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Road Rater and Benkelman Beam Pavement Deflections

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MEMO TO: G. F. Kemper  
State Highway Engineer  
Chairman, Research Committee

SUBJECT: Research Report 523; "Road Rater and Benkelman Beam Pavement Deflections;" Interim Report; KYHPR-70-49 and KYHPR-75-77; HPR-PL-1(14), Part II

When the experimental, full-depth asphaltic concrete pavement was placed on US 60 near Ashland, a Road Rater was included as a means of evaluating pavement performance. The use of the Road Rater in this manner has been reported in Research Report 501; "Pavement Evaluation Using Road Rater Deflections." As a part of that study, Road Rater responses were compared to those of the more conventional and commonly used Benkelman beam. This report has been prepared to document the relationships and correlations between Road Rater responses and those of the Benkelman beam.

Respectfully submitted,

James H. Havens  
Director of Research

ds  
Enclosure

cc: Research Committee
**Title and Subtitle**  
Road Rater and Benkelman Beam Pavement Deflections

**Abstract**

The Benkelman beam has been one of the most commonly used methods of measuring surface deflections of a highway pavement. A Benkelman beam is based on a simple lever-arm principle and uses dial guages to measure surface deflection under an applied load. In 1971, the Commonwealth of Kentucky purchased a Road Rater for use by the Department of Transportation, Division of Research. The Road Rater applies a sinusoidal force to the pavement at a fixed frequency; surface wave velocities are measured and electronically integrated to obtain surface deflections. Since 1971, work has progressed toward the development of a pavement evaluation methodology using Road Rater deflections. Analyses presented in this report will illustrate some relationships between the Benkelman beam and Road Rater deflections. Theoretical and field measured deflections are considered.

**Key Words**
- Benkelman Beam
- Road Rater
- Pavement Evaluation
- Surface Deflections

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ROAD RATER AND BENKELMAN BEAM PAVEMENT DEFLECTIONS

KYHPR-75-77; HPR-PL-1(14), Part II
KYHPR-70-49; HPR-PL-1(14), Part II

by

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in cooperation with the
U. S. DEPARTMENT OF TRANSPORTATION
Federal Highway Administration

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INTRODUCTION

Developing a rational overlay design procedure involves analyses to determine the condition of the pavement at a given point in time. In Kentucky, a methodology has been developed for evaluation of a pavement structure using Road Rater deflection measurements (1-5). This procedure uses field measured Road Rater deflections to estimate moduli of elasticity for subgrade materials and expresses pavement deterioration in terms of reduced layer thicknesses having qualities similar to new pavements.

In terms of deflection measuring devices, the Road Rater and Benkelman beam are comparable only in the sense that both measure surface deflection. The Road Rater loading is dynamic and consists of a vibrating load which impulses the pavement. Frequency and amplitude of vibration are pre-selected variables which control the dynamic load induced by the Road Rater. The forced motion of the pavement due to the vibratory load is measured by velocity pickup sensors normally located at 0 feet (0 m), 1 foot (3.1 m), 2 feet (6.1 m), and 3 feet (9.1 m) from the center of the test head. Deflection measurements for each sensor are displayed on meter scales and may be read directly by the operator. For a given condition, Road Rater deflections corresponding to each of the sensors may be used to plot a surface deflection basin.

On the other hand, the Benkelman beam operates on a simple lever-arm principle and uses dial mechanisms to measure surface deflections. In Kentucky, Benkelman beam tests are conducted at creep speed of the test vehicle (approximately 0.5 Hz). The test vehicle consists of a two-axle, six-tire dump truck with a load of 18 kips (80 kN) on the rear axle. Two Benkelman beams are used in the Kentucky test procedure with the tips of the beams placed between the two dual tires at each end of the axle. The maximum surface deflection is read as the vehicle tires roll past the tip (point) of the Benkelman beam. The movement of the pavement is measured by dial mechanisms attached to the beam.

While Road Rater deflections and Benkelman beam deflections can be compared (6), there is a marked difference in the sensitivity of their measurements to changing conditions in the pavement structure. The Benkelman beam is not nearly as sensitive as the Road Rater. A portion of the lost sensitivity may be attributed to the limitations associated with dial mechanisms. Dial readings for Benkelman beam tests are limited by reading the dial while the needle is in motion and by the friction pins and gears of the dial mechanism itself. On the other hand, Road Rater deflections are measured electronically and displayed on meter scales to be read by the operator. Determining a surface deflection basin using Benkelman beams requires using at least three beams. However, a deflection basin may be readily plotted using deflections from the four Road Rater sensors.

DEFLECTIONS AND THICKNESS DESIGN

In a 1971 analysis (7), thickness requirements were determined for 33-percent asphaltic concrete structures and a modulus of elasticity of 480 ksi (3.31 GPa) (corresponding to the Benkelman beam test condition, i.e., a test frequency of 0.5 Hz) and are the basis for a proposed design criterion in Kentucky (1-5, 8). The modulus in that development was assumed to be a function of the percentage of the thickness of asphaltic concrete in the total structure. The variation was assumed to be a straight-line relationship (log-log) and described the change in asphaltic concrete modulus as the temperature sensitivity of rutting varies (7).

On the other hand, the method of pavement evaluation using Road Rater deflections (1-5) is based upon a constant modulus of elasticity of $E_1 = 1,200$ ksi (8.27 GPa), a frequency of vibration of 25 Hz, and a mean pavement temperature of $70^\circ\text{F}$ (21.1°C). Thus, it was necessary to develop curves for thickness versus repetitions of an 18-kip (80-kN) EAL (equivalent axleload) for proportions of asphaltic concrete of the total thickness other than 33 percent for a constant modulus of $E_1 = 480$ ksi (3.31 GPa). These curves were developed using limiting strain criteria and the relationships contained in APPENDIX C of Reference 7 (Figures 1-4).
Figure 1. Thickness Design Curves for Pavement Structures Having 33 Percent Asphal­tic Concrete Thickness of the Total Pavement Thickness and Asphaltic Concrete Modulus of 480 ksi (3.31 GPa).
Figure 2. Thickness Design Curves for Pavement Structures Having 50 Percent Asphaltic Concrete Thickness of the Total Pavement Thickness and Asphaltic Concrete Modulus of 480 ksi (3.31 GPa).
Figure 3. Thickness Design Curves for Pavement Structures Having 75 Percent Asphaltic Concrete Thickness of the Total Pavement Thickness and Asphaltic Concrete Modulus of 480 ksi (3.31 GPa).
Figure 4. Thickness Design Curves for Pavement Structures Having 100 Percent Asphaltic Concrete Thickness of the Total Pavement Thickness and Asphaltic Concrete Modulus of 480 ksi (3.31 GPa).
SIMULATION OF BENKELMAN BEAM TESTS IN KENTUCKY

Benkelman beam deflections have been simulated by elastic theory using the Chevron N-Layer computer program. In Kentucky, the test vehicle is a two-axle, six-tire dump truck with 18 kips (80 kN) on the rear axle. Assuming equal load distribution, each rear tire applies a 4.5-kip (20-kN) load to the pavement. Superpositioning principles were used to compute the deflections between the two tires of the rear duals. Superpositioning is applicable provided the deformations are small and do not substantially affect the action of external forces. If the principles of superpositioning are to apply, a linear relationship between displacement and external force must exist or be assumed to exist (1-5, 9-11). Thus, the deflection sensed by the Benkelman beam is the sum of the deflections caused by each of the four tires on the rear axle at their respective distances from the point of measurement. This approach may be used to calculate deflections at any desired location on the pavement and for any axle configuration and loading.

An array of conditions (thicknesses of asphaltic concrete, dense-graded aggregate thicknesses, and moduli of elasticity for asphaltic concrete, dense-graded aggregate, and subgrade) was used in the Benkelman beam simulation. For three-layer pavements, the thicknesses of asphaltic concrete were 5 inches (127 mm), 8 inches (103 mm), and 14 inches (356 mm). Dense-graded aggregate thicknesses were 8 inches (203 mm), 14 inches (356 mm), and 20 inches (508 mm). Subgrade moduli used in the simulation ranged from 6 ksi (41.4 MPa) to 60 ksi (413.5 MPa) on 12-ksi (82.7-MPa) increments. Full-depth thicknesses of asphaltic concrete were 10 inches (254 mm), 14 inches (356 mm), and 18 inches (457 mm).

Moduli of granular bases were calculated as a function of the moduli of the confining layers of asphaltic concrete and subgrade. Estimation of the modulus of the crushed stone layer is obtained by the relationship $E_2 = F \times E_3$, where there is an inverse linear relationship between log F and log $E_3$. The ratio of the modulus of the base ($E_2$) to the modulus of the subgrade ($E_3$) is equal to 2.8 at a California Bearing Ratio (CBR) of 7 and is equal to one when the modulus of the asphaltic concrete ($E_1$) and the subgrade modulus ($E_3$) are equal: $E_1 = E_2 = E_3$. Subgrade moduli ($E_3$) in psi may be approximated by the product of the CBR and 1500. This method appears adequate for a CBR of 18 to 20 (1-5).

A value for Poisson's ratio ($\mu$) for the material in each layer and a tire (contact) pressure corresponding to a given load is required as input to the Chevron N-layer computer program. The following constants were used in the simulation (1-5):

Poisson's Ratio:
- Asphaltic Concrete: $\mu = 0.40$
- Granular Base: $\mu = 0.40$
- Subgrade: $\mu = 0.45$

Load per tire: 4.5 kips (20 kN)
Tire (contact) pressure: 80 psi (0.55 MPa)

Analyses (5) have shown that changes in Poisson's ratio and tire pressure have relatively insignificant effects upon the calculated deflections. Results of the simulation of Benkelman beam deflections are presented in APPENDIX A.

COMPARISON OF ROAD RATER AND BENKELMAN BEAM DEFLECTIONS

Deflections for the Road Rater and Benkelman beam may be compared directly so long as the conditions of their measurement are similar (6). A log-log plot of Benkelman beam versus Road Rater No. 1 Sensor deflections (both computed by elastic theory) for equivalent conditions is illustrated in Figure 5 and shows the effects of total thickness and thickness of asphaltic concrete to be a family of curves. Benkelman beam deflections were obtained from the results of the simulation previously described. Road Rater deflections were obtained by a similar simulation described in References 1 and 2. The magnitude of the Road Rater deflections were obtained from Appendix A of Reference 2.

Figure 5 shows the relationship between Road Rater and Benkelman beam deflections using elastic theory. A similar relationship exists for field measured deflections (Figure 6). The dashed lines in Figure 6 represent theoretical lines (from Figure 5) for the specific structures. The deflections are plotted to an arithmetic scale in Figure 6 while log scales are used in Figure 5. The points on Figure 6 represent pairs of field measured Road Rater and Benkelman beam deflections. Both Road Rater and Benkelman beam deflections were adjusted to the moduli of asphaltic concrete corresponding to the mean pavement temperature and their respective test frequencies. The adjustment factor systems for temperature will be discussed in a later section.
Figure 5. Theoretical Deflections: Benkelman Beam Deflections for an 18-kip (80-kN) Axleload versus Road Rater No. 1 Sensor Deflections.
The data points shown in Figure 6 also may be compared in another manner. The theoretical relationships of deflection for Benkelman beam versus Road Rater (Figures 5 and 6) may be used in conjunction with one or the other field measurement to predict the theoretical equivalent of that field measurement. For example, Figure 7 illustrates the situation when field measured Benkelman beam deflections are used to predict theoretically equivalent Road Rater deflections. These measurements were taken on a full-depth asphaltic concrete pavement on US 60 in Boyd County, Kentucky, in July 1972. At that time, the pavement was almost new and had suffered little or no deterioration. A complete analysis for the Boyd County (US 60) data is presented in APPENDIX B. Figure 7 combines all data presented in APPENDIX B.

The figures in APPENDIX B compare field measured pairs of Road Rater and Benkelman beam deflections with their corresponding theoretical values. These values have been adjusted to a 70°F (21.1°C) reference. Initial comparisons indicated unreasonable amounts of scatter. However, when the limits of operator error in reading the dials of the Benkelman beam and the meters of the Road Rater were considered, the majority of the scatter was explained. Also, some of the scatter could be explained by inappropriate selection of adjustment factors for temperature.

Road Rater deflections are displayed on meter scales ranging from 0 to 100 with divisions for every two units. Normal reading error is ± 1 unit on the meter. The true deflection is determined by multiplying the meter reading by the scale factor. In most instances, the scale factor is 1 x 10⁻⁵ inches (2.54 x 10⁻⁶ mm).

Figure 6. Benkelman Beam Deflections for an 18-kip (80-kN) Axleload versus Road Rater No. 1 Sensor Deflections: Dashed Lines Represent Theoretical Deflections and Points Represent Field Measurements.
Figure 7. Plot of Field Measured Road Rater No. 1 Sensor Deflections versus Predicted Road Rater No. 1 Sensor Deflections Using Measured Benkelman Beam Deflections and Elastic Theory.
Benkelman beam deflections are recorded by dial gauges. The number of divisions on the dial face is one of the main contributors to operator error. Also, since the Benkelman beam operates on lever-arm principles, the location of the fulcrum must also be considered. For the Kentucky Benkelman beam, the dial is located 4 feet (1.22 m) from the fulcrum, and the tip of the beam is 8 feet (2.43 m) from the fulcrum. Therefore, the dial reading for the Kentucky Benkelman beam is multiplied by 2 to obtain the true deflection. One division on the dial is $1 \times 10^{-3}$ inches $(2.54 \times 10^{-2} \text{ mm})$. Therefore for an error of ± 1 dial reading, the error in deflection is ± $2 \times 10^{-3}$ inches $(5.08 \times 10^{-2} \text{ mm})$.

The dashed lines on the figures in APPENDIX B illustrate different levels of error in Benkelman beam deflections with corresponding levels of error for the Road Rater. These figures indicate that an operator error of ± 1 dial reading of the Benkelman beam is more significant than an error of ± 1 unit on the Road Rater meter scale for a scale factor of $1 \times 10^{-5}$ inches $(2.54 \times 10^{-4} \text{ mm})$. All Road Rater deflections presented in APPENDIX B were determined using a scale factor of $1 \times 10^{-5}$ inches $(2.54 \times 10^{-4} \text{ mm})$. When the plots of Benkelman beam deflections versus Road Rater deflections were compared with the theoretical relationships and the reading tolerance (dashed lines) superimposed on each plot, the following results were obtained: 45 percent of the points were within ± $1 \times 10^{-3}$ inches $(2.54 \times 10^{-2} \text{ mm})$ of the theoretical Benkelman beam deflection; 71 percent were within ± $2 \times 10^{-3}$ inches $(5.08 \times 10^{-2} \text{ mm})$; and 84 percent were within ± $3 \times 10^{-3}$ inches $(7.62 \times 10^{-2} \text{ mm})$ of the theoretical deflections (APPENDIX B). The remaining points were analyzed individually using Road Rater deflection data for Sensors 1, 2, and 3 (1-5). When the Road Rater deflection basins were evaluated, every point indicated some type of abnormal behavior. In most cases, a foundation material problem was indicated. Only ten percent of the abnormal points indicated a problem in the bound layer. This was not surprising since the pavement was only 1 year old at the time of testing.

In most cases when Benkelman beam deflections were plotted versus Road Rater deflections, most points indicating foundation problems plotted below the theoretical line. On the other hand, problems with the bound layer normally plotted above the line. There were only three exceptions noted in this general pattern. Circled points indicate foundation material problems and points inside squares indicate possible bound-layer problems. These same points are shown in Figure 7. The dashed lines represent deflection tolerances corresponding to those shown in APPENDIX B. Note that the same separation of points is shown in Figure 7 as was shown in the figures in APPENDIX B.

One possible explanation for the separation of the two problem types may be related to the deflection basin. The Road Rater applies a relatively small load and measures surface deflections at specified distances from the load. A plot of the deflection basin for the Road Rater can readily be developed. Benkelman beam deflections are measured as the vehicle creeps past the tips of the beams. A surface deflection is measured, but the location of that deflection on the bowl is not known. For the Kentucky test procedure, rebound is considered and sufficient time is allowed for the dial to cease moving. Therefore, the deflection approaches a maximum deflection.

One example of an abnormal situation resulted from concurrent Road Rater and Benkelman beam tests for a site in Kentucky. Tests were taken on a layer of compacted subgrade overlying a layer of soft soil of known high moisture content overlying bedrock. Geologic and topographic conditions of the area made drainage less than adequate. Road Rater tests indicated abnormally high values, but Benkelman beam deflections at the same site were relatively low. Cracking and subsidence of the entire testing area was observed when the truck for the Benkelman beam test was driven onto the test site. When the truck was removed, the Benkelman beam indicated very little movement, yet rebound of the compacted subgrade could be visually observed. The load due to the test truck was distributed over a very large area such that both the truck and the Benkelman beam were completely within the deflection bowl.

TEMPERATURE ADJUSTMENTS FOR ROAD RATER AND BENKELMAN BEAM DEFLECTIONS

Deflection adjustment factors for temperature have been developed for the Road Rater (1, 2). Figure 8 was taken from References 1 and 2 and illustrates the temperature adjustment-factor relationship for the Kentucky Road Rater operating at a constant frequency of 25 Hz, the reference testing frequency for the Kentucky Road Rater is 25 Hz. The reference temperature for Road Rater tests in Kentucky is 70°F $(21.1°C)$, which corresponds to an asphaltic concrete modulus $E_1 = 1,200$ ksi $(8.27$ GPa) at 25 Hz $(1, 2, 8)$.  

![Figure 7: Dashed lines represent deflection tolerances corresponding to those shown in APPENDIX B. Note that the same separation of points is shown in Figure 7 as was shown in the figures in APPENDIX B.](image-url)
Figure 8. Average Pavement Temperature versus Road Rater Deflection Adjustment Factors for Full-Depth Deflection Adjustment Factors for Full-Depth and Three-Layered Asphaltic Concrete Pavements: 70°F (21.1°C), 25 Hz Reference.
Deflection adjustment factors for temperature have been developed (6, 12, 13) for use with Benkelman beam deflections but for a reference temperature of 60°F (15.6°C). These curves were readjusted to a reference temperature of 70°F (21.1°C) and includes a minor adjustment in the position of the curve for full-depth asphaltic concrete. The full-depth curve was refined when additional field data were analyzed. The resulting adjustment factors are shown in Figure 9. Benkelman beam tests are conducted at vehicle creep speeds, approximately 0.5 Hz. The modulus of asphaltic concrete associated with 70°F (21.1°C) and 0.5 Hz is \( E_1 = 480 \) ksi (3.31 GPa) (8).

![Figure 9. Average Pavement Temperature versus Benkelman Beam Deflection Adjustment Factors for Full-Depth and Three-Layered Asphaltic Concrete Pavements: 70°F (21.1°C), 0.5 Hz Reference.](image)
VARIATIONS IN DEFLECTIONS RESULTING FROM CHANGING LOADS

Normal Benkelman beam testing utilizes an 18-kip (80-kN) load on a single, four-tired axle. The deflection is measured between the dual tires at either end of the axle. One analysis of deflection data should include the effects of load on the magnitude of the deflection. To investigate this situation, five structures included in the AASHO Road Test were used. The crushed stone base thickness was held constant at 6 inches (152 mm) while asphaltic concrete thicknesses varied from 2 to 5 inches (51 to 127 mm), and moduli were constant at $E_1 = 600$ ksi (4.14 GPa), $E_2 = 19.4$ ksi (13.4 MPa), and $E_3 = 6$ ksi (4.4 MPa). These values are representative of the mean annual conditions of the AASHO Road Test.

Theoretical surface deflections were calculated for a range of loads from 2 kips (8.9 kN) to 8 kips (35.6 kN) per tire in increments of 0.5 kips (4.4 kN) per tire. Superposition principles were used to calculate theoretical deflections at various locations relative to the two tires at the end of the axle. The most critical point based on strain criteria at the bottom of the asphalt layer was located between the dual tires, specifically at the edge of the inside tire. Deflections measured by a Benkelman beam are measured at a point midway between the two tires, but there was only a small difference in the magnitudes of deflections at the two different locations.

To evaluate the effects of load on deflection, a reference load per tire of 2.5 kips (11.1 kN) was selected. Ratios of given tire loads to a 2.5-kip (11.1-kN) tire load were computed and compared to the ratio of surface deflections at the corresponding tire loads, as shown in Figure 10. Ratios of surface deflection were averaged for the five different asphaltic concrete thicknesses. It can be seen from Figure 10 that there is approximately a one-to-one relationship. Thus, if the tire load is doubled, then the corresponding deflection will be approximately doubled. This is a theoretical verification of the laws of superposition by which a linear relationship between force and displacement must exist, or be assumed to exist (1, 2, 10, 11, 12). Application of these concepts may also be used relative to load variations on the loaded feet of the Road Rater.

RELATIONSHIPS BETWEEN THEORETICAL DEFLECTIONS AND REPETITIONS OF AN 18-KIP (80-kN) AXLELOAD

When the asphaltic concrete and subgrade moduli and percentage of asphaltic concrete are held constant, the total thickness of the pavement is associated with a specific number of repetitions of an 18-kip (80-kN) axleload. Relationships illustrating this condition are presented in Figures 1-4. Likewise, for the same constant condition, there is a specific theoretical deflection corresponding to either a dynamic load for the Road Rater or a static load for Benkelman beam testing.

Theoretical deflections corresponding to the Kentucky Road Rater were calculated for a matrix of thicknesses and moduli using the Chevron N-layer Computer Program (14) and elastic theory. These deflections are presented graphically in Appendix A of Reference 2. Figures 11-15 illustrate similar conditions for deflections corresponding to an 18-kip (80-kN) axleload which is appropriate for Benkelman beam deflection tests in Kentucky. The information presented in Figures 11-15 was obtained from the appendices of Reference 6 and were calculated using the Chevron program and elastic theory.

As the total thickness of the pavement changes, there is a change in the number of repetitions and also a change in the magnitude of deflection for a specific loading. Figure 16 displays the Benkelman beam deflections and their corresponding number of repetitions for specific percentages of asphaltic concrete and subgrade moduli. Figure 17 displays the Road Rater No. 1 Sensor deflections and corresponding number of repetitions for the same conditions. Moduli of asphaltic concrete for both figures (16 and 17) correspond to a mean pavement temperature of 70°F (21.1°C). The difference in moduli is associated with the different frequencies of testing (1, 2, 8). For Benkelman beam tests at 70°F (21.1°C) and 0.5 Hz, the modulus of elasticity of the asphaltic concrete is $E_1 = 480$ ksi (3.31 GPa). For Road Rater tests at 70°F (21.1°C) and 2.5 Hz, the modulus is $E_1 = 1,200$ ksi (8.27 GPa).
Figure 10. Effects of Tire Load on Magnitude of Deflection.
Figure 11. Relationship between Percentage Asphaltic Concrete, Total Pavement Thickness, and Magnitude of Benkelman Beam Deflections (18-kip (80-kN) axle-load): CBR = 4, $E_1 = 480$ ksi (3.31 GPa)
Figure 12. Relationship between Percentage Asphaltic Concrete, Total Pavement Thickness, and Magnitude of Benkelman Beam Deflections (18-kip (80-kN) axle-load): CBR = 8, $E_1 = 480$ ksi (3.31 GPa).
Figure 13. Relationship between Percentage Asphaltic Concrete, Total Pavement Thickness, and Magnitude of Benkelman Beam Deflections (18-kip (80-kN) axle-load): CBR = 12, $E_1 = 480\, (3.31\, \text{GPa})$. 

PERCENTAGE AC OF TOTAL THICKNESS

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LINES OF EQUAL BENKELMAN BEAM DEFLECTION

CBR = 12
$E_1 = 3.31\, \text{GPa}$
(480,000 PSI)

MILLIMETERS x $10^{-1}$

INCHES x $10^{-3}$

TOTAL THICKNESS

TOTAL THICKNESS

0

100

200

300

400

500

600

700

2.54 (10)

3.175 (12.5)

3.81 (15)

5.08 (20)

6.35 (25)

7.62 (30)

8.89 (35)

10.16 (40)
Figure 14. Relationship between Percentage Asphaltic Concrete, Total Pavement Thickness, and Magnitude of Benkelman Beam Deflections (18-kip (80-kN) axle-load): CBR = 16, $E_I = 480$ ksi (3.31 GPa).
Figure 15. Relationship between Percentage Asphaltic Concrete, Total Pavement Thickness, and Magnitude of Benkelman Beam Deflections (18-kip (80-kN) axle-load): CBR = 20, $E_1 = 480$ ksi (3.31 GPa).
Figure 16. Benkelman Beam Deflections for an 18-kip (80-kN) Axleload versus Number of Repetitions of an 18-kip (80-kN) Equivalent Axleload for Selected Percentages of Asphaltic Concrete: $E_1 = 480$ ksi (3.31 GPa).
Figure 17. Road Rater No. 1 Sensor Deflections versus Number of Repetitions of an 18-kip (80-kN) Equivalent Axleload for Selected Percentages of Asphalbic Concrete: $E_1 = 1,200$ ksi (8.27 GPa).
Figure 17 requires a note of caution. The No. 1 Sensor deflections are those corresponding to a pavement condition wherein the material in all layers is of high quality and all layers are behaving in a normally expected manner. Figure 17 will not apply to pavement structures where the asphaltic concrete has deteriorated by cracking or viscoelastic creeping or the unbound layers have an excessive water content.

**SUMMARY**

Benkelman beam deflections computed by elastic theory have been successfully related to Road Rater deflections computed by elastic theory. Theoretical relationships for Road Rater versus Benkelman beam deflections have been verified by field measurements. The degree of sensitivity to variations in a pavement structure is much higher for the Road Rater than for the Benkelman beam.

A theoretical analysis of load variation and magnitude of surface deflection indicated that there is a linear relationship between external force and magnitude of displacement. This supports the assumptions for the use of superpositioning in simulation of the Benkelman beam and Road Rater.

Relationships have been developed which show the variations in Road Rater and Benkelman beam deflections and repetitions of an 18-kip (80-kN) equivalent axleload (EAL) for some selected percentages of asphaltic concrete.

**REFERENCES**


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APPENDIX A

THEORETICAL DEFLECTIONS FOR
BENKELMAN BEAM TESTING IN KENTUCKY
ASPHALTIC CONCRETE THICKNESS (MILLIMETERS)

E₁ = 480,000 PSI
TWO LAYER PAVEMENT SYSTEM

E₃ = 6000

E₃ = 18000

E₃ = 30000

E₃ = 42000

E₃ = 60000

SIMULATION BENKELMAN BEAM DEFLECTION
TWO TIRES - 80 PSI EACH, 4500 LB PER TIRE
9000 LB WHEEL, 18,000 LB AXLE
DEFLECTION AT 6 BETWEEN TIRES
**ASPHALTIC CONCRETE THICKNESS (MILLIMETERS)**

- \( E_f = 480,000 \text{ PSI} \)
- THREE LAYER PAVEMENT SYSTEM

\( E_2 = 19500, E_3 = 6000 \)

\( E_2 = 43200, E_3 = 18000 \)

\( E_2 = 63600, E_3 = 30000 \)

\( E_2 = 80850, E_3 = 42000 \)

\( E_2 = 105000, E_3 = 60000 \)

**SIMULATION BENELMAN BEAM DEFLECTION**

TWO TIRES - 80PSI EACH, 4500LB PER TIRE
9000LB WHEEL, 18000LB AXLE
DEFLECTION AT 6 INCHES BETWEEN TIRES
APPENDIX B

BENKELMAN BEAM DEFLECTIONS VERSUS ROAD RATER DEFLECTIONS:
THEORETICAL AND FIELD MEASUREMENTS

US 60 Boyd County, Kentucky
US 60 EAST
STA 155 +33 TO 182 +66
DESIGN THICKNESS 12.0" AC
CORE THICKNESS 12.0" DGA
TEST DATE 6/23/72
ALL DEFLECTIONS ADJUSTED
TO 70°F BASE
○ SHOULDER LANE
△ MEDIAN LANE

NOTE:
READING TOLERANCES
ROAD RATER No.1 SENSOR DEFLECTION (MILLIMETERS X 10^-4)

US 60 EAST
STA 182 + 66 TO 210 + 00
DESIGN THICKNESS 10.0" AC
CORE THICKNESS 10.3" AC

TEST DATES
SHOULDER LANE 6/26/72
MEDIAN LANE 6/27/72
ALL DEFLECTIONS ADJUSTED TO
A 70°F BASE

• SHOULDER LANE
△ MEDIAN LANE

NOTE:
READING TOLERANCES

ROAD RATER No.1 SENSOR DEFLECTION (INCHES X 10^-5)
ROAD RATER No. 1 SENSOR DEFLECTION (MILLIMETERS X 10^-4)

US 60 EAST
STA 210 +00 TO 245 +00
DESIGN THICKNESS 18.0"AC
CORE THICKNESS 17.4"AC
TEST DATES
SHOULDER LANE 6/26/72
MEDIAN LANE 6/27/72
ALL DEFLECTIONS ADJUSTED TO
A 70" BASE
○ SHOULDER LANE
△ MEDIAN LANE

NOTE:
READING TOLERANCES

ROAD RATER No. 1 SENSOR DEFLECTION (INCHES X 10^-3)
ROAD RATER No. 1 SENSOR DEFLECTION (MILLIMETERS x 10^-4)

US 60 EAST
STA 245 +00 TO 285 +00
DESIGN THICKNESS 16.0" AC
CORE THICKNESS 16.9" AC
TEST DATES
SHOULDER LANE 6/26/72
MEDIAN LANE 6/27/72
ALL DEFLECTIONS ADJUSTED TO
A 70°F BASE
○ SHOULDER LANE
△ MEDIAN LANE

NOTE:
READING TOLERANCES

ROAD RATER No. 1 SENSOR DEFLECTION (INCHES x 10^-5)
ROAD RATER No. 1 SENSOR DEFLECTION (MILLIMETERS X 10^-4)

US 60 EAST
STA 321 + 50 TO 347 + 50
DESIGN THICKNESS 18.0" AC
CORE THICKNESS 18.2" AC
TEST DATES
SHOULDER LANE 6/27/72
MEDIAN LANE 7/6/72
ALL DEFECTIONS ADJUSTED TO
A 70°F BASE
O SHOULDER LANE
Δ MEDIAN LANE

NOTE:
READING TOLERANCES
ROAD RATER No. 1 SENSOR DEFLECTION (MILLIMETERS X 10^-4)

US 60 EAST
STA 347+50 TO 373+50
DESIGN THICKNESS 16.0" AC
CORE THICKNESS 17.5" AC
TEST DATES
SHOULDER LANE 6/27/72
MEDIAN LANE 7/6/72
ALL DEFLECTIONS ADJUSTED TO
A 70°F BASE
Ο SHOULDER LANE
△ MEDIAN LANE

NOTE:
READING TOLERANCES

ROAD RATER No. 1 SENSOR DEFLECTION (INCHES X 10^-5)
US 60 EAST
STA 399+50 TO 425+68
DESIGN THICKNESS 6.5" AC, 19.0" DGA
CORE THICKNESS 6.8" AC, 19.0" DGA
TEST DATES
SHOULDER LANE 7/6/72
MEDIAN LANE 7/12/72
ALL DEFLECTIONS ADJUSTED TO
A 70°F BASE
O SHOULDER LANE
△ MEDIAN LANE

NOTE:
READING TOLERANCES

ROAD RATER No. 1 SENSOR DEFLECTION (INCHES x 10^-5)

ROAD RATER No. 1 SENSOR DEFLECTION (MILLIMETERS x 10^-4)