allow meaningful comparison of roughness values measured at different times.

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Use of Road Rater Deflections in Pavement Evaluation

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There is a need to predict the future performance of pavements by using deflections measured at any time so that deflection data can be used to determine the strategy for pavement maintenance. The road rater is a relatively new instrument for evaluating pavement performance. This paper presents some basic principles of road rater operation, its method of measuring pavement response, and criteria for evaluating the future performance of flexible pavements that contain bituminous concrete base courses. The response of experimental pavements to 80-kN (18 000-lb) axle loads and road rater loading is analyzed and is related to the actual performance of the experimental pavements. A model 400 road rater was operated at a frequency of 25 Hz. The BISAR computer program was used to obtain spring pavement temperature and subgrade moisture condition. Critical responses analyzed include maximum vertical compressive strain at the top of the subgrade, maximum tensile strain at the bottom of the base course, and maximum surface deflection. Based on the results of the analysis, equations are developed that interrelate various pavement responses and permit the calculation of critical responses to 80-kN axle loads from the road rater deflection basin. A permissible ratio of surface curvature index to maximum deflection is also established based on the fatigue property determined in the laboratory. This value may be used to evaluate pavements for rehabilitation purposes.

Predicting pavement performance is an essential step in the development of maintenance programs to extend the service life of a pavement beyond its original design life. Warrants for overlays are currently based mainly on the functional performance of a pavement, which is essentially a measure of riding comfort. The design of overlays, however, is based on surface deflection data, which primarily measure the structural performance of the pavement. There is thus a need to predict the future performance of pavements by using deflections measured at any time so that deflection data can be used to determine the strategy for pavement maintenance.

Various types of instruments are available for measuring the deflections of a pavement surface under load. The Benkelman beam was developed during the WASHO Road Test in 1952. The underlying principles of operation for this instrument are relatively simple and have been well defined (1, 2). One disadvantage of the Benkelman beam test is the limited rate of progress that can be achieved in the routine evaluation of roads. This has prompted the development of mechanized versions of the instrument that are aimed at providing a much greater rate of progress. The most common of these instruments are the traveling deflectometer developed by the California Division of Highways (3) and the Lacroix deflectograph developed in France (4). Other types of instruments have been developed for measuring specific features of the deflection basin, such as the curvature meter developed in South Africa (5) and the slopemeter (6). All of these instruments are used in measuring the deflection characteristics of a pavement surface under a dual wheel load that is either stationary or moving at a very slow speed.

Dynamic testing techniques have been developed to simulate the effect of vehicle speed in reproducing repeated impulsive loadings at a point in the pavement. One method that has the advantage of fast operation uses a stationary vibrating load to replace the moving wheel load; the response of the pavement is monitored through a number of geophones (accelerometers). The road rater (7), the Dynaflect (8), and other instruments (9) have been developed for this purpose. Because of its relatively high degree of mobility, the road rater has been adopted by the Pennsylvania Department of Transportation (PennDOT) for the routine evaluation of state highway pavements.

The road rater technique for measuring pavement response is simple, but use of the instrument for evaluating pavement performance is by no means well established. This paper presents some basic principles of road rater operation, its method of measuring pavement response, and criteria for evaluating the future performance of flexible pavements that contain bituminous concrete base courses. The evaluation criteria were developed based on the results of an analysis of road rater deflections and performance data collected at the Pennsylvania Transportation Research Facility (10).

PAVEMENT RESPONSE UNDER ROAD RATER LOADING

The road rater is composed of three basic types of elements: loading, sensing, and monitoring. The loading element consists of a vibrating weight and two rectangular steel plates that rest on the pavement surface. The weight varies from 72 to 295 kg (160 to 650 lb), depending on the model, and vibrates vertically at various frequencies. The loading plates have dimensions of 10.2 by 17.8 cm (4 by 7 in) each and are spaced 26.7 cm (10.5 in) apart center to center. The sensing element consists of four geophones 0.33 m (1 ft) apart; one sits at the middle of the two loading plates, as shown in Figure 1. The monitoring element is simply a readout unit for the four geophones. The road rater is mounted at the front of a van. A more detailed description of the components and the operation of the road rater is given by Bhajandas, Cumberledge, and Hoffman (11).

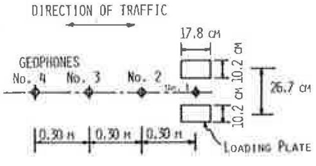
The vibratory motion of the weight induces a simple harmonic loading. The peak force of the road rater loading is

$$F_{peak} = 19.73\,Wf^2D \quad (1)$$

where

W = weight (kg),
f = frequency of vibration (Hz), and
D = peak-to-peak displacement (cm).

Figure 1. Arrangement of geophones and loading plates of a road rater.



Note: 1 cm = 0.4 in; 1 m = 3.3 ft.

Equation 1 is derived as follows. The weight (W) vibrates sinusoidally in the vertical direction at a frequency f. Displacement at any time t can be expressed in terms of the angular velocity ($\omega = 2\pi f$), as follows:

$$\chi = \chi_o \cdot \sin \omega t \quad (2)$$

where

χ = displacement at time t and
χ_o = peak displacement.

The acceleration of motion can be obtained from

$$\ddot{\chi} = -\chi_o\,\omega^2 \sin \omega t \quad (3)$$

The maximum values of displacement and acceleration occur when the sine function equals unity. Thus,

$$\chi_{max} = \pm\chi_o \quad (4)$$

and

$$\ddot{\chi}_{max} = \pm\chi_o\,\omega^2 \quad (5)$$

The peak force is induced by the maximum acceleration, which equals

$$F_{peak} = m\ddot{\chi}_{max} = m(\pm\chi_o\,\omega^2) \quad (6)$$

Substituting $m = (W/g)$, $\chi_o = (D/2)$, and $\omega = 2\pi f$ into Equation 6 yields

$$F_{peak} = \pm 0.0511\,Wf^2D \quad (7)$$

where D is the peak-to-peak displacement that can be measured directly from the road rater.

The road rater used in Pennsylvania is a model 400, which has a vibrating weight of 72 kg (160 lb). The device is commonly operated at a frequency of 25 Hz, but other frequencies used have ranged between 10 and 40 Hz. The peak-to-peak displacement for the model 400 road rater is 1.803 mm (0.071 in). In these conditions, peak force is 1615 N (362.8 lbf), and the contact pressure under each plate is 89.6 kPa (13 lbf/in^2). During testing, the loading plates are subjected to a downward static force. A static force of 6672 N (1500 lbf) is used for the road rater and the van. Because only the difference in pavement response to maximum and minimum downward forces is monitored, the magnitude of the static force has no direct influence on monitored pavement response. Thus, the pavement response under the road rater loading can be analyzed by using the peak force alone.

In this analysis, the 10.2- by 17.8-cm (4- by 7-in) loading plates were approximated by two circular areas spaced 26.7 cm (10.5 in) apart center to center; each has a 7.6-cm (3-in) radius. The contact pressure for a frequency of 25 Hz is 89.6 kPa (13 lbf/in^2). In these conditions, surface deflections at four geophones can be determined, and surface curvature index (SCI) and base curvature index (BCI) can be computed. SCI is defined as the difference between the first and second geophone readings and BCI as the difference between the third and fourth geophone readings (12).

The deflection profiles of pavement systems were analyzed for the loading conditions described above by using the BISAR (bitumen structures analysis in roads) computer program. The pavement systems analyzed were composed of an elastic layer that had a finite thickness overlaying the elastic half space. Results of the analysis are shown in Figures 2 and 3. Figure 2 indicates that the ratio of SCI to maximum surface deflection

(δ_{max}) increases as the moduli ratio of lower to upper portions of the pavement structure (E_2/E_1) increases; the slope of the curves decreases slightly as the E_2/E_1 ratio increases. Figure 3 shows that the BCI/SCI ratio decreases as the E_2/E_1 ratio increases. Both figures imply that, when the upper portion of a pavement structure undergoes deterioration faster than the lower portion, the SCI/δ_{max}ratio will increase and the BCI/SCI ratio will decrease. Therefore, the deflection profile determined from road rater measurements can be used to evaluate the relative strength between the upper and lower portions of a pavement structure.

EXPERIMENTAL PAVEMENTS AND FIELD TESTING

Field studies of road rater deflections were conducted at the Pennsylvania Transportation Research Facility. This accelerated live testing facility—a 1.6-km (1-mile), one-lane highway constructed in August 1972—is composed of sections of various lengths and thicknesses and different types of base materials (Figure 4). Four different base course materials were used: bituminous concrete, aggregate cement, aggregate-lime-pozzolan, and aggregate bituminous base. The subbase material was a crushed limestone natural to central Pennsylvania. The subgrade soil had classifications that ranged from A-4 to A-7 but was predominantly A-7. The wearing surface for the entire facility was constructed of one type of material. This paper deals only with the pavements that contain bituminous concrete base.

By the end of December 1974, the pavement sections constructed during the first cycle of research had been subjected to about 1 million applications of equivalent 80-kN (18 000-lb) axle loads (EAL_{18}). By the end of May 1977, a total of about 1.5 and 0.5 million axle loads respectively had been applied to pavement sections constructed during the first research cycle and pavement sections constructed during the second cycle. Traffic loading was provided by a conventional truck tractor that pulled a semitrailer and a full trailer. Complete information on design, construction, material properties, and traffic operation has been given in several research reports (13, 14).

Field performance measurements of the test pavements were conducted periodically; these included measurements of surface deflection (by use of the Benkelman beam and the road rater), rut depth, surface roughness, and surface cracking. In addition, data on subgrade moisture, pavement temperature, and meteorological conditions were collected regularly. Table 1 gives the results of the crack survey for the pavement sections that contain bituminous concrete base. A complete record of the field data accumulated so far is available elsewhere (15).

Material Properties

The modulus of elasticity of each constituent pavement material was determined by using repeated-load laboratory tests on laboratory-compacted test specimens. The specimens were 15.2 cm (6 in) in diameter and 25.4 cm (10 in) high. The repeated loading had a frequency of 20 cycles/min and a duration of 0.1 s. For the range of confining pressures and deviator stresses that occurred under loading by the test vehicle, the resilient modulus of the crushed limestone subbase material was 331 MPa (48 000 lbf/in^2). At 23 percent water content, the subgrade modulus was about 55 MPa (8000 lbf/in^2). Modulus values of surface and base materials for various temperatures are given elsewhere (14).

Fatigue properties of the surface and base course materials were determined by conducting fatigue tests on laboratory-compacted beam specimens. The repeated loading had the same frequency and duration as that used in the testing of the resilient modulus. These test results are given by Root (17).

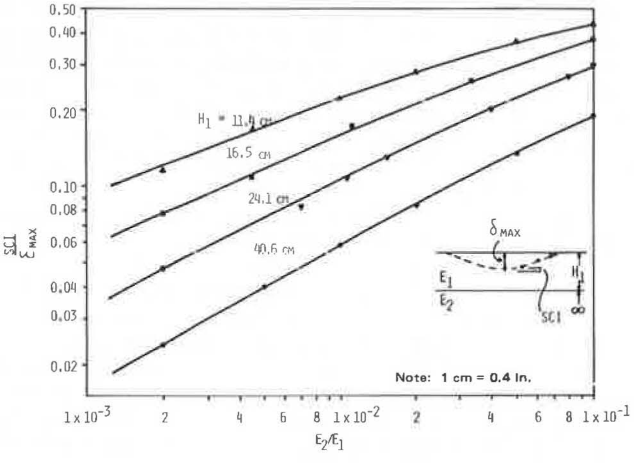
Data on the change of moduli values with number of axle load applications were required to determine the variation in pavement response during pavement service life. For this purpose, regression analyses were performed for the Benkelman beam deflection data for the

Table 1. Results of crack survey.

Section	Layer Thickness (cm)			Number of Equivalent 80-kN Axle Loads at First Appearance of Significant Cracking (000 000s)
	Surface	Base	Subbase	
1B	3.8	15.2	35.6	-
1C	3.8	15.2	20.3	1.37
1D	3.8	15.2	15.2	1.32
2	6.4	15.2	20.3	-
6	6.4	20.3	20.3	-
7	3.8	20.3	20.3	-
8	3.8	10.2	20.3	0.386
9	6.4	10.2	20.3	1.052
14	3.8	20.3	0	0.906
H	3.8	12.7	0	0.359

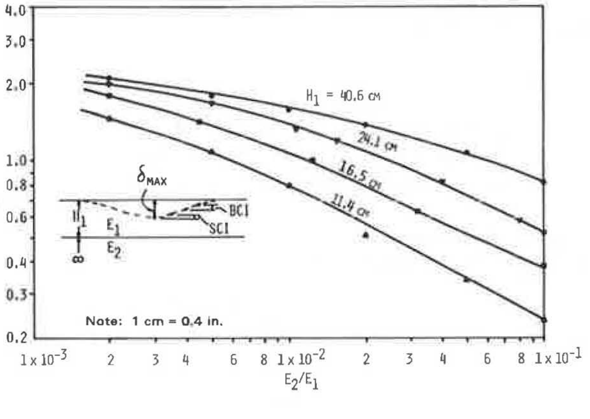
Note: 1 cm = 0.39 in; 1 kN = 224.8 lb.

Figure 2. SCI/δ_{max} versus E_2/E_1.



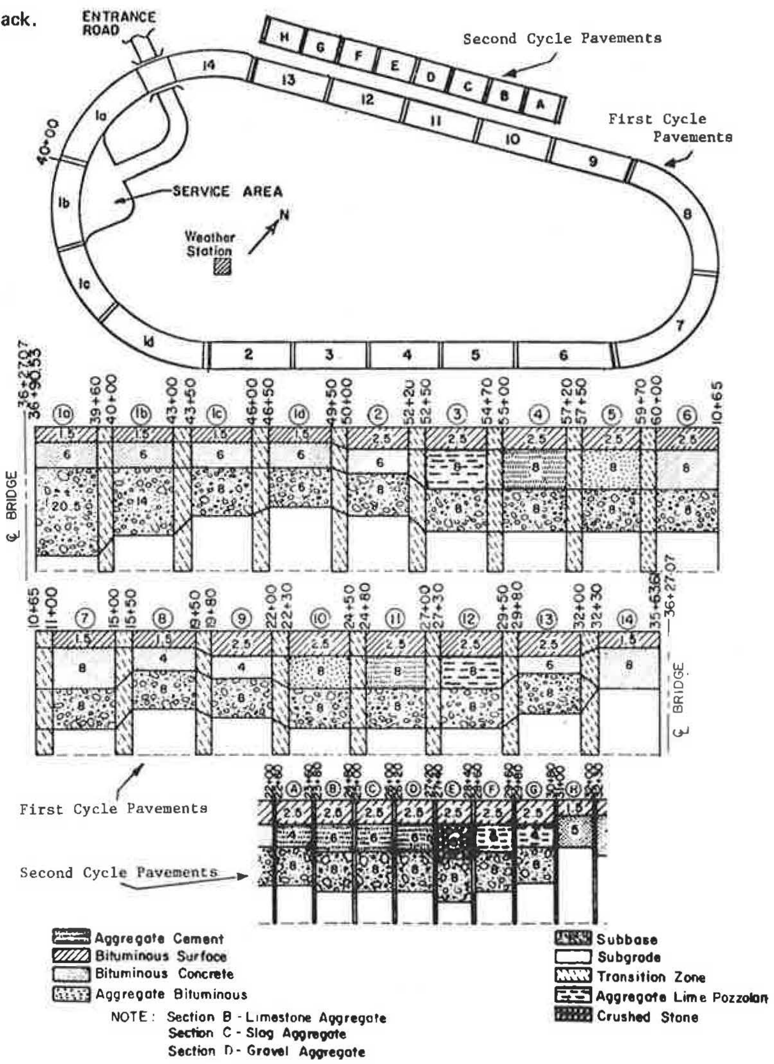
Note: 1 cm = 0.4 in.

Figure 3. BCI/SCI versus E_2/E_1.



Note: 1 cm = 0.4 in.

Figure 4. Plan view and longitudinal profile of test track.



sections that contained bituminous concrete base. Results of the regression analyses give deflection equations for these pavement sections.

Benkelman beam spring season deflection equations for the bituminous concrete base sections at the Pennsylvania Transportation Research Facility are as follows (because the values are derived in U.S. customary units of measurement, no SI units are given): For bituminous concrete base sections 1C, 2, 6, 7, 8, 9, and 13,

$$\delta \times 10^3 = 86.632 - 15.898H_1 - 89.739(\log H_2) + 18.219H_1(\log H_2) - 2.460H_1(\log H_2)(EAL)^2 + 7.818(EAL)^2 \quad (8)$$

For full-depth bituminous concrete sections 14 and H,

$$\delta \times 10^3 = 20.145 - 0.650H_2 - 15.989H_2\sqrt{EAL} + 144.580\sqrt{EAL} \quad (9)$$

where

δ = Benkelman beam deflection (in 0.001 in);
H_1 = surface layer thickness (in);
H_2 = base layer thickness (in); and
EAL = 18 000-lb equivalent axle loads.

Note that the original deflection model contains several other influential factors. These equations are reduced from the original model to spring temperature and moisture conditions. A pavement temperature of 15.6°C (60°F) and a subgrade moisture of 23 percent were used because these are the most critical conditions that affect pavement performance. These equations permit the calculation of spring season deflections at any time during the service life of the experimental pavements.

The field data for subgrade moisture indicate that the subgrade moisture content reached a maximum of approximately 23 percent for all test sections. Thus, it would be conservative to assume that the subgrade modulus in the spring season remains constant throughout the entire service life of the experimental sections. Subbase modulus is also assumed to be independent of the number of axle load applications. It is generally recognized that, during the early stages of pavement service life, a pavement will undergo some degree of compaction that will cause a slight increase in the modulus. But results of field plate load tests conducted during the construction of the research facility and after termination of traffic at the end of the first cycle of study did not give a clear indication of this effect.

Based on the computed spring season deflections and the preceding assumptions, the modulus of elasticity of the combined surface and base layer at any number of axle load applications was determined by using the BISAR computer program. The moduli values needed for the analysis of pavement response to road rater loading were determined in the following way. First, road rater deflections were taken at the top of each constituent layer during construction. The deflection values were then corrected to correspond with spring season conditions by using the PennDOT method of correction (16). Based on these corrected deflections, the modulus of elasticity of each layer was computed by using the BISAR computer program. The change in modulus of elasticity with number of axle load applications was determined by using these initial moduli values in conjunction with the variation in modulus of elasticity for the Benkelman beam deflections already determined. It was assumed that the ratio of modulus of elasticity for Benkelman beam loading to modulus for road rater loading remains constant for each constituent layer. The initial values for modulus of elasticity for road rater loading and Benkelman beam loading for each pavement section analyzed are given below (1 MPa = 145 lbf/in^2):

Layer	Benkelman Beam	Road Rater
Combined surface and base by section		
1B	7 586	11 034
1C	6 896	9 655
1D	6 896	10 345
2	8 276	11 724
6	13 793	16 552
7	13 793	17 241
8	7 586	8 965
9	6 896	10 345
14	8 276	8 965
H	12 414	13 793
Subbase	331	379
Subgrade	55	69

Response

The response of the test pavements was analyzed for both traffic and road rater loadings by using the BISAR computer program and the material properties obtained above. In the analysis, the surface and base courses were combined into a single layer, and only spring weather conditions were considered. The traffic loading used was an 80-kN (18 000-lb) dual-wheel axle load and a tire pressure of 55 kPa (80 lbf/in^2).

The critical responses analyzed were maximum tensile strain in the surface and base layers, maximum vertical compressive strain in the subgrade, and maximum surface deflection. These critical responses were considered because maximum tensile strain and maximum surface deflection have been associated with fatigue cracking whereas maximum vertical compressive strain has been related to rutting.

Results of the analysis give relations between the pavement response measured by means of a Benkelman beam and that measured by means of a model 400 road rater operated at 25-Hz frequency. For pavements that contain bituminous concrete base, the ratio of Benkelman beam deflection to road rater maximum deflection is proximately 14.5. The maximum tensile and maximum compressive strains under 80-kN (18 000-lb) axle loads are both about 12.5 times those that occur under road rater loading. These two strain relations are useful for evaluating pavement behavior when a road rater is used.

Figure 5. Road rater maximum tensile strain as a function of surface curvature index.

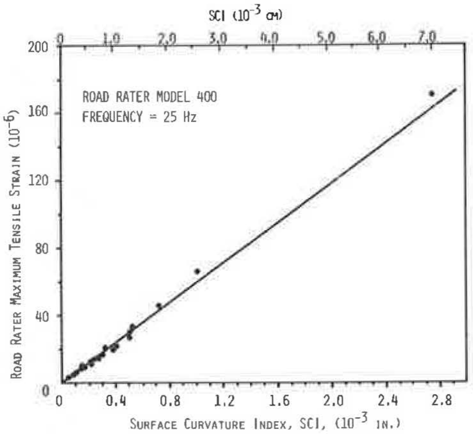
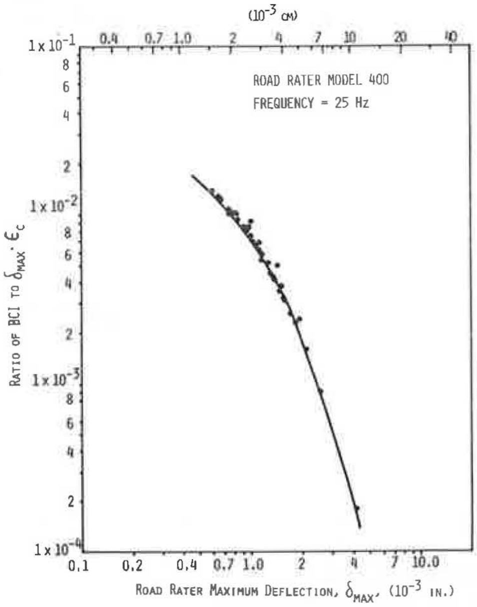


Figure 6. Relation between BCI/$\delta_{max}\epsilon_c$ and δ_{max}.



The relation between maximum tensile strain (ϵ_t) under road rater loading and SCI is shown in Figure 5. This relation indicates that maximum tensile strain is directly proportional to SCI. Figure 6 shows the relation between maximum surface deflection (δ_{max}) and the ratio of BCI to the product of maximum surface deflection and maximum vertical compressive strain at the top of the subgrade (ϵ_c), i.e., BCI/($\delta_{max}\epsilon_c$). Based on Figures 5 and 6,

$$\epsilon_t = 59.0(\mathrm{SCI}) \qquad (10)$$

and

$$\log \epsilon_c = 2.1 + \log(\mathrm{BCI}) + (0.6 + 1.7\log \delta_{max})\log \delta_{max} \qquad (11)$$

where δ_{max}, SCI, and BCI are in 0.0025 cm (0.001 in) and ϵ_t and ϵ_c are in micrometers per millimeter.

The results of the analysis indicate that SCI can be related to maximum tensile strain in the base course whereas BCI is strongly related to maximum compressive strain at the top of the subgrade. By using Equations 10 and 11, it is possible to calculate maximum tensile strain in the base course and maximum compressive strain at the top of the subgrade under road rater loading from the profile of measured surface deflection. Then maximum tensile and compressive strains under 80-kN (18 000-lb) axle loads can be estimated. These two maximum strains are important factors in the evaluation of pavement performance.

Figure 7. Variation of maximum tensile strain under road rater loading with number of equivalent 80-kN (18 000-lb) axle loads.

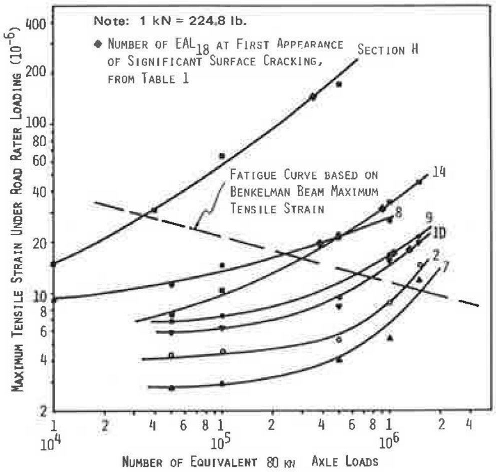
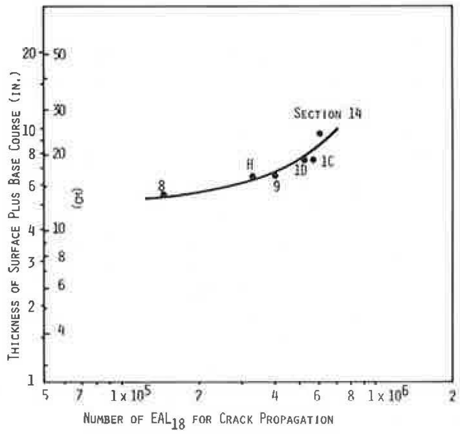


Figure 8. Number of equivalent 80-kN (18 000-lb) axle loads required for crack to propagate through base and surface layers.



CRITERIA FOR EVALUATION OF PAVEMENT PERFORMANCE

Evaluation criteria are developed by plotting maximum tensile strain in the base course under road rater loading against the number of 80-kN (18 000-lb) axle load applications for pavement sections that contain bituminous concrete base (Figure 7). Note that the data for tensile strain were analyzed based on deflections in the spring season. Figure 7 indicates that maximum tensile strain increases with an increase in the number of 80-kN axle load applications. At any tensile strain, the number of repetitions of 80-kN axle loads required to cause fatigue failure can be determined by first converting the road rater strains to Benkelman beam strains and then substituting the Benkelman beam strain values into the fatigue equation. As the maximum tensile strain increases with traffic, the number of load applications required to cause fatigue failure will decrease as shown in Figure 7.

Figure 7 also shows the number of 80-kN (18 000-lb) axle loads at the first appearance of significant surface cracking (taken from Table 1). The difference in the number of axle loads between the appearance of cracking and the initiation of a crack at the bottom of the base layer is the number of axle loads required for the crack to propagate through the base and surface layers. As expected, the number of axle loads for crack propagation increases as the thickness of the surface plus the base layer increases (Figure 8).

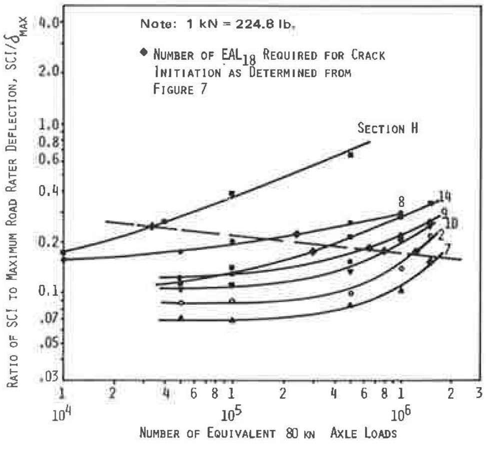
The evaluation of pavement performance is usually based on maximum surface deflection. Many researchers, however, have found that maximum surface deflection alone is not sufficient to indicate pavement performance. For instance, Ford and Bissett (18) found that the ratio of the radius of the deflection basin to maximum surface deflection is a better criterion for evaluating pavement performance. Dehlen (5) found distinct relations between both maximum deflection and minimum radius of curvature and the condition of the pavement surface. Kung (19) concluded that the slope of a deflection basin is highly correlated with the condition of the pavement surface. Leger and Autret (20) proposed that the product of maximum deflection and minimum radius of curvature is a valuable indicator of pavement condition. All of these findings were the results of studies of pavements in specific environmental and traffic conditions. Precaution should be taken, therefore, in directly applying these findings to other environmental, structural, and traffic conditions.

These research findings were developed primarily for 80-kN (18 000-lb) axle loads. Few findings of this type are available for road rater loading. The rapidly increasing use of the road rater in pavement evaluation has created a heavy demand for research findings in this area.

The pavement response data analyzed here have been used to plot maximum surface deflection (i.e., deflection at road rater sensor 1), SCI, the ratio of SCI to maximum deflection (SCI/δ_{max}), and several other possible combinations against number of 80-kN axle loads. In these graphs, the numbers of axle loads required to initiate cracking in the base courses were entered, and a line was drawn to connect these numbers. It was found that the ratio of SCI to maximum surface deflection gives a better relation between layer thickness and number of axle loads to fatigue failure. Figure 9 shows the variation of the SCI/δ_{max} ratio with axle load application for bituminous concrete sections. The figure shows that fatigue cracks are initiated in the base course of bituminous concrete sections when the ratio SCI/δ_{max} is in a range of 0.15 to 0.25.

According to this finding, there is a critical SCI to maximum surface deflection ratio. When that critical value is reached, cracks will start to develop at the

Figure 9. SCI/δ_{max} ratio under road rater loading versus equivalent 80-kN (18 000-lb) axle loads.



bottom of the base course and the base course will begin to lose its structural integrity. As a consequence, the rate of decrease in pavement serviceability will accelerate, and major repair of the pavement system may soon become necessary. Therefore, the critical value of the SCI to maximum deflection ratio could possibly be used as a criterion for determining the need for pavement overlay.

Note that, because the distance between sensors 1 and 2 is exactly 0.3 m (1 ft), the SCI value can be related to the minimum radius of curvature (R) of the deflection basin. Assume that the deflection curve between sensors 1 and 2 is circular, as shown in Figure 10. $R^2 = 1^2 + (R - SCI)^2$; $2R \cdot SCI = 1 + (SCI)^2$; $R = \frac{1}{2}[(1/SCI) + SCI]$. Because the units SCI and R are usually 0.0025 cm (0.001 in) and 0.3 m (1 ft) respectively, the following equation (empirically derived in U.S. customary units) results:

$$R = \frac{1}{2}\left(\{1/[SCI \times (10^{-3}/12)]\} + SCI \times (10^{-3}/12)\right) \tag{12}$$

or

$$R \cong (6 \times 10^3)/SCI \tag{13}$$

in feet. Thus, the ratio SCI/δ_{max} is essentially a measure of the reciprocal of the product of the radius of curvature and the maximum deflection, which is the factor proposed by Leger and Autret (20).

SUMMARY AND CONCLUSIONS

The road rater is a relatively new instrument for evaluating pavement performance. There is a need to predict the future performance of a pavement by using road rater deflections.

In this study, the BISAR computer program was used to analyze the response of experimental pavements to 80-kN (18 000-lb) axle loads and road rater loading. The experimental pavements contained four different types of base course material, but only pavements containing bituminous concrete base were analyzed. Equations were developed that interrelate various pavement responses and permit determinations of maximum tensile strain in the base course and maximum compressive strain at the top of the subgrade—strains attributable to 80-kN axle loads from the road rater deflection basin.

Based on a fatigue property determined in the laboratory, a permissible ratio of SCI to maximum deflection measured at road rater sensor 1 was determined for pavements that contain bituminous concrete base. This value may be used to evaluate pavements for rehabilitation purposes.

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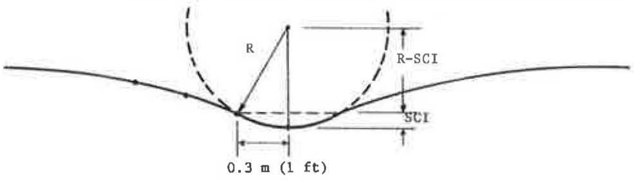
Figure 10. Surface curvature index and minimum radius of curvature.



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Evaluation of Concrete Pavements With Tied Shoulders or Widened Lanes

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Field and laboratory pavements were instrumented and load tested to evaluate the effect of widened lanes, concrete shoulders, and slab thickness on measured strains and deflections. Eight slabs were tested in the field and two in the laboratory. Pavement slabs were 203, 229, or 254 mm (8, 9, or 10 in) thick. Other major design variables included the width of lane widening, the presence or absence of dowels or of a concrete shoulder, joint spacing, and the type of shoulder joint construction. Generally, there was good agreement between measured strains and values calculated by using Westergaard's theoretical equations. Concrete shoulders were effective in reducing the magnitude of measured strains and deflections. A chart is presented to show the allowable reduction in thickness of the outer lane of the main-line pavement when there is a tied concrete shoulder. Lane widening of about 406 mm (16 in) was as structurally effective as a concrete shoulder in reducing edge strains and deflections. However, it should be remembered that a concrete shoulder provides the added advantage of draining runoff farther from the pavement edge. Because of the possibility of load encroachments on a widened lane, it is recommended that lanes be widened by a minimum of 0.46 m (1.5 ft) plus any additional width required to avoid encroachment. Under the conditions considered, tied-butt, tied and keyed, and keyed-joint constructions were equally effective in reducing load-induced pavement strains and deflections.

Existing pavements represent a major investment of highway funds. A road can seldom be abandoned or replaced. Every year many kilometers of pavements require rehabilitation to cope with increased traffic. Overlays are built for the purpose of restoring pavement serviceability and improving structural capacity, but this practice is expensive and alternative solutions are needed.

One alternative to resurfacing is the use of a widened lane or a paved concrete shoulder. This type of construction could be used not only to strengthen existing pavements but also to strengthen new pavements and thus defer rehabilitation. Another approach for the design of new pavements that include a tied concrete shoulder would be to reduce the thickness of the outer lane of the main-line pavement.

In addition to strengthening a pavement, concrete shoulders and lane widening provide a benefit not obtained by resurfacing in that runoff water is drained farther away from the wheel paths of traffic. A recent study for the Federal Highway Administration (1) determined that accumulation of water in the joint between an asphalt shoulder and a concrete pavement was a major factor in reducing pavement performance. Because of this problem, several states have installed costly longitudinal and transverse drainage systems. Thus, concrete shoulders and widened lanes have the potential for curing many drainage problems as well as providing additional slab strength.

Many design features contribute to pavement life. The effect of some of these features can be evaluated analytically. For example, analytical tools can be used to determine the effect of pavement thickness or subbase strength on pavement life. Thus, when analytical procedures are available, the engineer can combine a knowledge of pavement life with data on construction and maintenance cost to provide the most economical design.

Analytical tools often are unavailable or require the use of unknown or unverified coefficients. For example, tied shoulders reduce load deflections and stresses, but the amount of the reduction is a function of the unknown continuity across the joint between the pavement edge and the shoulder. In these cases, the most direct method of evaluating design features is a planned series of field data measurements extended by laboratory tests and analytical procedures. This paper reports on a project that incorporated these features. The principal objective of the project was to determine the effect of widened lanes, tied concrete shoulders, and slab thickness on measured strains and deflections. Field and laboratory pavements were instrumented, and measurements of load strains and deflections were obtained. The measured data were then analyzed to determine the effects of the variables on pavement life.

PAVEMENT TEST SECTIONS

Field measurements were obtained on four experimental pavement projects located in the state of Minnesota. All fieldwork was done under a contract between the Minnesota Department of Transportation and the Portland Cement Association (PCA).

Project 1 is a roadway 8.23 m (27 ft) wide that consists of a 4.57-m (15-ft) wide inside lane, a 3.66-m (12-ft) wide outside lane, and a 3.05-m (10-ft) wide outside tied and keyed concrete shoulder. Shoulders are tied at 762-mm (30-in) spacing by no. 5 tie bars 762 mm