = 0.43
Subbase: Average k_1 = 8.3 ksi, Average k_2 = 0.38
Omitting Site C Average k_1 = 5.9 ksi, Average k_2 = 0.42

Subgrade Modulus

Plots similar to Figure 7 were made for subgrade modulus. The same trends were exhibited—low modulus in winter and spring, when rainfall is high and temperature low, and high modulus in summer and fall, when rainfall is low and temperature high. Plots of modular ratios (Figure 8b) were made for each site. The plots indicated that consistent groupings were January to June and July to December. Yearly average ratios and average ratios by group are given in Table 6.

Ratios of minimum to maximum (E_{min}/E_{max}) are also shown in Table 6. They range from 0.70 to 0.84. The ratios do not indicate dramatic seasonal moduli variations.

The analysis indicated that characterization with average values would be adequate for design. Moduli measured during January through June were to be multiplied by a correction factor of 1.06, and those measured during July through December were to be multiplied by 0.96.

An example will demonstrate that yearly average subgrade modulus is close to effective roadbed soil resilient modulus computed with the procedure recommended in the 1986 *AASHTO Guide*. The calculations are summarized in Table 7 for Site 8, which had the smallest E_{min}/E_{max} ratio. The average subgrade modulus is 17.9 ksi. The relative damage factors shown in Table 7 were computed using methods outlined in the 1986 *AASHTO Guide*. Using the average relative damage factor of 0.018, an effective roadbed soil resilient modulus

TABLE 5 COMPARISON OF FWD AND LABORATORY MODULUS FOR UNBOUND GRANULAR BASE-SUBBASE

Site	Layer	FWD Modulus, E (ksi)	Lab. Modulus, M_R (ksi)	E/M_R
1	Base	58	24	2.42
	Subbase	58	18	3.22
	Subgrade	27	16	1.68
3	Base	80	15	5.33
	Subgrade	19	12	1.58
5	Base	34	10	3.40
	Subbase	34	10	3.40
	Subgrade	13	10	1.30
6	Base	31	18	1.72
	Subbase	31	22	1.41
	Subgrade	9	6	1.50
7	Base	32	22	1.45
	Subbase	32	40	0.80
	Subgrade	15	11	1.36
8	Base	60	7	8.57
	Subgrade	18	7	2.57
A	Base	25	29	0.86
	Subbase	25	19	1.32
	Subgrade	10	16	0.62
B	Base	45	17	2.65
	Subbase	45	12	3.75
	Subgrade	18	10	1.80
C	Base	50	17	2.94
	Subbase	50	34	1.47
	Subgrade	15	13	1.15
D	Base	45	15	3.00
	Subbase	45	7	6.43
	Subgrade	15	21	0.71

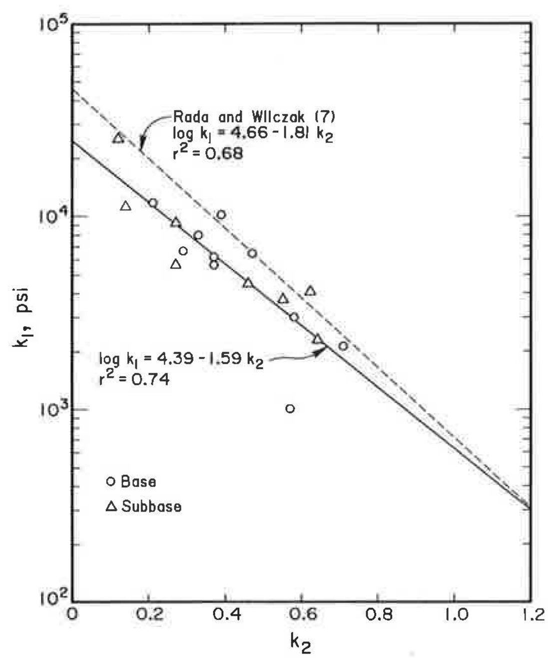

FIGURE 10 Comparison of material coefficients.

TABLE 6 SUBGRADE DATA FROM SEASONAL SITES

	Material Classification				Avg. E/Emax			
Site	Unified	AASHTO	Description	Avg. E	J - D	J - J	J - D	E_{min}/E_{max}
1	SC	A-2-6	Brown Silty Clay (w = 20%)	27 ksi	0.92	0.87	0.96	0.80
2	SC	A-2-6	Reddish Black Clay (w = 22-25%)	7.5 ksi	0.84	0.80	0.87	0.72
3	SP	A-2-6	Clayey Sand (w = 5%)	19 ksi	0.87	0.84	0.90	0.78
4	-	-	Red Sandy Clay	9.5 ksi	0.91	0.86	0.96	0.84
5	SP-SM	A-3	Red Clayey Sand (w = 13%)	13 ksi	0.85	0.83	0.86	0.72
6	SP	A-3	Tan Sandy Clay (w = 15%)	9 ksi	0.92	0.87	0.96	0.82
7	SP	A-3	Red Sandy Clay (w = 9%)	15 ksi	0.88	0.83	0.93	0.73
8	SW-SM	A-1-b	Red Sandy Clay (w = 14%)	18 ksi	0.84	0.74	0.95	0.70

1. Moisture contents as sampled.
2. Average modulus and modular ratio for 3 year period. Ten (10) locations, spaced at approximately 200', tested at approximately 2 month intervals.

TABLE 7 EXAMPLE CALCULATION OF EFFECTIVE ROADBED SOIL RESILIENT MODULUS

Month	Average Modulus, ksi	Relative Damage Factor (u_f)
J	17.4	0.017
F	16.6	0.020
M	15.1	0.024
A	14.7	0.027
M	15.0	0.024
J	15.3	0.023
J	17.8	0.016
A	21.1	0.012
S	20.1	0.012
O	20.5	0.012
N	19.9	0.012
D	20.9	0.012
Average	17.9	0.018

of 17.3 ksi is computed, which is only 3.5 percent smaller than the average subgrade modulus.

Figure 11 shows three effects of FWD load magnitude on subgrade modulus. For Sites 1 and 5, FWD load had essentially no effect on moduli (Figure 11a). For Sites 3, 4, and 7, moduli increased with load (Figure 11b). Moduli differences between loads of 9 and 15 kips ranged from 1 to 2 ksi for Sites 4 and 7 to 2 to 4 ksi for Site 3. These represent differences of 10 to 20 percent. For Sites 2, 6, and 8, moduli decreased with load (Figure 11c). Moduli differences ranged from 0 to 1 ksi for Sites 2 and 6 to 2 to 3 ksi for Site 8. Again, these represent differences of 10 to 20 percent.

As with base-subbase modulus, load magnitude does not appear to be an important consideration for subgrade modulus. However, the percentage differences that occur over a load range of 9 to 15 kips justify testing at representative multiple loads and using average values. For the subgrade, simulation of heavier vehicles with loads that may be applied over a large area is critical. Large FWD loads may be required to obtain similar stresses in the subgrade.

To compare laboratory and FWD moduli, the effects of the state of stress (confinement of triaxial specimens) must be considered. The first stress invariant (Θ) and the deviator stress (σ_d) were calculated at the top of the subgrade beneath the center of a 15-kip FWD load. These parameters were used in either Equation 4 or the equation below, as appropriate, to compute subgrade modulus.

$$M_{R(SG)} = k_3(\sigma_d)^{k_4} \quad (5)$$

The moduli thus computed, as well as modular ratios, are given in Table 5. Modular ratios ranged from 0.62 to 2.57 with a mean value of 1.42 and a standard deviation of 0.53. FWD moduli were consistently higher than laboratory moduli, although much less than base-subbase. As with unbound granular base-subbase, disturbance of cementation bonds or thixotropic strengthening may have been a cause of the observed differences. However, the use of one parameter at a single location in the subgrade to represent the state of stress probably contributes more to the observed differences.

CONCLUSIONS

Reasonable estimates of pavement material and subgrade soil moduli may be backcalculated by using pavement surface deflection basins obtained with an FWD. Deflection basins should

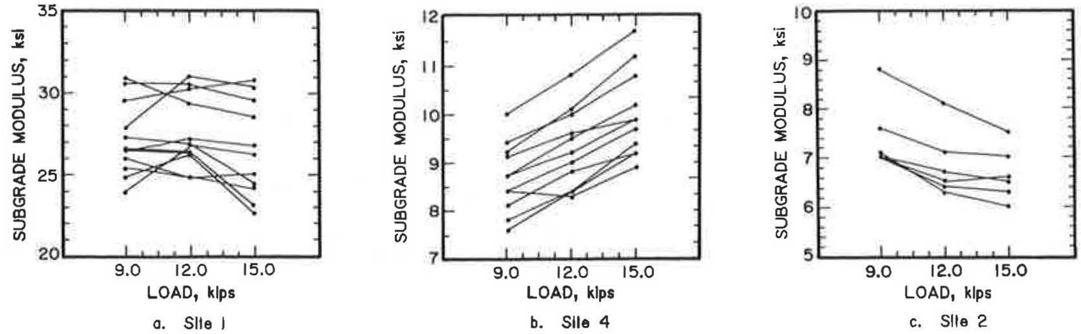

FIGURE 11 Effects of FWD load level on subgrade modulus.

be measured at multiple loads representative of anticipated truck traffic. The average temperature at middepth of asphalt-aggregate surface layers should be obtained during FWD testing. A limited number of small test pits should be excavated to determine layer thicknesses as well as moisture content and density data for modeling base and subgrade layers.

A three-layer pavement structure model was relatively simple, efficient, and provided reasonable moduli estimates. Base, subbase, and, where density and moisture content measurements indicate they are applicable, improved roadbed layers should be included in Layer 2. Subgrade and, where density and moisture content measurements indicate they are applicable, improved roadbed layers should be included in Layer 3. A stiff boundary layer should be used to limit subgrade depth.

To adjust the asphalt-aggregate modulus backcalculated from FWD data to a standard design temperature, a modified version of a curve recommended in the 1986 *AASHTO Guide* was developed. Load rate should also be considered in selecting asphalt-aggregate design modulus. Seasonal variations have only a limited influence on base-subbase and subgrade moduli. A simplified procedure was developed to convert values backcalculated from FWD measurements to average conditions.

Laboratory moduli for asphalt-aggregate measured with indirect tension tests (ASTM D4123) compared well with FWD moduli. As expected, characterization of unbound granular base-subbase was most difficult, and FWD and laboratory values correlated poorly. In general, fair agreement was demonstrated between FWD and laboratory (AASHTO T274) moduli of subgrade soils.

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