Pavement Response to Road Rater and Axle Loadings

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ABSTRACT

The response of flexible pavements to 18-kip (80-kN) single axle and Road Rater loadings was investigated. A Benkelman beam was used to measure surface deflection under the axle loading; and a model 400 Road Rater was operated at 25-Hz frequency to monitor pavement deflection. The pavement deflection data were analyzed and the pavement layer moduli were evaluated. The modulus values, in turn, were used to analyze the critical response of the test pavements. Results of the study indicate that, at least for the conditions investigated, summer deflection measurements are as effective as spring season measurements for pavement condition evaluation. The layer modulus values evaluated from the Road Rater deflection basins are not necessarily equal to those obtained from the Benkelman beam deflection basins. Critical pavement response to axle loading can be estimated from the corresponding Road Rater data by using the developed relationships. These relationships and other data may provide a basis for the development of a generally accepted pavement evaluation criterion for use in pavement management programs.

Numerous devices are frequently used to evaluate the structural capacity and to predict the future performance of flexible pavements; these include Benkelman beam, Road Rater, Dynaflect, and falling weight deflectometer, among others. The Benkelman beam was available long before the other devices. Since its development, the Benkelman beam has been widely adopted for pavement evaluation. As a result, a wealth of Benkelman beam deflection data and various evaluation criteria have been developed (1-4). Other devices have also received considerable study, and different deflection criteria for evaluation of pavement performance have been proposed (5-8).

Although various evaluation criteria already exist, a generally accepted one has not yet been available. Primary reasons for this may be that (a) each study was conducted under its specific environmental and pavement conditions and (b) the test loading conditions varied considerably among these studies. In considering loading condition, it should be noted that these various testing devices employ different types of loading for testing. The Benkelman beam uses the actual axle loading, whereas the other devices use loadings that differ considerably among themselves and are smaller than the axle loading.

In the development of a generally accepted evaluation criterion, it is essential to have a fundamental understanding not only of the behavior of pavement response to each type of loading but also of the relationship among the pavement responses to the various loadings. Pavement response to one type of loading with respect to actual axle loading is of particular importance.

This study was undertaken to investigate pavement response to Road Rater and axle loadings. The deflection under axle loading was determined using a Benkelman beam. In this study, the deflection data were used to evaluate the pavement layer moduli, which, in turn, were employed to analyze critical pavement responses including the maximum tensile strain at the bottom of a stabilized base course and the maximum vertical compressive strain at the top of the subgrade. From all of these data, relationships between the Road Rater and the Benkelman beam (axle) loadings were developed for surface deflections, modulus values, and critical strains.

TEST PAVEMENTS AND MATERIALS

This study was conducted as a part of the research project undertaken at the Pennsylvania Transportation Research Facility. The research facility was constructed in 1972 and was composed of 17 test pavements. Of these pavement sections, one section (Section 8) was overlaid and three sections (Sections 10 through 12) were replaced by eight shorter sections in 1975. All pavements were 12 ft (3.7 m) wide.

The subgrade soil was a silty clay that had classifications ranging from A-4 to A-7 according to the AASHO classification and CL according to the unified soil classification. The subbase material was a crushed limestone. The base course materials were bituminous concrete, aggregate cement, aggregate-lime-pozzolan, aggregate bituminous, and crushed stone. In the aggregate-cement base course, three types of aggregate were used--limestone, slag, and gravel. The wearing surface was an ID-2A bituminous concrete.

The traffic on the research facility was provided by a conventional truck tractor pulling a semitrailer and one or two full trailers. A total of about 2.4 million and 1.3 million applications of 18-kip (80-kN) equivalent axle loads (EALs) have been applied to the pavements constructed in 1972 and 1975, respectively. More detailed information on the research facility can be found elsewhere (9).

MAXIMUM SURFACE DEFLECTION

Pavement surface deflections were measured biweekly in the wheelpaths by using a Benkelman beam and a Road Rater. Because spring season deflections are widely used for pavement evaluation, the deflection data obtained during the months of March, April, and May are selected and discussed first. It is neither possible nor necessary to present all of the spring season deflection data; thus, for the purpose of discussion, pavement sections that are more representative of each pavement group (in terms of base course material type) are selected. The pavement sections selected and their base course materials are those of Section 3 (aggregate-lime-pozzolan), Section 5 (aggregate bituminous), Section 7 [bituminous concrete, 8 in. (203 mm) thick], Section 9 [bituminous concrete, 4 in. (102 mm) thick], Section 14 (full-depth bituminous concrete), A (limestone aggregate cement), D (gravel aggregate cement), and E (crushed stone). The maximum Road Rater deflections of these sections are plotted against 18-kip (80-kN) EALs in Figure 1. Note that the Road Rater used is a model 400, which has a vibrating mass of 160 lb (72 kg) and is operated at a frequency of 25 Hz.

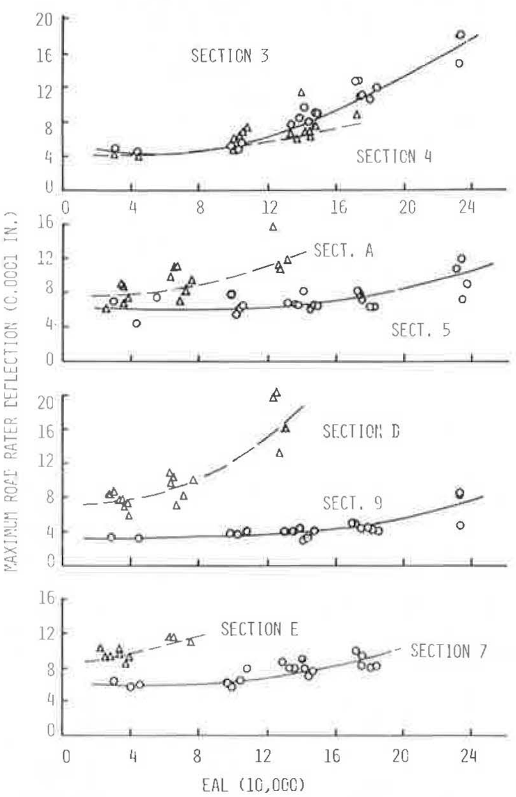

FIGURE 1 Variation of maximum Road Rater spring season deflection with equivalent axle load.

Figure 1 shows, as would be expected, that the maximum Road Rater deflections increase with increasing EAL; the rate of increase differs for different pavement sections. Also, for each pavement, the rate of increase becomes greater in the later stages of pavement service life. The increase in pavement deflection is primarily due to the progressive deterioration of the pavement structure as evidenced by the gradual decrease in the present serviceability index (PSI) of the pavement sections. The PSI data of all of the test pavements are documented in a research report (10) and are also summarized in an earlier paper (9). An attempt was made to establish relationships between the increased deflection and the dropped PSI; however, no apparent correlation between the two was found.

The maximum Benkelman beam deflections also increase with EAL in a manner similar to that of the maximum Road Rater deflections. Again, no correlation between the increase in deflection and the drop in PSI was found for Benkelman beam deflections.

The maximum Benkelman beam and Road Rater deflections are correlated in Figure 2, in which there are 137 data points for pavements with bituminous concrete base and 52 data points for other pavements.

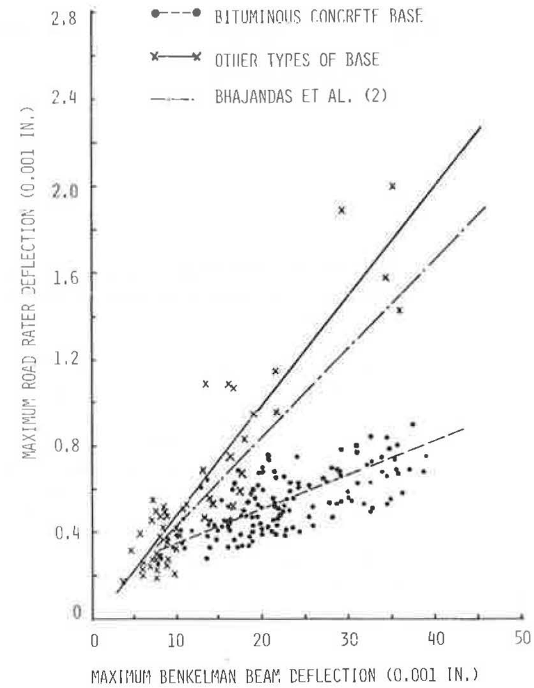

FIGURE 2 Correlations between maximum Road Rater and Benkelman beam deflections.

The correlation analysis was performed using the SAS computer program (11). Both linear and nonlinear relationships were considered in the analysis. It is interesting to note that the data points for pavements with bituminous concrete base form a distinct group and are located below the data points for other base course materials. Results of the analysis yield the following equations:

$$RRD = 0.15 + 0.018\ BBD \quad (1)$$

with $R^2 = 0.669$ and $\bar{R}^2 = 0.665$ for pavements containing bituminous concrete base courses, and

$$RRD = -0.04 + 0.051\ BBD \quad (2)$$

with $R^2 = 0.849$ and $\bar{R}^2 = 0.846$ for pavements containing other types of base course materials. In Equations 1 and 2, RRD designates Road Rater deflections and BBD stands for Benkelman beam deflections, both in units of 10^{-3} in., R^2 is the coefficient of determination, and $\bar{R}^2$ is the adjusted coefficient of determination for degree of freedom.

The trend of correlation shown in Figure 2 is quite clear. Due to the wide scatter of data points, however, the values of R^2 and $\bar{R}^2$ are low especially for the bituminous concrete pavements. The correlations indicate that when the deflection is large, the Road Rater deflection corresponding to a given Benkelman beam deflection is considerably smaller for pavements with bituminous concrete bases than for pavements with other types of base course materials. Although this could possibly be due to a viscous damping effect of the bituminous concrete under the vibratory Road Rater loading, exact causes for this effect are not clearly understood. The available correlation developed by Bhajandas et al. (5) between Road Rater deflections, which were determined at 25-Hz frequency, and Benkelman beam deflections is also included in Figure 2. Note that their correlation was developed on the basis of only 52 samples and no indication of the type of base course materials in the pavements was given. Their correlation is shown bracketed between the two developed in this study.

SURFACE DEFLECTION BASIN

Because of the seasonal change in pavement temperature and subgrade moisture content, it is expected that pavement deflections will vary with the seasons. Due to the low pavement temperature and subgrade moisture content in the winter, winter deflections are the smallest. However, the spring season deflections are not necessarily the largest as generally thought. A comparison of spring and summer Road Rater deflection basins is shown in Figure 3 and given in Table 1. The deflection basins are presented in terms of the readings at Sensors 1 (S_1, maximum deflection) and 4 (S_4), surface curvature index (SCI, which is the difference in readings between Sensors 1 and 2), and base curvature index (BCI, which is equal to $S_3 - S_4$). The ratio between the spring and the summer data is plotted against the spring data. The figure shows that for 15 of the 16 pavement sections containing bituminous concrete base course, S_1 values obtained in the spring (March, April, and May) are smaller than those determined in the summer (June, July, and August); this is in agreement with the findings of the AASHO Road Test (3). For other pavement sections, however, the spring season deflections are approximately equal to the summer data. The values of S_4 are greater in the spring than in the summer for the majority of the pavement sections regardless of the type of base course material. It also appears that the ratio of S_4 readings between spring and summer increases with increasing spring season values. The figure also shows that the SCI data generally follow the trend of S_1 data, whereas the BCI data resemble S_4 data.

The smaller S_1 values in the spring than in the summer for bituminous concrete pavements can be attributed to lower pavement temperature in the spring. Because bituminous concrete is temperature dependent, the higher pavement temperature in the summer decreases the material stiffness. As a result, the summer deflections are greater than those of the spring. Although the stiffness of the base course affects S_1 deflection greatly, its effect on S_4 deflection is not as great. Available information (12) has shown that S_4 deflection is influenced most by subgrade condition. Generally speaking, the softer the subgrade is, the greater the S_4 deflection will be. For the test pavements, the subgrade moisture content is significantly higher in the spring (approximately 20 percent) than in the summer (about 18 percent). Because the stiffness of the subgrade decreases with increasing moisture content, the greater moisture content in the spring will result in a lower subgrade stiffness. As a consequence, the S_4 deflections are greater in the spring than in the summer. Figure 3 also shows that the effect of pavement temperature on SCI is as significant as that of S_1. However, BCI values are less sensitive to subgrade moisture variation than are S_4 values.

Table 2 gives the ratio of spring to fall deflection data. The data indicate that a great majority of the ratios are greater than unity, which indicates that spring season deflections are greater than those in the fall. Because the pavement temperature in the fall is close to that in the spring, the greater deflection observed in the spring can be attributed to the higher subgrade moisture content.

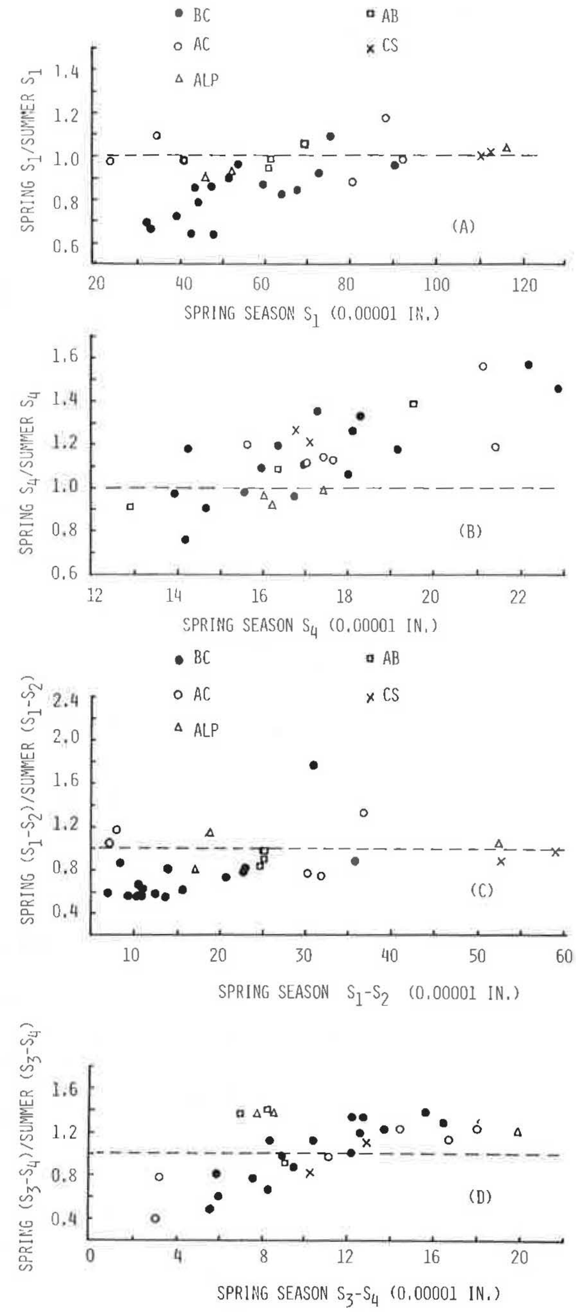

FIGURE 3 Average Road Rater deflections in spring and summer.

The available subgrade moisture data show that the moisture contents in the spring and fall are approximately 20 and 17 percent, respectively.

The maximum Benkelman beam deflection data show a similar trend of variation with seasons, but the difference between seasons is not as great as that of Road Rater deflection data. According to these observations, the deflection data obtained in the summer, which are greater than the spring season deflections, could be more effective for evaluation of fatigue life of bituminous concrete pavements. A primary reason for this is that, in the summer, the higher pavement temperature decreases the stiffness of bituminous concrete and therefore increases the tensile strain at the bottom of the bituminous con-

TABLE 1 Average Road Rater Deflection Data

Section No.	Base Course Material[a]	S_1			S_4			$S_1 - S_2$			$S_3 - S_4$		
		Sp[b]	Sp/Su[c]	Sp/F[d]	Sp	Sp/Su	Sp/F	Sp	Sp/Su	Sp/F	Sp	Sp/Su	Sp/F
1B	BC	44.24	0.78	0.99	17.28	1.36	1.11	11.02	0.63	1.11	10.42	1.12	1.41
		51.37	0.89	1.13	15.94	1.10	0.97	12.40	0.59	1.24	12.59	1.19	1.76
1C		42.70	0.63	0.90	18.00	1.06	1.07	10.44	0.56	0.91	9.51	0.87	1.33
		59.32	0.86	1.08	18.12	1.26	1.05	15.56	0.61	1.18	13.78	1.22	1.52
1D		47.96	0.62	0.92	19.16	1.18	1.25	13.54	0.55	0.89	8.25	0.66	1.11
		72.97	0.92	1.18	16.93	1.11	1.08	22.77	0.77	1.25	16.42	1.30	1.53
2		39.01	0.71	1.06	16.31	1.20	1.14	10.51	0.67	1.30	7.59	0.77	1.23
		53.69	0.96	1.31	18.51	1.33	1.11	13.89	0.82	1.86	12.19	1.01	2.17
6		31.77	0.69	1.03	16.71	0.95	1.05	8.33	0.85	1.69	5.86	0.81	1.26
		43.51	0.85	1.22	22.18	1.57	0.84	9.24	0.56	2.07	5.58	0.49	1.13
7		32.81	0.66	0.91	14.62	0.90	0.88	6.92	0.57	0.97	8.38	1.10	1.58
		47.50	0.85	1.13	22.89	1.45	1.24	10.95	0.56	1.29	5.97	0.60	1.18
8		67.25	0.83	1.00	13.89	0.97	0.91	23.22	0.84	0.97	12.22	1.34	1.40
		75.73	1.09		14.13	0.76		30.94	1.78		9.04	0.99	
9		60.70	0.81	1.05	14.20	1.18	1.02	20.62	0.74	0.97	12.70	1.34	1.82
		90.08	0.95	1.16	15.56	0.98	0.97	35.68	0.88	1.19	15.61	1.40	1.73
4	AC	23.13	0.97	0.87	15.61	1.20	1.05	7.50	2.12	1.57	3.20	0.78	0.89
		34.09	1.09	1.25	21.09	1.56	1.17	7.78	1.17	3.93	3.05	0.40	2.75
A		94.29	0.98	1.03	21.43	1.18	0.88	30.25	0.77	1.17	17.94	1.23	1.11
B		40.42	0.97	1.15	17.05	1.11	0.88	7.11	1.04	2.84	11.08	0.97	2.00
C		80.81	0.87	0.90	17.42	1.14	1.02	31.78	0.75	0.76	14.41	1.23	1.87
D		88.95	1.18	1.39	17.64	1.12	0.89	36.83	1.34	2.14	16.68	1.14	1.43
3	ALP	46.05	0.89	1.06	16.20	0.92	1.05	18.56	1.14	1.32	8.58	1.38	1.50
		52.14	0.93		16.07	0.96		17.18	0.80		7.76	1.36	
		116.52	1.04	1.35	17.46	0.99	0.81	52.33	1.04	1.87	19.93	1.21	1.38
5	AB	60.95	0.93	1.20	16.31	1.09	1.16	25.53	0.92	1.54	6.87	1.35	1.00
		61.05	0.98		12.87	0.90		24.85	0.86		8.24	1.40	
		69.32	1.05	1.42	19.51	1.38	1.21	25.09	0.96	2.23	9.16	0.94	1.22
E	CS	110.58	1.00	1.14	17.11	1.21	1.19	58.85	0.98	1.33	10.29	0.84	1.21
		112.55	1.02	1.21	16.77	1.27	1.17	52.70	0.90	1.25	12.92	1.11	1.40

[a] Base course materials: BC = bituminous concrete, AC = aggregate cement, ALP = aggregate-lime-pozzolan, AB = aggregate bituminous, CS = crushed stone.
[b] Sp = deflection data obtained in spring season in units of 10^{-5} in.
[c] Sp/Su = ratio of spring season to summer data.
[d] Sp/F = ratio of spring season to fall data.

TABLE 2 Layer Modulus Computed from Spring Season Road Rater Deflection Basins

Section No.	Layer Thickness[a] (in.)	Base Course Material[b]	EAL (10^6)	Layer Modulus (10^3 psi) Surface	Base	Subbase	Subgrade
1C	1.5–6–8	BC	1.4	730	899	31	21
			1.8	708	952	36	24
			2.3	811	879	34	22
1D	1.5–6–6	BC	1.4	536	794	32	22
			1.8	480	544	31	36
			2.3	811	879	34	22
2	2.5–6–8	BC	1.4	774	809	42	25
			1.8	742	951	39	28
			2.3	940	902	38	23
7	1.5–8–8	BC	1.0	837	964	38	21
			1.4	664	740	34	28
			1.8	841	873	41	23
			2.3	647	768	43	26
9	2.5–4–8	BC	0.3	643	798	15	28
			1.4	443	619	16	29
			1.8	596	732	18	24
			2.3	538	509	14	21
3	2.5–8–8	ALP	0.3	200	500	100	34
			1.4	50	150	35	28
5	2.5–8–8	AB	0.3	150	100	117	35
A	2.5–4–8	AC	0.3	100	2,830	50	21
			0.6	60	1,455	60	21
			0.9	80	800	45	20
			1.3	20	100	40	20
C	2.5–6–8	AC	0.3	100	1,000	30	32
			0.6	300	470	22	32
			0.9	26	168	15	28
D	2.5–6–6	AC	0.3	300	504	15	30
			0.6	300	212	19	28
			0.9	70	100	18	26
			1.3	20	40	11	24
E	2.5–8–8	CS	0.3	220	45	30	40
			0.6	800	36	27	31
			0.9	500	45	24	26

[a] Thicknesses of surface, base, and subbase courses, respectively.
[b] Base course materials: BC = bituminous concrete, AC = aggregate cement, AB = aggregate bituminous, ALP = aggregate-lime-pozzolan, CS = crushed stone.

crete base. Because tensile strain is related to fatigue cracking in a power function, it is often used to evaluate the fatigue life of pavement structures.

For maximum surface deflection, the deflection basin also varies with EAL. The general trend of Road Rater deflection basin variation with EAL is shown in Figure 4. Figure 4 shows the Road Rater deflection basins at three levels of EAL for pavement Sections 3 and 5. It is seen that as EAL increases, the deflection basin becomes deeper and narrower, and the radius of curvature at the loading point becomes smaller. For the Benkelman beam deflections, the trend of deflection basin variation with EAL is not as well defined as is that for the Road Rater deflection basins. This is probably because the accuracy of Benkelman beam readings is not as high as that of the Road Rater readings. Note that the Benkelman beam readings were taken with a dial gauge, whereas the Road Rater readings were monitored using accelerometers.

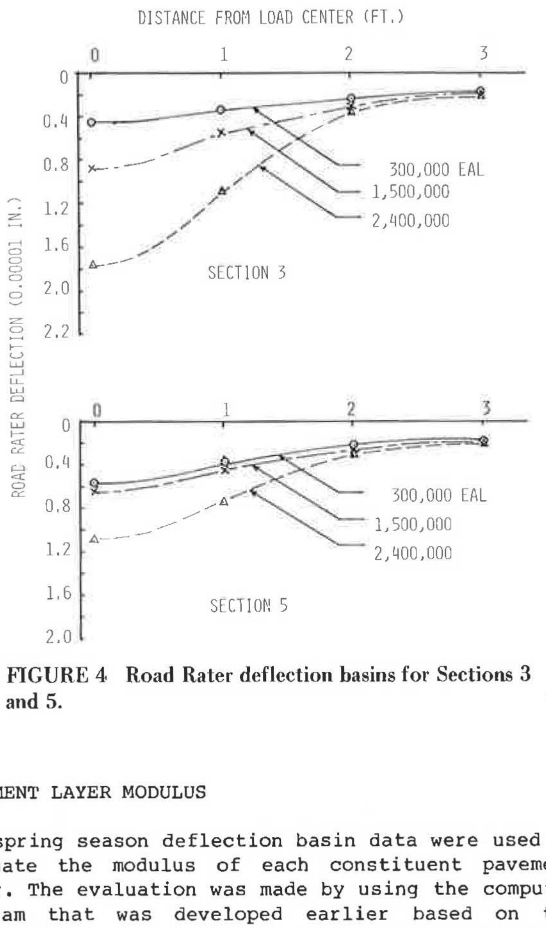

FIGURE 4 Road Rater deflection basins for Sections 3 and 5.

PAVEMENT LAYER MODULUS

The spring season deflection basin data were used to evaluate the modulus of each constituent pavement layer. The evaluation was made by using the computer program that was developed earlier based on the method of successive iteration (12,13). It should be noted that, for modulus evaluation, each of the four sensor readings of the Road Rater was plotted against EAL and smooth curves were drawn through the data points. From these curves, the deflection data at a desired level of EAL were read to obtain deflection basins for use as input to the computer program. In the computer analysis, the Poisson's ratios used were 0.45, 0.35, and 0.45 for the bituminous concrete surface, crushed limestone subbase, and silty clay subgrade, respectively; and 0.35, 0.30, 0.20, and 0.15 for the bituminous concrete, aggregate bituminous, aggregate cement, and aggregate-lime-pozzolan base courses, respectively. Also, the 4- x 7-in. (10.2- x 17.8-cm) loading plates of the Road Rater were approximated by two circular areas spaced 10.5 in. (26.7 cm) apart center to center; each has a 3-in. (7.6-cm) radius. The contact pressure under each plate is 13 psi (89.6 kPa).

For the Road Rater deflection basins thus obtained, layer modulus values at different EALs were evaluated for most of the test pavements and the results of evaluation are summarized in Table 2. The data in the table indicate that a great majority of the subgrade modulus values fall within 20,000 and 30,000 psi (138 and 207 MPa) with few fluctuating between 30,000 and 40,000 psi (207 and 276 MPa). This type of fluctuation is as would be expected; primary reasons are that (a) the subgrade material may not be uniform in terms of its soil composition and compaction conditions (including moisture content and dry density) throughout the entire test pavements and (b) it is difficult to obtain theoretical deflection basins (the basins computed from the theory of elasticity) that will fit perfectly to the measured deflection basins because of possible nonuniformity in pavement materials and layer thickness. Recall that the evaluation of modulus employed the procedure of successive iteration for which a set of layer moduli must first be assumed to compute deflection basins. The computed deflection basin is then compared with the measured one and the difference, if any, between the two deflection basins serves as the basis for adjusting the assumed modulus values. The adjustment is made by using the successive iteration procedure until the difference between the two deflections is less than 10 percent of the measured values.

Except for pavement Sections 3 and 5, the modulus of the subbase course of each pavement varies within a narrow range. Specifically, the subbase modulus fluctuates between 31,000 and 43,000 psi (214 and 297 MPa) for Sections 1C, 1D, 2, and 7; between 14,000 and 18,000 psi (97 and 124 MPa) for Section 9; between 40,000 and 60,000 psi (276 and 414 MPa) for Section A; between 15,000 and 30,000 psi (103 and 207 MPa) for Section C; between 11,000 and 19,000 psi (76 and 131 MPa) for Section D; and between 24,000 and 30,000 psi (166 and 207 MPa) for Section E. When the previously mentioned factors, which could possibly cause modulus variation, are considered, this range of variation in each section can be considered normal. However, for Section 3, the difference between the highest and the lowest values is as much as threefold. Also, the highest subbase modulus values for Sections 3 and 5 are considerably greater than those of other sections. This is rather unexpected and possible causes of this wide variation are not yet fully understood. One interesting trend of variation is that the subbase modulus appears to decrease with EALs for some sections (2, 3, C, and E). The data also show that the overall range of subbase modulus values is considerably broader than that of subgrade modulus values. There is no trend indicating how the subbase modulus variation is related to the type of base course material, however.

For the pavements containing bituminous concrete base course (Sections 1C, 1D, 2, 7, and 9), both the surface and the base course moduli fluctuate within an expected range. There is no apparent trend of variation of layer modulus with layer thickness. For other sections, except Sections 5 and E, the base course modulus decreases with EAL. The decrease in the base course modulus could possibly be attributed to progressive deterioration of the base course with traffic volume. The surface course modulus of these sections fluctuates randomly without a definite pattern. The data on Sections 3, A, and C indicate, as expected, that the aggregate-lime-pozzolan base, limestone aggregate cement base, and slag aggregate cement base courses have considerably greater moduli than does the bituminous concrete surface course.

TABLE 3 Layer Modulus Computed from Spring Season Benkelman Beam Deflection Basins

Section No.	Layer Thickness (in.)[a]	Base Course Material[b]	EAL (10^6)	Layer Modulus (10^3 psi) Surface	Base	Subbase	Subgrade
1C	1.5-6-8	BC	1.4	25	300	10	29
1D	1.5-6-6	BC	1.4	20	100	8	21
2	2.5-6-8	BC	1.4	30	400	10	32
6	2.5-8-8	BC	1.4	40	300	10	28
7	1.5-8-8	BC	1.4	50	200	12	33
9	2.5-4-8	BC	1.4	50	200	10	20
3	2.5-8-8	ALP	1.4	85	100	18	20
5	2.5-8-8	AB	1.4	75	60	14	34
4	2.5-8-8	AC	1.4	500	750	16	58
A	2.5-4-8	AC	0.3	220	2,000	14	48
B	2.5-6-8	AC	0.3	500	1,000	10	51
C	2.5-6-8	AC	0.3	50	450	12	30
D	2.5-6-8	AC	0.3	150	500	12	49
E	2.5-8-8	CS	0.3	55	30	12	49

[a]Thickness of surface, base, and subbase courses, respectively.
[b]Base course materials: BC = bituminous concrete, AC = aggregate cement, AB = aggregate bituminous, ALP = aggregate-lime-pozzolan, CS = crushed stone.

Furthermore, the gravel base course has a smaller modulus than does the bituminous concrete surface, as indicated by Section E. Comparison of the modulus of the gravel base with that of the limestone subbase in Section E indicates that the base course material is slightly stiffer than the subbase course. This is as would be expected because the Road Rater loading induces greater confining pressures in the base course than in the subbase; the greater confinement causes higher stiffness for the gravel material.

For the Benkelman beam deflections, because fewer deflection basins are available and also because the variation of deflection basins with EAL is not as well defined as that of the Road Rater deflections, the analysis of layer modulus is made for only one level of EAL, which is 0.3 million for Sections A, B, C, D, and E and 1.4 million for the other sections. The deflection basins obtained at and near this level of EAL are averaged; for each averaged deflection basin, the deflection values at four locations--at the center of the dual loading tires and at 1, 3, and 5 ft (0.3, 0.9, and 1.5 m) off the center--are used as input to the computer program. The analysis is made for 18-kip (80-kN) single axle loading with dual tires each having 80 psi (552 kPa) tire pressure. Results of the analysis are summarized in Table 3.

The data in Table 3 show that both subgrade and subbase modulus values fluctuate without a definite pattern with respect to type of base course material. For each type of base course material, the base course modulus varies within a reasonable range. The modulus of surface course, which has the same material for all test pavements, appears to be smaller for pavements that contain a bituminous concrete base course. Reasons for this effect are not yet known.

For comparison of the modulus values evaluated from the Benkelman beam and the Road Rater deflection basins, the ratio between the two sets of values is plotted against the values obtained from the Road Rater deflections in Figure 5. Because the difference between the two sets of surface moduli is somewhat erratic, it is not included in the figure. Figure 5 demonstrates that the ratio of the two sets of subgrade modulus values fluctuates around unity, indicating that regardless of the type of base course material, the Benkelman beam and the Road Rater deflection basins give practically the same subgrade modulus. For the subbase modulus, however, the values obtained from Benkelman beam deflections

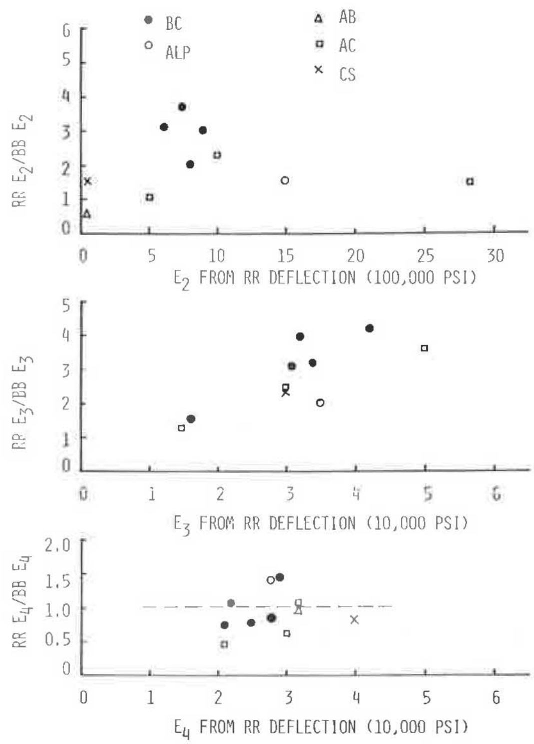

FIGURE 5 Ratio of layer modulus between Road Rater and Benkelman beam loadings.

are considerably lower especially for pavements containing a bituminous concrete base course. The difference between the two sets of base course moduli is not as great as is that for the subbase modulus. It appears that the modulus of bituminous concrete base computed from the Road Rater deflections is significantly higher than that computed from the Benkelman deflections, whereas the modulus of other base course materials is practically the same. Reasons for the observed modulus variations are not yet available. Additional study is needed to better understand the behavior of modulus variation.

The resilient modulus of each constituent pavement material was determined from laboratory repeated load tests on specimens 6 in. (152 mm) in diameter. The laboratory testing was conducted at a room temperature of about 70°F (21°C). The test specimens for the surface, base, and subbase materials were prepared in the laboratory to the same composition and density as those in the field. For the subgrade soil, both undisturbed and remolded specimens were tested.

The repeated load had a frequency of 20 cycles per minute and a duration of 0.1 sec. The stationary confining pressure and cyclic deviatoric pressure used in the testing are given in Table 4. For each test condition, a minimum of three tests were performed. Resilient modulus values obtained from the laboratory testing are summarized in Table 5. Also included in Table 5 for comparison are the range and average values of layer modulus obtained from Tables 2 and 3.

TABLE 4 Confining and Deviatoric Pressures Used in Laboratory Repair Load Test

Test Material	Confining Pressure (psi)	Deviatoric Pressure (psi)
Surface	20, 30, and 40	10, 30, and 50
Base	10, 20, and 30	10, 25, and 40
Subbase	10 and 20	10, 20, and 30
Subgrade	5 and 10	5, 10, and 20

The data in Table 5 indicate that for the bituminous concrete surface, bituminous concrete base, and aggregate bituminous base course materials, the resilient modulus is practically equal to the layer modulus obtained from Benkelman beam deflection basins. The resilient modulus values for other base course materials are considerably greater than the layer modulus values. Also, the resilient modulus values are slightly greater for the limestone subbase and smaller for the silty clay subgrade compared with the layer modulus values. Although a slight difference between the two different sets of moduli can be expected, possible reasons for resilient modulus larger than layer modulus for one and smaller for the other are yet to be investigated.

Critical Pavement Response

The modulus values were used to analyze critical responses of the test pavements subjected to 18-kip (80-kN) single axle (Benkelman beam) loading and Road Rater loading. The analysis was made using the bituminous structures analysis in roads (BISAR) computer program; the critical responses analyzed included the maximum tensile strain at the bottom of a stabilized base course or maximum tensile strain at the bottom of a surface course for the pavement section containing crushed stone base course, and the maximum vertical compressive strain on top of the subgrade.

Because there are more data on the variation of Road Rater deflection basins with EAL, the maximum tensile strain (ε_t) at the bottom of a stabilized course (surface course for Section E and base course for other sections) and the maximum vertical compressive strain (ε_v) at the top of a subgrade are analyzed for the Road Rater deflection basins selected at different levels of EAL. Some of the results of the analysis are shown in Figures 6 and 7, which show the variation of vertical compressive

TABLE 5 Resilient Modulus and Layer Modulus

Layer	Material	Resilient Modulus (10^3 psi)		Layer Modulus[a] (10^3 psi) from: Road Rater Deflection		Benkelman Beam Deflection	
		Range	Average	Range	Average	Range	Average
Surface	Bituminous concrete	85–200	140	20–837	442	20–500	132
Base	Bituminous concrete	250–450	320	509–064	801	100–400	250
	Limestone aggregate cement	3,000–4,500	3,600	100–2,830	1,296	750–2,000	1,250
	Slag aggregate cement	2,500–4,000	3,200	168–1,000	546		450
	Gravel aggregate cement	2,000–3,800	2,500	40–504	214		500
	Aggregate-lime-pozzolan	1,500–3,500	2,400	150–500	325		100
	Aggregate bituminous	58–200	100		100		60
Subbase	Crushed limestone	42–64	48	11–117	35	8–18	12
Subgrade	Silty clay	6–20	8	20–40	26	20–58	36

[a]Values obtained from Tables 2 and 3.

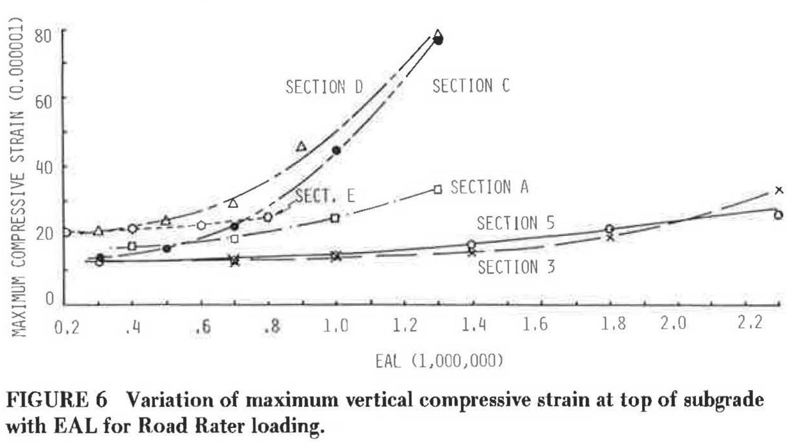

FIGURE 6 Variation of maximum vertical compressive strain at top of subgrade with EAL for Road Rater loading.

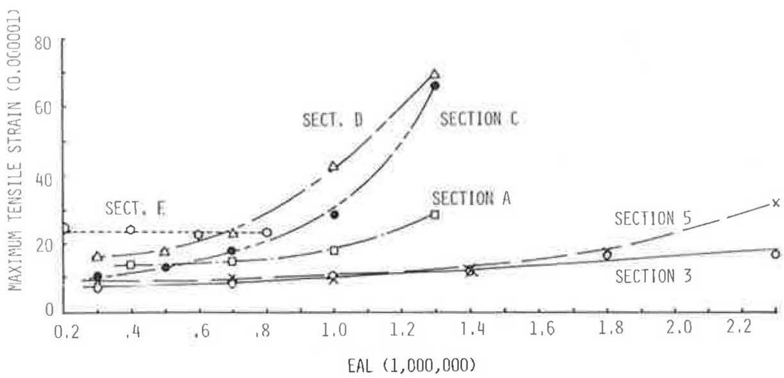

FIGURE 7 Variation of maximum horizontal tensile strain at bottom of stabilized course with EAL for Road Rater loading.

strain and horizontal tensile strain, respectively, with EAL. It is seen that, for most pavement sections, both strains increase with increasing EAL. The shape of the curve, generally speaking, follows that of the maximum surface deflection (Figure 1) except for Sections 3 and E. For Section 3, the rate of increase in strains is not as pronounced as is that of the surface deflection; and for Section E, the strains remain essentially constant throughout the entire range of EAL.

In addition to the results shown previously, each of the analyzed strain values is shown in Figure 8 in terms of the ratios between the two values, one obtained from the Benkelman beam and the other from the Road Rater ($BB\varepsilon_t/RR\varepsilon_t$ and $BB\varepsilon_v/RR\varepsilon_v$). The figure demonstrates that the ratio of maximum tensile strain ($BB\varepsilon_t/RR\varepsilon_t$) fluctuates around 20.0 for the data points of pavements containing bituminous concrete base courses and around 15.0 for the data points of the other types of base course materials. For the maximum vertical compressive strain, the ratio $BB\varepsilon_v/RR\varepsilon_v$ fluctuates around 10.0 regardless of the type of base course materials.

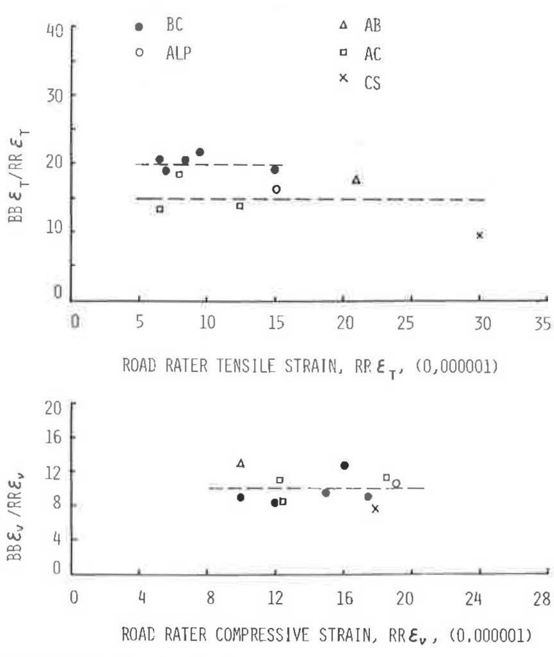

FIGURE 8 Ratio of critical strains between Road Rater and Benkelman beam loadings.

The results of computer analyses, which were discussed in an earlier report (14), indicated that for both maximum tensile and maximum vertical compressive strains, the values for Benkelman beam loading are 12.5 times those that occur under the Road Rater loading. It should be noted that the analysis was made for pavements containing bituminous concrete base courses only. Furthermore, in the analysis, the surface and base courses were treated as one layer, and the modulus values of the pavement layers were estimated on the basis of maximum surface deflection without consideration of the entire deflection basin. Because of these limitations, the current values of 20.0, 15.0, and 10.0 should be closer to the actual values and therefore should be more useful for practical applications.

SUMMARY AND CONCLUSIONS

The response of flexible pavements to two different types of loading--18-kip (80-kN) single axle and Road Rater loadings--was analyzed. The pavement response to the single axle loading on dual tires was measured using a Benkelman beam. The Road Rater used was a model 400, which was operated at 25-Hz loading frequency. The flexible pavements investigated contained different types of base courses including bituminous concrete, aggregate bituminous, aggregate cement, aggregate-lime-pozzolan, and crushed stone.

Pavement surface deflections obtained from these two types of loadings were analyzed; factors considered in the analysis were weather, base course materials, and cumulative axle load application. Also, the surface deflection basins were used to evaluate layer moduli, which in turn were used to analyze the maximum tensile strain at the bottom of the stabilized base course or at the bottom of the surface course of pavements without stabilized base courses and the maximum vertical compressive strain at the top of the subgrade.

Results of the analysis indicate that, for the conditions studied, spring season deflections are not necessarily the largest, as is generally thought, especially for pavements with bituminous concrete base courses. For other pavements, the spring season deflections are approximately equal to the summer data. For the spring season deflection data, the maximum surface deflection, maximum horizontal tensile strain, and maximum vertical compressive strain increase with increasing cumulative axle load applications as would be expected. From the results of the analysis, relationships between Road Rater and single axle loadings were established for layer modulus, maximum surface deflection, maximum tensile strain, and maximum vertical compressive strain.

On the basis of the results of this study, it may be concluded that, at least for the conditions investigated, summer deflection measurements are as effective as, if not more so than, spring season deflection measurements for evaluation of pavement condition. The layer modulus values evaluated from the Road Rater deflection basins are practically the same as those obtained from the Benkelman beam deflection basins for the subgrade and base course materials. The subbase modulus obtained from the Road Rater deflection basins is considerably higher than that evaluated from the Benkelman beam deflection basins. For the surface course material, however, no definite trend in the relative magnitude between the two sets of layer modulus values is found. Furthermore, the resilient modulus obtained from the laboratory repeated load test is reasonably close to the layer modulus for most pavement layers except for aggregate cement and aggregate-lime-pozzolan base courses. For these base course materials, the resilient modulus is considerably greater than the layer modulus. Under 18-kip (80-kN) single axle loading, the maximum surface deflection, maximum horizontal tensile strain, and maximum vertical compressive strain can be estimated from the corresponding values caused by the Road Rater loading by using the developed relationships. These relationships and other data may provide a useful basis for the development of a generally accepted pavement evaluation criterion for use in pavement management programs.

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