Design Pamphlet for the Determination of Design Subgrade in Support of the 1993 AASHTO Guide for the Design of Pavement Structures

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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 to characterize the subgrade soil. Two companion pamphlets — *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) and *Design Pamphlet for the Backcalculation of Pavement Layer Moduli in Support of the 1993 AASHTO Guide for Design of Pavement Structures* (FHWA-RD-97-076) — provide additional, related guidance on selecting appropriate design values to characterize the pavement materials and interpretation of pavement deflection data. The procedures presented were developed through the 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 suggested procedures to determine the design resilient modulus of subgrade soils in support of the 1993 AASHTO Guide for the Design of Pavement Structures. The design pamphlet includes recommendations for the subsurface characterization and exploration of subsurface soils, laboratory test procedures, and determination of design resilient modulus using relative damage coefficients based on a serviceability criteria and the damage coefficients to minimize permanent deformations in the subgrade.

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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

C - Cohesion of the soil
D_p - Thickness of the pavement structure and stabilized sub grade layer, if present
D_s - Depth into the subgrade
E - Modulus of elasticity backcalculated from deflection basin measurements
j - Number of seasons
$K_{1,}$ K_2, K_3, K_5 - Nonlinear elastic constants and coefficients of the constitutive equation and determined by the use of linear regression techniques.
k_0 - At-rest earth pressure coefficient
k_p - Passive earth pressure coefficient
M_R - Resilient modulus of the subgrade or roadbed soil
N - Allowable number of load applications for a specific axle weight and configuration and tire pressure
P_a - Atmospheric pressure
P_o - At-rest lateral earth pressure in the subgrade at a depth of D_s
U_{rs} - Damage factor based on a subgrade vertical compressive strain criteria
u_f - Relative damage based on a serviceability design criteria
θ - Bulk stress
ϕ - Angle of shearing resistance
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
ϵ_v - Vertical compressive strain at the top of the subgrade layer
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 DESIGN SUBGRADE MODULI 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 for the design of flexible pavements in the 1993 American Association of State Highway and Transportation Officials (AASHTO) Guide for the Design of Pavement Structures.(1) This value is simply a measure or estimate of the elastic property of the material at a given stress state (i.e. assumed to be the modulus of elasticity). Section 2.3.1 of the 1993 Guide overviews the procedure for determining the "Effective Roadbed Soil Resilient Modulus" that is needed for flexible pavement design, but there are practical details that are not adequately addressed. The purpose of this design pamphlet is to provide some additional details and recommendations for determining the design resilient modulus for flexible pavement design (new construction or reconstruction).

SUBSURFACE CHARACTERIZATION FOR PAVEMENT DESIGN

Subsurface Exploration

The subsurface investigation should be sufficiently detailed to define the depth, thickness, and areal extent of all major soil and rock strata that will be affected by construction. Disturbed and undisturbed samples of the subsurface materials must be obtained for laboratory analyses (and/or tested in the field) to determine their engineering properties. The extent of the program depends on the nature of both the project and the site specific subsurface conditions. The standard penetration and dynamic cone penetrometer tests can be used to determine the insitu strength characteristics of subsurface soils.

Procedures for the exploration of pavement sites cannot be reduced to a single guideline to fit all existing conditions. To acquire reliable engineering data, each job site must be explored and analyzed according to its subsurface conditions. The engineer in charge of the subsurface exploration must furnish complete data in order that an impartial and thorough study of practical pavement thickness designs can be made. Suggested steps which can be followed are listed below:

1. Make a complete and thorough investigation of the topographic and subsurface conditions.

2. Conduct exploratory borings at a spacing and depth prescribed by the engineer. The spacing and depth of these borings are dependent on the variability of the existing soil conditions, both vertically and horizontally. These borings should also be used to determine the water table depth. Take sufficient and appropriate auger, split tube, or undisturbed samples of all representative subsoil layers. Prepare boring logs and soil profiles.

3. Classify all soils using the AASHTO (or Unified) soil classification system. Table 1 relates the Unified soil classification of a material to the relative value of a material for use in a pavement structure. A moisture-density test should be used to determine the compaction characteristics for soil and untreated pavement materials. AASHTO T99 should be used for coarse-grained soils and aggregate materials, and low plasticity fine-grained soils; whereas, AASHTO Tl80 should be used for medium to high plasticity fine-grained soils. The degree of compaction required for the in-place density should be expressed as a percentage of the maximum density from the specified test procedure.

4. Examine the boring logs, soil profiles, and classification tests and select representative soil layers for laboratory testing. Determine the insitu resilient modulus for each major soil type encountered.

5. Use the soil profile along the roadway alignment to relate resilient modulus to each type of subgrade soil encountered. Select a design subgrade resilient modulus that is representative of each soil type. The designer may want to consider using different layer thicknesses and/or pavement structures for each soil type.

Table 1. Summary of soil characteristics for supporting pavement structures.

Major Divisions		Name	Subgrade Strength When Not Subject to Frost Action	Potential Frost Action	Compressibility and Expansion	Drainage Characteristics
Gravel and Gravity Soils	GW	Well-graded gravels or gravel-sand mixtures, little or no fines	Excellent	None to Very Slight	Almost None	Excellent
	GP	Poorly graded gravels or gravel-sand mixtures little or no fines	Good to Excellent	None to Very Slight	Almost None	Excellent
	*d GM - - u	Silty gravels, gravel-sand silt mixtures	Good to Excellent	Slight to Medium	Very Slight	Fair to Poor
			Good	Slight to Medium	Slight	Poor to Practically Impervious
	CC	Clayey gravels, gravel-sand-clay mixture	Good	Slight to Medium	Slight	Poor to Practically Impervious
Sand and Sandy Soils	SW	Well-graded sands or gravelly sands, little or no fines	Good	None to Very Slight	Almost None	Excellent
	SP	Poorly graded sands or gravelly sands, little or not fines	Fair to Good	None to Very Slight	Almost None	Excellent
	*d SM - - u	Silty sands, sand-silt mixtures	Fair to Good	Slight to High	Very Slight	Fair to Poor
			Fair	Slight to High	Slight to Medium	Poor to Practically Impervious
	SC	Clayey sands, sand-clay mixtures	Poor to Fair	Slight to High	Slight to Medium	Poor to Practically Impervious

*The subdivision of the GM and SM groups is on the basis of Atterberg limits; a suffix d is used when the liquid limit is 25 or less and the plasticity index is 5 or less; the suffix u is used for all other cases.

Table 1. Summary of soil characteristics for supporting pavement structures (continued).

Major Divisions		Name	Subgrade Strength When Not Subject to Frost Action	Potential Frost Action	Compressibility and Expansion	Drainage Characteristics
Silts and Clays LL is less than 50	ML	Inorganic silts and very fine sands, rock flour, silty or clayey fine sand or clayey silts with slight plasticity	Poor to Fair	Medium to Very High	Slight to Medium	Fair to Poor
	CL	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays silty clays, lean clays	Poor to Fair	Medium to High	Slight to Medium	Practically Impervious
	OL	Organic silts and organic silt-clays or low plasticity	Poor	Medium to High	Medium to High	Poor
Silts and Clays LL is Greater than 50	MH	Inorganic silts, micaceous or diatomaceous fine sand or silty soils, elastic silts	Poor	Medium to Very High	High	Fair to Poor
	CH	Inorganic clays of high plasticity, fat clays	Poor to Fair	Medium to Very High	High	Practically Impervious
	OH	Organic clays of medium to high plasticity, organic silts	Poor to Very Poor	Medium	High	Practically Impervious
Highly Organic Soils	Pt	Peal and other highly organic soils	Not Suitable	Slight	Very High	Fair to Poor

Boring Location and Depth

Regardless of the type of project, the borings should be spaced to establish in reasonable detail the stratigraphy of the subsurface materials. Borings should also be located to obtain a basic knowledge of the engineering properties of the overburden and bedrock formations that will be affected by or will have an effect upon the proposed pavement structure, and to locate and determine the quality and approximate quantity of construction materials, if required.

Number of Borings. The number and spacing of the borings should be consistent with the type and extent of the project and with the nature of the subsurface conditions. Rigid rules for the number and spacing of the borings cannot and should not be established. In general, emphasis should be placed on locating the borings to develop typical and representative geologic cross sections. The spacing of the borings is dependent on the subsurface variability of the project site. Typically, the spacing varies from 500 to 1,500 ft (150 to 450 m).

Depth of Borings. Just as rigid rules cannot be established for the spacing of borings, similar types of rules have no place in determining the depth to which the borings are drilled. However, general guidelines are available for planning explorations. Two major factors control the depth of exploration; namely, the magnitude and distribution of the traffic loads imposed on the pavement structure under consideration, and the nature of the subsurface conditions.

The planned exploration depths along the alignment of a highway depend on the knowledge of subsurface conditions as based on geological soil surveys and previous explorations. In areas of light cut and fill with no special problems, explorations should extend a minimum of 5 ft (1.5 m) below the proposed subgrade elevation. A few of the borings should extend to a depth 20 ft (6 m) below the planned surface elevation. However, where deep cuts are to be made, large embankments are to be constructed, and/or subsurface information indicates the presence of weak (or water saturated) layers, the boring depth should be increased. No specific guidelines are given, except that the borings should be deep enough to provide information on any materials which may cause problems with respect to stability, settlement, and drainage.

All borings should extend through unsuitable foundation strata (for example, unconsolidated fill; highly organic materials; or soft, fine-grained soils) to reach relatively hard or compact materials of suitable bearing capacity. Borings in potentially compressible fine-grained strata of great thickness should extend to a depth where the stress from superimposed traffic loads and/or thick embankments is so small that consolidation will not significantly influence surface settlement. Where stiff or compact soils are encountered at the surface and the general character and location of rock are known, borings should extend into sound rock. Where the location and character of rock are unknown, or where boulders or irregularly weathered materials are likely to be found, the boring penetration into rock should be increased.

Sample Recovery for Identification/Classification and Testing of Soils

Sampling within the bore holes may be either continuous or intermittent. In the former case, samples are obtained throughout the entire length of the hole; in the latter (primarily used in areas of deep cuts), samples are taken about every 5 ft (1.5 m) and at every change in material. Initially, it is preferable to have a few holes with continuous sampling so that all major soil strata present can be identified. Every attempt should be made to obtain 100 percent recovery where conditions warrant. The horizontal and vertical extent of these strata can then be established by intermittent sampling in later borings, if needed.

In order to obtain a basic knowledge of the engineering properties of the materials which will have an effect on the design, undisturbed samples (such as those obtained with thin wall samplers or double tube core barrel rock samplers) should be taken, if at all possible. The actual number taken should be sufficient to obtain information on the shear strength, consolidation characteristics, and resilient modulus of each major soil stratum. If undisturbed samples cannot be recovered, disturbed samples should be recovered. Disturbed samples can be obtained by split barrel samplers. Disturbed samples permit visual identification and classification of the materials encountered, as well as identification by means of grain size, water content, and Atterberg Limit Tests.

Undisturbed samples should comply with the following criteria:

1) The samples should contain no visible distortion of strata, or opening or softening of materials;

2) Specific recovery ratio (length of undisturbed sample recovered divided by length of sampling push) should exceed 95 percent; and

3) The samples should be taken with a sampler with an area ratio (cross sectional area of sampling tube divided by full area or outside diameter of sampler) less than 15 percent.

At least one representative undisturbed sample should be obtained in cohesive soil strata, in each boring for each 5 ft (1.5 m) depth, and/or just below the planned surface elevation of the subgrade. Recommended procedures for obtaining undisturbed samples are described in

AASHTO Standard T207, Thin-Walled Tube Sampling of Soils (ASTM Standard D1587). All samples (disturbed and undisturbed) and cores should be wrapped or sealed to prevent any moisture loss, placed in protective core boxes, and transported to the laboratory for testing and visual observations.

SELECTION OF RESILIENT MODULUS TEST SPECIMENS

Once in the laboratory, soil samples should be carefully reviewed and identified for resilient modulus testing. Two types of specimens can be tested: disturbed and undisturbed. Undisturbed specimens should be free of visual defects and represent their natural conditions (moisture content and density). For disturbed or reconstituted specimens, bulk material should be recompacted to as close to the natural conditions as possible.

Number of Test Specimens

The number of test specimens depend on the number of different soils identified from the borings, and the condition of those soils. Most of the test specimens should be taken from as close to the top of subgrade as possible to a depth 2 ft (0.6 m) below the planned subgrade elevation. However, a few tests should be performed on the soils encountered at a greater depth, especially if those deeper soils are softer (or weaker). No guidelines regarding the number of tests are provided, with the exception that all of the major soil types encountered near the surface should be tested with replicates, if possible. Stated simply, resilient modulus tests should be performed on any soil type that may have a detrimental impact on pavement performance.

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. Coefficient of variations exceeding 25 percent for the resilient moduli measured at the same stress state are not uncommon. This potential high variability in test results requires increased testing frequencies (i.e., more than two or three resilient modulus tests along a project). As a general guide and suggested testing frequency, three resilient modulus tests should be performed on each major subgrade soil found along the highway alignment. 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.

Condition of Test Specimens

The condition of test specimens refers to the dry density and moisture content of the specimen. For undisturbed test specimens, the dry density and moisture content are the same as found during the sampling operation. Unfortunately, the variability in test results between undisturbed specimens of the same soil type can be quite high, because of the difference in dry densities and moisture contents of the soil that can exist along a roadway (both vertically and horizontally). Increased variability will require increased testing frequencies to be confident in the data. More importantly, the moisture content of some fine-grained soils may increase significantly after pavement construction. For this case, the resilient modulus measured at the moisture content expected during construction may not be representative of the actual condition several years after construction. This potential change must be considered in planning the resilient modulus test program for pavement structural design.

Test specimens can be compacted in the laboratory to the same dry density, but at different moisture contents for resilient modulus testing. The resilient moduli can then be determined directly for varying moisture contents. Unfortunately, remixing and recompacting undisturbed test specimens (especially for some clays), even at the same moisture content and dry density, can significantly alter the resilient modulus test results.

Obviously, the moisture content can be measured on soil samples recovered from the borings. The important question to be answered is: What will the moisture content be for a particular season and/or time? This is a difficult question to answer, even at a moderate confidence level.

The density used in the resilient modulus test program should be the insitu density after construction. The moisture content of the soils beneath pavement structures do vary seasonally, and is the parameter most difficult to predict. For some cohesionless soils, the moisture content may decrease and increase from the optimum moisture content depending on the surface and subsurface drainage characteristics and with the amount of rainfall at the site. However, for some cohesive soils (such as expansive clays), the moisture contents below a pavement tend to increase to values above optimum. Thus, the moisture content to be used in the resilient modulus test should be representative of the more critical moisture condition measured during the year (i.e., higher moisture contents). Experience and experimental test results should be used to determine the moisture content for the critical part of a year, and that value is to be used in the test program, as a minimum.

LABORATORY RESILIENT MODULUS TESTS

Constitutive Relationships

Repeated load triaxial compression tests are used to measure the resilient modulus of subgrade soils. These tests are performed over a range of vertical stresses and confining pressures to evaluate the nonlinear elastic behavior of soils. 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 roadbed soils, the modulus is dependent on the stress state used. Various types of relationships have been used to represent the repeated load resilient modulus test results of coarse-grained and fine-grained soils. The two relationships referred to in the 1993 AASHTO Design Guide are:

For coarse-grained soils:

$$M_R = K_1(\Theta)^{K_2} \tag{1}$$

where: θ = bulk stress
K_1 and K_2 are regression constants

For fine-grained soils:

$$M_R = K_1(\sigma_d)^{K_3} \tag{2}$$

where: σ_d = deviator stress
K_1 and K_3 are regression constants

More recently, other constitutive relationships have been used to represent the laboratory test results of all unbound pavement materials and subgrade soils. Two of these relationships are:

$$M_R = K_1(\sigma_d)^{K_2}(1+\sigma_3)^{K_5} \tag{3}$$

where: σ_3 = confining pressure
K_1, K_2, K_5 are regression constants

$$M_R = K_1 p_a \left[\frac{\theta}{P_a} \right]^{K_2} \left[\frac{\sigma_d}{P_a} \right]^{K_3} \tag{4}$$

where:

p_a = atmospheric pressure
K_1, K_2, K_3 = nonlinear elastic constants and coefficients

Equation 4 is suggested for use to represent the laboratory data, because it has been found to consistently result in a higher multiple correlation coefficient and is applicable to a diverse range of unbound pavement materials and subgrade soils.(2)

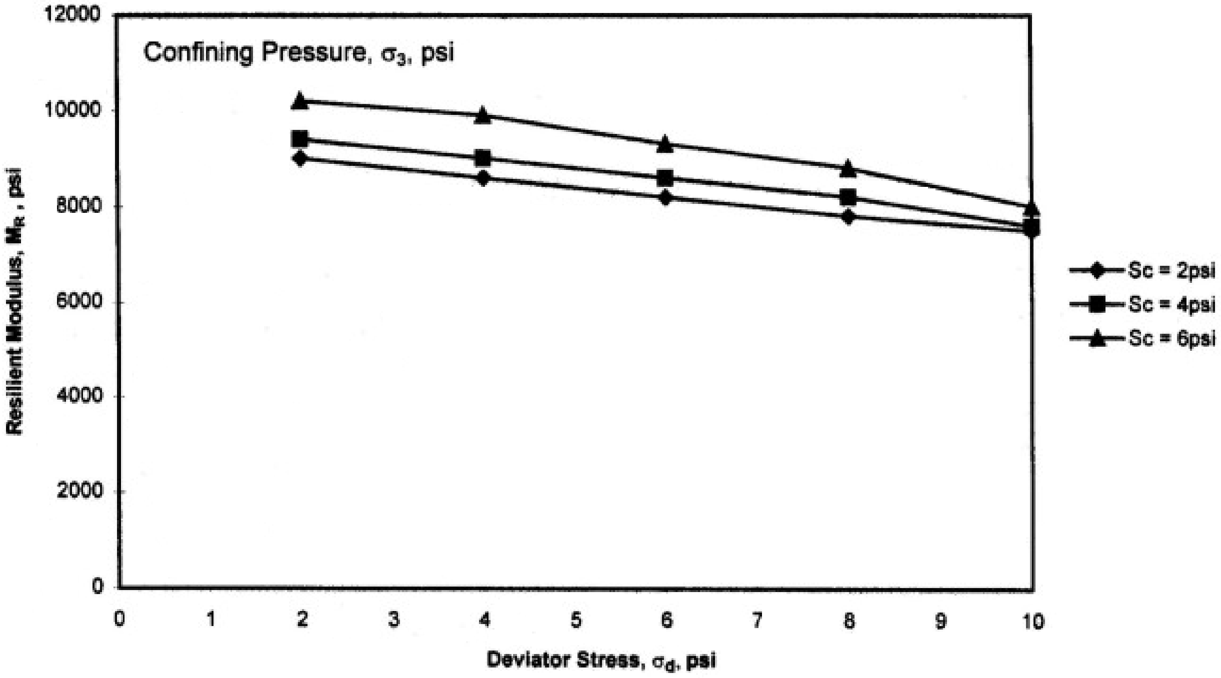
Test Procedure and Analysis of Test Results

Repeated load resilient modulus tests were performed as part of the Strategic Highway Research Program (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 vertical loads and confining pressures recommended for use that include most stress states that occur in the subgrade soils under highway wheel loads. 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 1 for one of the General Pavement Studies (GPS) sites included in the LTPP program. 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 parameters for the test results from the noted GPS site are also included in figure 1.

The nonlinear elastic coefficients and exponents (K-values) should be determined for each test specimen to ensure that the multiple correlation coefficient exceeds 0.90 (i.e., equation 4 is applicable to the test results). The repeated-load resilient modulus test results from similar soils and test specimen conditions can be combined. Thus, a "pooled" K_1, K_2, and K_3 is determined and assigned to each major soil strata, both vertically and along the horizontal alignment of the roadway. If the multiple correlation coefficient for a particular test specimen is less than 0.90, the test results and equipment should be checked for possible errors and/or test specimen disturbance during testing (i.e., possible air leaks in the membrane surrounding the test specimen). If no errors or disturbances are found, the use of a different constitutive relationship should be considered.

Subgrade (Clay) From GPS Site No. 481174

$$M_R = 688.4\, P_a(\Theta/P_a)^{0.11}(\sigma_d/P_a)^{-0.08}$$



(psi) x 6.895 x 10^3 = P_a

Figure 1. Example of repeated load triaxial resilient modulus test results of a clay soil.

For uniform subsurface conditions, the pooled K_1, K_2, and K_3 values can be determined and used for the entire site. For sites with variable subsurface conditions, the pooled K_1, K_2, and K_3 values representative of the weaker soils (lower moduli) can be used to determine the insitu resilient modulus and that value just assumed for the entire project for simplicity. Unfortunately, use of the simplified approach will result in more costly designs (i.e., requires greater layer thicknesses for areas with better support or greater strengths).

Conversely, the designer may want to consider using the pooled K-values for each soil type. This will allow the designer to consider using different layer thicknesses and/or pavement structures for each type of soil or subsurface condition encountered. The more detailed approach is suggested for use.

DETERMINATION OF INSITU RESILIENT MODULUS

In order to determine the insitu resilient (or elastic) modulus from laboratory repeated load triaxial compression tests, 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 a resilient modulus that is representative of the insitu stress state.

1. Determine the earth pressure coefficient, k:

   For cohesive soils (such as clays), the at-rest earth pressure coefficient, k_o, is normally considered to be a function of Poisson's ratio, v, and is:

   $$k_o = v / (1 - v) \qquad (5)$$

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

   $$k_o = 1 - \sin\phi \qquad (6)$$

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:

$$k_P = \tan^2(45 + \frac{\phi}{2}) + \frac{2C}{\sigma_Z}\tan(45 + \frac{\phi}{2}) \qquad (7)$$

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 less than 8 in (0.2 m) in thickness and surface layers less than 1 in (25.4 mm) 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 subgrade from the imposed wheel loads (at the calculation depth) are usually very small.

2. Compute the insitu lateral stress, σ_3:

$$\sigma_3 = \sigma_3' + p_o \qquad (8)$$

where:

$$p_o = K_o(D_s\gamma_s + D_p\gamma_p) \qquad (9)$$

σ_3' = Lateral stress computed with elastic layer theory from a load applied to the pavement's surface.
p_o = At-rest earth pressure 18 in (0.5 m) into the subgrade. For uniform conditions, 18 in (0.5 m) is typically used; however, if variable soil conditions exist vertically and the subsurface soils are divided into two layers, the depth should be to the mid-depth of the top layer and 18 in (0.5 m) into the lower layer.
k_o = At-rest earth pressure coefficient
D_s = Depth into the subgrade
γ_s = Unit weight of the subgrade or road bed soil
D_p = Thickness of the pavement structure and stabilized subgrade layer, if present.
γ_p = Weighted average unit weight of the pavement structure and stabilized subgrade, if present

3. Compute the insitu deviator stress, σ_d:

$$\sigma_d = \sigma_d' + p_o(k_o^{-1} - 1) \qquad (10)$$

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:

$$\theta = \sigma_x' + \sigma_y' + \sigma_z' + \left[1 + 2k_o\right]\left[D_s\gamma_s + D_p\gamma_p\right] \qquad (11)$$

where:

σ_x', σ_y', σ_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.

5. Determine the insitu resilient modulus:

The insitu resilient modulus for a particular subgrade soil can be determined by substituting the total deviator stress (equation 10) and bulk stress (equation 11) into equation 4. As a result, an insitu resilient modulus can be calculated for each design area and major soil strata.

For those conditions when different soil types are encountered vertically in a particular boring or area, the insitu resilient modulus should be determined for each subsurface layer, as noted above. If the smaller resilient modulus is calculated at the top of the subgrade, then that value should be used in design for simplicity. If the larger resilient modulus is calculated at the top of the subgrade, both values can be considered separately or the equivalent stiffness concept can be used to decrease the larger resilient modulus to an equivalent value for the entire subgrade. In other words:

$$M_R(Equivalent) = \frac{D_{S1}^3 M_{R1} + D_{S2}^3 M_{R2}}{(D_{S1})^3 + (D_{S2})^3} \qquad (12)$$

DETERMINATION OF DESIGN RESILIENT MODULUS

Seasonal Variation Considerations

The resilient modulus of subgrade soils is normally very sensitive to changes in moisture content. Since moisture contents of the subgrade can increase with time, subgrade materials must be tested at a moisture content that is higher than that at construction. If the pavement structure includes some type of positive drainage system, the subgrade soils should be tested or characterized at moisture contents slightly above the optimum value. This assumes that the drainage system is properly built and maintained. If frost is allowed to penetrate the subgrade material and no drainage feature is included, however, the moisture content will probably increase during spring thaw and a much higher moisture content should be used in the test program. This increase is both climate and soil dependent. Consequently, considerable focus is given to this parameter; seasonal variations in resilient modulus. In fact, most (if not all) of the compensation for seasonal variability in the AASHTO Guide is handled through the selection of the design or effective resilient modulus for the subgrade soil.

The "Guide" allows the use of two different procedures for determining the seasonal variation of the subgrade resilient modulus. One of these methods is to obtain a laboratory relationship between resilient modulus and moisture content of the soil. The resilient modulus is then varied for each of the different seasons within a year by the expected change in moisture content of the soil. As stated previously, the difficulty is in predicting the moisture contents of the subgrade soils by month or season. This procedure also requires an extensive laboratory testing program. An alternate procedure is to backcalculate the resilient modulus for different seasons using deflection basins measured on the pavement’s surface. Predicting changes in the moisture content of subgrade soil is very difficult, if not totally impossible at a relative high confidence level. Thus, backcalculation of layer moduli has been considered to be a reasonable alternate for measuring seasonal variation of the roadbed soil elastic moduli.

If the seasonal moduli are determined through the use of backcalculation techniques, then those subgrade moduli must be multiplied by an adjustment factor, M_R (Lab)/E(FWD). This factor adjusts the backcalculated modulus to an equivalent laboratory measured value. The reason for this adjustment is that the design procedure is based on laboratory measured moduli, and the use of backcalculated moduli will result in an insufficient pavement thickness for designs based on the serviceability criteria.

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 elastic moduli from deflection basins to the resilient moduli measured in the laboratory using the repeated load triaxial compression test at an equivalent insitu stress state.

Pavement/Material Type	**Mean C-Value**	**Coefficient of Variation, %**
- Subgrade soils below a stabilized subgrade	0.75	13
-Subgrade soils below a pavement without an unbound granular base and/or subbase layer, & no stabilized subgrade	0.52	37
-Subgrade soil below a pavement with an unbound granular base and/or subbase layer, but no stabilized subgrade	0.35	49

The above C-values (or adjustments to the backcalculated elastic layered moduli for subgrade soils) were determined using the sensor spacing set as a standard by SHRP (0, 8, 12, 18, 24, 36, 60 in) (0, 0.2, 0.3, 0.5, 0.6, 0.9, 1.5 m). Any deviation from this standard spacing can have an affect on these C-values. However, these differences have been found to be relatively small (less than 15 percent) for the other more common sensor spacing used; sensors equally spaced at 12 in (0.3 m).

Effective Roadbed Resilient Modulus -Serviceability Criteria

A major difference between the "new" AASHTO procedure and the other pavement design methods is that the weighted mean or average value representing the subgrade modulus are to be used. The AASHTO procedure establishes an estimate of relative damage (u_f)for each of the seasonal moduli values provided. The relationship provided in the Guide is given below:

$$u_f = 1.18x10^8 xM_R^{-2.32} \tag{13}$$

where:

u_f = Relative Damage based on a serviceability design criteria
M_R = Roadbed Soil Resilient Modulus

Figure 2 is the AASHTO Chart for determining the "Effective Roadbed Resilient Modulus" for designs based solely on a serviceability criteria. To be technically correct, however, the design (based on the AASHTO design equation: serviceability) should be based on the roadbed soil in its weakest condition. In other words, the use of figure 2 may result in an insufficient pavement thickness to protect the subgrade.

Design Subgrade Resilient Modulus - Subgrade Rutting Criteria

Permanent deformation damage factors, (based on rutting in the subgrade) can be used to ensure that there is sufficient cover to prevent overstressing and excessive permanent deformation in the subgrade during periods of increased moisture. The following equations can be used to calculate an equivalent annual or design resilient modulus for the subgrade soil based on permanent deformation in the subgrade.

$$U_{rs} = 4.022\ x\ 10^{7}\left[M_R \right]^{-1.962} \qquad (14)$$

$$M_R(Design) = \sum_{i=1}^{j} \frac{(M_R)_i (U_{RS})_i}{(U_{RS})_i} \qquad (15)$$

where:

U_{rsi} = Damage factor based on a subgrade vertical compressive strain criteria in season i

M_{Ri} = Resilient modulus of the subgrade soil in season i

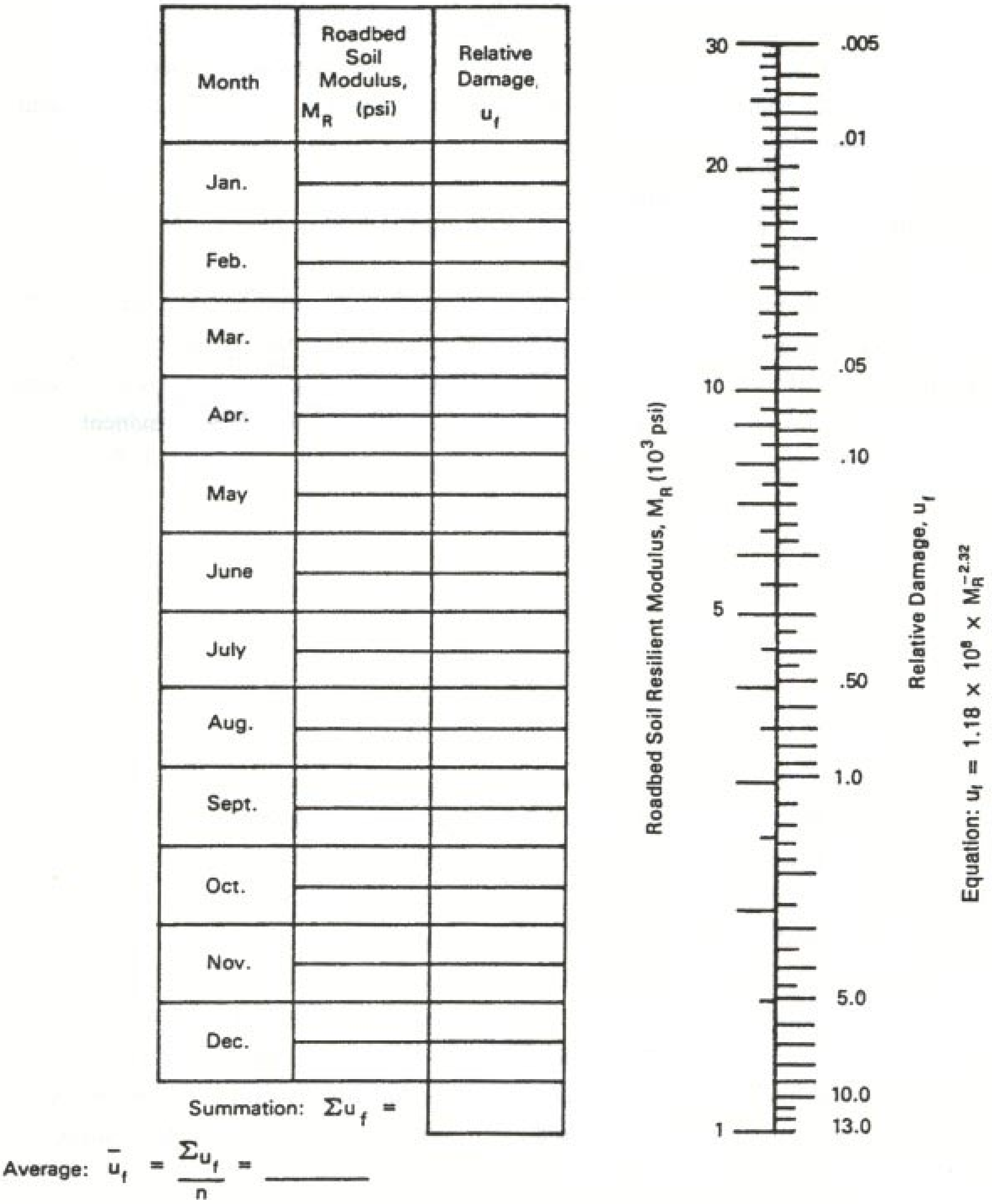
j = number of seasons

The effective roadbed resilient modulus based on serviceability criteria (figure 2) is usually greater than the design resilient modulus that is based on minimizing permanent deformations in the subgrade from wheel loads (equations 14 and 15). Thus, flexible pavement designs based on a serviceability criteria should always be checked using subgrade vertical compressive strain criteria, as shown below.(2)

$$Log\ N = 0.955\ (\log M_{RDesign}) - 4.082\ (Log \in_v) - 10.90 \qquad (16)$$

where:

N = allowable number of load applications for a specific axle weight and configuration and tire pressure



Month	Roadbed Soil Modulus, M_R (psi)	Relative Damage, u_f
Jan.		
Feb.		
Mar.		
Apr.		
May		
June		
July		
Aug.		
Sept.		
Oct.		
Nov.		
Dec.		

Summation: $\Sigma u_f =$ ________

Average: $\bar{u}_f = \frac{\Sigma u_f}{n} =$ ________

Effective Roadbed Soil Resilient Modulus M_R(psi) = _________ (corresponds to $\bar{u}_f$)

Figure 2. Chart for estimating effective roadbed soil resilient modulus for flexible pavements designed using the serviceability criteria.(1)

ϵ_v = vertical compressive strain at the top of the subgrade layer

The above equation was developed to limit the observed rutting at the pavement's surface to a value less than 0.5 in (13 mm).

All layer thicknesses should be sufficient to reduce or limit the vertical compressive strain to an acceptable level for each soil type, as defined by the repeated load triaxial compression test. The moisture content and density of the material being tested should be those expected over time and not at construction.

EXAMPLE PROBLEM AND SUMMARY OF 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 subsurface exploration program to identify the different types of subsurface soils and recover samples for classification and resilient modulus testing.

   From the borings, subdivide the project site into sections with similar subsurface conditions. For this example, it is assumed that uniform conditions exist over the project site, consisting of an 18-ft (5.5 m) layer 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. Select undisturbed test specimens from each major soil type for resilient modulus testing.

3. Perform laboratory resilient modulus tests and analyze the test results. For the example, seven resilient modulus tests were performed on the soils sampled within the top 8-ft (2.4 m) (two shelby tube pushes) and three tests performed on the soils sampled between 10 and 15 ft (3 and 7 m). Results from the test program are summarized in table 2. As the subsurface soils are similar, all test results were pooled and the results shown at the bottom of table 2.

Table 2. Summary of repeated load triaxial compression test results for the example problem.

Specimen Number	Depth of Specimen, ft. (m)	Nonlinear Elastic Constants (Equation 4)			Multiple Correlation Coefficient
		K_1	K_2	K_3	
1	0.5-1.0 (0.15-0.30)	298	0.12	-0.30	0.98
2	4.0 -4.5 (1.2-1.4)	321	0.18	-0.39	0.91
3	3.0 -3.5 (0.9-1.1)	350	0.10	-0.41	0.95
4	6.0-6.5 (1.8-2.0)	289	0.15	-0.32	0.92
5	2.0-2.5 (0.6-0.8)	316	0.20	-0.42	0.95
6	4.5-5.0 (1.4-1.5)	331	0.14	-0.38	0.97
7	1.0-1.5 (0.3-0.45)	283	0.23	-0.35	0.91
8	14.5-15.0 (4.4-4.6)	363	0.11	-0.40	0.94
9	10.5-11.0 (3.2-3.4)	311	0.14	-0.31	0.98
10	12.0-12.5 (3.7-3.8)	324	0.17	-0.32	0.93
Pooled Results		329	0.16	-0.38	0.81

4. Determine the insitu resilient modulus.

4.1 Determine the at-rest earth pressure coefficient for the cohesive clay subgrade. with a Poisson's ratio of 0.45.

$$k_o = v/(1 - v)$$

$$= 0.45/(1 - 0.45)$$

$$k_o = 0.818$$

4.2 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 10 in (0.25 m) of a crushed aggregate base with a resilient modulus of 35 ksi (241 Mpa) were assumed.

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:

$$\gamma_p \frac{148\ pcf\ (6\ inches) + 132\ pcf\ (10\ inches)}{(6\ inches) + (10\ inches)}$$

$$\gamma_p = 138\,pcf(674\ kg/m^2)$$

The at-rest lateral earth pressure is:

$$p_o = k_o\ (D_s\,\gamma_s\ + D_p\ \gamma_p)$$

$$= 0.818\ (1.5\ ft.\ (105\ pcf) + 1.3\ ft.\ (138\ pcf)$$

$$= 275.6\ psf$$

$$p_o = 1.91\ psi\ (13.2\ kPa)$$

The minimum lateral stress is computed with elastic layered theory for an 18-kip (80-kN) single axle load at a depth of 18 in (0.5 m) into the subgrade.

$$\sigma'_3 = 3.5\ psi$$

Thus, the insitu lateral stress is:

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

$$= 3.5 + 1.9$$

$$\sigma_3 = 5.4\ psi\ (37.2\ kPa)$$

4.3 Compute the insitu deviator stress for the assumed pavement structure. Fist, the deviator stress is compute with elastic layered theory for an 18-kip (80-kN) single axle load at a depth of 18 in (0.5 m) into the subgrade.

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

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

$$= (8.3 - 3.6) \ psi$$

$$\sigma'_d = 4.7 \ psi \ (32.4 \ kPa)$$

Thus, the insitu deviator stress is:

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

$$= 4.7 + 1.91 (0.818^{-1} - 1)$$

$$\sigma_d = 5.12 \ psi \ (35.3 \ kPa)$$

4.4 Compute the insitu bulk stress.

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

$$= (-3.6) + 1.4 + 8.3 + [1 + 2(0.818)] [2.340]$$

$$\theta = 12.3 \ psi \ (84.8 \ kPa)$$

4.5 Determine the insitu resilient modulus.

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

$$= 329(14.7)\left[\frac{12.3}{14.7}\right]^{0.16}\left[\frac{5.1}{14.7}\right]^{-.38}$$

$$M_R = 7{,}028\,psi(48.5\,MPa)$$

5. Determine the design resilient modulus.

5.1 To illustrate the seasonal variation of the subgrade 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 subgrade is wet and the insitu resilient modulus is 60 percent of its normal value and for 2 months the subgrade is beginning to "dry out" and is 80 percent of the normal value. As such, the resilient modulus during the year is:

9 Months - 7,028 psi (48.5 MPa)
2 Months - 5,622 psi (38.8 MPa)
1 Month - 4,217 psi (29.1 MPa)

5.2 Determine the effective roadbed resilient modulus for the AASHTO design method based on a serviceability criterion (figure 2).

$$U_f = 1.18 \times 10^8 (M_R)^{-2.32}$$

$$U_f = \frac{\sum U_f}{n} = \frac{9(.1404) + 2(.2356) + (.4591)}{12}$$

$$U_f = 0.183$$

Thus, the effective roadbed soil resilient modulus is given below and is the value to be used with the AASHTO design procedure:

M_R *(Serviceability Based) = 6,266 psi (43.2 MPa)*

5.3 Determine the design resilient modulus using the subgrade rutting criteria.

$$U_{rs} = 4.022\ x\ 10^{-7}(M_R)^{-1.962}$$

$$M_R(Design) = \sum \frac{(M_R)(U_{rs})}{(U_{rs})}$$

$$= \frac{9(7.028)(1.1401) + 2(5.622)(1.7667) + (4.217)(3.1059)}{9(1.1401) + 2(1.7667) + (3.1059)}$$

$$M_R(Design - Rutting\ Based) = 6{,}218\,psi\ (42.9\,MPa)$$

Elastic layered theory is used to calculate the vertical compressive strain at the top of the subgrade under an 18-kip (80-kN) single axle wheel load.

$$\varepsilon_v = 4.28 \text{ x } 10^{-4} \text{ in./in.}$$

The number of allowable 18-kip (80-kN) single axle wheel load applications is:

$$\text{Log N} = 0.955 (\text{Log M}_{\text{RDesign}}) - 4.082 (\text{Log } \varepsilon_v) - 10.90$$

$$= = 0.955 (\text{Log } 6.218) - 4.082 (\text{Log } 4.28 \text{ x } 10^{-4}) - 10.90$$

$$\text{Log N} = 6.4733$$

$$\text{N} = 2{,}974{,}000$$

If the design number of 18-kip (80-kN) equivalent single axle loads (ESAL's) is less than the above value, then there is sufficient cover to prevent extensive permanent deformations in the subgrade. If the design of 18-kip (80-kN) ESAL's are greater than the above value, then the pavement structural thickness as defined by AASHTO will need to be increased.

REFERENCES

1. *AASHTO Guide for Design of Pavement Structures*, American Association of State Highway and Transportation Officials, Washington, DC, 1993.

2. Von Quintus, Harold L. and Brian Killingsworth, *Analysis Relating to Pavement Material Characterizations and their Effects on Pavement Performance*, Publication Number FHWA-RD-97-085, Federal Highway Administration, May 1997.