Design Pamphlet for the Determination of Layered Elastic Moduli for Flexible Pavement Design in Support of the 1993 AASHTO Guide for the Design of Pavement Structures

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Research and Development
Turner-Fairbank Highway Research Center
6300 Georgetown Pike
McLean, VA 22101-2296

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 selecting appropriate design values to characterize the pavement materials. 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 Backcalculation of Pavement Layer Moduli in Support of the 1993 AASHTO Guide for the Design of Pavement Structures* (FHWA-RD-97-076)—provide additional, related guidance on interpretation of pavement deflection data and characterization of 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.

Charles J. Nemmers, P.E.
Director
Office of Engineering
Research and Development

NOTICE

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16. Abstract

This design pamphlet details suggested procedures to determine the design resilient modulus of different pavement materials in support of the 1993 *AASHTO Guide for the Design of Pavement Structures*. These suggested procedures do consider the seasonal variation of resilient moduli to estimate structural layer coefficients for flexible pavement design.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

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

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
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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LIST OF ABBREVIATIONS AND SYMBOLS

AASHTO	-	American Association of State Highway and Transportation Officials
ASTM	-	American Society for Testing and Materials
FWD	-	Falling Weight Deflectometer
GPS	-	General Pavement Studies
LTPP	-	Long Term Pavement Performance
SHRP	-	Strategic Highway Research Program
a_2	-	AASHTO structural layer coefficient for the granular base/materials
C	-	Cohesion of the material and/or soil
C-Value	-	A factor converting backcalculated layer moduli to laboratory measured values
D_P	-	Layer thickness
D_S	-	Depth into the subgrade, below pavement layers
E	-	Modulus of elasticity backcalculated from deflection basin measurements
E_{RT}	-	Total resilient modulus of asphalt concrete mixtures and/or asphalt stabilized base mixtures, as measured in the laboratory
j	-	Number of seasons
K_1, K_2, K_3, K_5	-	Nonlinear elastic constants and coefficients of the constitutive equation determined by the use of linear regression techniques.
k_o	-	At-rest earth pressure coefficient
k_p	-	Passive earth pressure coefficient
M_R	-	Resilient modulus of the unbound pavement layer, stabilized subgrade, and/or subgrade or roadbed soil
p_a	-	Atmospheric pressure
p_o	-	At-rest lateral earth pressure in the subgrade at a depth of D_s
PCC	-	Portland cement concrete
SHAs	-	State Highway Agencies
T	-	Pavement temperature
U_f	-	Damage factor based on asphalt concrete tensile strain (fatigue cracking) criteria
u_f	-	Relative damage based on a serviceability design criteria
θ	-	Bulk stress
ϕ	-	Angle of shearing resistance

LIST OF ABBREVIATIONS AND SYMBOLS (Continued)

γ_p	-	Weighted average unit weight of the pavement structure and stabilized subgrade, if present
γ_s	-	Unit weight of the subgrade or roadbed soil
σ_d	-	Deviator stress
σ_3	-	Confining pressure
σ_x , σ_y	-	Normal horizontal or lateral stresses
σ_z	-	Normal vertical stress
υ	-	Poisson's ratio

DESIGN PAMPHLET FOR THE DETERMINATION OF LAYERED ELASTIC MODULI FOR FLEXIBLE PAVEMENT DESIGN IN SUPPORT OF THE 1993 *AASHTO GUIDE FOR THE DESIGN OF PAVEMENT STRUCTURES*

INTRODUCTION

Resilient modulus is the primary material property that is used to characterize the roadbed soil and other structural layers for flexible pavement design in the 1993 *AASHTO Guide for the Design of Pavement Structures*.(1) Resilient modulus is simply a measure or estimate of the elastic property of the material at a given stress state or temperature (i.e., assumed to be the modulus of elasticity) and is used to estimate the structural layer coefficients of different pavement materials in the AASHTO Guide. Specifically, section 2.3.5 of part II of the 1993 Guide overviews the use of resilient modulus to estimate the layer coefficients for structural design and evaluation.

For the roadbed soils, the seasonal variation of resilient moduli is considered and used directly to determine the design or effective roadbed soil resilient modulus. However, seasonal variation of the resilient moduli for pavement materials is <u>not</u> used or considered in the design process, even though the resilient modulus of pavement materials can vary substantially throughout the year. The purpose of this design pamphlet is to provide additional information for selecting and using a design resilient modulus for those pavement materials that can vary from season to season for flexible pavement design and evaluation.

DETERMINATION OF INSITU RESILIENT MODULUS

Two different procedures can be used to determine the insitu resilient modulus at a particular time and its seasonal variation throughout the year. One of these methods is the use of laboratory testing procedures. An alternate procedure is to backcalculate the resilient modulus from deflection basins measured on the pavement's surface. The Guide allows the use of both procedures.

Backcalculated Layered Elastic Moduli

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 process. AASHTO recommends that layered 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.

Numerous backcalculation procedures have been developed and used. Two of the more recent include the ASTM Standard Guide D5858 and the procedure developed as a product from the Strategic Highway Research Program (SHRP).[2, 3] A third procedure was developed and written under FHWA Contract No. DTFH61-95-C-00029, which combines the SHRP and American Society for Testing and Materials (ASTM) procedures.[4] Either of these procedures can be used; however, it should be noted that there is no unique solution for a specific deflection basin based on elastic layer theory. The layer moduli determined from the backcalculation process represent equivalent elastic moduli.

Unfortunately, layered elastic moduli backcalculated from deflection basins (E[FWD]) and laboratory measured resilient moduli (E[Lab]) are not equal for a variety of reasons. The more important reason is that the uniform confining pressures and repeated vertical stresses used in the laboratory do not really simulate the actual confinement and stress state variation that occurs in a pavement layer under the falling weight deflectometer (FWD) test load or wheel load. Consequently, all of the backcalculated or insitu moduli need to be adjusted to values that are consistent with the laboratory determined values for use with the AASHTO Guide. In other words:

$$M_R(\text{Lab}) = C \times E\ (\text{FWD}) \qquad (1)$$

These adjustments (or C-values) are dependent on the material and pavement type and have been determined through the use of specific laboratory test procedures and moduli calculated from deflection basins measured with the FWD.[5] It should be remembered and understood that these adjustments to the insitu condition should only be applied to the backcalculated moduli for use in pavement structural evaluation and rehabilitation design procedures that were developed, calibrated, and validated using laboratory measured moduli. The following paragraphs present the C-values to be used for different pavement materials.

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 (ASTM D4123).

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

Note: C-values greater than 1.0 for temperatures less than 41°F (5°C) should not be used. For mid-depth asphalt concrete temperatures greater than 104°F (40°C), caution should be used in selecting the value to be used. Linear extrapolations should definitely not be used to determine the C-value outside the above range. More importantly, the C-values listed above where determined from testing uncracked surfaces. If cracks are within the measured deflection basin, the above values may not be appropriate.

Unbound Granular Base/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 (SHRP Test Protocol P46).

Layer Type and Location	Mean C-Value	Coefficient of Variation, %
• Granular Base/Subbase under a Portland Cement Concrete Surface	1.32	74
• Granular Base/Subbase under an Asphalt Concrete Surface or Base Mixture	0.62	44
• Granular Base/Subbase between a Stabilized Material and Asphalt Concrete Surface or Base Mixture	1.43	80

Note: For determining the above C-values, elastic layered theory was used to calculate the stress-state at the one-fourth depth (from the top of the layer) of the granular base/subbase layer thicknesses.

Embankment Materials. The correction or adjustments to the calculated equivalent elastic modulus for embankment materials from deflection basins measured with the FWD are dependent on the materials above the embankment. 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 (SHRP Test Protocol P46).

Pavement/Material Type	Mean C-Value	Coefficient of Variation, %
• Embankment Materials below a Stabilized Subbase	1.32	80
• Embankment Materials below a Pavement without an Unbound Granular Base and/or Subbase Layer and no Stabilized Subgrade	0.52	37
• Embankment Materials below a Pavement with an Unbound Granular Base and/or Subbase Layer, but not Stabilized Subgrade	0.35	49

Note: As shown in the above lists of C-values, the coefficients of variation are large. Reasons for these large coefficients of variation are that the laboratory measured resilient moduli (M_R[Lab]) are determined on intact or discrete specimens under controlled moisture, density, and temperature conditions of the test specimens. Whereas, the calculated layered elastic moduli (E[FWD]) represent the combined influence of larger areas with layer thickness variations (resulting from normal construction practice or surface distortions); temperature, moisture, and density gradients and variations; and possible layer and material discontinuities (as an example, cracks and stripping).

Laboratory Measured Resilient Modulus

Resilient moduli can be measured in the laboratory at different stress states for unbound aggregate materials and at different temperatures for asphalt concrete mixtures. These relationships between stress and strain are then used for selecting a design resilient modulus for specific pavement layers. The purpose of this section of the design pamphlet is to simply overview the test procedures used for determining the insitu resilient moduli from laboratory repeated load resilient modulus tests.

Repeated load resilient modulus tests were performed as part of the SHRP Long Term Pavement Performance (LTPP) program. SHRP Test Protocol P-46 (Resilient Modulus of Unbound Granular Base/Subbase materials and Subgrade Soils) specifies the laboratory procedures and vertical loads and confining pressures recommended for testing base and subbase materials, and SHRP Test Protocol P-07 (Resilient Moduli of Asphalt Concrete Mixtures) specifies the procedures, temperatures, and loading rates to be used for asphalt concrete mixtures.

Asphalt Concrete Mixtures. Repeated load indirect tensile tests are used to measure the indirect tensile resilient modulus of asphalt concrete mixtures, as specified in section 2.3.5 of part II of the 1993 AASHTO Guide. These tests are performed over a range of temperatures to evaluate the temperature dependency of this viscoelastic material.

For diagnostic studies, roadway cores are recovered and tested in the laboratory. Each individual mixture should be tested separately. For new asphalt concrete mixtures, test specimens are prepared and compacted in the laboratory to a specified air void level (either measured from field cores or specified during construction) and then aged in the laboratory to simulate field conditions. As a minimum, three test specimens (or cores) per mixture should be tested at each test temperature specified in SHRP Test Protocol P-07 or ASTM D4123. If the variability of test results (resilient modulus measured at the same temperature) exceeds a coefficient of variation of 25 percent, then additional tests should be performed. Figure 1 shows the range and typical temperature dependency of the resilient modulus test results for dense-graded asphalt concrete mixtures that are considered to have good performance characteristics.

The actual temperature varies throughout the thickness of the asphalt concrete layer. Figure 2 shows a comparison of the temperature measured at the surface to the temperatures measured at three different depths in an asphalt concrete surface or base. To determine the insitu resilient

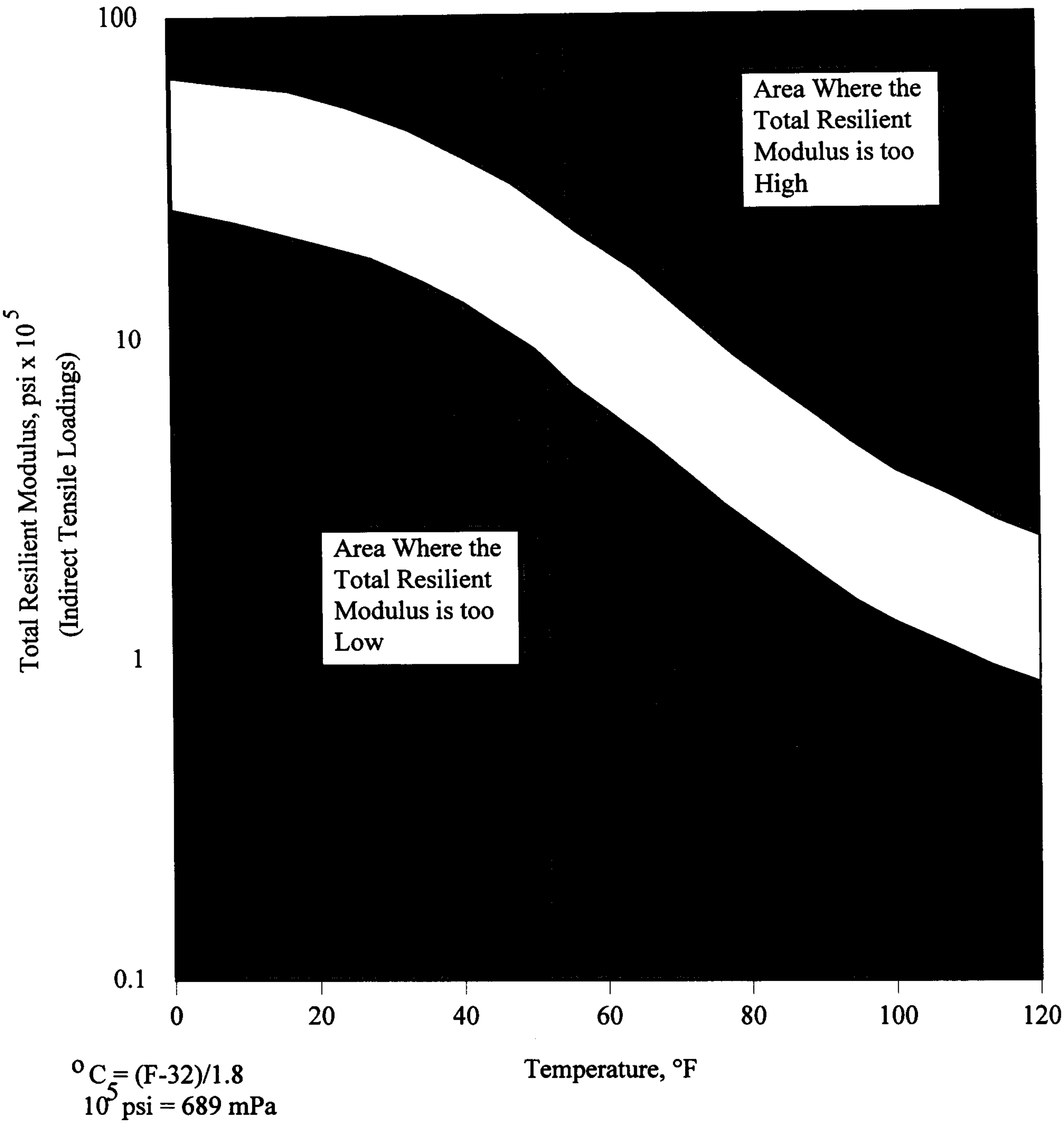


Figure 1. Typical range of resilient modulus for different test temperatures, as measured by load indirect tensile testing techniques.

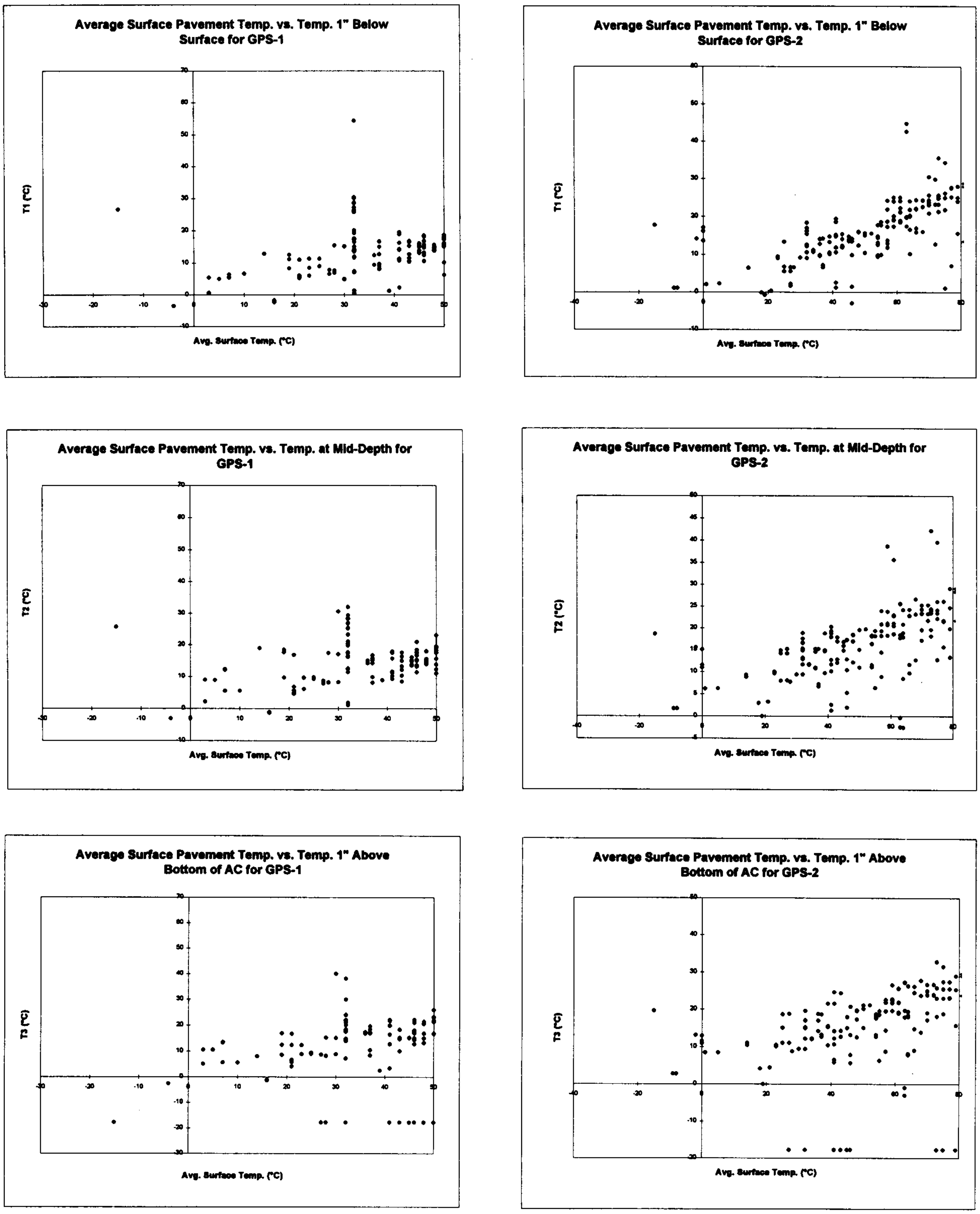


Figure 2. Example of the temperature determined at various depths in a dense graded asphalt concrete surface material.

modulus for a specific mixture or layer placed along a roadway, the temperature at the mid-depth thickness of the asphalt concrete layer should be used.

Unbound Granular Base or Subbase Materials. Repeated load triaxial compression tests are used to measure the resilient modulus of unbound granular base or subbase materials. These tests are performed over a range of vertical stresses and confining pressures to evaluate the nonlinear elastic behavior of these pavement materials. Thus, the resilient modulus test does not result in a single modulus value but defines the modulus at different stress states. In other words, for most granular or coarse-grained materials, the insitu modulus is dependent on the stress state used. An example of the repeated load resilient modulus test results (in terms of resilient modulus as a function of stress states) is shown in figure 3 for one of the general pavement study (GPS) sites included in the LTPP program.

Various types of relationships have been used to represent the repeated load resilient modulus test results of coarse-grained soils and crushed aggregate base and subbase materials. One of these relationships is included in the AASHTO Guide, which has been used quite extensively by the industry. That relationship is:

$$M_R\ (\text{Base}) = K_1\ (\theta)^{K_2} \tag{2}$$

where:

θ = bulk stress or the sum of the principal stresses $(\sigma_1 + \sigma_2 + \sigma_3)$

However, the constitutive relationship suggested for use to represent the laboratory test results of all unbound pavement materials and subgrade soils is:

$$M_R = K_1\ p_a \left[\frac{\theta}{P_a}\right]^{K_2} \left[\frac{\sigma_d}{P_a}\right]^{K_3} \tag{3}$$

where:

σ_d	=	deviator stress
θ	=	bulk stress
p_a	=	atmospheric pressure
K_1, K_2, K_3	=	nonlinear elastic constants and coefficients

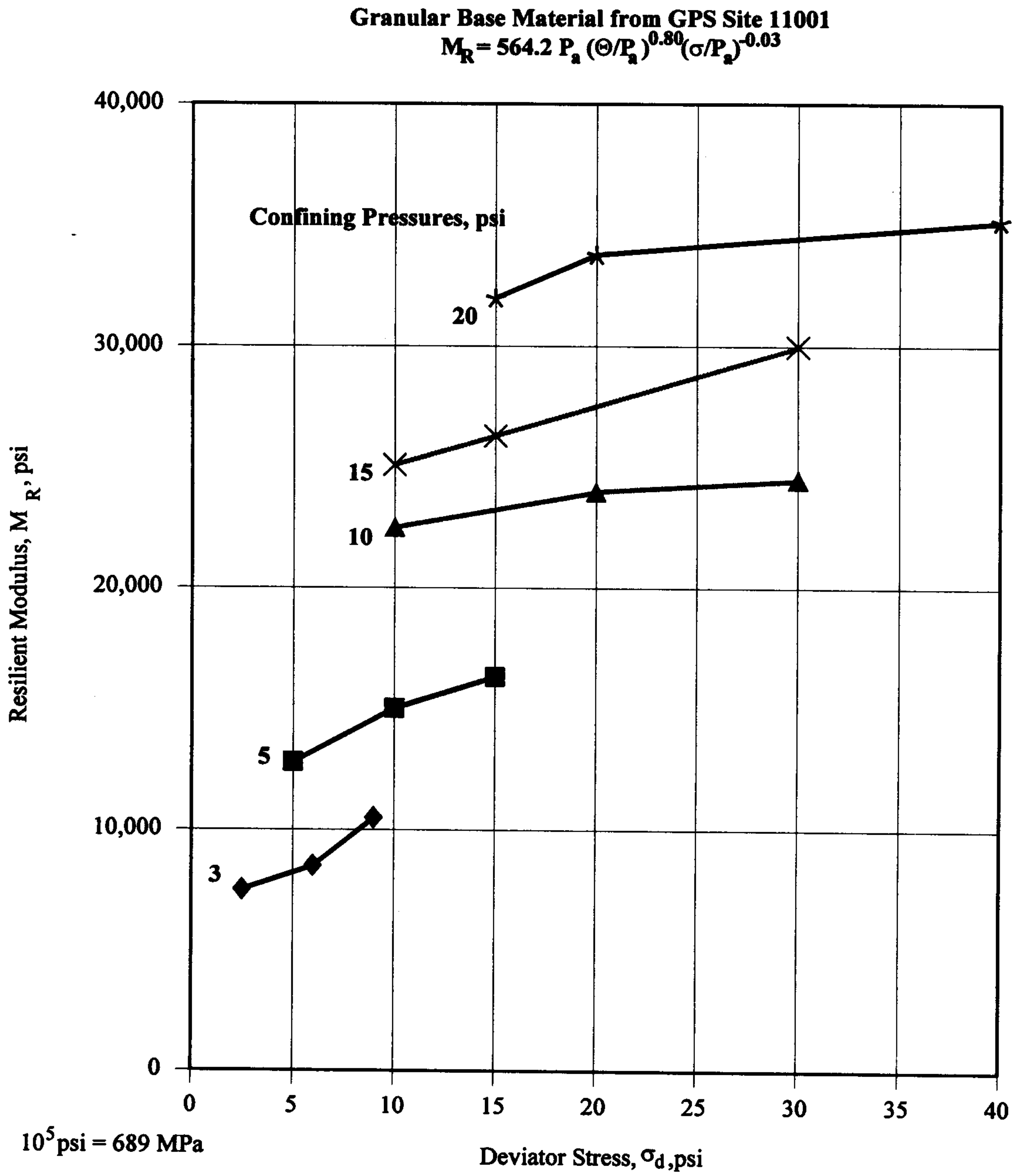


Figure 3. Example of repeated load triaxial resilient modulus test results of a granular base material.

Linear regression analyses can be used to determine the nonlinear elastic parameters (K_1, K_2, K_3) for the above equation. The nonlinear elastic coefficients and exponents (K-values) should be determined for each individual test specimen to ensure that the multiple correlation coefficient exceeds 0.90 (i.e., equation 3 is applicable to the test results). The repeated-load resilient modulus test results from similar base and subbase materials and conditions can be combined. Thus, a pooled K_1, K_2, and K_3 can be determined and assigned for each unbound base and subbase layer. The nonlinear elastic parameters for the test results from the referenced GPS site are also included in figure 3.

Condition of Test Specimens. The resilient moduli of unbound granular or crushed aggregate base and subbase materials are highly dependent on the moisture content and unit weight of the material. Test specimens should be compacted to the unit weight measured from test pits (for rehabilitation designs) or to the value specified during construction (designs for new construction or reconstruction).

Unlike unit weight, the moisture contents of the base and subbase layers do vary throughout the year. This variation in moisture content can be substantial and is dependent on many different factors, making it difficult to predict. As a minimum, test specimens should be compacted in the laboratory at the as-built moisture content (or the optimum value) and at the value expected during increased rainfall or during spring thaw. This higher moisture content level should be based on experimental results and experience. Three test specimens should be tested at each condition and the results averaged for each moisture content included in the test program.

Number of Test Specimen. Another important point to remember (in selecting the number of specimens to be tested) is that the resilient modulus measured from repeated load tests can be highly variable. As a general guide for the suggested testing frequency, three resilient modulus tests should be performed on each unbound base and subbase layer. If the variability of test results (resilient moduli measured at the same stress state) exceeds a coefficient of variation of 25 percent, then additional resilient modulus tests should be performed.

Determination of Insitu Stress State. To determine the insitu resilient (or elastic) modulus from laboratory repeated load triaxial compression tests (SHRP Test Protocol P-46 or AASHTO T294), the actual lateral and vertical stresses must be known and include the at-rest earth pressures. To determine these values, densities and layer thicknesses of the pavement structure must be initially estimated or assumed. The following steps are used to determine resilient modulus that is representative of the insitu stress state.

1. Determine the earth pressure coefficient, k:

For cohesive soils used in embankment materials (such as silty or sandy clays), the at-rest earth pressure coefficient, k_o, is normally considered to be a function of Poisson's ratio, ν, and is:

$$k_o = \nu/(1-\nu) \tag{4}$$

For noncohesive soils and materials (such as crushed stones, gravels, and sands), the at-rest earth pressure coefficient is a function of the angle of shearing resistance, ϕ, and is:

$$k_o = 1 - \sin\phi \tag{5}$$

As the wheel or test load is applied to the pavement and the pavement begins to deflect, the resulting pressure exerted by the soil approaches a maximum value known as the passive earth pressure. The passive earth pressure coefficient, k_p, is:

$$k_p = \tan^2\left(45 + \frac{\phi}{2}\right) + \frac{2C}{\sigma_z}\tan\left(45 + \frac{\phi}{2}\right) \tag{6}$$

where:

σ_z = total vertical stress
C = cohesion of the soil

For pavement structural analyses, both the passive and at-rest earth pressures have been used to determine the actual stress-state in the subgrade. For thin pavements (pavements with unbound aggregate base layers of less than 8 in (0.2 m) in thickness and surface layers of less than 1 in (2.5 cm) in thickness and without stabilized subgrades) under heavy loads (greater than an 18-kip (80 kN) axle load), the passive earth pressure coefficient should be used. However, the at-rest earth pressure coefficient is used for most types of pavement structures because the deformations in the lower pavement layers from the imposed wheel loads (at the calculation depth) are usually very small.

2. Compute the insitu lateral stress, σ_3:

$$\sigma_3 = \sigma'_3 + p_o \tag{7}$$

where:

$$p_o = k_o (D_s \gamma_s + D_p \gamma_p) \tag{8}$$

σ'_3	=	Lateral stress computed with elastic layer theory from a load applied to the pavement's surface
p_o	=	At-rest earth pressure one-quarter the depth of the pavement layer
k_o	=	At-rest earth pressure coefficient
D_s	=	Depth into the layer
γ_s	=	Unit weight of the base or subbase layer
D_p	=	Thickness of the pavement structure above the layer being evaluated
γ_p	=	Average unit weight of the pavement structure above the layer being evaluated

3. Compute the insitu deviator stress, σ_d:

$$\sigma_d = \sigma'_d + p_o(K_o^{-1} - 1) \tag{9}$$

where:

σ'_d = Deviator stress computed with elastic layer theory from a wheel load applied to the pavement's surface.

4. Compute the insitu bulk stress, θ:

$$= \sigma'_x + \sigma'_y + \sigma'_z + [1 + 2K_o]\ [D_s\gamma_s + D_p\gamma_p] \tag{10}$$

where:

$\sigma'_x, \sigma'_y, \sigma'_z$ = Normal stresses computed with elastic layer theory in the horizontal (transverse and longitudinal) and vertical direction, respectively, from a wheel load applied at the pavement's surface.

Determination of the Insitu Resilient Modulus. The insitu resilient modulus for a particular pavement layer can be determined by substituting the total deviator stress (equation 9) and bulk stress (equation 10) into equation 3. As a result, an insitu resilient modulus can be calculated for each design area and pavement layer.

DETERMINATION OF DESIGN RESILIENT MODULUS

The 1986 and 1993 versions of the AASHTO Guide clearly describe a method for estimating the structural layer coefficients required for flexible pavement designs based on the serviceability criteria. As the 1993 Guide states in section 2.3.5 of part II:

> "...A value for this coefficient is assigned to each layer material in the pavement structure in order to convert actual layer thicknesses into structural number (SN). This layer coefficient expresses the empirical relationship between SN and thickness and is a measure of the relative ability of the material to function as a structural component of the pavement..."

Relationships are provided in the AASHTO Guide between resilient modulus and layer coefficient for different pavement materials. However, seasonal variations of resilient moduli are not directly considered in the design process for estimating the layer coefficient of pavement materials. The following sections of this design pamphlet summarize the methods that can be used to consider seasonal variations in the design process.

Asphalt Concrete Materials

The structural layer coefficient for asphalt concrete mixtures are empirical values that cannot be measured directly in the laboratory. The Guide recommends that the following relationship be used to determine the structural layer coefficient for asphalt concrete mixtures (a_1).

$$a_1 = 0.40 Log\left[\frac{E_{RT}}{450}\right] + 0.44 \qquad (11)$$

where:

E_{RT} = The resilient modulus, as measured using repeated load indirect tensile loading techniques in accordance with ASTM D4123.

The AASHTO Guide does not specify whether the "instantaneous" or "total" resilient modulus (measured from ASTM D4123) should be used in the above equation. The instantaneous value is more representative of the elastic (independent of time) response, whereas the total resilient modulus includes the time-dependent viscoelastic response. The total resilient modulus should be used in the above equation because it includes time-dependent responses.

As required by the AASHTO Guide, the total resilient modulus of the asphalt concrete (E_{RT}) is to be measured at a temperature of 68 °F (20 °C), regardless of the environment. In actuality, the asphalt concrete resilient moduli vary with pavement temperature (figure 1), but no consideration is given to local environmental conditions. The resilient modulus measured at 68 °F (20 °C) for most well compacted mixes that are resistant to excessive permanent deformations will significantly exceed the modulus that is required for the commonly assumed layer coefficient of 0.44 for asphalt concrete mixtures. The average value used by most State highway agencies (SHAs) is 0.42.

The repeated load indirect tensile test results (SHRP Test Protocol P-07 or ASTM D4123) and the average seasonal pavement temperatures estimated at the mid-depth of the asphalt concrete layer are used to determine the seasonal total resilient moduli. The equivalent annual resilient modulus or the design modulus [E_{RT}(Design)] can be determined in accordance with the following equation.

$$E_{RT}(Design) = \frac{\sum_{i=1}^{j} E_{RT}(T)_i \ x \ DF_i}{\sum_{i=1}^{j} DF_i} \tag{12}$$

where:

$$DF_i = 7.4754 \text{ x } 10^{10} \, [E_{RT}(T)]^{-1.908} \tag{13}$$

DF_i = Fatigue cracking damage factor in season i

$E_{RT}\ (T)_i$ = The total resilient modulus (using indirect tensile loading conditions) for the average mid-depth pavement temperature (T) for season i (measured in the laboratory or backcalculated from deflection basins and adjusted to laboratory conditions)

j = Number of seasons (equal traffic assumed for each season)

The equivalent annual total resilient modulus for an asphalt concrete mixture is used in equation 11 to estimate the structural layer coefficient for that mixture. In most cases, the equivalent annual total resilient modulus calculated from equation 12 will result in a value significantly less than the total resilient modulus measured at 68 °F (20 °C).

Unbound Granular Base and Subbase Materials

As for the structural layer coefficients for asphalt concrete mixtures, the layer coefficients for unbound granular base and subbase materials are empirical values that cannot be measured directly in the laboratory. The Guide does provide a relationship that equates the resilient modulus of the granular base material to the base layer coefficient, as given below.

$$a_2 = 0.249(\log_{10}M_R)-0.977 \quad (14)$$

where:

a_2 = Structural layer coefficient of the granular base

M_R = Resilient or elastic modulus of the unbound granular base

Using the AASHTO Guide, resilient moduli should be measured from testing representative specimens of the granular base or subbase material at their optimum moisture contents. Drainage coefficients have been added to the design process to adjust for anticipated exposure to moisture and the quality of drainage. Table 2.4 in the 1993 AASHTO Guide provides the recommended drainage coefficients to be used for modifying the structural layer coefficients of moisture sensitive unbound pavement materials.

These drainage coefficients are dependent on the quality of drainage and exposure to moisture levels approaching saturation but are empirical values, which can not be measured from laboratory tests. Consequently, very few SHAs have formally adopted these drainage coefficients for use in flexible pavement design, and variability of the base resilient modulus for varying drainage and moisture conditions are not directly accounted for by other methods in the Guide.

Most well-compacted granular base materials at optimum moisture conditions have moduli considerably greater than the modulus required for a coefficient of 0.14 (equation 14), which is the value assumed by most SHAs for aggregate base courses. The greater the elastic modulus, the larger the structural layer coefficient. Thus, the stiffer the material, the better the material or the thinner the material that needs to be provided. Unfortunately, the layer moduli and corresponding layer coefficients can vary, significantly increasing or decreasing the structural capacity of a given pavement structure. This is a well documented problem where spring thaw is common (going from very stiff structures to very weak or soft structures).

If the AASHTO drainage coefficients are used in the design process, resilient modulus tests should be performed on test specimens prepared and compacted at the optimum condition. If the AASHTO drainage coefficients are not used in design, resilient modulus should be determined from testing representative specimens of granular base materials in their weakest condition. For most sites, this condition is generally observed during spring thaw (March and April) or during seasons of increased rainfall. To accurately establish this correction factor, the designer must know the difference between the modulus of the base material at its optimum moisture content and its modulus at a moisture content equivalent to conditions that exist in the spring or during wet seasons.

Repeated load resilient modulus testing of representative specimens of aggregate base course materials equal to the moisture conditions encountered during wet seasons should be conducted to determine the design resilient moduli for estimating base structural layer coefficients when using the AASHTO serviceability criteria. Recognizing that a substantial testing effort is required in the laboratory, nondestructive testing on a representative structure in the spring or the critical season is probably the most efficient method for establishing the structural layer coefficients for design.

The true benefit associated with quantifying actual values is in identifying those cases where the layer coefficient is less than the commonly assumed value of 0.14. An oversight of this nature can significantly reduce the life of a pavement structure. However, using the AASHTO drainage coefficients or actual layer moduli of the base material in its weakest condition may be too conservative and inappropriate for some materials and pavements.

Damage factors (U_f) for unbound aggregate base and subbase layers (based on fatigue cracking of the asphalt concrete surface) can be used to ensure that there is sufficient cover or surface thickness to prevent overstressing of the base and subbase materials and inducing high tensile strains in the asphalt concrete surface layer during periods of increased moisture. Equations 15 and 16 can be used to calculate an equivalent annual modulus of the granular base or subbase layer based on a fatigue cracking criteria of the asphalt concrete surface.

$$U_f = 1.885 \times 10^3 (M_R)^{-.721} \quad (15)$$

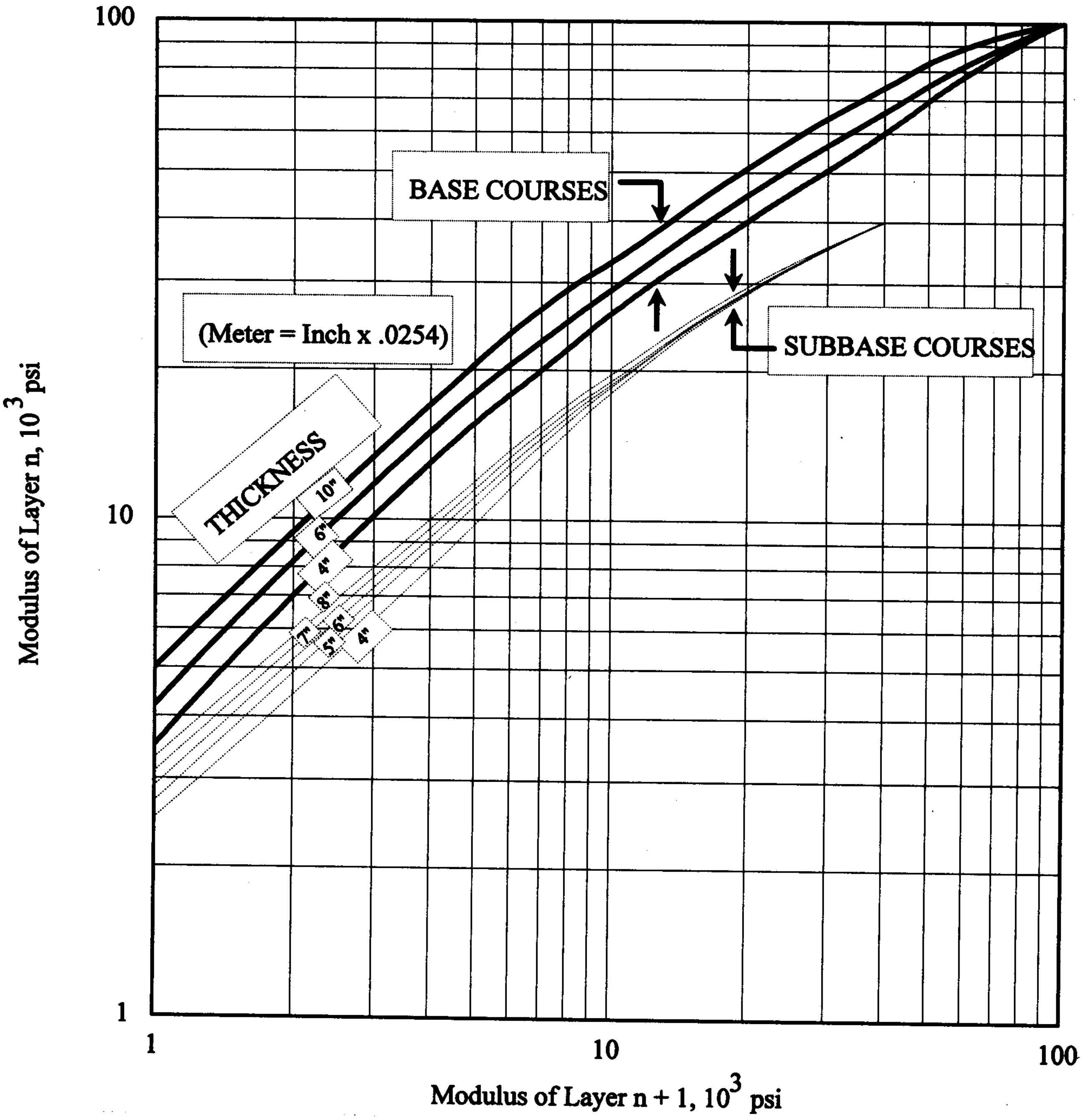
$$M_R(Base) = \frac{\sum_{i=1}^{j} (M_R)_i \ x \ (U_f)_i}{\sum_{i=1}^{j} (U_f)_i} \quad (16)$$

The surface layer thickness should be sufficient to reduce or limit the tensile strains in the asphalt concrete to an acceptable level. The equivalent annual resilient moduli for unbound aggregate base and subbase materials are used in equation 14 to estimate the structural layer coefficient. The insitu resilient modulus of the unbound aggregate base and subbase layer is dependent upon the resilient modulus of the layer directly beneath the base and subbase layer. For unbound coarse-grained (or noncohesive) materials, large modulus ratios between adjacent layers can result in high tensile stresses at the bottom of the base or subbase layer. These high tensile stresses will tend to decompact the material resulting in lower resilient moduli. Thus, criteria have been historically used to set upper modulus limits for unbound coarse-grained base and subbase layers so that the high tensile stresses do not occur. Figure 4 is the criteria developed by the Corps of Engineers, which sets upper limits on the resilient modulus of unbound layers. This criteria can be used with equation 14 for estimating the structural layer coefficient.

EXAMPLE PROBLEM AND SUMMARY OF THE PROCEDURE TO DETERMINE THE DESIGN RESILIENT MODULUS

This section of the design pamphlet describes an example problem using the procedures previously discussed. The example problem is presented in a step-by-step procedure, which summarizes all steps discussed to determine the design resilient modulus.

1. Conduct a pavement and subsurface exploration program to measure the layer thicknesses, identify the different types of pavement materials and subsurface



Pa = psi x 6.895 x 10^3

Figure 4. Limiting modulus criteria of unbound and subbase layers.[(6)]

soils, and recover bulk samples of the aggregate base for classification, moisture content, and resilient modulus testing.

From the borings, subdivide the project site into sections with similar pavement and subsurface conditions. For this example, it is assumed that uniform conditions exist over the project site, consisting of a 6 in (0.15 m) asphalt concrete layer and a 10 in (0.25 m) crushed aggregate base layer over 18 ft (5.5 m) of expansive clay which is underlain by a very stiff shale (an apparent rigid layer). The average unit weight of the clay is 105 pcf (513 kg/m^2).

2. At the field moisture content, compact test specimens of the aggregate base material to the insitu density.

3. Perform laboratory resilient modulus tests and analyze the test results. For the example, five resilient modulus tests were performed on the aggregate base. Results from the test program are summarized in table 1. As the aggregate base is similar, all test results were pooled and the results are shown at the bottom of table 1.

Table 1. Summary of repeated load triaxial compression test results for the example problem.

Specimen Number	Nonlinear Elastic Constants (Equation 3)			Multiple Correlation Coefficient
	K_1	K_2	K_3	
1	1548	0.75	-0.01	0.93
2	1524	0.85	-0.02	0.91
3	1555	0.81	-0.05	0.95
4	1565	0.78	0.02	0.98
5	1580	0.86	-0.03	0.90
Pooled Results	1561	0.82	-0.03	0.78

4. Determine the insitu resilient modulus.

a. Determine the at-rest earth pressure coefficient for the crushed aggregate base with an angle of shearing resistance, ϕ, of 52°.

$$k_o = 1 - \sin\phi$$

$$= 1 - \sin(52)$$

$$k_o = 0.212$$

b. Compute the insitu lateral stress for an assumed pavement structure.

For this example, 6 in (0.15 m) of an asphalt concrete with a total resilient modulus of 250 ksi (1724 mPa) during the summer months, and a clay subgrade with a resilient modulus of 15 ksi (241 mPa) were assumed. The aggregate base thickness was 10 in (0.25 m).

The density of the asphalt concrete is 148 pcf (722 kg/m^2), and the density of the crushed aggregate base is 132 pcf (644 kg/m^2). The weighted average unit weight of the pavement is:

$$\gamma_p = \frac{148\,pcf\ (6\,in) + 132\,pcf\ (2.5\,in)}{(6\,in) + (2.5\,in)}$$

$$\gamma_p = 143\,pcf (2291\,kg/m^3)$$

Note: One fourth the thickness of the aggregate base is used because the stress state of the aggregate base is calculated at that depth.

The at-rest lateral earth pressure is:

$$p_o = k_o(D_p \gamma_p)$$

$$= 0.212 \quad 0.71 ft.(143 pcf)$$

$$= 21.5 psf$$

$$p_o = 0.15 psi (1.03 kPa)$$

The minimum lateral stress is computed with elastic layered theory for an 18-kip (80 kN) single axle load at a depth of 2.5 in (63.5 mm) into the aggregate base. An initial assumed value for the aggregate base of 20,000 psi (137.9 mPa) is used in the calculations.

$$\sigma'_3 = 0.2 psi \ (in \ tension)$$

Thus, the insitu lateral stress is:

$$\sigma_3 = \sigma'_3 + p_o$$

$$= 0.2 - 0.15$$

$$\sigma_3 = 0.05 psi (34.5 Pa)$$

c. Compute the insitu deviator stress for the assumed pavement structure.

First, the deviator stress is computed with elastic layered theory for an 18-kip (80 kN) single axle load at a depth of 2.5 in (63.5 m) into the aggregate base.

$$\sigma'_d = \sigma_z - \sigma_x$$

$$= (11.7 - 1.0) psi$$

$$\sigma'_d = 10.7 psi (73.8 kPa)$$

Thus, the insitu deviator stress is:

$$\sigma_d = \sigma'_d + P_o(k_o^{-1} - 1)$$

$$= 10.7 + 0.15 (0.212^{-1} - 1)$$

$$\sigma_d = 11.3 psi (77.9 kPa)$$

d. Compute the insitu bulk stress.

$$\theta = \sigma'_x + \sigma'_y + \sigma'_z + [1 + 2k_o][D_p \gamma_p]$$

$$= (-0.2) + 1.0 + 11.7 + [1 + 2(0.212)][0.70]$$

$$\theta = 12.9 psi (88.9 kPa)$$

e. Determine the insitu resilient modulus.

$$M_R K_{1Pa}\left[\frac{\theta}{P_a}\right]^{K_2}\left[\frac{\sigma_d}{P_a}\right]^{K_3}$$

$$=1561\,(14.7)\left[\frac{12.9}{14.7}\right]^{0.82}\left[\frac{11.3}{14.7}\right]^{-.03}$$

$$M_R=20{,}770\,psi\,(143.2\,mPa)$$

Note: The computed insitu resilient modulus of 20,770 psi (143.2 mPa) is compared to the elastic modulus that was assumed for the elastic layered theory computations; in this case, a value of 20,000 psi (137.9 mPa) was used. If these values are significantly different, the computed insitu resilient modulus is used as the assumed value and the steps repeated until the calculated modulus equals the assumed value.

5. Determine the design resilient modulus.

a. To illustrate the seasonal variation of the aggregate base resilient modulus, it is assumed that this variation was defined from previous deflection testing throughout the year. For simplicity, it is assumed that for 1 month the base is wet and the insitu resilient modulus is 50 percent of its normal value and for 2 months the base is beginning to dry out and is 75 percent of the normal value. As such, the resilient modulus during the year is:

9 Months - 20,770 psi (143.2 mPa)
2 Months - 15,578 psi (107.4 mPa)
1 Month - 10,385 psi (71.6 mPa)

b. Determine the design resilient modulus using the fatigue cracking criteria.

$$U_f = 1.885 \; x \; 10^3 \; (M_R)^{-.721}$$

$$M_R(Design) = \sum \frac{(M_R)(U_f)}{(U_f)}$$

$$= \frac{9(20{,}770)(1.454) + 2\ (15{,}578)(1.789) + (10{,}385)(2.396)}{9(1.454) + 2\ (1.789) + (2.396)}$$

$$M_R(Design - Fatigue\ Based) = 17{,}012\,psi(117.3\,mPa)$$

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