Pavement Evaluation Using Dynamic Deflections

Gary W. Sharpe*   Herbert F. Southgate†
Robert C. Deen‡

*Kentucky Department of Transportation
†Kentucky Department of Transportation
‡Kentucky Department of Transportation

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G. W. Sharpe, H. F. Southgate, and R. C. Deen
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ABSTRACT

Dynamic test deflections have been duplicated by elastic theory using the Chevron N-layered computer program. Dynamic surface deflections obtained using the Road Rater have been used in conjunction with elastic theory to analyze pavement behavior. A procedure has been developed to use field measured Road Rater deflections to estimate the elastic moduli of the foundation material and to determine the equivalent thicknesses of new material which approximate the behavior of the structure. The estimated moduli and (or) equivalent thicknesses may be used as inputs to design overlay thicknesses. An analysis of the deflections of the first three sensors of the Road Rater also makes it possible to distinguish weaknesses in asphaltic concrete layers from weaknesses in the supporting foundation.
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by

Gary W. Sharpe
Research Engineer

Herbert F. Southgate
Chief Research Engineer

and

Robert C. Deen
Assistant Director

Division of Research
Bureau of Highways
DEPARTMENT OF TRANSPORTATION
Commonwealth of Kentucky

offered for publication by the
Transportation Research Board

November 1978
INTRODUCTION

Foundation (subgrade) stiffness is one of the factors affecting the behavior of a pavement structure. Variations in subgrade support occur mainly as a result of variations in moisture contents and soil types. A significant decrease in subgrade stiffness or modulus of elasticity will result in a loss of ability to support the pavement structure and lead to increased distress in the layers of the structure. Signs of distress are rutting, increased roughness, and cracking (1).

Non-destructive tests have been empirically correlated with field strength tests. There has been some considerable use of elastic theory and dynamic testing to estimate layer moduli (2-7). Equipment includes the Dynaflect, the California traveling deflectometer, the Benkelman beam, and the Road Rater. Since 1971 in Kentucky, Road Rater deflections have been under study as indicators of the characteristics of individual layer components of the pavement structure.

Estimates of subgrade strength are necessary to evaluate overall pavement conditions. A "design" condition exists when there is no loss of "effective" thickness in any of the layers. A knowledge of as-built thicknesses of layers is necessary before an evaluation of the pavement structure can be made. Those thicknesses should be available from construction and (or) maintenance records. Generally, conditions involve deterioration in the layers of the structure. This means that the individual layers are behaving similar to another combination of layer thicknesses composed of new-quality materials or that the structure is behaving as an "effective" structure. In this case, it becomes necessary to estimate layer thicknesses of the deteriorated or "effective" structure.

The analysis of deflections involves the shape of the deflection bowl (2, 6). When the logarithm of Road Rater deflections are plotted versus distance from the load, a secant line may be drawn through two points on the deflection bowl. The combination of the slope of this line and the magnitudes of deflections is indicative of types of problems in the pavement structure.

ROAD RATER SIMULATION BY ELASTIC THEORY

CHARACTERISTIC OF THE ROAD RATER

The testing head on the Kentucky Road Rater consists of a vibrating mass weighing 72.6 kg (160 pounds), which impulses the pavement; the forced motion of the pavement is measured by velocity sensors normally located at 0 mm (0 feet), 305 mm (1 foot),
610 mm (2 feet), and 914 mm (3 feet) from the center of the test head. Frequency of the vibrator may be chosen from pre-selected frequencies of 10, 20, 25, 30, and 40 Hz. The vibrating mass is lowered to the pavement by a hydraulic system. At a hydraulic pressure of 4.82 MPa (700 psi), the static load for the Kentucky unit is 7.428 kN (1,670 pounds).

The response of a pavement to the vibrating mass of the Road Rater was determined for several full-depth asphaltic concrete pavements and conventional three-layer pavements. Resonant frequencies of the total pavement structure were usually multiples of approximately 7 Hz. The thickness of the asphaltic concrete layer appeared to cause the resonant frequency to shift 1 or 2 Hz at the 21 and (or) 28 Hz normal resonant frequencies. Resonance at these frequencies was indicated by oscillations of the meter's needle as opposed to the normally "rock steady" behavior. In all cases, the meter response remained steady at 25 Hz, which thus was chosen as the reference frequency.

A frequency of 25 Hz and an amplitude of vibration of 1.524 mm (0.06 inch) results in a peak to peak dynamic force of 2.668 kN (600 pounds). Once the dynamic force is set for a given frequency and amplitude, the other preset frequencies will vary the amplitude of the vibrating mass such that the dynamic force remains constant for all of the pre-selected frequencies. The composite loading consists of a static load of 7.428 kN (1,670 pounds) with a dynamic force of 2.668 kN (600 pounds), peak to peak, oscillating about the static load.

SUPERPOSITION PRINCIPLES

The Road Rater loading is transmitted to the pavement by means of two "feet" symmetrically located on either side of a beam extending ahead and carrying the sensors. Superposition principles are applicable in computing the deflection at each sensor location. A combined load may be subdivided into its component loads. 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 (8, 9, 10). Applying superposition principles to the Road Rater, the deflection resulting from the load applied to one "foot" must be added to the deflection due to the load applied by the other "foot". For the symmetrical conditions of the Road Rater, deflection calculations only need to be made for one "foot" and the radii corresponding to each sensor location.
The dynamic loading (sine wave) of the Road Rater can be approximated by a square wave, such that the maximum value of the square wave is equal to $1/\sqrt{2}$ times the peak value of the sine wave. The peak to peak loadings of the Road Rater are 8.37 kN (1,882 pounds) and 6.49 kN (1,458 pounds). From symmetry, the loads on each "foot" of the test head are equal to 4.19 kN (941 pounds) and 3.24 kN (729 pounds). The dynamic deflection is defined by $\Delta_{\text{total}} = (\Delta_{4.19} \cdot \Delta_{3.24}) \times 2$, where $\Delta_{4.19}$ and $\Delta_{3.24}$ represent the deflections calculated by the Chevron computer program from the peak loading conditions.

**INPUT PARAMETERS FOR SIMULATION USING THE CHEVRON COMPUTER PROGRAM**

In addition to load, required inputs to the Chevron computer program include a contact pressure corresponding to the load, number of layers, and thickness, Young’s modulus, and Poisson’s ratio for each layer. The contact pressure of the low and high loads are inputed in order to maintain the correct area for each “foot”. The following constants were used in simulating the Road Rater (11):

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

- Load = 4.186 kN (941 pounds): Contact pressure = 0.231 MPa (33.5 psi)
- Load = 3.243 kN (729 pounds): Contact pressure = 0.183 MPa (26.5 psi)

The asphaltic concrete thicknesses were 50.8, 127.0, 203.2, 279.4, and 355.6 mm (2, 5, 8, 11, and 14 inches); dense-graded aggregate thicknesses were 50.8, 203.2, 355.6, 508.0, and 685.8 mm (2, 8, 14, 20, and 27 inches). Full-depth asphaltic concrete thicknesses were 101.6 to 508.0 mm by 50.8-mm intervals (4 to 20 inches by 2-inch intervals). Moduli values for asphaltic concrete varied from 1.38 GPa (200 ksi) to 13.79 GPa (2,000 ksi) on 1.38-GPa (200-ksi) increments. Subgrade moduli of elasticity varied from 0.041 GPa (6 ksi) to 0.41 GPa (60 ksi) on 0.041-GPa (6-ksi) increments.

**REFERENCE CONDITIONS**

The modulus of elasticity of asphaltic concrete varies as a function of frequency of loading and temperature. Conditions for the current Kentucky thickness design procedures and the method for conducting Benkelman beam tests correspond to a modulus
of 3.31 GPa (480 ksi) at 0.5 Hz and a pavement temperature of 21.1°C (70°F). The reference frequency for the Road Rater was selected at 25 Hz, and the corresponding asphaltic concrete modulus at 21.1°C (70°F) is 8.27 GPa (1,200 ksi).

Moduli of granular bases ($E_2$) are a function of the moduli of the confining layers of asphaltic concrete ($E_1$) and subgrade ($E_3$). Estimation of the modulus of the crushed stone layer is accomplished 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 $E_1$ equals $E_3$: $E_1 = E_2 = E_3$ (11) -- which is the case of a Boussinesq semi-infinite half-space. Subgrade moduli ($E_3$) in psi may be approximated by the product of the CBR and 1,500 (11, 12, 13). This method of estimating base moduli appears adequate for normal design considerations up to a CBR of 18 to 20 (11, 12, 13, 14).

For a constant structure and asphaltic concrete modulus, a theoretical relationship between deflection and subgrade modulus of elasticity ($E_3$) may be developed from the simulated Road Rater deflections. An example of such a relationship is illustrated by Figure 1. There is a separate line for each sensor on the Road Rater. Figure 1 also contains a fourth line labeled No. 1 projection. This line is calculated using No. 2 and No. 3 deflections and will be discussed later. The theoretical relationships illustrated by Figure 1 were developed for a constant structure and the reference asphaltic concrete modulus for the Road Rater ($E_1 = 8.27$ GPa(1,200 ksi)).

**ADJUSTMENTS FOR NON-REFERENCE CONDITIONS**

**MODULI OF ASPHALTIC CONCRETE FROM FIELD TEST DATA**

Field measurements include Road Rater deflections, surface temperature, time of day, and frequency of vibration. Surface temperature, time of day, and the mean air temperature history for the previous 5 days are necessary to find the temperature distribution using the method developed by Southgate and Deen (15, 16). The 5-day mean air temperature history can be obtained from weather records.

The modulus of elasticity of asphaltic concrete is a function of frequency of loading and mean pavement temperature, illustrated in Figure 2. Figure 2 may be used to develop a relationship between modulus and temperature for the reference frequency of 25 Hz or any other frequency desired (17), which may be representative of other dynamic loads.
Thus a moduli distribution through the asphaltic concrete layer for the reference frequency of 25 Hz can be determined for any temperature distribution. For layers thinner than 152.4 mm (6 inches), the better results were obtained when the pavement modulus was the average of the moduli on 12.7-mm (1/2-inch) intervals beginning at the 25.4-mm (1-inch) level. For asphalt thicknesses greater than 152.4 mm (6 inches), the most representative modulus appeared to be the mean of the moduli on 25.4-mm (1-inch) intervals beginning at the 25.4-mm (1-inch) level.

**ADJUSTMENT FACTORS FOR ROAD RATER DEFLECTIONS**

Because of the significant effects of temperature on modulus of elasticity of asphaltic concretes, it was necessary to develop a system to adjust deflection measurements to a reference temperature and modulus. The adjustment factor system uses ratios of deflections at reference conditions to deflections resulting from arrayed variables of layer thicknesses and moduli.

For a given thickness of asphaltic concrete, adjustment factors vary according to changes in thickness of dense-graded aggregate and modulus of the subgrade. Adjustment factor variations are minimal for variations in dense-graded aggregate thicknesses and subgrade moduli when compared to the variation in adjustment factor for variations in asphaltic concrete thicknesses. Adjustment factors for all dense-graded aggregate thicknesses for a constant subgrade modulus and thickness of asphaltic concrete were averaged into a single line. Treating other thicknesses the same produces similar relationships. Investigation of other subgrade moduli indicated minor variation in adjustment factor values for the same thickness of asphaltic concrete. Averaging the adjustment factors for each thickness of asphaltic concrete and across subgrade moduli produced the adjustment factor curves shown in Figure 3.

Two-layered pavements have similar variations in adjustment factor relative to subgrade moduli and asphaltic concrete thicknesses. Averaging the adjustment factors for all subgrade moduli and a constant thickness of asphaltic concrete results in Figure 4.

A mean pavement modulus can be found using the distribution of asphaltic concrete moduli through the pavement. The necessary adjustment factor (a multiplier) required to bring the field deflection to a deflection at a reference modulus is determined by entering the appropriate adjustment factor chart (three layers -- Figure 3, or two layers -- Figure 4) with the mean pavement modulus of elasticity.
An alternate method of presenting the adjustment factors from Figures 3 and 4 is shown in Figure 5. The adjustment factor system presented in Figure 5 adjusts deflections to a specific condition -- 25 Hz, 21.1°C (70°F) mean pavement temperature, and \( E_1 = 8.27 \text{ GPa (1,200 ksi)} \). The same method of calculating ratios of deflections was used in developing Figure 5 as was used to develop Figures 3 and 4. The only difference is that Figures 3 and 4 were developed on a basis of mean pavement modulus while Figure 5 was computed on the basis of mean pavement temperature. A reduction in frequency while holding pavement modulus constant results in a reduced pavement temperature. Thus, if the frequency is reduced, the adjustment factor curves will not shift, but the mean pavement temperature scale will shift according to the chosen frequency. Also, mean pavement temperature is a function of asphaltic concrete thickness. The effects of asphaltic concrete thickness and subgrade modulus were averaged in the development of Figure 5. Figures 3 and 4 adjust Road Rater deflections to a reference modulus \( E_1 = 8.27 \text{ GPa (1,200 ksi)} \) regardless of the frequency of loading. Figure 5 adjusts Road Rater deflections to a reference temperature and frequency and the corresponding asphaltic concrete modulus -- 25 Hz, 21.1°C (70°F), and \( E_1 = 8.27 \text{ GPa (1,200 ksi)} \).

The adjustment factor system presented in Figures 3-5 was developed using theoretical deflection data corresponding to the No. 1 Sensor. A similar system could have also been developed using deflection data corresponding to either the No. 2 or No. 3 Sensors. For comparison purposes, adjustment factors corresponding to the No. 2 and No. 3 Sensors were computed for the same conditions and using the same methodology. A comparison of the three different adjustment factors indicated an average difference of ± 0.032 for the adjustment factors corresponding to the No. 1 and No. 2 Sensors and an average difference of ± 0.048 for the No. 1 and No. 3 Sensors. The differences were obtained for a range of asphaltic concrete moduli from \( E_1 = 1.38 \text{ GPa (200 ksi)} \) to \( E_1 = 13.79 \text{ GPa (2,000 ksi)} \). The greatest differences in adjustment factors occurred at lower values of moduli and thin layers of asphaltic concrete. For example, a comparison of differences in adjustment factors for moduli greater than 4.14 GPa (600 ksi) indicated differences of ± 0.021 and ± 0.037 for the No. 1 Sensor versus the No. 2 and No. 3 Sensors, respectively. Based on these analyses, the deflection adjustment factor curves shown in Figures 3-5 were assumed to be adequate for use with deflections for the No. 1, No. 2, and No. 3 Sensors of the Kentucky Road Rater.
EVALUATION OF THE PAVEMENT STRUCTURE

DESCRIBING THE SHAPE OF THE DEFLECTION BOWL

An empirical evaluation of Road Rater deflection data involves extrapolating a straight line through the magnitudes of the deflections of the No. 2 and No. 3 Sensors when log deflection is plotted versus arithmetic distance from the load head. Extrapolation of the line to the position corresponding to the No. 1 Sensor results in the No. 1 projection (Figure 6):

No. 1 projection = \[ 10^{(2 \log \text{No. 2 deflection}) - \log \text{No. 3 deflection}} \]

The slope of the semi-log line (secant line), the difference in magnitude between the No. 1 projection and the No. 1 Sensor deflection, and the magnitudes of all deflections are indicative of the shape of the deflection bowl. This concept may be applied to theoretical deflections and as well as field-measured deflections.

ESTIMATING SUBGRADE MODULI

Knowing layer thicknesses, relationships can be developed (from elastic theory) between theoretical deflections and subgrade moduli. An example for one structure is shown in Figure 1. Field deflections for No. 2 and No. 3 Sensors and their corresponding No. 1 projection may be used as inputs in the subgrade moduli estimation process to obtain three values for the subgrade modulus. The average modulus of the subgrade is calculated from the three estimates. The No. 1 Sensor is closest to the point of application of the load and is most indicative of the condition of the pavement slab. For this reason, the deflection of the No. 1 Sensor is not used in estimating the subgrade modulus. Sensors No. 2 and No. 3 are farther from the point of application of the load and are therefore more indicative of the condition of the foundation or supporting layers of the structure. The deflection of the No. 4 Sensor is not used in the pavement evaluation process because there is little variability in deflection corresponding to changes in structural conditions of the pavement.

Subgrade moduli corresponding to the No. 2 and No. 3 deflections and the No. 1 projections were estimated for four pavements (54 test sites). At the time of testing, each of these test pavements was less than 2 years old and showed no visible signs of deterioration. The average difference between subgrade moduli for any of the three
predictors was 24.8 MPa (3.6 ksi) with a standard deviation of 22.1 MPa (3.2 ksi). When these three estimates of subgrade modulus were averaged and compared to the magnitude of the subgrade modulus estimated from the No. 2 Sensor deflection, the mean difference between average subgrade modulus and modulus estimated from the No. 2 deflection was only 4.95 MPa (0.718 ksi) with a standard deviation of 7.58 MPa (1.10 ksi). Using the data from these four pavements and in the interest of simplification of the system, the No. 2 Sensor deflection was selected as the sensor to be used to estimate subgrade modulus.

The variability in estimated subgrade modulus may be related to the operator’s ability to read the correct deflection on the Road Rater’s meters, the selection of the most appropriate deflection adjustment factor, and the accuracy of graphical interpolations in reading the subgrade modulus corresponding to a given deflection. Some error of interpolation for the correct structure could also be induced while building the theoretical curves (Figure 1) from the matrix of conditions used in the Road Rater simulation.

A log-log plot of No. 1 deflections versus the estimated subgrade moduli (from Sensor No. 2) should be made for field deflections, similar to Figure 7. The No. 1 measured deflection was selected because it showed the greatest sensitivity to the condition of the asphaltic concrete layer; the No. 2 deflections were more indicative of the condition of the supporting foundation.

If the field deflections and the estimated subgrade moduli match the theoretical values for the original structure, the pavement is behaving as expected (Figure 7). Over a length of pavement, it is normal to have a range in subgrade modulus due to moisture content and soil type variations. If pavement performance (deflections) does not match the original theoretical structure line, the pavement is behaving as a thinner, “effective” structure (Figure 8).

Use of reduced thickness as an expression of deterioration is only one option available. Deterioration could also be expressed in terms of reduced layer moduli for constant layer thicknesses. Deterioration in terms of reduced thicknesses was selected because of its adaptability to overlay design. The “effective” structure, expressed in terms of reduced layer thicknesses having properties similar to new pavement, could be used as an input parameter for overlay design.
ESTIMATING EFFECTIVE STRUCTURE

To evaluate the "effective" structure, lines of equal deflection (No. 1 Sensor) were drawn for a matrix of layer thicknesses and subgrade moduli for a constant reference modulus for asphaltic concrete \( E_1 = 8.27 \) GPa (1,200 ksi) (Figure 9). It was assumed that the "effective" structure was defined by effective layer thicknesses and the modulus of the subgrade. In Figure 9, the subgrade modulus is held constant. One method \((18)\) of estimating the amount of deterioration (percentage net worth) is presented in graphical form in Figure 10 in terms of percentage of residual or net worth versus percentage of the design thickness. Figure 10 is a modification of a concept used in Florida and revealed in informal conversations. There it was assumed that the asphaltic concrete had a residual value of 50 percent of its original value at a pavement serviceability index (PSI) of 1.5. Figure 10 is based on the assumption of 30 percent residual value at a PSI of 1.5. A relationship of percentage of original asphaltic concrete thickness versus percentage of the original dense-graded aggregate was developed using Figure 10 and is shown in Figure 11.

Deflection increases along a deterioration curve (Figure 9) as the thicknesses of the individual layers decrease. Ratios of the deflection of the deteriorated structure to the deflection of the original structure (an expression of the degree of deterioration) versus deteriorated structure in terms of percentage of the original thickness of each layer are illustrated in Figure 12, where the modulus of the subgrade is a constant. A sensitivity analysis was made of the ratio of deflections versus percentage of asphaltic concrete in the original design thickness as the subgrade modulus varied. The analysis showed that, for a normal range of subgrade moduli (42 MPa (6 ksi) to 206 MPa (30 ksi)), there was very little change in the ratio of deflections versus percentage of original thickness relationship.

PROCEDURE FOR EVALUATING EFFECTIVE STRUCTURE

The "effective" structure is determined from plots of deflection versus subgrade modulus and ratio of deflections versus percentage of the original thicknesses. The procedure follows:

1. For a given subgrade modulus, read the theoretical deflection corresponding to the original structure from the plot of No. 1 deflections versus subgrade moduli (Figure 8).
A plot of No. 1 projected deflections versus No. 1 Sensor deflections in log-log form may be used to identify variations in pavement structure. The solid lines (Figures 16 and 17) show the theoretical relationships of No. 1 projected deflections and No. 1 Sensor deflections for a constant structure and asphaltic concrete modulus. Subgrade moduli varies along the line. The points about the line represent field-measured deflections. The variation in position of the theoretical line due to changes in the magnitudes of the deflections by ± one unit (2.54 x 10^-4 mm or 1 x 10^-5 inches) and the associated change in calculated No. 1 projection is indicated by the two dashed lines. The zone inside these lines represents a normal variation due to reading the meters of the Road Rater.

Figures 16 and 17 illustrate conditions that may occur in the life of a pavement structure. The following situations have been observed from limited field evaluations:

1. Test data for new construction consisting of high-quality material and construction control will lie in the zone of normal variation and have relatively low deflection magnitudes.

2. If the subgrade remains in good condition, but cracking or some other problem has caused deterioration of the pavement slab, the data will plot on the lower side of the zone of normal variation.

3. Two conditions are indicated when the data plots in the higher range of the zone of normal variation as compared to deflection magnitudes in Condition No. 1. Changes in types of soil with the pavement remaining in good condition, and the layers acting in concert, causes the deflections to shift to the higher magnitudes. However, a deteriorated slab coupled with excessive water content in the subgrade will result in a very similar shift in deflection magnitudes. Again, the layers act in concert with each other. Interpretation should be made comparing these locations with the majority of the test data for the length of roadway under investigation.

4. Subgrades having excessive water content will produce test data which will plot above the zone of normal variation. This condition and pattern of deflections was confirmed by test data obtained by LaBelle Consultants (20). They performed Road Rater tests, cored the pavements, obtained subgrade samples, and determined the moisture contents of the subgrade. Those locations having high water contents (possibly free water) produced deflections for which the difference between the No. 1 projected and measured deflections was considerably greater than the theoretical analyses would have indicated. One possible
explanation is that water is a much better transmitter of sound or vibrations than is soil. Thus, the vibrations are transmitted more easily and their magnitudes remain greater at a fixed distance from the source than those transmitted through normal subgrades. Therefore, the No. 2 and 3 Sensors measure higher deflections for soils having excessive water than for those soils having normal water contents.

SUMMARY

1. Dynamic deflections measured by the Road Rater have been rationally analyzed and duplicated by elastic theory.
2. Road Rater deflections have been used to estimate in-place subgrade moduli.
3. A system has been developed which relates deflection behavior of the pavement to “effective” layer thicknesses with new-material qualities. These “effective” layer thicknesses may be considered as the residual structure after deterioration and may be used as inputs for overlay design.
4. A method of analyzing Road Rater deflections has been developed which makes it possible to identify the type of deterioration in the pavement structure (slab problems or foundation problems).

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ACKNOWLEDGEMENTS

The concepts, data, and analyses reported in this paper are a result in part of Research Study KYHPR-75-77, Development of a Rational Overlay Design Method for Pavements, conducted as a part of Work Program HPR-PL-1(14), Part II, funded by the Federal Highway Administration and the Kentucky Department of Transportation. The contents of the report reflect the views of the authors who are responsible for the facts and accuracy of the data presented. The contents do not necessarily reflect the official views or policies of the Kentucky Department of Transportation nor of the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.
Figure 1. Theoretical Relationships, Road Rater Deflection versus Subgrade Modulus of Elasticity for a Constant Structure and Asphaltic Concrete Modulus.
Figure 2. Influence of Temperature and Frequency upon Dynamic Modulus of Elasticity (17).
Figure 3. Asphaltic Concrete Thickness versus Temperature Adjustment Factor for Three-Layered Pavements.
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Figure 15. Deflection versus Distance from Load Head and Determination of No. 1 Projection: Example Difference between No. 1 Sensor Deflection (1M) and No. 1 Projection (1P) for a Pavement with a Foundation Support Problem.
Figure 16. Relationship between Road Rater No. 1 Projection and Road Rater No. 1 Sensor Deflection; Field Measurements Indicate a Normal Relationship.

\[ E_t = 8.27 \text{ GPa (1,200,000 PSI)} \]

TEST DATE 7/6/77

127.0 mm AC (5")
177.8 mm DGA (7")

ZONE OF NORMAL VARIATION

FOUNDATION SUPPORT

PROBLEM

SLAB PROBLEM

STATION A
STATION B
STATION C
Figure 17. Relationship between Road Rater No. 1 Projection and Road Rater No. 1 Sensor Deflection; Field Measurements Indicate a Foundation Support Problem.