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NONDESTRUCTIVE EVALUATION OF RIGID PAVEMENTS

USING ROAD RATER DEFLECTIONS

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Road Rater deflections have been used to determine in-place structural conditions of rigid and composite pavements, based on modifications of principles and experience with the structural evaluation of flexible pavements. Details of the use of elastic layer theory to simulate deflection measurements associated with loadings for the Kentucky Road Rater are presented. Included is an illustration of the use of field deflection measurements to "back calculate" in-place moduli. The procedures are generally iterative and involve matching measured deflections with theoretical deflections. Elastic layer principles have been used to simulate deflections only at the midslab position. Relationships regarding deflections at other locations on the slab currently involve empirical analyses. Evaluations involving the effects of pavement temperature, time of day, season, etc. are still empirical. In summary, major aspects of this paper will be twofold. One will be related to procedures and principles applied to the use of deflections and layer elastic theory to estimate effective parameters representative of existing in-place pavement conditions. The second will be related to the application of deflection measurements and evaluation methodologies to determine appropriate recommendations of rehabilitation strategies and scheduling for rigid pavements.

Highway and street networks are essential elements in the economic development and growth for any region, state, or nation. Highway and street networks were developed at a rapid pace in past years. Now, however, highway and transportation agencies are faced with the burden of protecting financial investments associated with these transportation systems. The lack of adequate funding has further added to this burden. Thus, it is necessary to select and schedule rehabilitation activities on a timely basis for efficient and effective utilization of available and oftentimes insufficient funding.

A number of tools and methodologies are available to highway engineers and administrators to assist in making decisions relating to selection of appropriate rehabilitation strategies. Visual surveys and observations of pavement conditions (ride quality (roughness), faulting and deterioration of joints, cracking, etc.) are often the basis of decisions. Unfortunately, observations and measurements of surface conditions may not always provide an accurate representation of pavement conditions. These traditional procedures may not show imminent structural distress and deterioration.

To assess the structural capacity of a pavement system, pavement deflections have been used as an additional input variable to the decision-making process of selecting and scheduling rehabilitation strategies. Early deflection testing equipment included the Benkelman beam, which involved a simple fulcrum and lever principle to measure surface deflection (at some point on the pavement) associated with a fixed wheel load or axleload. More recently, deflection testing has involved the use of dynamic testing equipment. Dynamic deflections may be induced and measured by such apparatus as the Road Rater, Dynaflect, and falling weight deflectometer. Other deflection testing devices have been developed by such organizations as the Federal Highway Administration and Army Corps of Engineers (Waterways Experiment Station). Results of deflection analyses, along with other more conventional expressions of pavement condition and performance, permit a more complete analysis of the structural adequacy of a pavement section, resulting in more efficient decisions relating to rehabilitation strategies.

The objective of this paper is to summarize and document research and developments relating to the use and application of dynamic deflection measurements (specifically Road Rater deflections) for evaluation of rigid pavements in Kentucky. Procedures have been developed to theoretically simulate measured Road Rater deflections and associated stresses and strains using elastic theory as expressed in the Chevron N-layer computer program (1).

Evaluation of Pavements Using Deflection Measurements

The simplest approach to evaluate pavements using deflection measurements involves comparisons of deflection measurements for one test location versus other test locations. This procedure serves to

isolate strong locations relative to weak locations and may be used to evaluate any pavement structure or component of the pavement structure: subgrade, aggregate base, asphaltic concrete layer, portland cement concrete slab, or composite pavement structures.

More sophisticated analysis procedures involve "back-calculation" of effective elastic layer moduli using measured deflections. Back-calculation procedures generally involve matching a measured deflection bowl with a theoretical deflection bowl determined using elastic layer theory (2, 3, 4, 5). Back-calculated effective pavement condition is herein defined as the combination of layer thicknesses and layer moduli that result in a theoretical deflection bowl that matches the measured deflection bowl (5, 6, 7, 8). Back-calculation procedures are generally iterative in nature and generally require computer capabilities for efficient processing of data.

Evaluation procedures for the use of deflection measurements to determine effective pavement condition for flexible pavements have been developed and verified in Kentucky (9, 10, 11). Many concepts developed for flexible pavements have been modified for application to the evaluation of rigid pavements. Evaluation procedures for flexible pavements typically result in an expression of pavement condition in terms of an effective thickness of asphaltic concrete at some reference asphaltic concrete modulus and an effective modulus of elasticity for the subgrade (5, 6, 7, 8). Alternatively, behavior of flexible pavement sections also may be expressed in terms of effective layer moduli at the constructed layer thicknesses and an effective subgrade modulus of elasticity.

Procedures have been developed to use deflection measurements for determination of effective layer moduli and subgrade moduli for rigid pavement structures. Effective moduli determinations have been developed on the basis of deflection measurements obtained at the centroid portion of a rigid pavement slab. Evaluation of a rigid pavement also requires analyses of load-transfer efficiency at joints and cracks and also consideration of deflection measurements at edge and corner locations relative to deflections at the centroid of the pavement slab. Relationships illustrating the effects of time of day and temperature gradient will be discussed in this paper.

Basis for the Evaluation Methodology

Simulation of Dynamic Deflections by Elastic Theory

Loading. The testing head of the Kentucky Road Rater consists of a vibrating mass of 72.6 kg (160 lb) that impulses the pavement through two "load feet," symmetrically located on either side of a beam that extends ahead and supports velocity sensors. The forced motion of the pavement is measured by the velocity sensors typically located at 0, 305, 610, and 914 mm (0, 1, 2, and 3 feet) from the center of the test head. When the vibrating mass is lowered to the pavement under a hydraulic pressure of 4.82 MPa (700 lbf/sq in.), the static load is 7.43 kN (1,670 lbf). At a frequency of 25 Hz and a double-amplitude of vibration of 1.52 mm (0.06 inch), the Road Rater has a double-amplitude dynamic force oscillation (about the static load) of 2.67 kN (600 lbf). The dynamic force may be varied by changing either the amplitude or frequency of vibration.

The dynamic loading (sine wave) of the Road Rater may 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 maximum and minimum square-wave loadings for the Kentucky Road Rater are 8.37 and 6.49 kN (1,822 and 1,458 lbf) for a dynamic load of 2.67 kN (600 lbf) and static load of 7.43 kN (1,670 lbf). From symmetry, the maximum and minimum loads on each foot of the test head are equal to 4.19 and 3.24 kN (941 and 729 lbf), respectively. Experience with asphaltic concrete pavements has indicated that elastic layer theory and the Chevron N-layer computer program can be used to simulate measured Road Rater deflections by calculating the deflections associated with the peak and minimum square-wave loadings for the Road Rater (2). Measured deflections generally matched the difference between deflections associated with maximum and minimum Road Rater loadings. Certain adjustments were necessary to accommodate asphaltic concrete moduli variations associated with variations in temperature, frequency, and other factors. Specifics for those evaluation procedures are presented elsewhere (5, 6, 7, 8). Experience gained in the development of evaluation procedures for flexible pavements have formed the basis for development of evaluation procedures for rigid pavements.

Input Parameters. Inputs required by the Chevron N-layered program (1) (used to calculate stresses, strains, and deflections) include a contact pressure corresponding to the applied load; the number of layers; and the thickness, Young's modulus, and Poisson's ratio of each layer. Contact pressures of the maximum and minimum loads were varied to maintain the correct area for each loading foot.

The modulus of a granular base (E_2) was estimated as a function of the moduli of the confining layers, i.e., the modulus of the portland cement concrete (E_1) and the modulus of the subgrade (E_3). Estimation of the modulus of the crushed-stone layer may be determined from $E_2 = F \times E_3$, where there is an inverse linear relationship between log F and log E_3. The ratio of E_2 to E_3 is equal to 2.8 at a California bearing ratio (CBR) of 7 and to 1 when E_1 equals E_3, i.e., $E_1 = E_2 = E_3$ (5, 6, 7, 8, 12, 13), the case of a Boussinesq semi-infinite half space. Laboratory triaxial testing also has indicated variations in modulus as a function of confining pressure (14). Experience in Kentucky has indicated a modulus ratio of 2.8 (crushed-stone base to subgrade) at a CBR of 7 for asphaltic concrete pavements (13). Modulus of the subgrade (in psi) can be approximated by the product of CBR and 1,500, a method of estimating moduli adequate for normal design considerations up to a CBR of about 17 to 20 (15, 16). This same relationship was used to approximate moduli of crushed-stone bases under portland cement concrete slabs.

The Chevron N-layer computer program was used to simulate Road Rater deflections for a matrix of layer thicknesses, layer moduli, and subgrade moduli. Thicknesses of portland cement concrete varied from 102 to 508 mm (4 to 20 inches) on 51-mm (2-inch) increments. Thickness of crushed-stone base also was varied from 102 to 508 mm (4 to 20 inches) at 51-mm (2-inch) increments. Elastic moduli for the portland cement concrete was 13.8 GPa (2,000,000 psi), 27.6 GPa (4,000,000 psi), and 41.4 GPa (6,000,000 psi). Subgrade moduli varied from 41.4 to 414 MPa (6,000 to 60,000 psi) at 41.4-MPa (6,000-psi) increments. Moduli for crushed-stone base layers were approximated using procedures previously presented. Poisson's ratio for the various layers were assumed as follows:

Portland cement concrete -- $\mu = 0.18$
Crushed-stone base -- $\mu = 0.40$

Subgrade -- μ = 0.45

Theoretical Deflections. The matrix of theoretical deflections determined using the Chevron N-layer computer program may be used to develop relationships for back calculation of effective pavement conditions when compared with measured Road Rater deflections. Figure 1 illustrates a relationship between theoretically simulated Road Rater deflections and thickness of portland cement concrete pavement for a constant subgrade modulus, portland cement concrete modulus and thickness, and associated moduli of a crushed-aggregate innerlayer. Relationships similar to Figure 1 may be developed for other subgrade conditions, other moduli of the portland cement concrete slab and crushed-aggregate base, and other pavement layer thicknesses.
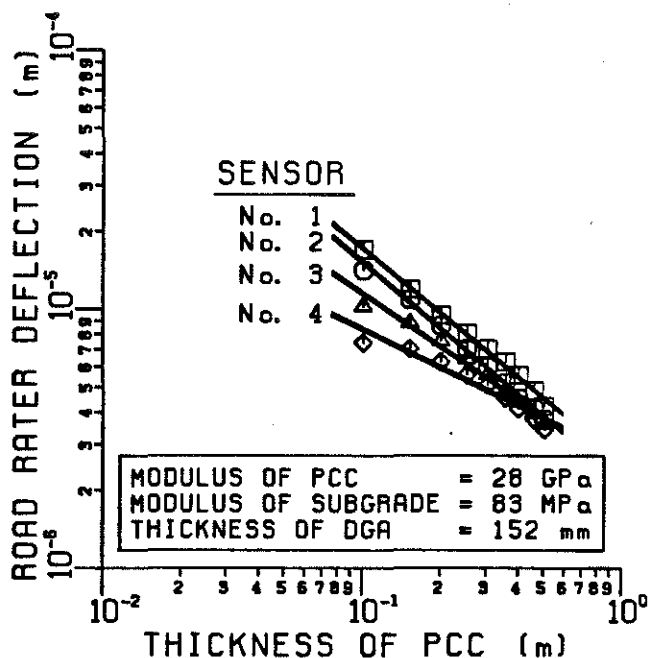

Figure 1. Illustration of theoretically simulated Road Rater deflections versus thickness of portland cement concrete for a constant pavement structure.

Relationships between theoretically simulated deflections and moduli of the portland cement concrete pavement also may be developed (see Figure 2). The relationship illustrated in Figure 2 is representative of those developed when the modulus of the subgrade is held constant as well as all layer thicknesses. Since moduli of the crushed-stone base, as presented earlier, are dependent upon moduli of the confining layers, moduli for the crushed-stone base of Figure 2 also must vary as the modulus of the slab varies.

Layer thicknesses are generally known or may be determined from construction and maintenance records. Therefore, relationships involving deflection versus subgrade moduli for a constant pavement structure (constant thickness and modulus for the portland cement concrete layer and constant thickness of crushed-stone base) may be more readily adaptable for back calculations of effective subgrade moduli. Figure 3 illustrates an example of a relationship of deflection versus subgrade modulus for one constant pavement structure. Similar relationships may be developed for other combinations of layer thicknesses and moduli for portland cement concrete.
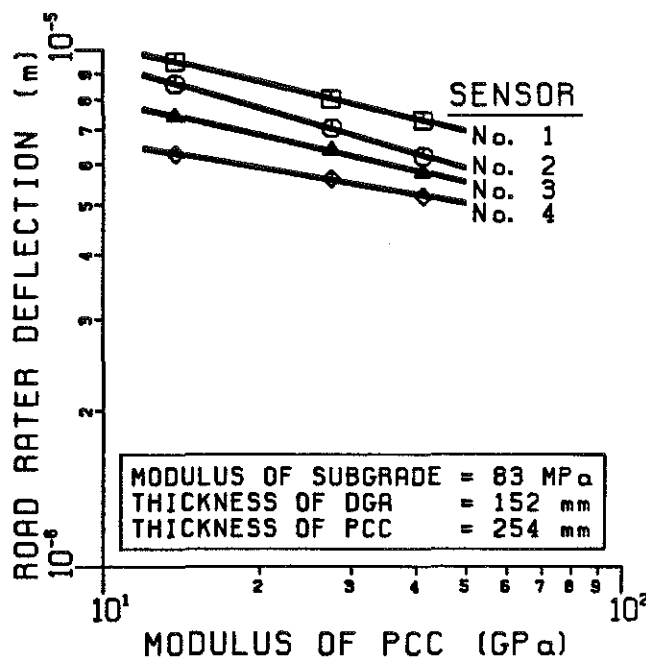

Figure 2. Illustration of theoretically simulated Road Rater deflections versus moduli of portland cement concrete for a constant layer thickness.
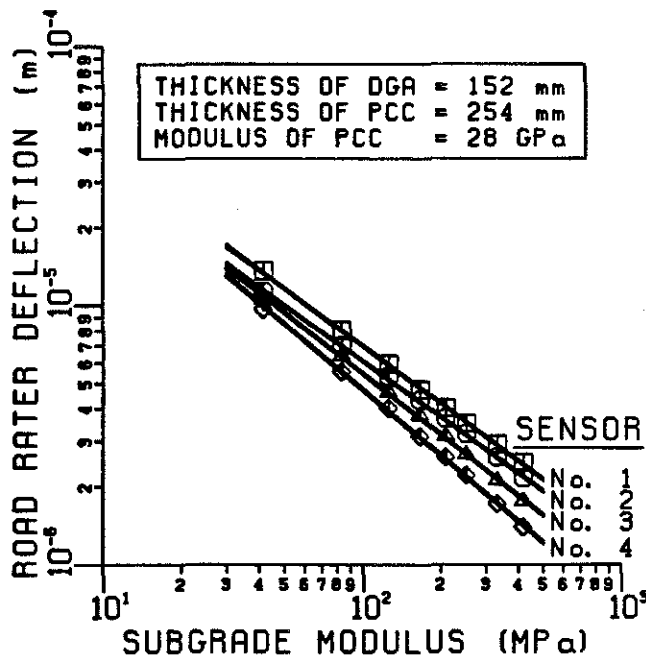

Figure 3. Illustration of theoretically simulated Road Rater deflections versus moduli of the subgrade for a constant pavement structure.

Back Calculation of Effective Subgrade Moduli

Relationships illustrated by Figure 3 may be used to back calculate effective subgrade moduli using measured Road Rater deflections. Back calculation of moduli are generally iterative, typically involving an initial assumption for the modulus of elasticity for portland cement concrete using layer thicknesses determined from construction and/or maintenance records. Deflection measurements then may be used in combination with an appropriate theoretical relationship as illustrated by Figure 3. Deflection

measurements then may be used to determine subgrade moduli corresponding to each sensor position of the Road Rater. If all assumptions were absolutely correct, there were no errors in measurement, and the modeling procedures were completely correct, the predicted subgrade moduli for all sensors would be identical. Unfortunately, this rarely occurs. Additionally, research by others has demonstrated that predicted subgrade moduli determined from "back-calculation" techniques have indicated moduli somewhat greater than determined from laboratory or other destructive analyses because of nonlinear stress dependency characteristics of some materials (17, 18, 19, 20). Research in Kentucky has involved correlations of predicted subgrade moduli determined from deflection testing versus subgrade moduli approximated by an in-place penetration test modeled after the California bearing ratio test. A description of the specifics of this test procedure follows:

The in-place California bearing ratio (CBR) test was developed as a modification of the laboratory CBR test in ASTM D 1883-73. The pavement is cored to expose the subgrade. A flat-bed truck with a water tank is used to provide a large reaction for smooth penetration of a piston. The mechanism for penetration consists of a screw jack and gearbox connected with a shaft to transmit the load to the piston. The gearbox mechanism is necessary to maintain the rate of penetration as specified in ASTM D 1883-73. Penetration and load are measured with a dial mechanism and a proving ring. It also should be noted that the in-place CBR test is performed on

material in the in situ condition whereas laboratory versions of the CBR test require soaking (saturating) the sample to approximate "worst expected conditions."

Table 1 summarizes results of a random analysis of deflection measurements and in-place CBR tests conducted for one specific pavement section. In-place CBR tests and deflections were conducted at seven different locations. Road Rater deflection measurements were obtained at the same locations prior to coring the pavement to perform the in-place CBR test. The core was salvaged for destructive testing to estimate the modulus of elasticity for the portland cement concrete.

Deflection measurements were used to estimate effective subgrade moduli at each sensor location using relationships illustrated by Figure 3. The predicted subgrade modulus is a function of the assumed modulus of the portland cement concrete. Results of these analyses are summarized in Table 1.

Correlation of subgrade moduli versus in-place CBR were determined for each sensor location and modulus of elasticity of the portland cement concrete. Predicted moduli for the four sensors were not significantly different for various test locations. Therefore, average subgrade moduli for each test site were correlated with in-place CBR tests for the various assumed moduli for the portland cement concrete. Results of these correlations for the three moduli are summarized in Figure 4.

CBR may be converted to modulus of elasticity (in psi) by multiplying by 1,500 (21). In Figure 4, the slopes of the various lines are much greater than the

Table 1. Summary of deflection tests, in-place CBR tests, predicted subgrade moduli, and verification of effective pavement conditions.

| | ROAD RATER DEFLECTIONS (micrometers) | | | | IN-PLACE CBR | PREDICTED SUBGRADE MODULI (MPa) FOR | | | EFFECTIVE SLAB MODULUS (GPa) |
| | | | | | | ASSUMED MODULUS FOR SLAB (GPa) | | | |
LOCATION	No. 1	No. 2	No. 3	No. 4		14	28	41	10
8W	7.1	6.6	4.5	3.8	4	115	110	97	141
2E	6.6	5.8	4.3	4.0	3	125	117	103	150
11E	5.0	4.0	2.5	2.2	5	241	207	186	260
27E	7.1	6.0	4.0	R	3	141	114	99	153
40E	7.8	7.1	5.5	5.0	3	95	88	77	116
50E	7.6	6.3	4.5	3.8	3	114	109	96	140
54E	5.3	5.3	3.8	4.0	6	148	135	119	175
Mean	6.6	5.9	4.2	3.8	3.9	148	124	111	162
Std Deviation	1.0	0.9	0.9	0.8	1.2	37	38	35	47
80th Percentile	7.5	6.7	4.9	4.5	2.9	116	91	81	122

SIMULATED ROAD RATER DEFLECTIONS

Simulation A	6.4	5.6	4.5	3.5
Simulation B	7.1	6.4	5.1	3.9
Simulation C	4.6	3.9	3.0	2.3
Simulation D	5.4	4.6	3.5	2.6
Simulation E	7.6	6.8	5.6	4.5
Simulation F	8.4	7.6	6.2	4.9

CASE STUDY (includes deflections from 62 test sites)

Mean	5.8	5.3	3.1	2.7
Std Deviation	2.5	1.9	1.4	1.0
80th Percentile	8.0	6.9	4.4	3.7

EFFECTIVE SUBGRADE MODULI AT EFFECTIVE PCC MODULUS OF 10 GPA

BASED ON MEASURED DEFLECTIONS	BASED ON DEFLECTIONS ADJUSTED TO APPROXIMATE DESIGN CBR
250	63
111	28
156	40

NOTE: Moduli values used for simulations in Table 2
1 inch = 25.4 mm
1 psi = 6.895 kPa
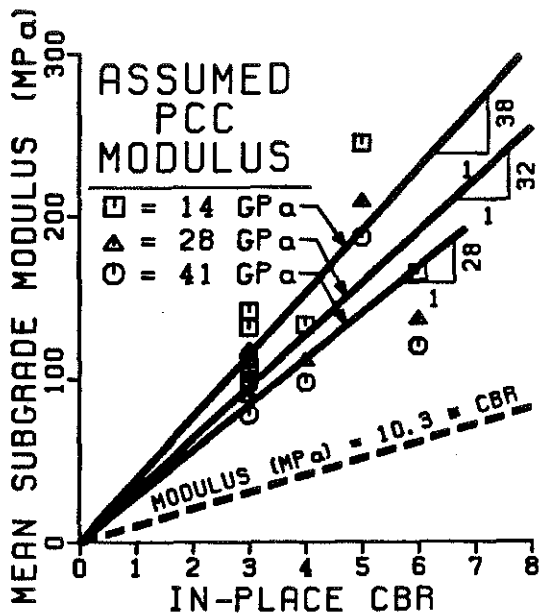
Figure 4. Average back-calculated subgrade moduli versus in-place CBR values.
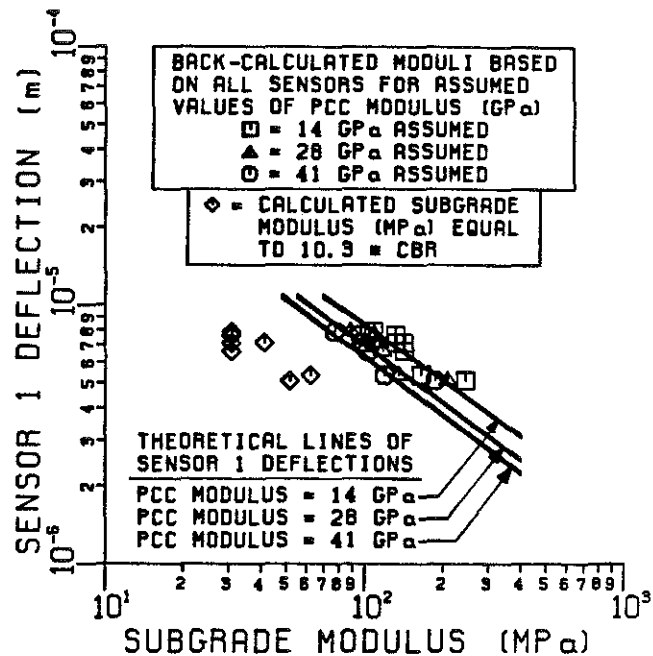

Figure 5. Plot of No. 1 Road Rater deflection measurement versus estimated subgrade moduli by (a) in-place CBR and (b) back-calculated moduli by deflection testing.

constant 1,500 normally used to convert CBR to elastic moduli in psi for all three moduli initially assumed. Figure 4 provides additional illustration of stress dependency variations associated with the two test methods.

The in-place CBR test is a penetration test and is generally associated with high stress concentrations whereas the Road Rater applies a dynamic load to the pavement surface. Stress levels are low at the subgrade level because of stress distribution characteristics. Elastic theory (1) assumes a linear model for stress dependency whereas others (17, 18, 19, 20) have demonstrated nonlinear stress dependent characteristics of various paving materials, and particularly of unbound materials.

Figure 3 and other similar figures for assumed moduli of portland cement concrete were used to determine back-calculated moduli summarized in Table 1. Average moduli were determined for each test site for the various moduli assumed for the slab and are presented in Table 1. Average moduli for each test site were then plotted versus the deflection corresponding to the first sensor of the Road Rater. Figure 5 illustrates this relationship. Additionally, in-place CBR converted to elastic moduli by multiplying by 1,500 also are plotted on Figure 5. The Mean No. 1 deflection was 6.7 x 10⁻³ mm (26.3 x 10⁻⁵ inch). The mean subgrade modulus estimated from in-place CBR tests was 40 MPa (5,800 psi) and the mean back-calculated subgrade modulus from deflection measurements on the basis of the three assumed moduli for the portland cement concrete was 130 MPa (18,847 psi). Theoretical relationships of deflection measurements (No. 1 Sensor) versus subgrade moduli also are superimposed on Figure 5. Notice that the mean modulus from in-place CBR tests are approximately one-third the back-calculated subgrade moduli by deflection testing. The deflection level of theoretical (predicted) deflections are approximately two times measured deflections at the mean subgrade modulus estimated from in-place CBR tests. Others (20) have observed similar variations and have attributed observed variations to nonlinear stress dependent characteristics of granular base and subgrade materials.

Pavement thickness design procedures (21, 22, 23, 24) have been developed whereby subgrade modulus of elasticity was converted to CBR by dividing by 1,500. One objective of this study was to use deflection analyses to predict input design or evaluation parameters (25, 26). Thus, it was necessary to make adjustments to convert back-calculated elastic moduli of the subgrade to corresponding moduli associated with in-place CBR tests, which more closely approximate subgrade moduli used for design of pavement thickness.

Determination of back-calculated subgrade moduli are dependent upon assumed moduli for the portland cement concrete pavement. Determination of the most appropriate modulus for the portland cement pavement layer is an iterative process whereby the assumed modulus of the portland cement concrete is varied until the minimum variation (squared residuals) of mean back-calculated subgrade moduli for all sensors (all locations on the deflection bowl) is determined. Figure 6 illustrates a procedure to shortcut this iterative process.

Figures 6a, 6b, 6c are plots of No. 1 Sensor deflection versus mean subgrade moduli back calculated from deflection measurements and plotted versus the corresponding deflection. Statistical procedures were used to determine the line that resulted in the minimum squared deviations for each series of back-calculated subgrade moduli. These lines may be used to predict effective moduli for the portland cement concrete. Figure 6d is a plot of predicted effective moduli for the portland cement concrete (determined from Figures 6a, 6b, and 6c) versus the assumed modulus of portland cement concrete used in the back-calculation exercise. A one-to-one line is also presented in Figure 6d. The effective modulus for the portland cement concrete may be estimated on the basis of the intersection or point of tangency (dependent upon the shape of the curve) with the one-to-one line. Extrapolation may be necessary in some situations.

The next phase of the evaluation procedure involves determination of adjustment factors
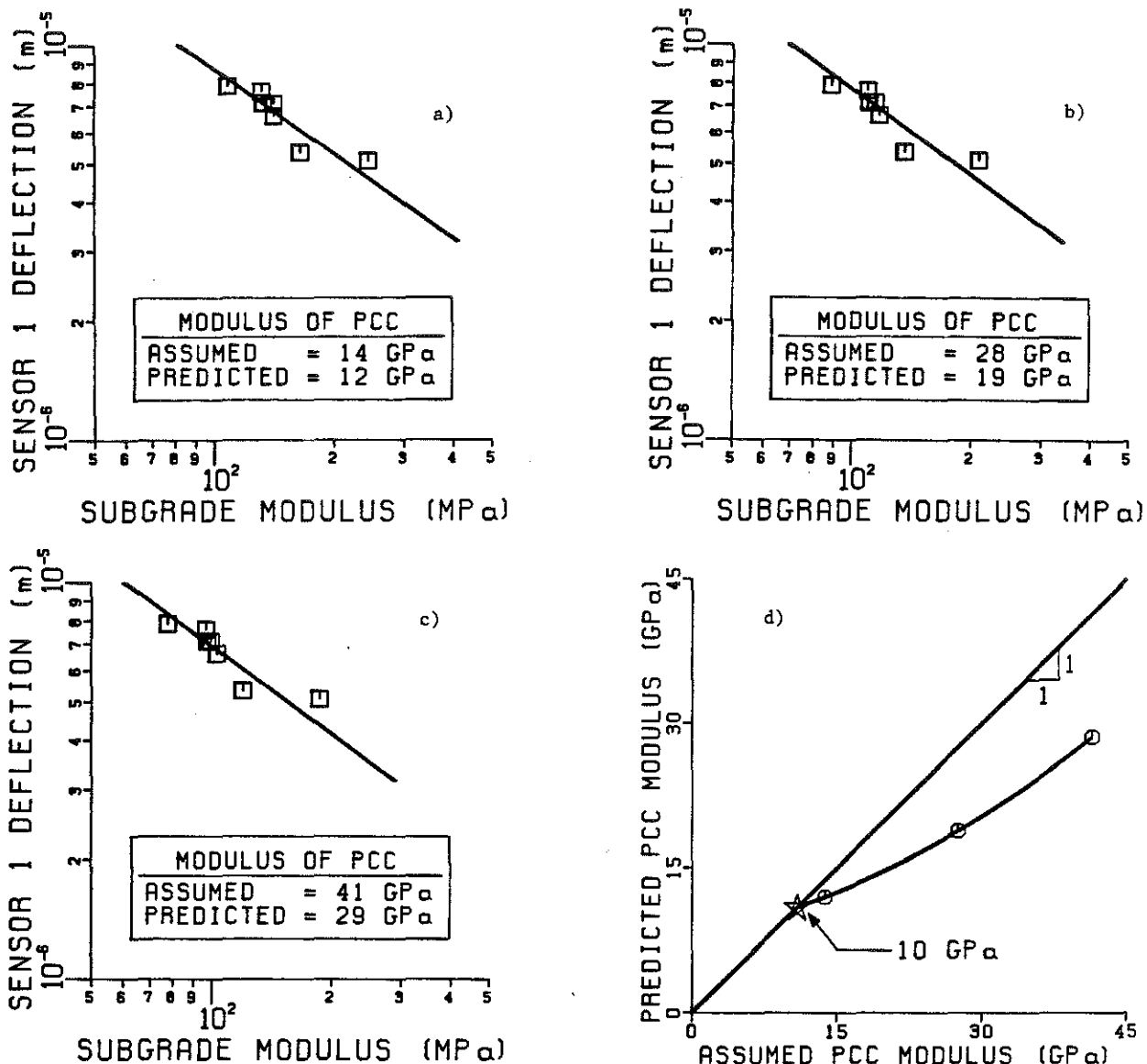
Figure 6. Estimation of effective modulus of portland cement concrete pavement.

necessary to convert back-calculated moduli from deflection measurements to effective subgrade moduli on the basis of in-place CBR tests. Elastic layer theory is used to develop a theoretical relationship of deflection for all sensors versus subgrade modulus for the effective modulus of portland cement concrete determined from Figure 6d. This relationship is presented in Figure 7.

Theoretical deflections corresponding to the mean subgrade modulus from in-place CBR tests may be determined for each sensor. Ratio's of these values to corresponding mean measured deflections may be used to compute deflection adjustment factors for each sensor.

Adjustment factors may be applied to all measured deflections. Adjusted deflections are then used to recalculate moduli of elasticity for each sensor. Average recalculated moduli of the subgrade may be compared with in-place CBR's and are presented in Figure 8.

Verification of Predicted Moduli of Portland Cement Concrete

Cores obtained during in-place CBR testing were evaluated to determined unconfined compressive strength and static-chord modulus using procedures in ASTM C-39 and ASTM C-469. Results of these analyses are summarized in Figure 9. The modulus estimated by the static-chord method (ASTM C-469) is somewhat less than estimated by Road Rater deflection measurements and also the modulus determined using ASTM C-215. While these variations may be attributed to differences in strain amplitude (27, 28, 29) and other variations of test methods, it was hypothesized that these differences were related to frequency of loading. It has been demonstrated that elastic modulus is a function of frequency of loading for linear viscoelastic solids (30).

Cores had been obtained previously from another pavement section. Moduli of elasticity had been estimated using two different methods:

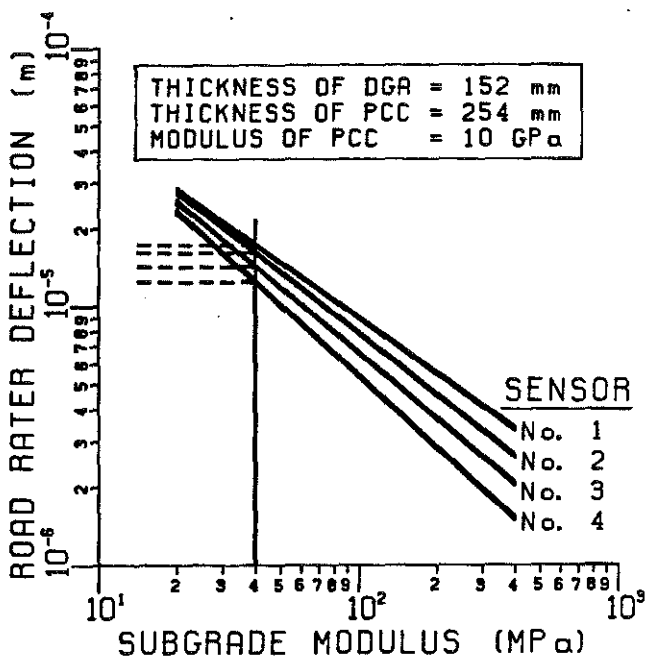a. ASTM C-469, Static Chord Modulus of Elasticity and

Figure 7. Deflection versus subgrade modulus.

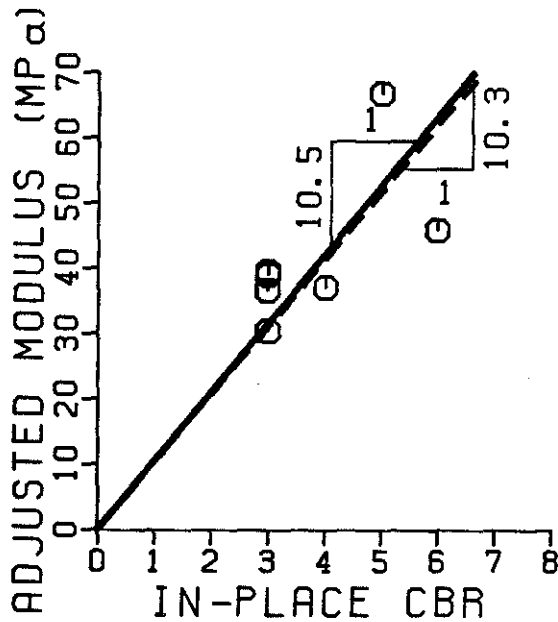Figure 9. Modulus of elasticity versus frequency of loading.

Figure 8. Comparison of back-calculated subgrade modulus determined from adjusted deflections versus in-place CBR.

b. ASTM C 215, Modulus of Elasticity by Fundamental Frequency.
The average modulus for each method was determined and plotted versus frequency of loading in Figure 9. The modulus determined from a static chord test (ASTM C-469) is truly a static modulus since it was derived during the compressive strength testing of the specimen. The frequency of loading in the static chord test was estimated from the mean compressive strength and standard loading rate of 241 kPa (35 psi) per second in ASTM C-469. It was assumed that the destructive one-way loading represented a half-cycle of loading. A straight line was used to connect the two average moduli. Research with
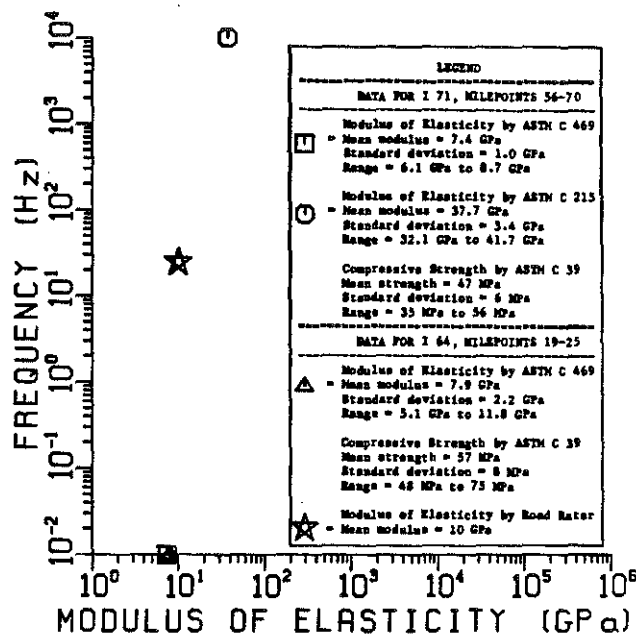
asphaltic concrete has indicated that similar relationships are likely a curve on a log-log plot, but a straight line has been used to approximate the relationship for frequencies less than 25 Hz (5, 6, 7, 8). Moduli by the static-chord method were very similar for both pavement sections. Therefore, it was determined appropriate to estimate the modulus at 25 hz using Figure 9. The modulus determined from Figure 9 compares favorably with the modulus of elasticity for the portland cement concrete determined from Figure 6d. Thus, the modulus estimated for the portland cement concrete was considered reasonable since the pavement section being considered had been in service since 1964 and some deterioration could be expected.

Determination of effective pavement conditions using deflection measurements generally involves determination of some combination of layer thicknesses and moduli that result in a theoretical deflection bowl reasonably matching the measured deflection bowl. The Chevron N-layer computer program may be used to compute theoretical deflections corresponding to effective pavement conditions determined from back-calculation techniques. The subgrade is subdivided to more closely simulate nonlinear stress dependent characteristics. Table 1 illustrates one theoretical deflection basin compared with measured deflections where variable subgrade layers are used in the simulation. Table 2 presents a range of combinations of layer moduli, determined from statistical analyses of back-calculated moduli, used to determine theoretical deflection basins using the Chevron N-layer computer program.

Utilization of Evaluation Procedures

Efficiency of Load Transfer at Joints and Cracks

Deflection measurements may be used to evaluate the efficiency of load transfer at joints and cracks of a rigid pavement. Procedures are empirical and are based on a comparison of deflection measurements at midslab to deflection measurements at the joint or

Table 2. Layer moduli used to verify effective pavement parameters
by simulation of measured Road Rater deflections.

PAVEMENT LAYER	THICKNESS (mm)	LAYER MODULUS (MPa)					
		SIMULATION A	SIMULATION B	SIMULATION C	SIMULATION D	SIMULATION E	SIMULATION F
Concrete Slab	254	10,342	10,342	10,342	10,342	10,342	10,342
Aggregate Base	152	427	160	600	225	372	130
Subgrade	51		40		63		30
	51		60		97		46
	51		83		124		61
	51		97		159		76
	51		117		186		90
	51		138		221		110
	Semi-infinite	159	159	250	250	122	122

NOTE: 1 inch = 25.4 mm
1 psi = 6.895 kPa

crack where the load is applied to one side of the joint or crack but deflections are measured on both sides. More specifically, deflection at the joint (or crack) is determined by placing the load feet of the Road Rater on one side of the joint (or crack) and positioning the joint (or crack) between the second and third sensors. Load-transfer efficiency is determined as the ratio of the difference between the second and third sensors of deflection at midslab to the similar difference for a deflection bowl at the joint.

Load-transfer efficiency was measured over the course of three or four years for a short pavement section not open to traffic. Traffic was diverted at an intersection, providing approximately 300 m (1,000 feet) available for testing. Load-transfer efficiencies were determined at random locations along this section on a periodic basis since 1979. Average load-transfer efficiency for this section was 0.79. The reduction from 1.0 is likely related to (a) normal errors associated with deflection measurements and (b) normal variations in construction procedures. Additionally, the temperature gradient and time of test may affect these measurements because of induced curling and warping of concrete slabs.

Temperature Gradients and Curling and Warping

Deflection measurements were obtained at various times and surface temperatures for two slabs for a section of interstate pavement in Kentucky. The pavement thickness was 250 mm (10 inches) of portland cement concrete and 150 mm (6 inches) of crushed-stone base. Figure 10 illustrates three contour maps for a grid of deflection measurements obtained at one of these slabs for three surface temperatures and times of day.

Figure 10 illustrates variations in measured deflections primarily associated with curling and warping of a concrete slab. Observed variations of deflection measurements and associated curling and warping are likely attributable to variations in temperature and/or moisture gradients within the concrete slab. Investigations of these conditions have not been the focus of significant research in Kentucky.

Data illustrated by Figure 10 were analyzed using the Statistical Analysis System (SAS) computer program to determine iso-deflection lines on the basis of a least squares statistical fit. Note the considerable variations of observed deflections for corner and edge locations of the slab versus deflections for the interior portion of the slab (Figures 10a, b, and c). In early morning hours of summer, the temperature of the slab would be expected to be cooler on the top than at the bottom. Thus, the corners and edges would be curled and warped upward. As the day progresses, the temperature of the upper portion of the slab increases and thermal expansion would be expected to eventually cause curling and warping downward by early evening hours. Figures 10a, b, and c apparently illustrate the effects of such conditions on measured deflections. Figure 10a illustrates deflections obtained at 8:55 EDT with a pavement surface temperature of 84°F. The correlation coefficient for Figure 10a is 0.890 and deflections at the center of the slab are approximately 1/7 of deflections at the edges and corners. Figure 10b illustrates deflections obtained at 11:52 EDT with a pavement surface temperature of 94°F. Deflections at the center of the slab remained relatively constant, but deflections at the corners and edges of the slab were lower than measured earlier in the morning. Deflections at the slab center were now 1/3 of deflections at the corners and edges. The tendency toward less variability of deflections for the entire slab (constant deflection) also is illustrated by the lower correlation coefficient (0.581). Figure 10c illustrates deflections obtained at 4:54 pm EDT with the pavement surface temperature at 100°F. Deflections were very similar for all locations on the slab. Some small variations were observed at corners and edges. Additionally, deflections at the center were slightly greater than for previous measurements, indicating curling and warping are tending to unseat the center of the slab. Also, the pattern of statistically fitted surfaces is considerably different from those observed for other times of day; also the very low correlation coefficient (0.385) indicates a tendency toward constant deflections for the entire slab.

There are two basic alternatives for the solution of problems associated with variations of deflection measurements associated with slab curling and warping. The first and likely the simplest solution involves limiting testing of the midslab to morning and midday hours and testing of joints and cracks to evening hours when the various portions of the slab are most closely seated against the subgrade. The more rational and probably more efficient method in the long run involves development of an adjustment procedure. Development of such a procedure will require an extensive research effort.
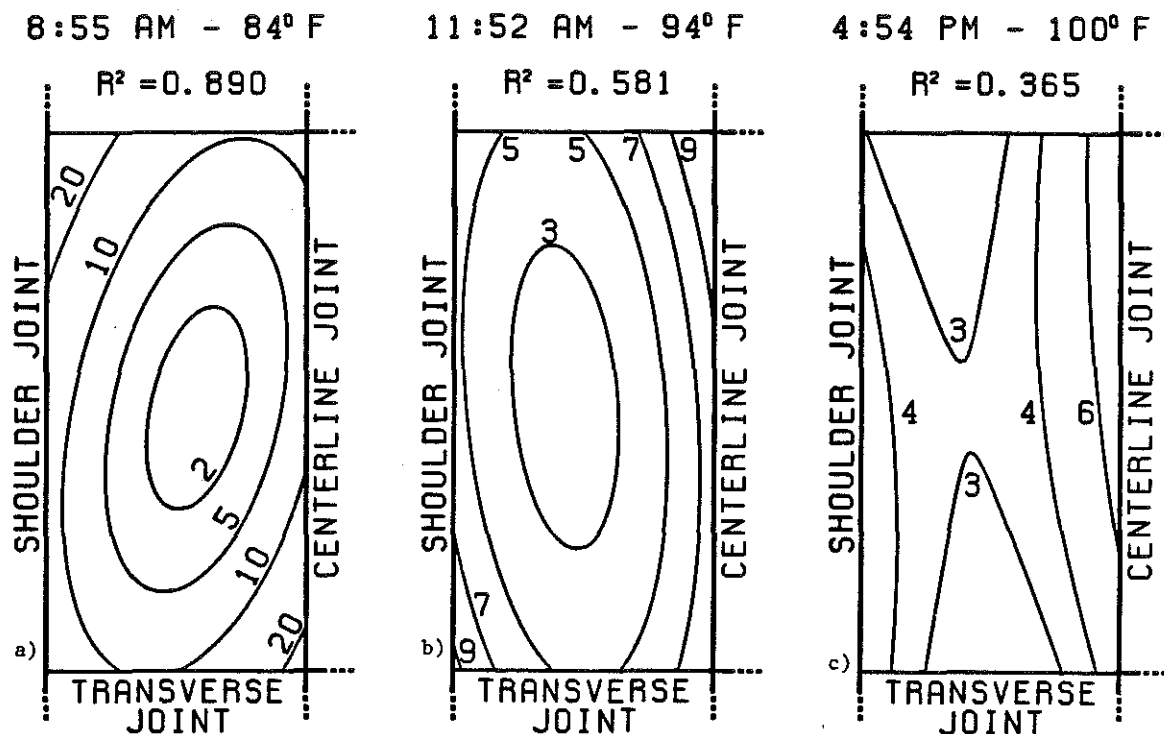
8:55 AM - 84° F   11:52 AM - 94° F   4:54 PM - 100° F

R² =0.890   R² =0.581   R² =0.365

Figure 10. Contour maps for a grid of No. 1 Sensor Road Rater deflections (micrometers) for various pavement temperatures and times of day.

A Case Study

A section of I 64 near Louisville required evaluation by deflection measurements in relation to an experimental paving project involving breaking and seating of an existing portland cement concrete pavement followed by an overlay with asphaltic concrete. Structural evaluation was required to establish the in-place condition of the existing pavement. Additionally, evaluations were completed after breaking and seating and again after placement of the overlay.

In-place CBR tests, coring, and destructive and nondestructive testing of cores were also a part of that study. Much of the data obtained was used to develop evaluation procedures previously presented. In addition to these special analyses, the total project was surveyed using the Road Rater. Deflection measurements were obtained at 0.16-km (0.1-mile) intervals with measurements at both midslab and at joints and major cracks.

The evaluation procedure previously presented and illustrated by Figures 1 through 7 was used to evaluate midslab measurements for effective subgrade modulus and effective modulus of the portland cement concrete pavement. Figure 11 illustrates a strip map of effective subgrade moduli for one section of this project. Figure 12 illustrates the determination of effective modulus of portland cement concrete for the same section. The mean and 80th-percentile effective subgrade moduli and corresponding effective moduli for the portland cement concrete pavement are summarized in Table 1. Additionally, the mean and 80th-percentile measured deflections and theoretical deflections associated with the mean and 80th-percentile effective moduli also are presented. Figure 13 is a strip chart of load-transfer efficiency for joints for this same pavement section. Figure 14 illustrates a similar strip chart for load-transfer efficiency for major cracks. Mean and

standard deviations for load-transfer efficiencies also are presented in Figures 13 and 14. It has been recommended that rehabilitation is not needed for those sections where load-transfer efficiency exceeds 0.75 (26). Visual observations and engineering judgment had already been used to recommend major rehabilitation.

Results of these analyses may be used in combination with other evaluations of traffic, vehicle loadings, and pavement condition and serviceability (ride quality, aggregate polishing and skid resistance, visual distress, pumping, etc.) to select appropriate rehabilitation alternative designs (25, 26). A decision already had been made to break and seat the existing portland cement concrete pavement and overlay with asphaltic concrete. However, with the combination and evaluation of all available data, results of structural evaluation analyses presented above do provide valuable information in the determination of rehabilitation strategies. Potential rehabilitation strategies may include (a) "do nothing," (b) pavement sealing and/or undersealing, (c) overlay with asphaltic concrete or portland cement concrete, (d) break and seat and then overlay with asphaltic concrete, (e) milling joints and cracks to improve smoothness and ride quality, and (f) milling to improve skid resistance,

Summary and Conclusions

Procedures and methodologies have been presented for the application of deflection measurements to estimate in-place conditions of a portland cement concrete pavement. Evaluation methodologies have been verified by comparison and correlation with destructive evaluations such as the in-place CBR test to estimate subgrade modulus and static-chord modulus (ASTM C-469) and modulus by fundamental frequency (ASTM C 215) to estimate the stiffness of portland
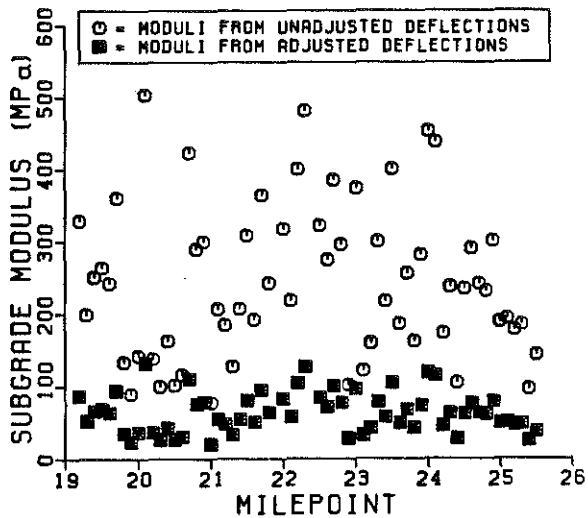
Figure 11. Strip map of effective subgrade modulus versus milepoint.
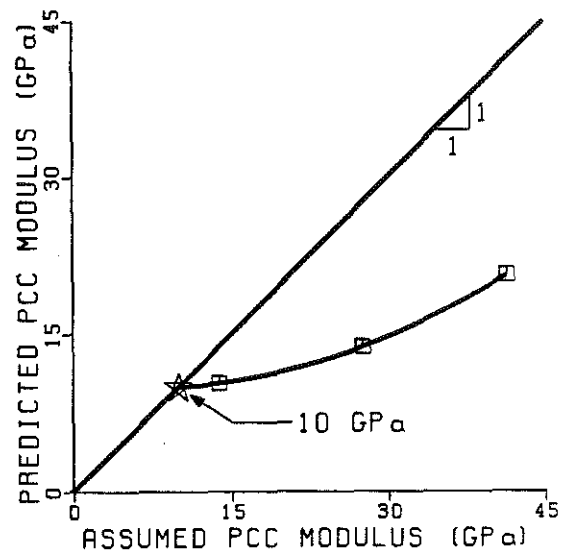

Figure 12. Determination of effective modulus of portland cement concrete.
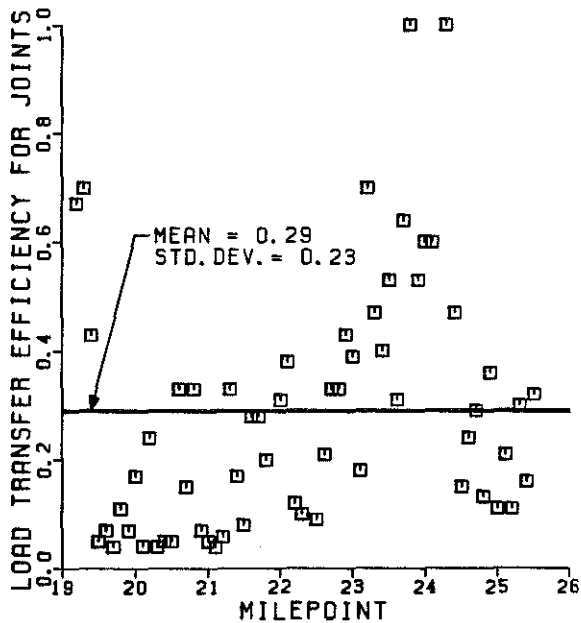

Figure 13. Strip map of load transfer efficiency for joints versus milepoint.
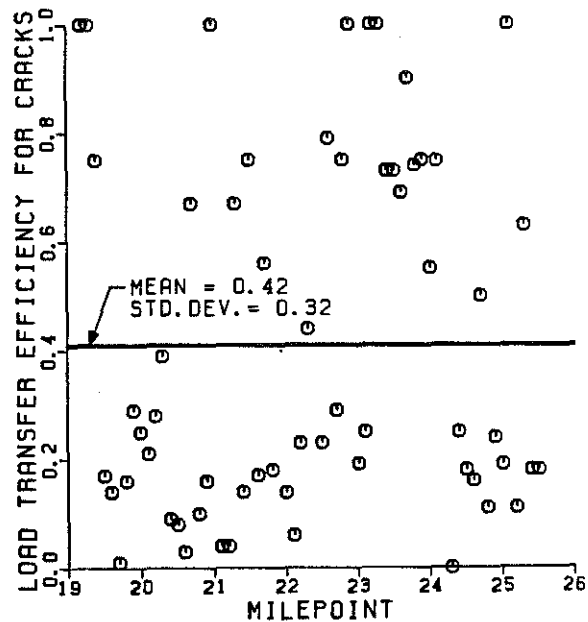

Figure 14. Strip map of load transfer efficiency for cracks versus milepoint.

cement concrete. Certainly, there may be other and perhaps more appropriate methodologies for verification of analyses procedures. For example, resilient moduli by repeated load testing, or subgrade bearing capacity by Dutch cone penetration tests or other methods also may be appropriate tests for comparison with back-calculated subgrade moduli from deflection measurements. Similarly, repeated load testing of portland cement concrete.pavement cores and associated moduli may be appropriate for correlation with back-calculated moduli (from deflection measurements).

Factors affecting variability of deflection measurements on portland cement concrete pavements are discussed briefly. Factors such as curling and warping of slabs, temperature gradients, and moisture gradients and the effects of these variables on deflection measurements require additional research

to define specific relationships and to develop adjustment procedures or testing methodologies to accommodate such variations. Additionally, a procedure has been presented to estimate the efficiency of load transfer using deflection measurements. This procedure is empirical, .and therefore, additional research is needed to define appropriate limiting criteria to be applied to these analyses.

The application of principles presented in this paper are illustrated by a typical case study. Results of these analyses may be useful for the determination and evaluation of pavement rehabilitation strategies and designs. Effective moduli determined by deflection measurements may be used as input parameters to determine overlay thickness requirements in the development of rehabilitation strategies. Additionally, principles

presented in this paper may be useful for determining effective moduli of other pavement structures such as the broken (cracked) concrete before overlaying with asphaltic concrete.

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