Design Pamphlet for the Backcalculation of Pavement Layer Moduli in Support of the 1993 AASHTO Guide for the Design of Pavement Structures

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LTPP

FOREWORD

A key challenge faced by engineers using the 1993 AASHTO Guide for Design of Pavement Structures (AASHTO Guide) is the selection of appropriate design values for the subgrade soil and for the pavement materials. Until now, the information available to help engineers choose appropriate values has been incomplete. This design pamphlet addresses this problem by presenting procedures for interpretation of pavement deflection data. Two companion pamphlets—*Design Pamphlet for the Determination of Design Subgrade Moduli in Support of the 1993 AASHTO Guide for the Design of Pavement Structures* (FHWA-RD-97-083) and *Design Pamphlet for the Determination of Layered Elastic Moduli in Support of the 1993 AASHTO Guide for the Design of Pavement Structures* (FHWA-RD-97-077)—provide additional, related guidance on selecting appropriate design values to characterize the pavement materials and the subgrade soil. The procedures presented were developed through analysis of the Long-Term Pavement Performance (LTPP) data, documented in the report *Analyses Relating to Pavement Material Characterization and Their Effects on Pavement Performance*, FHWA-RD-97-085.

Application of the procedures and guidelines developed through this analysis will facilitate and improve application of the AASHTO Guide flexible pavement design procedures. Their use will provide: (1) improved designs, (2) more realistic estimates of pavement performance, and (3) more consistent use of the AASHTO design parameters. Furthermore, although the procedures are specifically developed for use with the 1993 AASHTO Guide, their use will give agencies a "leg up" on implementation of the design procedures being developed for inclusion in the 2002 AASHTO Guide for Design of New and Rehabilitated Pavement Structures. Thus, this pamphlet and its companions are critically important to anyone who designs flexible pavements.

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16. Abstract

This design pamphlet details the procedures to backcalculate pavement layer moduli in support of the 1993 *AASHTO Guide for the Design of Pavement Structures*. The recommended procedure presented in this pamphlet was based on a combination of ASTM D5858 and the procedure developed as a product from the Long Term pavement Performance program of the Strategic Highway Research Program.

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Pavement Performance, Backcalculation, LTPP Data Base, Resilient Modulus, AASHTO Guide, Nondestructive Deflection Testing

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS					APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**	**Symbol**	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH					**LENGTH**		
in	inches	25.4	millimeters	mm	mm	millimeters	0.039	inches	in
ft	feet	0.305	meters	m	m	meters	3.28	feet	ft
yd	yards	0.914	meters	m	m	meters	1.09	yards	yd
mi	miles	1.61	kilometers	km	km	kilometers	0.621	miles	mi
		AREA					**AREA**		
in^2	square inches	645.2	square millimeters	mm^2	mm^2	square millimeters	0.0016	square inches	in^2
ft^2	square feet	0.093	square meters	m^2	m^2	square meters	10.764	square feet	ft^2
yd^2	square yards	0.836	square meters	m^2	m^2	square meters	1.195	square yards	yd^2
ac	acres	0.405	hectares	ha	ha	hectares	2.47	acres	ac
mi^2	square miles	2.59	square kilometers	km^2	km^2	square kilometers	0.386	square miles	mi^2
		VOLUME					**VOLUME**		
fl oz	fluid ounces	29.57	milliliters	mL	mL	milliliters	0.034	fluid ounces	fl oz
gal	gallons	3.785	liters	L	L	liters	0.264	gallons	gal
ft^3	cubic feet	0.028	cubic meters	m^3	m^3	cubic meters	35.71	cubic feet	ft^3
yd^3	cubic yards	0.765	cubic meters	m^3	m^3	cubic meters	1.307	cubic yards	yd^3
NOTE: Volumes greater than 1000 l shall be shown in m^3.									
		MASS					**MASS**		
oz	ounces	28.35	grams	g	g	grams	0.035	ounces	oz
lb	pounds	0.454	kilograms	kg	kg	kilograms	2.202	pounds	lb
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")	Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact)					**TEMPERATURE (exact)**		
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C	°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F
		ILLUMINATION					**ILLUMINATION**		
fc	foot-candles	10.76	lux	lx	lx	lux	0.0929	foot-candles	fc
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2	cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS					**FORCE and PRESSURE or STRESS**		
lbf	poundforce	4.45	newtons	N	N	newtons	0.225	poundforce	lbf
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa	kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

(Revised September 1993)

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BACKCALCULATION OF PAVEMENT LAYER MODULI IN SUPPORT OF THE 1993 AASHTO GUIDE FOR THE DESIGN OF PAVEMENT STRUCTURES

INTRODUCTION

The use of nondestructive deflection testing is an integral part of the American Association of State Highway and Transportation Officials (AASHTO) structural evaluation and rehabilitation design process. Specifically, the AASHTO Design Guide suggests the use of deflection tests for evaluating the effective structural capacity and to determine the seasonal variation of pavement structures. Section 3.5 in Part III of the Guide reviews the use and interpretation of deflection data for these purposes.(1)

AASHTO also recommends that elastic moduli (Young's Modulus) be backcalculated from deflection basins to define the load-response properties of individual layers in the pavement structure and to assist the engineer in selecting a reliable rehabilitation alternative to correct some surface distress or pavement deficiency. In fact, backcalculation of layer moduli is an alternate procedure included in the AASHTO Design Guide for determining the design moduli.

There has been a considerable effort within the past decade devoted towards backcalculating layer moduli from deflection basins.(2, 3) Numerous procedures have been developed and used. Two of the more recent include the American Society for Testing and Materials (ASTM) Standard Guide D5858 (Standard Guide for Calculating Insitu Equivalent Elastic Moduli of Pavement Materials Using Layered Elastic Theory) and the procedure developed as a product from the Strategic Highway Research Program (SHRP).(4, 5) The purpose of this design pamphlet is to provide a combined procedure that can be used for pavement diagnostic and rehabilitation studies in support of the 1993 AASHTO Design Guide. However, two statements should be noted and understood before backcalculating layer moduli from deflection basins. These statements are:

1. There is no unique solution for a specific deflection basin using elastic layered theory. The layer moduli determined from the backcalculation process represent equivalent elastic moduli and should be reviewed carefully for reasonableness. These layered elastic moduli should not be used arbitrarily.

2. The procedure covered in this design pamphlet is an iterative process to decrease the error term (difference between the measured and calculated deflection basins) to the lowest value possible, and certainly below the magnitude considered acceptable. The combination of layers and calculated elastic moduli resulting in the lowest error should be used for diagnostic and rehabilitation design studies.

BACKCALCULATION SOFTWARE

One of the more common analysis methods of deflection data is to backcalculate material response parameters for each layer within the pavement structure from deflection basin measurements. These methods and programs can be grouped into four basic categories. These categories are:

1. Static (Load Application) - Linear (Material Characterization) Methods
2. Static (Load Application) - Non Linear (Material Characterization) Methods
3. Dynamic (Load Application) - Linear (Material Characterization) Methods
4. Dynamic (Load Application) - Non Linear (Material Characterization) Methods

At present, interpretation of deflection basin test results is performed with static-linear analyses. Some of the software that has been used to backcalculate layer moduli over the past several years include BISDEF, CHEVDEF, ELMOD, ELSDEF, EVERCALC, ISSEM4, MODCOMP, MODULUS, and WESDEF. Although many of the software packages have similarities, the results generated from the same set of data by various programs can be different. These differences are a result of the type of iteration scheme used and the modulus calculation routine employed.(6) Moduli can be determined by either backcalculation or forward calculation schemes.(7, 8) As such, standardization of analysis procedures is a key topic within the industry. ASTM has a procedure (D5858) for analyzing deflection basin test results to determine layered elastic moduli.(4)

Most of the backcalculation procedures in use today are based on elastic layer theory to calculate Young's Modulus (modulus of elasticity) for each structural layer within the pavement, such that the difference between the measured and predicted basins is minimal. SHRP, as well as others, studied and evaluated many of these backcalculation procedures to select one method for characterizing the subgrade and other pavement layers and evaluating the performance of flexible and rigid pavements. The MODULUS 4.0 program was selected for flexible and composite pavements; whereas, a new procedure was developed for rigid pavements, as part of the SHRP P-020 Data Analysis Project.(9, 10)

Most of these programs are limited by the number of layers and the thickness of those layers within the pavement and are based on linear elastic material assumptions. Consequently, any discontinuity cannot be physically represented by the model. Thus, the calculated layer moduli represent effective or equivalent values that take into account anomalies (such as cracks and voids), thickness variations within each layer, and a combination of layers with similar materials or thin layers with thick layers.

Layer thickness is an extremely important feature when backcalculating layer moduli from deflection basin test results. A 10 percent difference in thickness can result in more than a 20 percent change in the calculated modulus.(6, 11) Thus, using accurate layer thicknesses becomes critically important.

Most of these analysis procedures become less reliable or unstable as the layer evaluation progresses from the subgrade to the surface. In fact, surface layer moduli that are calculated from measured deflection basins are normally considered poorly defined from deflection tests. This result has spawned the development of dynamic analysis tools and the use of other nondestructive deflection testing (NDT) techniques (such as wave propagation) for improving the accuracy of these predictions or calculations, as compared to moduli measurements made in the laboratory. Two dynamic-linear backcalculation programs that have been developed are UTFWIBM and SCALPOT, but both have had very limited use.(12, 13) Thus, for this design pamphlet, MODULUS 4.0 and 4.2 and WESDEF (all based on the elastic layer theory) are suggested for backcalculating the equivalent elastic modulus of each pavement structural layer, including the subgrade, from deflection basin measurements.(14, 15, 16)

BACKCALCULATION PROCESS

Backcalculation is a laborious process, requiring a high degree of skill, and the results are known to be moderately to highly dependent on the individual doing the backcalculation. There are several factors that affect the accuracy and applicability of backcalcualted layer moduli. Any analysis method that uses an iterative or searching procedure to match measured to calculated deflection basins will result in some error. The magnitude of this error depends on different factors, some of which include:

- Combining different layers into one structural layer, because of the limitation on the number of layers used in the analysis;

- Noise or inaccuracies contained in the sensor measurement itself; small deflections that are close in magnitude to the established random error for the sensors;
- Discontinuities (such as cracks) in the pavement, particularly if located between the load and the sensor, or variable rutting in the wheelpath resulting in a lateral difference in surface layer thicknesses;
- Inaccurate assumption on the existence and depth of an apparent stiff layer (depths to an apparent stiff layer of less than 5 ft (1.5 m) may require a dynamic analysis);
- Differences between assumed and actual layer thicknesses;
- Non-uniform load pressure distributions at the load-pavement contact area; and
- Non-linear, inhomogeneous, or anisotropic materials in the pavement structure (especially the subgrade).

To ensure that the backcalculation process is as consistent, productive, and straightforward as possible, a procedure (i.e., rigorous set of application rules) was developed by SHRP around the MODULUS program.(9) This procedure relies on the wealth of information stored in the Long Term Pavement Performance (LTPP) data base -- deflection, pavement structure and materials, and surface layer temperature data -- to generate the input for MODULUS. In addition, the procedure was automated to reduce opportunities for operator error or inconsistency.

The SHRP backcalculation rules address three major areas: definition of layer moduli ranges, modeling of the pavement structure, and evaluation of the analysis results. The first group of rules focuses on the definition of the moduli ranges required to run the MODULUS program, the second set of rules addresses the modeling of the pavement structure for purposes of backcalculation, and the third and final set of rules focuses on the evaluation of the backcalculation results. A similar guide was also written within ASTM to standardize this highly variable process.(4)

ASTM D5858 and the SHRP procedure were used to develop a guide for backcalculating layer moduli for design and diagnostic studies. The following briefly summarizes the steps involved in the backcalculation process:

(1) Normalize and review the measured deflection basins to ensure that the deflections decrease consistently with those sensors farther from the applied load. Identify unique deflection basins that are inconsistent with the elastic layer theory.

(2) Review the materials and soils recovered from the pavement cores and borings. Separate significantly different pavement materials and subgrade soils or subsurface conditions into different layers (i.e., above and below the water table) and identify the depth to a stiff or rigid layer.

(3) Identify potential problem layers included in the structure. For example, weak soils above stiffer soils, sandwich sections (a soft layer or material between two strong materials), and thin and thick layers relative to the adjacent layers.

(4) Determine the pavement cross-section to be used in the backcalculation process.

(5) Backcalculate the modulus of each layer and calculate the error term for each measured basin or the sum of the total percentage difference between the measured and calculated basins.

(6) For large errors, review the pavement structure used in the backcalculation process with the cores and borings. Recombine or separate layers, if necessary, to decrease the error term.

(7) Review the moduli ratios between adjacent unbound layers to identify unrealistic or improbable conditions (i.e., high moduli ratios causing large tensile stresses at the bottom of unbound layers).

(8) For those basins that consistently hit the upper limit set for the modulus of a particular material, the structure should be reviewed in an attempt to reduce the error term while maintaining reasonable modulus values. For basins that hit the lower limit for a particular material, the lower limit can be further reduced. Low modulus values may be reasonable because of contamination of underlying materials, the presence of cracks or internal damage (such as stripping), or the weakening of some unbound materials with an increase in moisture or a decrease in density.

A discussion on each of these steps is provided in the remainder of this design pamphlet. However, it should be clearly understood, that there is no unique solution for a specific deflection basin using the programs previously mentioned.

DEFLECTION TESTING

Data Consistency and Accuracy. Data consistency and accuracy are very important when comparing deflection data, and certainly when trying to distinguish or identify layer condition and features for predicting pavement performance. Several agency procedures and programs have been developed by SHRP and ASTM to ensure that the deflection data are uniform and accurate.(17) Calibration procedures have been developed to ensure that the data are accurate.(18) These procedures are currently in use at each of the four FHWA calibration centers that were developed under the SHRP-LTPP program.

ASTM Standard Guide D 4602 and Test Method D 4694 also provide procedures that can be used for nondestructive deflection testing of pavements using dynamic cyclic and impulse (impact) loading deflection equipment, respectively. These test procedures generally refer to the calibration and operation of various types of NDT equipment. It should be emphasized that proper calibration of the sensors is essential for measuring accurate pavement responses, especially those far away from the load.

Sensor Location and Spacing. An adequate number of sensors properly spaced must be used to measure the actual deflected shape of the pavement from the imposed load. The location and spacing of measurements are recommended in ASTM Standard Guide D 4695. As part of the LTPP program, the number and location of sensors were standardized for all pavement types. Seven sensors are used and spaced at 0, 8, 12, 18, 24, 36, and 60 in (0, 0.2, 0.3, 0.5, 0.6, 0.8 and 1.5 m) from the loading plate. This number and spacing of sensors have been found to be adequate for most pavement types, with the possible exception of very stiff or thick asphalt concrete pavements with a shallow rigid layer.

As a general guideline, historical records (or as built construction plans) can be reviewed to obtain the expected material types and layer thicknesses of the pavement structure and depth to a rigid or stiff layer. This pavement cross-section (material types and layer thicknesses) and assumed layer moduli and Poisson's ratios can be used with one of the elastic layer theory programs to calculate an expected deflection basin. The sensors can then be located and spaced to ensure that the critical parts of the deflection basin will be measured.

Number of Load Levels Used. Most pavement materials and subgrade soils are nonlinear. In other words, the equivalent elastic moduli are dependent on the stress state. Deflection basin testing can be used to estimate these nonlinear characteristics of pavement materials, but requires the use of three or more load levels (or drop heights). As a general guideline, the design wheel load should be one of the load levels used in the test program. More importantly, a load level that is representative of the expected heavier wheel load magnitudes should also be used, as a minimum. The heavier test load becomes important when using a mechanistic-empirical pavement evaluation procedure that is not applicable to the AASHTO equivalency factors based on serviceability. As a minimum, three load levels should be used (9, 12, and 16 kips) (40, 53 and 71 kN).

PROCEDURES FOR CALCULATING ELASTIC MODULI

1. Normalize Deflection Basins

Identify Problem Deflection Basins. To evaluate the different shapes or types of deflection basins, all measured basins should be normalized to the deflection measured by sensor number 1, which is directly under the load (i.e., see figure 1). These normalized deflection basin data can be divided into four categories or types of basins. These different categories are shown in figures 2 through 5 and defined below.

- Figure 2 shows typical normalized deflection basins for which the error terms are generally low (generally less than 1½ percent error per sensor) for both portland cement concrete (PCC) and asphalt concrete surfaced pavements. The use of the elastic layer theory is applicable in analyzing these basins.

- Figure 3 shows a Type I deflection basin. For this deflection basin, the deflections measured at some of the sensors are greater than the deflection measured by sensor 1, directly under the load. The Type I deflection basins generally have the greatest error terms and are not consistent with the elastic layer theory.

- Figure 4 shows a Type II deflection basin. These basins include a significant decrease in measured deflections between two adjacent sensors. Depending upon the magnitude of this drop or break in the deflection basin, some of the error terms can be large, while others with the smallest differences are close to a value of 2½ percent error per sensor.

- Figure 5 shows a Type III deflection basin. For these basins, the deflection measured at an adjacent sensor (but farther from the load) is greater than the deflection closer to the load. Some of these deflection basins have error terms ranging from greater than 10 percent to values less than 2½ percent error per sensor. The error depends upon the magnitude of the increase in deflection between two adjacent sensors.

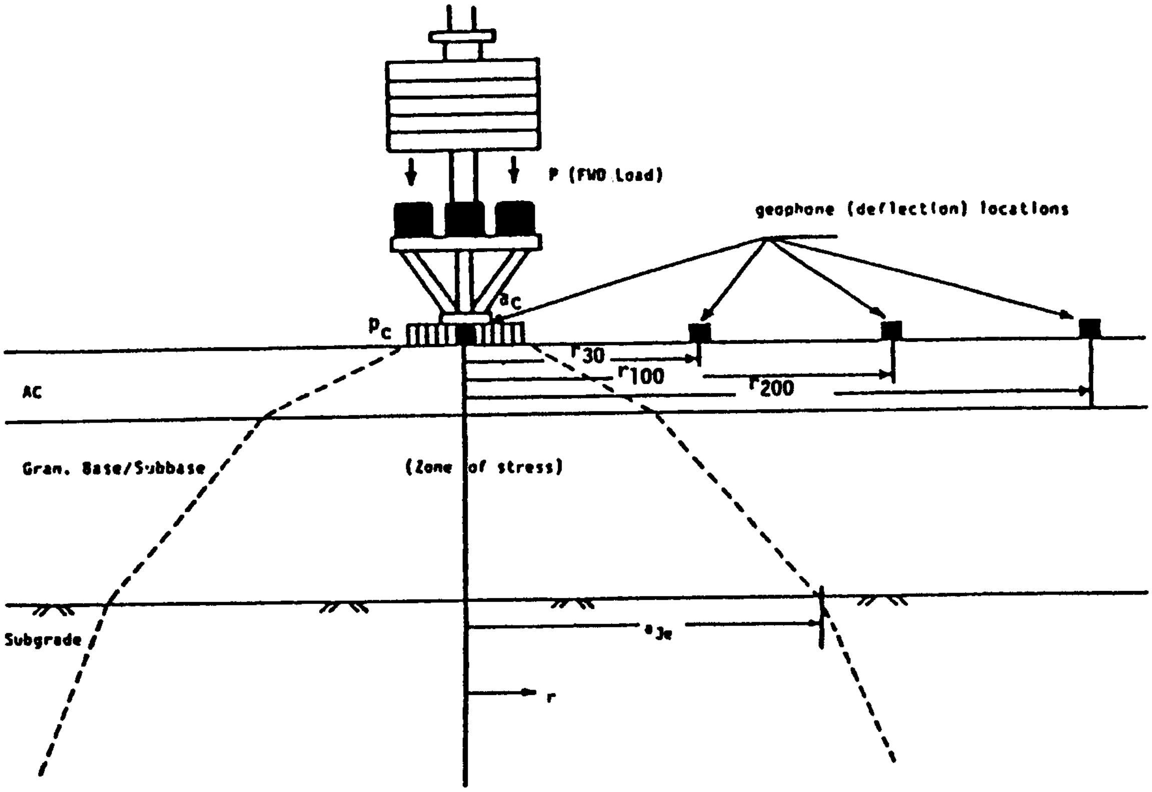

Figure 1. Schematic of Stress Zone within Pavement Structure under the FWD Load. (1)

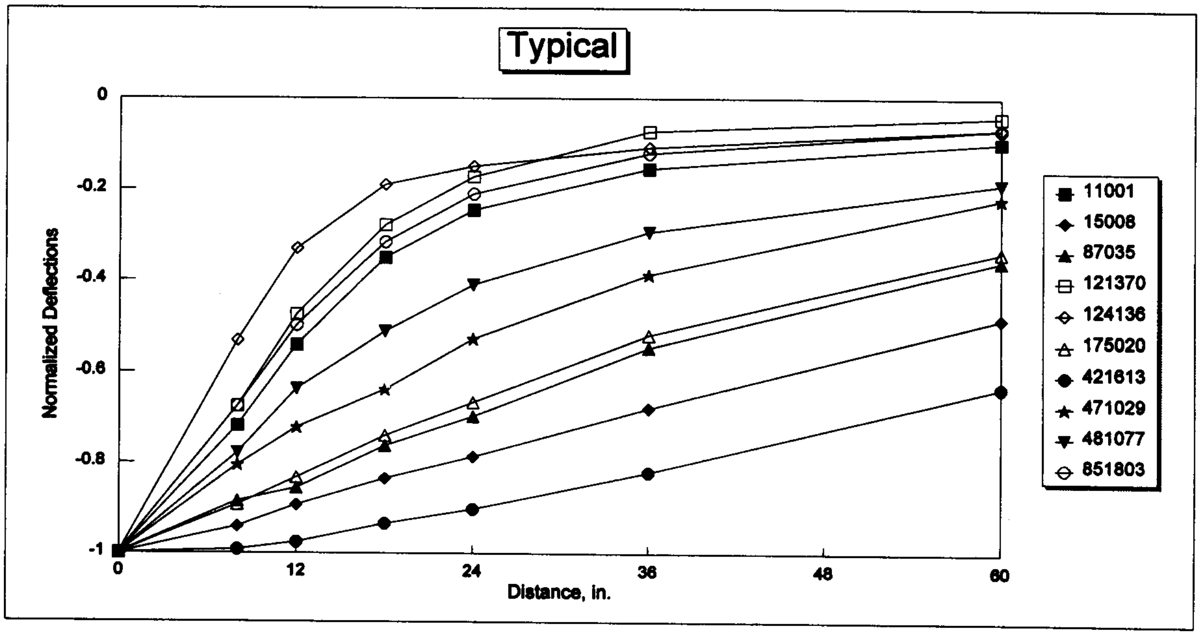

Figure 2. Typical Normalized Deflection Basin with Low Error Terms.

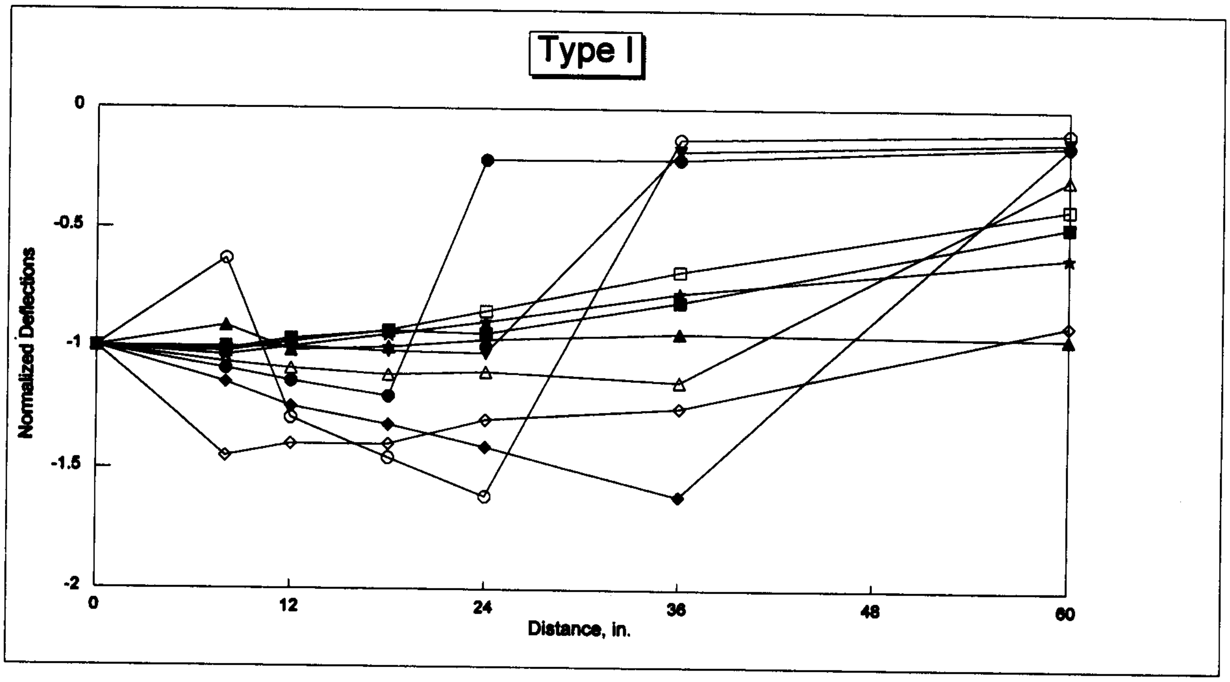

Figure 3. Type I Normalized Deflection Basin.

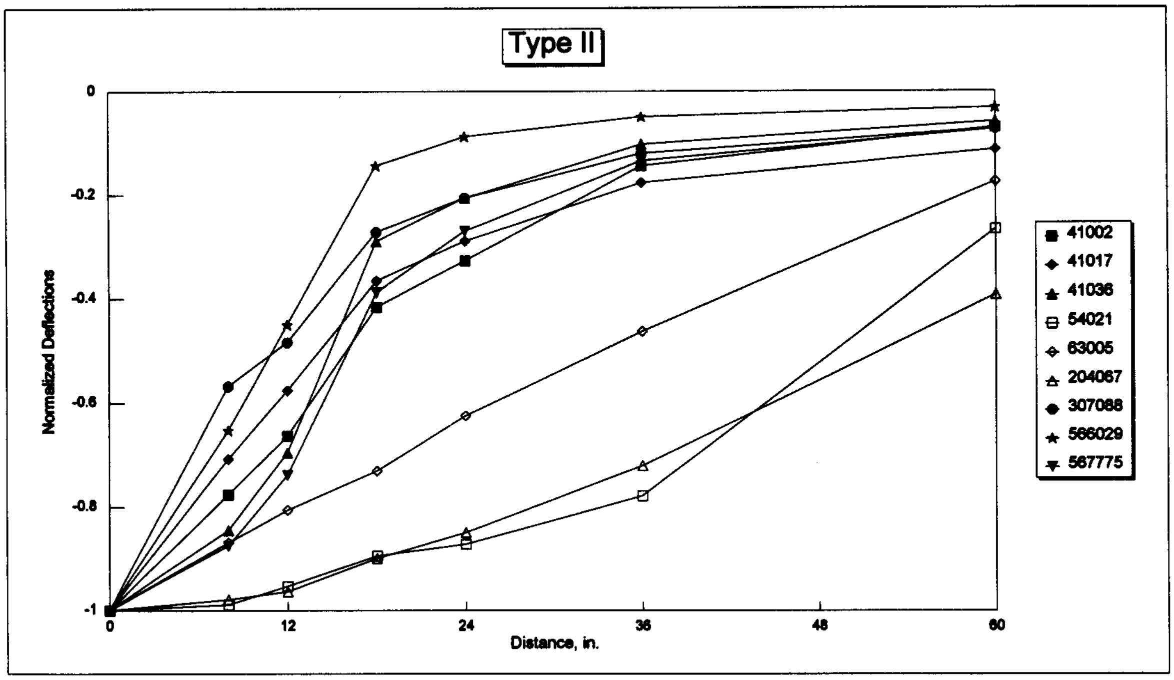

Figure 4. Type II Normalized Deflection Basin.

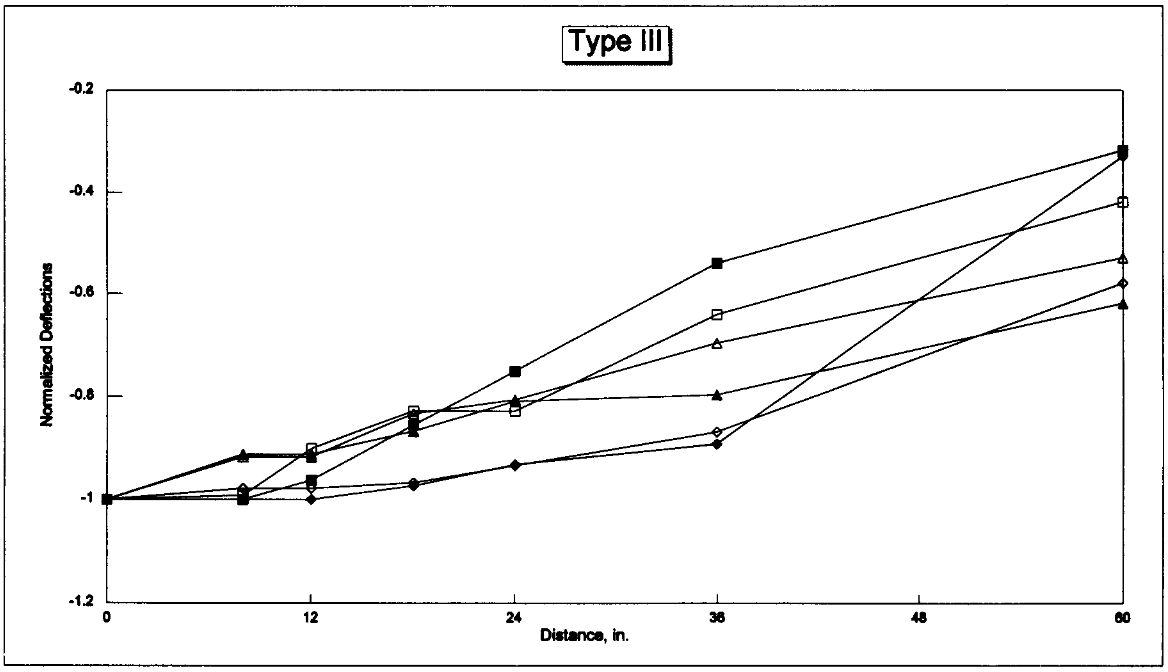

Figure 5. Type III Normalized Deflection Basin.

In general, a Type I and III deflection basin are characteristic of PCC surfaced pavements. It is believed that these unique deflection basins may be characteristic of those areas with voids, a loss of support, a severe thermal gradient causing curling and/or warping of the PCC slab, or a combination of these conditions. Conversely, a Type II deflection basin is characteristic of dense-graded asphalt concrete surfaced pavements. The error term for these types of basins has been found to decrease when a very stiff (or stabilized) layer above the subgrade is used in the pavement structure.

If a high percentage of the measured deflection basins are Type I, II, and III (as defined above), the use of equivalent elastic moduli may lead to a misinterpretation of the data. Elastic layered theory may not represent the actual load-response characteristics of the pavement-subgrade interaction. For those projects where a high percentage of the measured deflection basins are Type II, the spacing of the sensors should be checked. If the sensors have been properly spaced, and for those cases with a Type I or III deflection basin, the sensors should be recalibrated to ensure that the measurements are accurate and reliable.

Figures 6 and 7 show examples of a range in the normalized deflection basins calculated with elastic layer theory for typical asphalt concrete and PCC surfaced pavements.

Temperature Corrections. The deflection basins measured on a pavement's surface can be dependent on temperature. In fact, the moduli of surface mixtures, especially asphalt concrete, are temperature dependent. Thus, deflections measured at significantly different temperatures will be different. Surface, as well as pavement temperatures, should be recorded during deflection testing. In fact, many test procedures require that deflections be measured at the same point but during different times of the day to measure this temperature effect.

Some diagnostic and overlay design procedures based on deflection tests require that the deflections be adjusted to a standard temperature to lessen the scatter in the data. For backcalculating layer moduli, however, it is recommended that the actual deflection basin be used. Deflections should not be adjusted for temperature differences. After the layer moduli have been calculated, the moduli can then be adjusted to a standard temperature, based on laboratory test results, if needed.

Adjustment of Deflections to Reference Load. When using the falling weight deflectometer (FWD), the load is measured for each drop and does vary. It has been a common practice during the backcalculation process to use one load level for each drop height, rather than constantly changing the load for each measured deflection basin. In other words, the individual deflections are adjusted (or normalized) to a reference load magnitude (equation 1) to lessen the scatter in

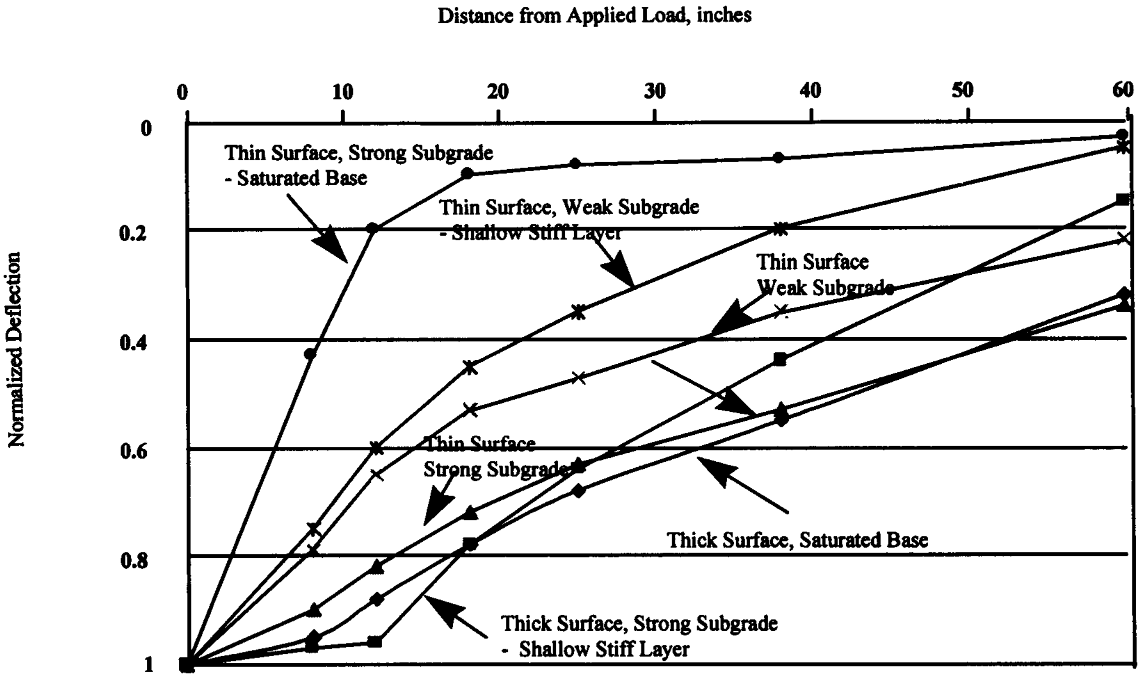

Figure 6. FWD Normalized Deflection Basins Calculated with Elastic Layer Theory on an Asphalt Concrete Surface Pavement.

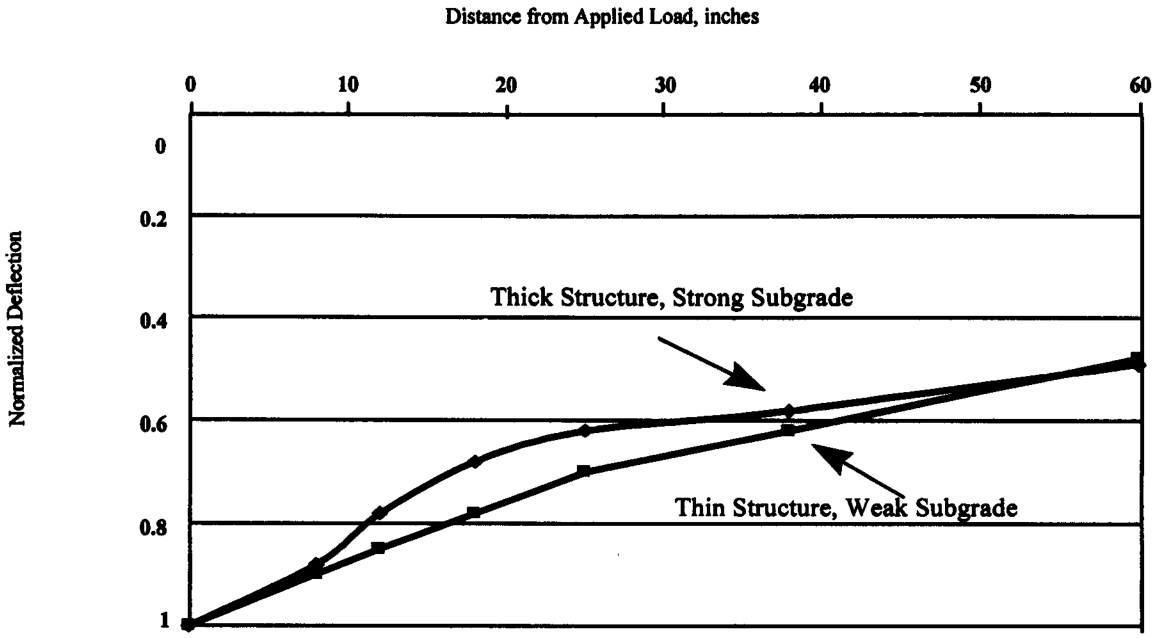

Figure 7. FWD Normalized Deflection Basins Calculated with Elastic Layer Theory on a PCC Surface Pavement.

the data when calculating statistical values about the measured deflections at specific sensors or deflection indices.

$$\Delta_{ir} = \Delta_i (P_r / P) \tag{1}$$

where:

Δ_{ir} = Adjusted or normalized deflection to reference load at sensor i;
Δ_i = Actual deflection measured by sensor i;
P_r = Reference load; and
P = Actual load applied to pavement.

The reference load is the mean load level measured for a specific drop height, or one of the standard load levels used (6, 9, 12, and 16 kips) (27, 40, 53, and 71 kN). It should be clearly understood, however, that the deflections measured from one drop height (i.e., a 16-kip (71 kN) load) should not be linearly adjusted to a different drop height (i.e., a 12-kip (53 kN) load), because of the nonlinear elastic properties of pavement materials and subgrade soils. As such, it is recommended that the deflection basins not be adjusted and that the actual measured loads be used in the backcalculation process.

2. Identify Pavement Segments with Different Load-Response Characteristics

For some diagnostic or overlay design procedures, results from deflection testing are initially used to designate design sections and aid in evaluating differences in material properties. Plots of deflection parameters as a function of longitudinal distance or station can be very helpful in defining pavement subsections with similar load response characteristics. Longitudinal profile graphs of maximum surface deflection (sensor 1), the deflection measurement farthest from the load (sensor 7), and the difference between sensors 1 and 2, as a minimum, should be prepared for the pavement being evaluated.

By evaluating these and other longitudinal profiles, pavement segments with significantly different pavement response characteristics can be visually or statistically designated as individual subsections. Subsections with similar deflections, or deflection basin characteristics, can be statistically checked by using the Student-t test to determine if two sets of data are significantly different.

Under variable topographical or geological conditions, backcalculation of layer moduli for each measurement location may be preferred or even necessary. In uniform situations, for simplification purposes, an actual representative or average deflection basin has been used for the limited analyses. However, some site-specific information can be missed or additional error introduced. Basins with large differences (greater than two standard deviations within the design section) that may occur can be overlooked by analyzing only a representative basin. Thus, averaging deflection basins from point-to-point, even within the same design section, is not recommended. More importantly, locations with notably different deflection magnitudes or problem basins should be evaluated individually.

If the pavement exhibits only occasional cracks, such as asphalt thermal cracking or concrete joints or cracks, the deflection basins selected for backcalculation should represent uncracked surfaces (or measurements should be taken with the load and all sensors at least 5 ft (1.5 m) from any cracks), because elastic layer theory does not consider these discontinuities. If the pavement surface has extensive cracking, the type and severity of cracks should be noted on the report with the backcalculated layered elastic moduli. These notations may be helpful in explaining the findings for specific locations.

3. Select Pavement Cross Section

Approximate material classifications and layer thicknesses can be initially obtained from historical or as-built construction records. However, all material types and layer thicknesses recovered from as-built construction plans should be verified using field cores or borings. A pavement coring program will provide more accurate thicknesses, preferably to the nearest 0.2 in (5 mm) for bound layers or 1 in (25 mm) for unbound layers, and the material type for each layer in the pavement structure. The borings can also be used to check for the existence of a shallow rigid layer (e.g., bedrock).

Engineering judgment may be needed or statistical methods may be used to estimate the number of cores required to determine layer thicknesses to a desired level of precision and degree of confidence.(19) It should be noted that any deviation between the assumed and actual in-place layer thicknesses will significantly affect the backcalculated layer moduli, as previously stated.

The success of low error terms in backcalculating layer moduli is dependent on the variability of the pavement structure. If extensive thickness or material variation is found from the pavement cores, then the error terms will likely increase, unless the pavement structure is also varied in the backcalculation process for each deflection basin. Obviously, it is impossible to take a core at each deflection basin, so average thicknesses are usually used in the backcalculation process.

In an effort to reduce unacceptable error terms (greater than 2.5 percent per sensor), each site should be studied to pursue an appropriate layer structure. If less than 10 percent of the measured deflection basins exceed an error of 2 percent per sensor, then the layer thicknesses used in the backcalculation process are considered appropriate and uniform. Conversely, if more than 30 percent of the deflection basins exceed an error of 2 percent per sensor, then more cores and borings may be needed to better define the thickness and material variations along the roadway. For those conditions where 10 to 30 percent of the basins exceed an error of 2 percent per sensor, the layer thicknesses used are considered adequate. Most of the high errors are generally related to thickness and material variations down the roadway. The following discusses the review of each material or layer in the pavement, including the subgrade.

Subgrade Layers. The subgrade can be divided into two layers for certain conditions. These conditions have to do with the depth to water table, depth to a rigid layer, and depth to a significant change in material type. Subdividing the subgrade by the depth to the water table has had a significant improvement in matching the calculated to measured deflection basins using the FWD. Modulus values above the water table are generally greater than those below the water table, as expected (i.e., the effect of moisture on the soils response to load).

The other condition has to do with the depth to a rigid layer. Obviously, if limestone or rock is encountered at a site, then there is really no question as to the depth to a rigid layer; however, there are cases where different soils are encountered at varying depths. For example, if a weak or soft material is encountered near the surface and is underlain by a relatively strong or stiffer layer, but not bedrock, the question becomes, does a strong layer (relative to the weaker layer) supporting a weaker layer represent a rigid layer in terms of the measured deflections? For these cases, the subgrade can be separated at that depth where those significant changes occur.

Unbound Base and Subbase Layers. Unbound base and subbase layers are generally considered two different layers, unless these materials are found to be similar from laboratory test results. For the backcalculation of layer moduli, thick granular base and subbase layers (exceeding 12 in (30 cm) in thicknesses) can be further subdivided into separate layers. In some cases, subdividing thick granular base and subbase layers can further reduce the error term, especially if contamination from clay fines exists in the lower layer or if the moisture content varies with depth. This is especially important for backcalculating layer moduli for sections with a Type II deflection basin (i.e., an irregularly shaped basin with a reverse curvature over a short distance).

Asphalt Concrete Layers. The asphalt concrete surface and base layers are generally combined into one layer for the backcalculation process. For this design pamphlet, however, these layers should be separated when there is a significant difference in materials. Separating the asphalt concrete layers, especially for overlaid pavements, may further reduce the error term. Asphalt-, cement-, and lime-treated base layers are nearly always considered different layers in the backcalculation process.

Number of Structural Layers. Based on recommended practice, the number of unknown layers (excluding a fixed apparent stiff layer) to be backcalculated should be no more than five and preferably less. To solve a number of unknowns (e.g., four layer moduli) an equal number of knowns (e.g., four deflections), as a minimum, should be used to define the deflection basin. Additional deflection points can be derived artificially by interpolating between actual measured points, but this process is not recommended because additional error can be introduced by incorrectly interpreting the changes in slope between two points. Therefore, if four deflection sensors were used, then a maximum of four unknown layers (three pavement layers and the subgrade) could be used in the structural evaluation. For a pavement where more than three to five layers were constructed, the thicknesses of layers of similar (same type of binder) materials may be combined into one effective structural layer for backcalculation purposes.

As discussed in the above paragraphs, there are cases where five or more different structural layers are required to represent pavements with diverse materials. Using five, and certainly more than five layers, does not always reduce the error term when using the WESDEF program. MODULUS 4.2 is restricted to a maximum of four layers, including the subgrade. For these conditions, an elastic layered theory program (i.e., ELSYM5) can be used separately to match the measured deflection basins. Under no circumstances, however, should the number of layers be allowed to exceed six.

Most backcalculation techniques iteratively progress toward the center of the deflection basin from the outer edge of the basin in determining layer moduli. For example, it is possible to estimate the minimum distance from the center of the applied load at which the deflections measured at the pavement surface are primarily a result of deflections in the subgrade (i.e., relatively independent of the overlying layers). Thus, a measured deflection beyond this distance can be used to directly solve the effective subgrade modulus at that stress level. Each succeeding deflection point can be attributed to strains that occur in response to the load in successively more layers, and it therefore provides some additional known information about the higher pavement layers. The effective moduli of these higher layers are then estimated using the deflections closer to the load and the previously estimated lower layer moduli.

Thin Layers in Pavements. For upper surface layers that are thin, or layers that are significantly thinner than the layer directly above it, the elastic moduli often cannot be accurately determined by most backcalculation methods. Thin layers are defined as those with thicknesses less than one quarter the diameter of the loaded area (e.g., 3 in (75 mm) or less for a 12 in (300 mm) loading plate). These thin layers, if possible, should be combined with a similar type of material directly above or below the thin layer, or the moduli of thin layers can be estimated and set as a known value.

For thin asphalt concrete layers (with very few cracks), the elastic moduli can be measured in the laboratory using SHRP Test Protocol P07 (or ASTM D 4123) or mathematically estimated using available regression equations.(5) The temperature at which the modulus is measured or estimated should correspond to that which existed in the field at the time the deflections were measured. For flexible pavements with single or double bituminous surface treatments, the surface layer is usually combined with the base material in the backcalculation procedure.

4. Locate Any Apparent Stiff Layer

Many backcalculation procedures include an apparent stiff (elastic modulus equal to 100,000 to 1,000,000 psi (700 to 7000 mPa)) layer at some depth below the pavement's surface. It is intended to simulate either bedrock or the depth where it appears that the vertical deflection is negligible. Research has shown that the results of the analysis can be significantly inaccurate by excluding such a layer or by not locating this stiff layer near its actual depth, particularly if the depth is less than 20 ft (6 m). The magnitude of this error is also affected by the modeling of the subgrade; for example, a nonlinear stress-dependent (softening) material would also lead to stiffer subgrade layers with depth, or decreasing stress, if included in the total number of layers.

5. Enter the Other Required Properties into the Selected Analytical Technique

For each deflection basin to be evaluated, enter the required data into the selected analytical technique. The NDT device loading characteristics, Poisson's ratios and thicknesses of all the assumed individual layers, deflection values and locations, and initial estimates of the layer moduli are usually included in the input data set. Typical ranges of Poisson's ratio values include the following:

Material	**Poisson's Ratio**
Asphalt concrete	0.25 to 0.40
Portland cement concrete	0.10 to 0.20
Asphalt stabilized treated base	0.25 to 0.40
Cement stabilized treated base	0.15 to 0.25
Unbound granular bases	0.20 to 0.40
Cohesive soil	0.30 to 0.45
Cement-stabilized soil	0.15 to 0.30
Lime-stabilized soil	0.20 to 0.35

Some backcalculation programs require that an estimate of the expected range of moduli be specified for each pavement layer. In the SHRP backcalculation procedure, predictive equations that rely on material property and field temperature data stored in the LTPP data base are used to establish the moduli range for asphaltic concrete layers. Moduli ranges for PCC layers and other stabilized materials are determined based on available laboratory test results, or just assumed. Similarly, moduli ranges for unbound granular base and subbase layers are estimated on the basis of material type.

In programs where seed moduli are required, their selection can affect the number of necessary iterations, the time required before an acceptable solution is achieved and possibly, the final moduli that are determined. If an extremely poor selection of a seed modulus is made, the analysis may possibly fail to find a solution within the specified tolerance between calculated and measured deflections. In this case, an alternate set of seed moduli may provide an acceptable solution before reaching the maximum allowable number of iterations. Ordinarily, if the tolerance is sufficiently narrow, the final moduli that are calculated are not significantly affected by the values chosen for the initial set of seed moduli. Typical values of seed moduli referred to in ASTM D5858 include the following:

Asphalt concrete	500,000 psi	(3500 mPa)
Portland cement concrete	5,000,000 psi	(35,000 mPa)
Cement-treated bases	600,000 psi	(4100 mPa)
Unbound granular bases	30,000 psi	(200 mPa)
Unbound granular subbases	15,000 psi	(100 mPa)
Cohesive soil	7,000 psi	(50 mPa)
Cement-stabilized soil	50,000 psi	(350 mPa)
Lime-stabilized soil	20,000 psi	(140 mPa)

As there are numerous factors that affect the modulus of pavement materials (i.e., saturated base course materials, contaminated granular materials, and stripping in asphalt concrete mixtures), both the range and starting (or seed) moduli for each layer should be based on observations of the materials recovered from the cores and borings. It is recommended that a few selected basins be taken from each design segment (or areas with a uniform pavement cross section) and used to determine the range and starting values separately.

6. Enter the Appropriate Deflection Basins

Backcalculation of layered elastic moduli can be completed for each individual basin measured or for an average deflection basin. Averaging of deflection data from station to station is not recommended because of material and construction variations. Averaging the deflection data from multiple drops or one load level at a specific point on the roadway has been considered acceptable practice to reduce the effect of the measurement error. However, if deflection hardening or softening is possible, depending on the strength of the pavement, averaging multiple tests from the same load level should not be done. In general, it is preferred to backcalculate the layer moduli for each measured basin, and then average the calculated moduli for the same layers.

7. Select the Maximum Tolerances for Deflection Matching

The accuracy of the final backcalculated moduli is affected by the tolerance allowed within the procedure for determining a match between the calculated and measured deflections. Two different approaches are commonly employed for evaluating this match. These are an arithmetic absolute sum percent error and a root mean square percent error. In both procedures, the engineer should keep in mind that the significance of random sensor error can be much greater at the outer sensor locations where the actual measured deflections are much smaller. As a result, different tolerance weighting factors for each sensor can be a consideration but are rarely used.

An arithmetic absolute sum percent error, e_{AAS}, is typically used to evaluate the match between the calculated and measured deflection basins and is defined as:

$$e_{AAS}=100 \sum_{i=1}^{n} | (\Delta m_i \ \Delta c_i) / \Delta m_i | \qquad (2)$$

where:

n = number of sensors used to measure basin;
Δ_{mi} = deflection measured by sensor i; and
Δc_i = deflection calculated at sensor i.

The magnitude of tolerance varies with the number of deflection sensors used to define the basin. No less than five deflection sensors should be used to describe the basin. It is suggested that the sum of the percent error at each sensor should not be greater than the values given in ASTM D5858. These values are:

- 18 percent if 9 deflection sensors are used,
- 14 percent if 7 deflection sensors are used, or
- 10 percent if 5 deflection sensors are used.

If the above requirements for the percent error cannot be met, then conditions may exist which violate the assumptions of elastic layer theory, or the actual layer compositions or thicknesses may be significantly different than those used in the backcalculation process. Additional field material sampling or coring at these locations may provide the information needed to resolve this problem. If this condition cannot be reconciled, then more complex models that can simulate dynamic loading, material inhomogeneities, or physical discontinuities in the pavement must be used.

8. Calculate the Modulus Ratios

Elastic moduli are calculated for each structural layer from the measured deflection basins to evaluate the insitu response characteristics of each structural layer. These layer moduli should be further examined for reasonableness based on material type and the overall pavement cross section.

Modulus ratios between two adjacent unbound layers should be calculated and reviewed for reasonableness. When moduli ratios of adjacent unbound layers exceed a value of about 3.5, large tensile stresses can occur at the bottom of the upper layer. These tensile stresses can result in decompaction of that layer reducing the modulus. Consequently, modulus ratios of adjacent unbound layers exceeding 4 are considered unrealistic, or suggest that the unbound material may, in fact, be responding as a bound or stabilized material.

The criteria originally established by the Corps of Engineers can be used to identify those deflection basins with high modulus ratios based on the pavement cross section and layer thicknesses (figure 8).(20) Thick granular base and subbase layers should be divided into two equal layers for results with high layer modulus ratios. Many of the revised layer thicknesses will reduce the modulus ratios, while maintaining an acceptable error term for the match between the measured and calculated deflection basins.

9. Adjust Backcalculated or Insitu Moduli to Laboratory Determined Values

As a final step, all of the backcalculated or insitu moduli (E[FWD]) should be adjusted to values that are consistent with the laboratory determined moduli (E[Lab]) for use with the AASHTO Design Guide. These adjustments (or C-values) are dependent on the material and pavement type, and were determined through the use of laboratory test procedures and calculated moduli from deflection basins measured with the FWD.(11) Mathematically speaking:

$$E(Lab) = C \times E\ (FWD) \tag{3}$$

It should be noted that these C-values were also determined using the backcalculated moduli from the deflection basins measured with the LTPP sensor spacing previously discussed. Any change in the sensor spacing may result in different C-values, because the spacing will have some effect on the backcalculated layer moduli.(11) Fortunately, this effect on the backcalculated moduli and C-values should be relatively small for sensor spacings similar to the LTPP standard (i.e., a 12 in (0.3 m) sensor spacing). Thus, for spacings similar to the LTPP standard, the C-values listed above can be used to adjust the backcalculated values to laboratory determined values.

These adjustments to the insitu condition should only be applied to the backcalculated moduli for use with pavement structural evaluation procedures and rehabilitation design procedures that were developed, calibrated, and validated with laboratory determined moduli.

Dense-Graded Asphalt Concrete Mixtures. The corrections or adjustments to the calculated equivalent elastic modulus for dense-graded asphalt concrete mixtures from deflection basins measured with the FWD are temperature dependent. The following lists the C-values to convert the calculated moduli to the total resilient moduli, as measured in the laboratory using the repeated load indirect tensile test.

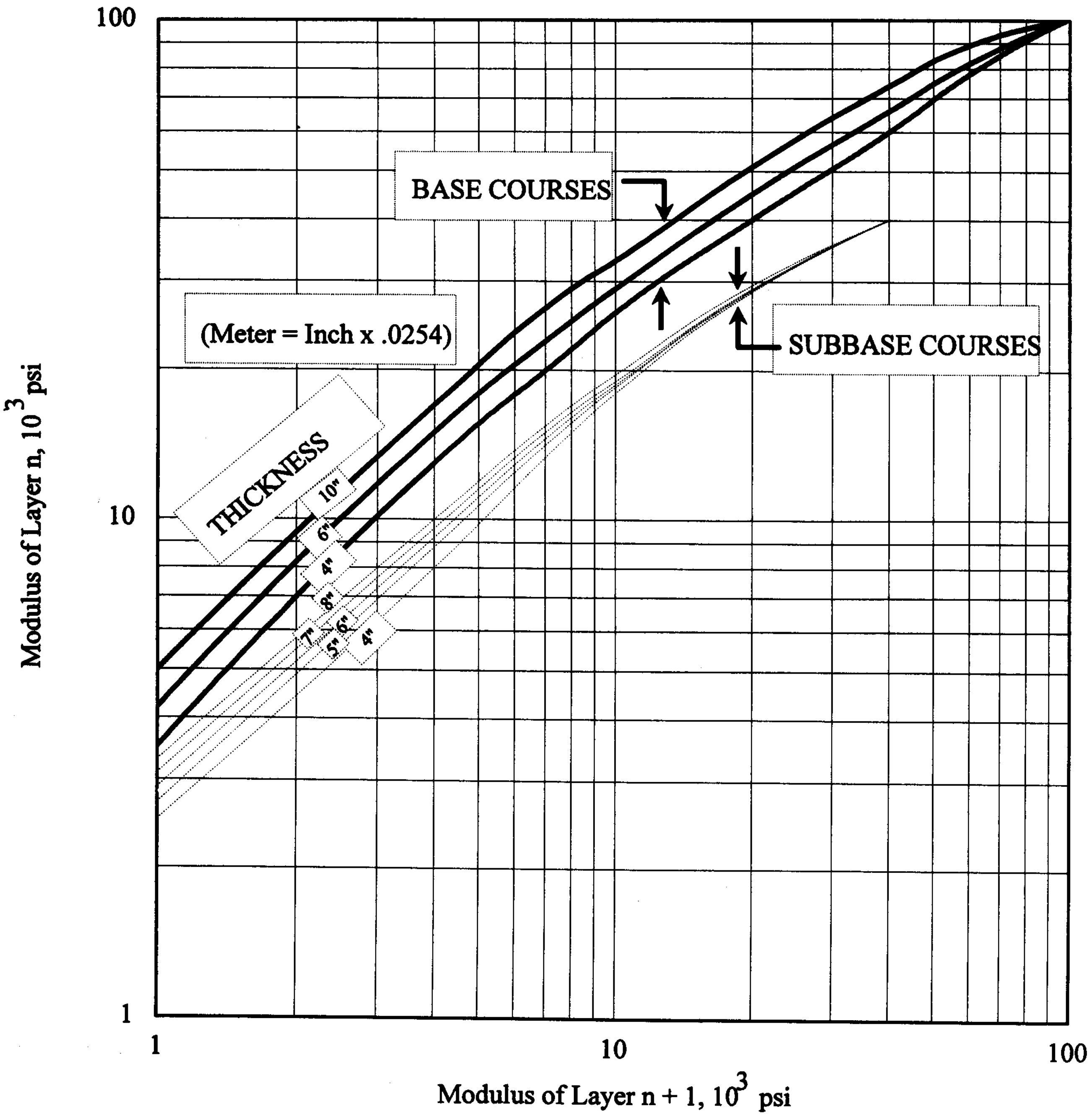

Figure 8. Limiting Modulus Criteria of Unbound Base and Subbase Layers.(19)

Temperature, °F (°C)	C-Value
41 (5)	1.0
77 (25)	0.36
104 (40)	0.25

Unbound Granular Base and Subbase Materials. The corrections or adjustments to the calculated equivalent elastic modulus for unbound granular (cohesionless) base and subbase materials from deflection basins measured with the FWD are pavement cross-section dependent. The following lists the C-values to convert the calculated moduli to the resilient modulus as measured in the laboratory using the repeated load triaxial compression test at an equivalent insitu stress state.

Layer Type and Location	C-Value
• Granular Base/Subbase under a PCC Surface	1.32
• Granular Base/Subbase under an Asphalt Concrete Surface or Base Mixture	0.62
• Granular Base/Subbase between a Stabilized material and Asphalt Concrete Surface or Base Mixture	1.43

Subgrade (or Embankment) Soils. The correction or adjustments to the calculated equivalent elastic modulus for roadbed or embankment soils from deflection basins measured with the FWD are dependent on the materials above the subgrade. The following lists the C-values to convert the calculated moduli to the resilient modulus, as measured in the laboratory using the repeated load triaxial compression test at an equivalent insitu stress state.

Pavement Material Type	C-Value
• Subgrade Soils below a Stabilized Subgrade	1.32
• Subgrade Soils below a Pavement without an Unbound Granular Base or Subbase Layer	0.52
• Subgrade Soil below a Pavement with an Unbound Granular Base or Subbase Layer	0.35

REPORTING OF RESULTS

Those items considered relevant and necessary for documenting the backcalculated layer moduli from deflection basin measurements are provided in ASTM D5858.(4) As a minimum, these items should include:

- The backcalculation program that was used to analyze the deflection basin data.
- The pavement cross section, layer thicknesses, and depth to an apparent stiff layer that was used in the backcalculation process.
- The deflection measuring device used (load level and sensor location).
- Pavement surface temperature.
- The measured deflection basin and resulting backcalculated layer moduli, as well as the calculated deflection basin.
- The error term for each deflection basin included in the analysis.

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