Resilient Modulus and AASHTO Pavement Design

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In the 1986 *AASHTO Guide for the Design of Pavement Structures*, subgrades and granular base layers are evaluated by the resilient modulus test. Inclusion of the resilient modulus test was prompted by the need for a rational evaluation method. Resilient modulus is a measure of a material's deflection behavior. Since pavement life and surface deflection are strongly related, resilient modulus is a fundamental and rational material property that needs to be included in pavement design. The effects of variations in subgrade resilient modulus on various design parameters and on the AASHTO design thickness are examined. The seasonal variations of subgrade resilient modulus with moisture fluctuation and freezing and thawing are discussed; and methods for selecting a single design resilient modulus are examined. However, resilient modulus does not measure all of the material properties that can influence pavement behavior. Consequently, resilient modulus should not be the only property used in selecting a pavement material or in judging the material's structural contribution to the pavement.

The 1986 *AASHTO Guide for the Design of Pavement Structures* (*1*) requires the use of the subgrade resilient modulus to design a flexible pavement. Resilient modulus is also included as the test for establishing the structural layer coefficient for base and subbase materials.

What is resilient modulus? How does resilient modulus relate to the "real world" structural capacity and performance of flexible pavements? How is a resilient modulus value selected for design? How is resilient modulus used in design? These are questions being asked by many experienced highway designers and materials engineers. The questions are particularly bothersome because the standard resilient modulus test (AASHTO T-274) is quite time consuming.

Before trying to understand the resilient modulus, the need to replace the soil support scale that was used in the previous *AASHTO Interim Guide for Design of Pavement Structures* (*2*) should be recognized. The fundamental basis for both guides is the AASHO Road Test that was conducted in 1958–1960. Although the Road Test is the most comprehensive pavement research project ever undertaken, it did not (and could not) include all variables that can affect the performance of a pavement. One major factor not examined was subgrade soil strength. Only one type of soil was used in the Road Test.

Following the Road Test, pavement design procedures were developed from the research findings. The design procedures required some method for considering different subgrade soil types. For rigid pavements, a rational method for including subgrade soil was available that involved incorporating Westergaard's modulus of subgrade reaction (*k*-value) and Spangler's theoretical formula for corner stresses (*3*). However, no similar approach was available for flexible pavements.

For flexible pavements, a "soil support" scale was established using engineering judgment supplemented with limited data from Road Test sections having the greatest thickness of crushed stone base. This scale was not based on any particular method of test. Each highway agency was left to adopt a test method and establish or select a relationship between that test and the "soil support" scale. Without an analytical basis and a unified method of test, there was little possibility of improving the soil support scale.

WHAT IS RESILIENT MODULUS?

Resilient modulus is a fundamental material property that is similar in concept to the modulus of elasticity. That is, resilient modulus is a stress-strain relationship. However, it differs from the modulus of elasticity in that it is determined from a repeated-load, triaxial-compression test ("unconfined compression" is used by some investigators) and is based on only the resilient (or recoverable) portion of the strain. Resilient modulus is defined as:

$$\text{Resilient modulus} = \frac{\text{stress amplitude}}{\text{strain amplitude}}$$

where

stress amplitude = load/area of the specimen
strain amplitude = recoverable deformation/original height

The general stress-strain behavior of a soil or granular material is illustrated in Figure 1. As the load is applied, the stress increases as does the strain. When the stress is reduced, the strain also reduces but all of the strain is not recovered after the stress is removed. The total strain, therefore, is composed of both a permanent (or plastic) component and a recoverable (or resilient) component. The plastic strain is not included in the resilient modulus.

The resilient modulus test is designed to simulate the behavior of soils and granular materials when subjected to traffic loading within a pavement system. Consequently, the sample preparation, conditioning, and testing are conducted so as to simulate field conditions. The standard method of test is prescribed by AASHTO T-274.

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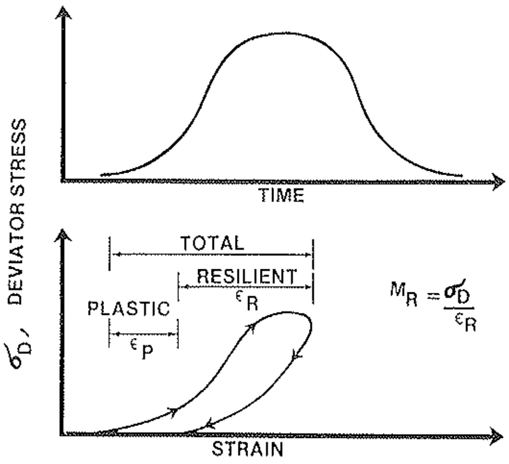


FIGURE 1 Typical load response in the resilient modulus test.

BASIS FOR RESILIENT MODULUS TESTING

The AASHO Road Test demonstrated that pavement surface deflection under load is a strong indicator of how well a pavement will perform (*4*): "The performance of the flexible pavements was predicted with essentially the same precision from load-deflection data as from load-design information."

Other studies (*5–9*) found similar relationships between pavement deflection and performance (Figure 2).

Surface deflection results from the accumulation of load-induced strain within the pavement and subgrade with the subgrade being the major contributor. At the AASHO Road Test (*4*), 60 to 80 percent of the deflection measured at the surface was found to develop within the subgrade. Consequently, the stress-strain relationship for the subgrade (resilient modulus) is a major factor contributing to surface deflection. It follows that subgrade resilient modulus is also a major factor in flexible pavement performance.

SIGNIFICANCE OF SUBGRADE RESILIENT MODULUS

Surface deflection is not itself detrimental to the pavement. However, deflection is an indicator of the factors that are detrimental. There are two major types of load-induced flexible pavement failure—fatigue cracking and rutting. Figure 3 illustrates the two prime structural parameters contributing to failure: the tensile strain that develops in the bottom of the asphalt (AC) layer and the stress or strain applied to the top of the subgrade.

Figures 4 and 5 illustrate the effect of subgrade resilient modulus on the AC tensile strain and the subgrade stress. These plots were developed using the ILLI-PAVE design algorithms developed by Thompson and Elliott (*11*). They represent the structural response of a conventional flexible pavement having a 3-inch AC surface and a 12-inch aggregate base when subjected to a 9,000-pound wheel load. The effects would be similar for other designs and other loads.

In Figure 4, the AC strain decreases as the resilient modulus of the subgrade increases. A strain decrease increases the fatigue life (load applications before cracking) for the AC surfacing.

Figure 5 shows the change in subgrade stress ratio with resilient modulus. The stress ratio is the load-induced deviator stress on the subgrade divided by the unconfined compressive strength of the soil. In analyzing the performance of the AASHO Road Test pavements, Elliott and Thompson (*12*) found a strong relationship between subgrade stress and load applications prior to cracking. As a result, the stress ratio was selected as the design parameter to guard against overstressing the subgrade. In Figure 5, the stress ratio decreases as the resilient modulus increases indicating an increasing pavement life.

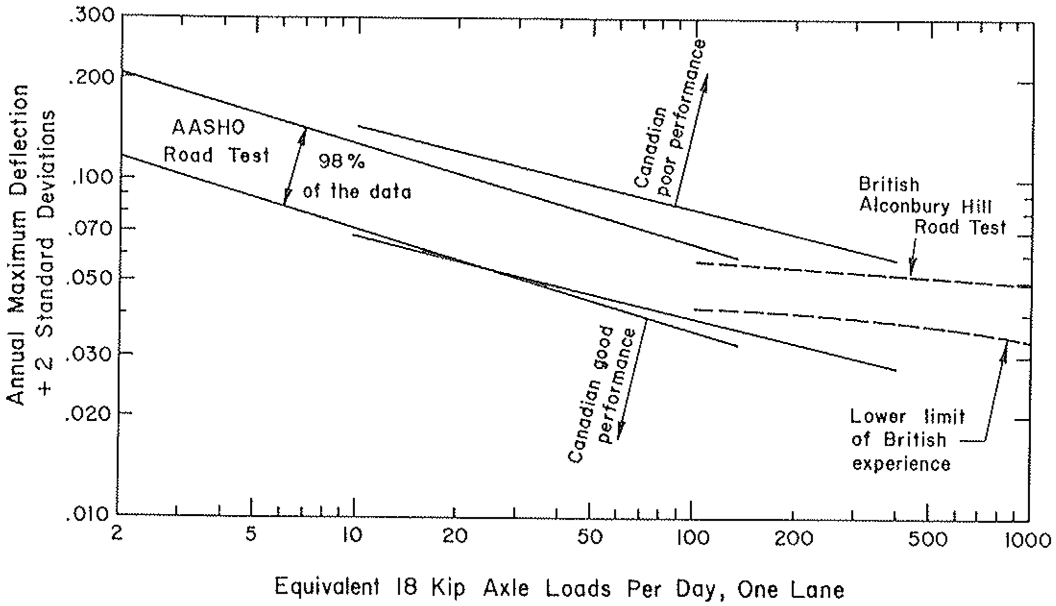


FIGURE 2 Reported deflection-life relationships (*10*).

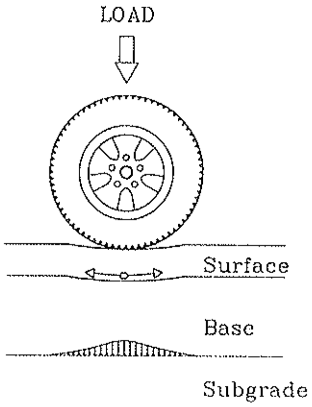


FIGURE 3 Primary structural responses that control pavement performance.

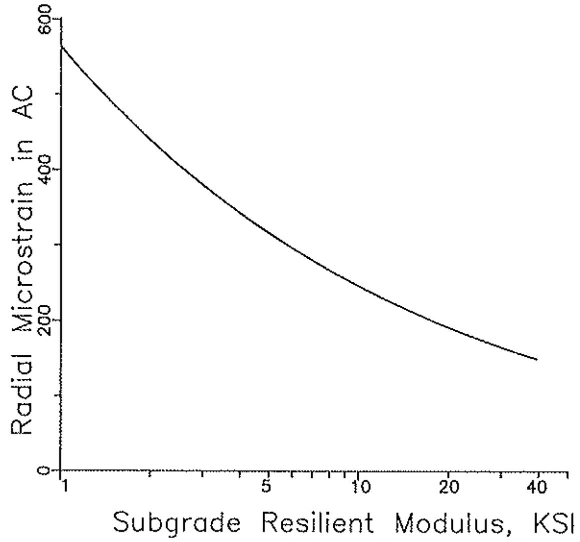


FIGURE 4 Effect of subgrade resilient modulus on asphalt radial strain.

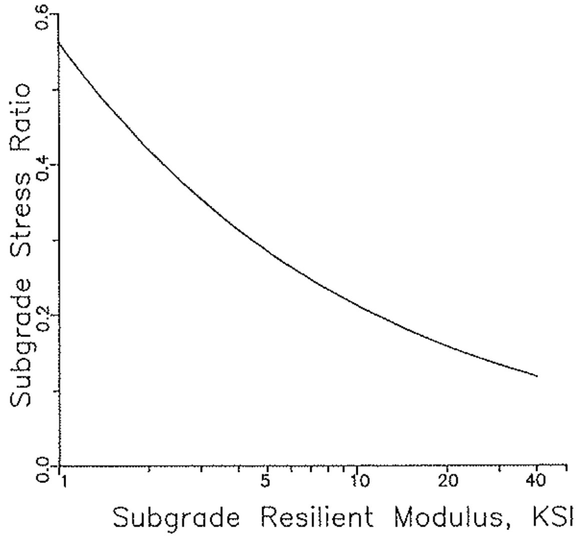


FIGURE 5 Effect of subgrade resilient modulus on subgrade stress ratio.

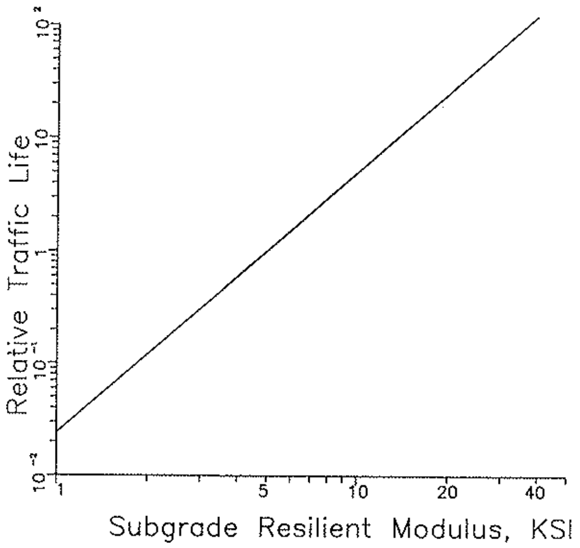


FIGURE 6 Effect of subgrade resilient modulus on relative traffic life.

EFFECT ON DESIGN BY AASHTO

Figures 6, 7, and 8 illustrate the effect of subgrade resilient modulus based on the 1986 AASHTO Guide.

Figure 6 is the relationship between resilient modulus and design traffic life. Relative traffic life is expressed as the total 18-kip equivalent single axle loads (ESALs) for any given resilient modulus divided by a base value. For this figure, the base value is the ESAL's for a resilient modulus of 5 ksi. For example, a pavement constructed on a subgrade having a resilient modulus of 10 ksi will carry nearly 5 times the traffic that the same pavement could carry if the resilient modulus were 5 ksi. Similarly, the 5-ksi soil would permit the pavement to carry approximately 8 times as much traffic as it could if built on a soil having a resilient modulus of 2 ksi.

Figure 7 shows the relationship between resilient modulus and the design structural number. For Figure 7, a structural

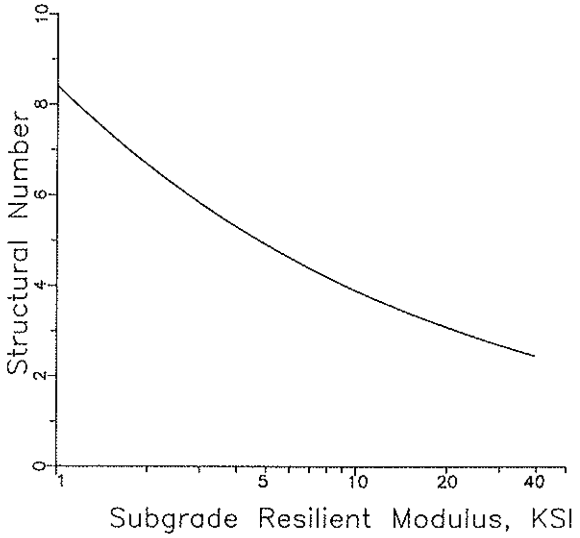


FIGURE 7 Effect of subgrade resilient modulus on design structural number.

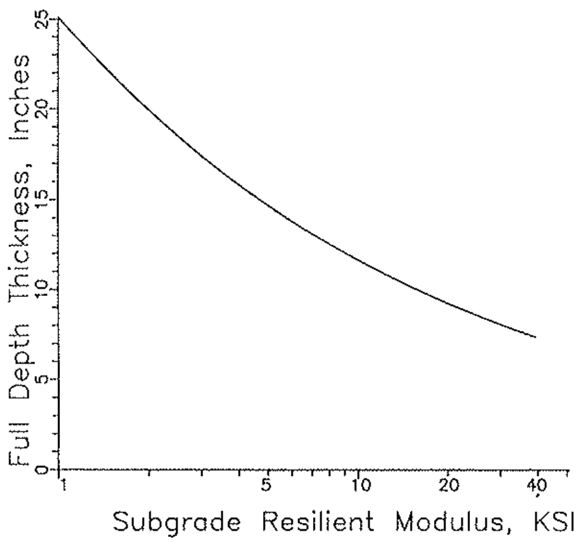


FIGURE 8 Effect of subgrade resilient modulus on design thickness.

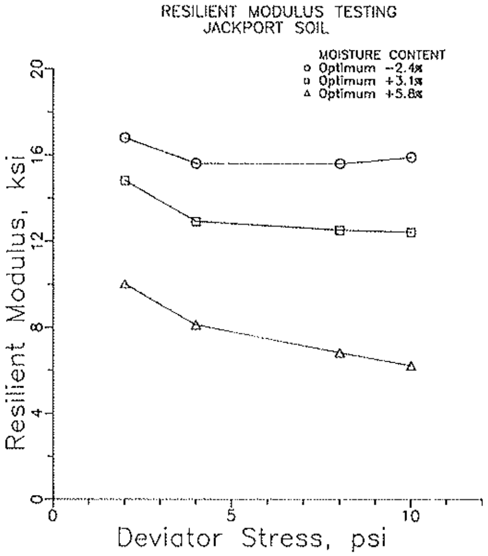


FIGURE 9 Effect of stress level and moisture content on the resilient modulus of a typical cohesive subgrade soil.

number of 5.0 was used with a resilient modulus of 5 ksi as the base. For the same traffic conditions, a structural number of 6.6 would be needed on a subgrade having a resilient modulus of 2 ksi. If the resilient modulus were 10 ksi, the required structural number would be 4.0.

Figure 8 was prepared to show the effects of resilient modulus on pavement thickness. The structural numbers from Figure 7 are converted to equivalent full-depth asphalt thicknesses. The conversion was made using structural layer coefficients of 0.44 and 0.30 for the AC surface and bituminous base, respectively; and assuming that the base thickness would be 3 times the surfacing thickness. For this example, the full-depth thickness would range from 20 to 15 to 12 inches for resilient moduli of 2, 5, and 10 ksi, respectively. In practical terms, figures 7 and 8 indicate that a 30 percent error in the resilient modulus will result in an error of 1 to 1.5 inches in selecting the appropriate total asphalt thickness.

SEASONAL VARIATIONS

Unfortunately, there is no simple test that will give the resilient modulus of a soil. In fact, the subgrade resilient modulus is not a single, fixed value. Rather, the resilient modulus changes due to a number of factors throughout the pavement's life.

There are several factors that affect the resilient modulus of a soil. Among these are moisture content, stress levels, and freeze-thaw cycles. Figure 9 illustrates the effects of stress level and moisture content on a typical cohesive soil. Of particular concern to the pavement designer is how these factors can influence the seasonal variation of the subgrade. A seasonal variation is to be expected because, in most areas of the country, roadbeds are softer in the spring than they are at other times of the year. This is demonstrated by the seasonal variation in pavement surface deflections. However, the seasonal variation is more pronounced for some soils than it is for others. This is shown by Figure 10, which is a plot of deflection test data from conventional flexible pavements in the vicinity of the AASHO Road Test.

Much of the variation in resilient modulus can be attributed to seasonal moisture changes. However, the springtime peak deflection commonly noted in northern states is also indicative of the effect of freeze-thaw. Figure 11 illustrates the dramatic reduction in resilient modulus following a single freeze-thaw cycle. Similar tests conducted on several Arkansas soils indicate that a resilient modulus reduction on the order of 50 percent can be expected as a result of freeze-thaw action.

SUBGRADE RESILIENT MODULUS SELECTION—AASHTO METHOD

Design by the AASHTO Guide requires the selection of an "Effective Roadbed Soil Resilient Modulus." Since the seasonal variation of resilient modulus is quite complex, the selection of a single resilient modulus value for use in design can be quite complex. The object, of course, is to select a single value that is representative of the entire year.

The 1986 Guide contains a specific recommended method for selecting the subgrade resilient modulus. It consists of estimating seasonal variations in resilient modulus and assigning relative damage factors on a monthly or bimonthly basis. The damage factors are summed and the average determined. The resilient modulus corresponding to the average damage factor is then used for design. The following steps are involved in selecting the subgrade resilient modulus.

Step 1. Develop a relationship between resilient modulus and subgrade moisture content. This involves conducting resilient modulus tests on the subgrade soil at various moisture contents representing the range of moisture variation expected. For example, using the resilient modulus for the 6-psi deviator stress data from Figure 9, a relationship between resilient modulus and moisture content is developed (Figure 12).

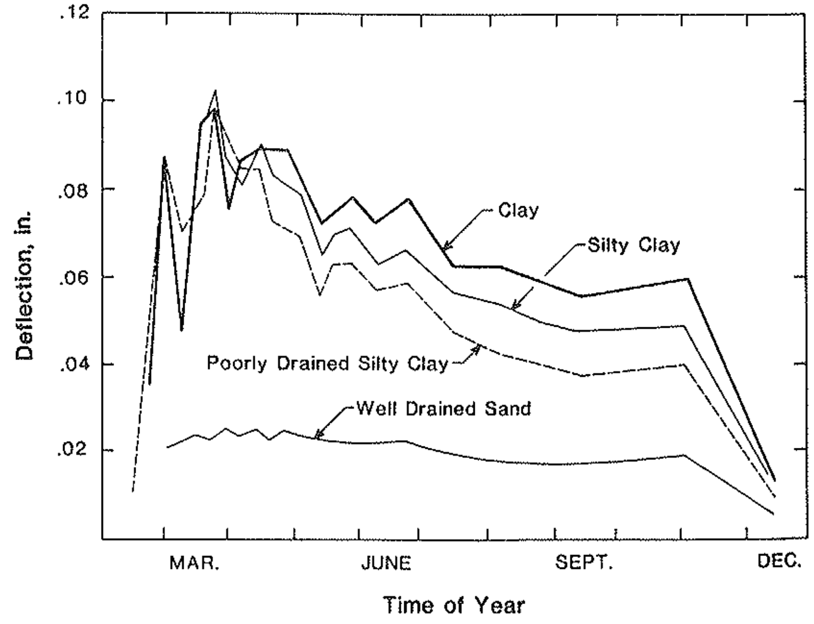


FIGURE 10 Seasonal variations in pavement deflections on various soils (data from Illinois Department of Transportation).

Step 2. Estimate the seasonal variation in moisture content. Although there is no standard approach for making this estimate, a practical approach might be to sample a similar subgrade. For this example it is assumed that moisture contents were determined four times during the year on a similar subgrade soil from a nearby pavement. From these a seasonal variation has been estimated as shown in Figure 13.

Step 3. Determine the monthly (or bimonthly) resilient modulus. Figures 12 and 13 are used to estimate the resilient modulus for each month of the year. The monthly values are entered on the AASHTO form (Figure 14). For example, the moisture content in March is about 25 percent. From Figure 12, the resilient modulus for 25 percent moisture content is 9,500 psi. Except for January and February, the resilient moduli for other months are found in a similar fashion. For January, it is assumed that the subgrade will be frozen resulting in a very high resilient modulus. February is assumed to be a period of thawing. To account for the freeze-thaw effect (Figure 11), the resilient modulus is determined in the normal fashion and reduced by 50 percent.

Step 4. Select a relative damage factor for each resilient modulus. Relative damage factors corresponding to the monthly resilient modulus values are selected using the scale on the right side of Figure 14. For the frozen subgrade (January), the resilient modulus would be high resulting in a low relative

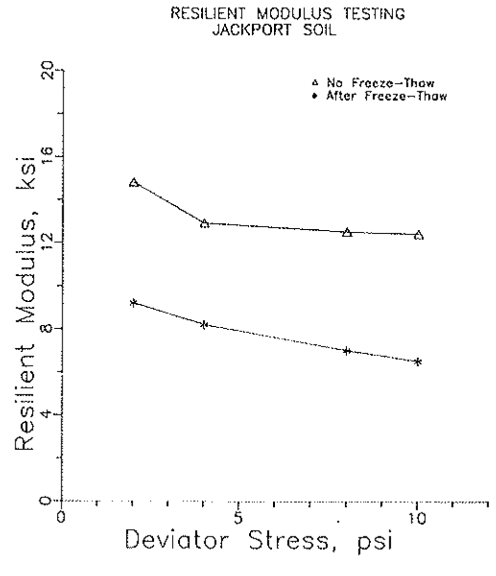


FIGURE 11 Effect of freeze-thaw on the resilient modulus of a typical cohesive subgrade soil.

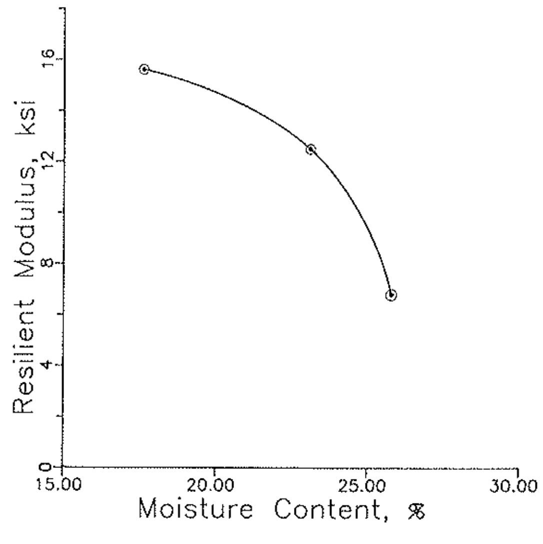


FIGURE 12 Moisture content-resilient modulus relationship for soil used in example.

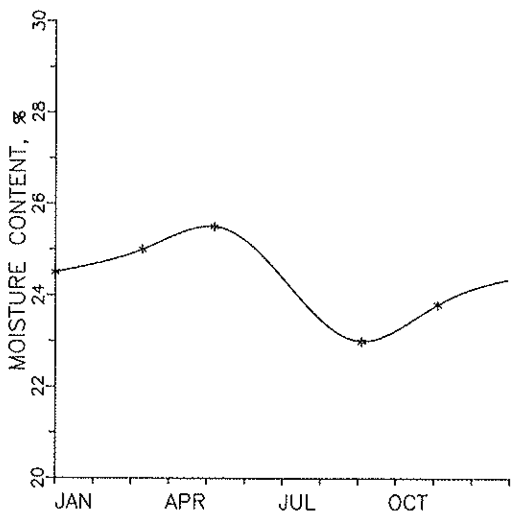


FIGURE 13 Seasonal moisture variation used in example.

damage factor. For practical purposes, a damage value of 0.0 is assigned.

Step 5. Use the average monthly relative damage factor to select the Effective Roadbed Soil Resilient Modulus. The average damage value (.063) is used with the scale on the right side of Figure 14 to select the Effective Roadbed Soil Resilient Modulus (9,900 psi) to be used in design.

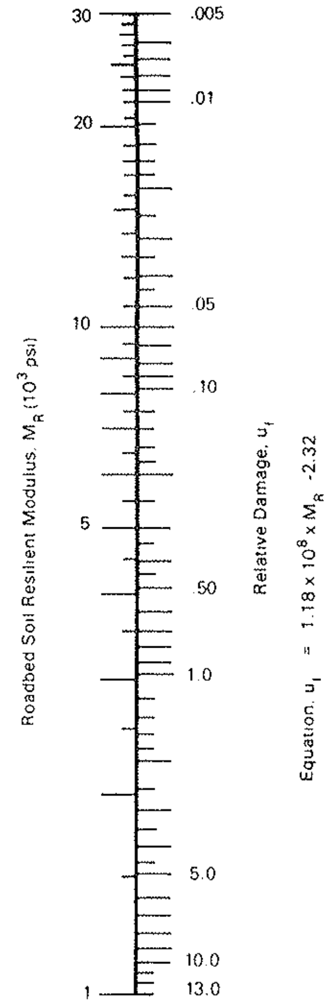
ALTERNATIVE SELECTION APPROACH

The above method requires testing each soil at several different moisture contents. An alternative approach would be to test each soil at a single representative "time-of-year" moisture content. Elliott and Thompson (*12*) conducted an analysis to find the appropriate "time-of-year" condition that would be representative of the entire year for the AASHO Road Test pavements. The study included (a) an investigation of the seasonal variation of resilient modulus at the AASHO Road Test, and (b) a determination of the seasonal load dam-

Month	Roadbed Soil Modulus, M_R (psi)	Relative Damage, u_f
Jan.	30,000	.005
Feb.	5,500	.25
Mar.	9,500	.070
Apr.	8,900	.081
May	8,600	.088
June	11,000	.050
July	12,700	.038
Aug.	13,000	.034
Sept.	13,100	.033
Oct.	12,800	.035
Nov.	12,700	.036
Dec.	12,300	.038

Summation: Σu_f = .758

Average: $\bar{u}_f = \frac{\Sigma u_f}{n}$ = .063



Effective Roadbed Soil Resilient Modulus, M_R (psi) = 9,900 (corresponds to $\bar{u}_f$)

FIGURE 14 Example determination of design resilient modulus by the AASHTO method.

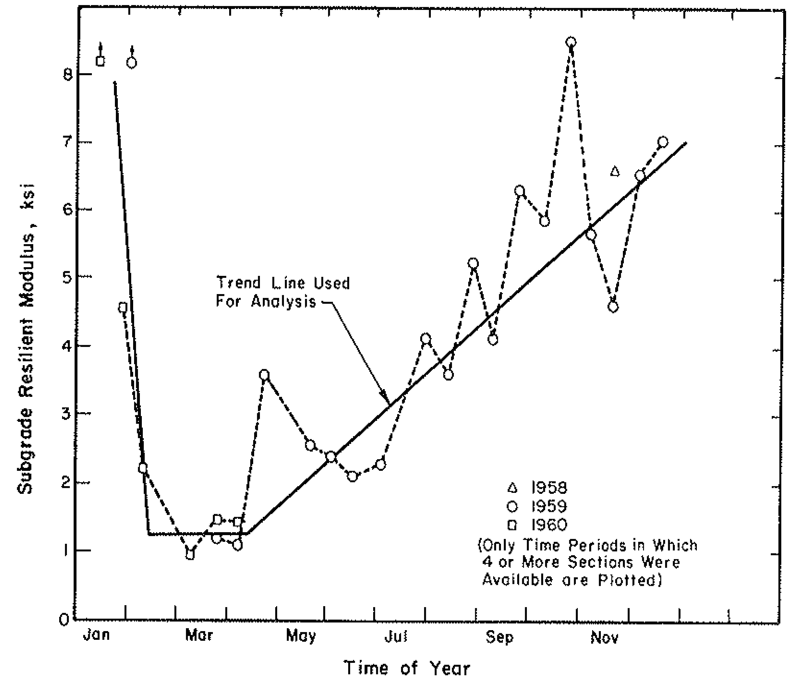


FIGURE 15 Seasonal subgrade resilient modulus variation at the AASHO Road Test (*12*).

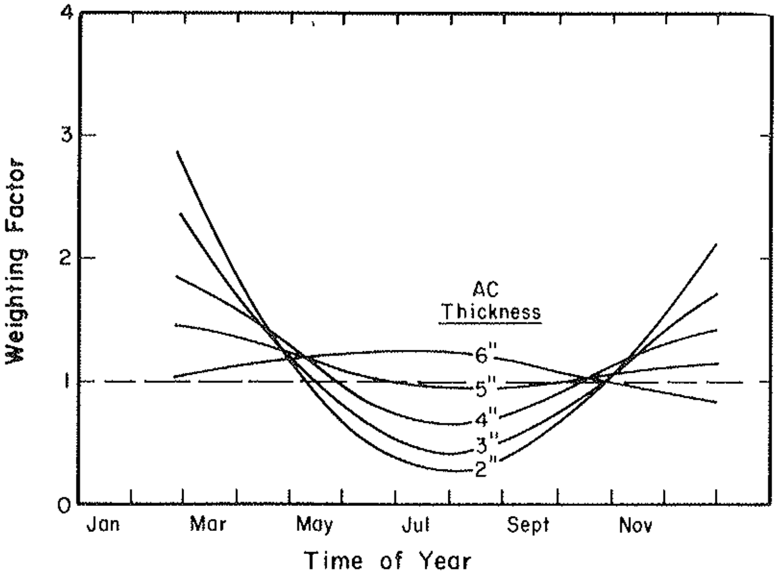


FIGURE 16 Seasonal weighting factors for various thicknesses of asphalt surfacing (*12*).

age effects for pavements with various thicknesses of asphalt. Their study was based on asphalt fatigue damage effects and included consideration of seasonal variation in the AC stiffness modulus as well as the subgrade resilient modulus.

The seasonal subgrade resilient modulus variation (based on analysis of deflection measurements taken during the AASHO Road Test) is shown on Figure 15. Figure 16 is the seasonal load damage effects expressed as a Weighting Factor. Elliott and Thompson concluded that no single resilient modulus could truly represent all pavement thicknesses. However, since all curves intersected in a fairly tight pattern in late April and mid-October, they stated that conditions during either of those periods should be acceptable for design purposes.

The disadvantage of using this alternative selection approach is the need to identify the representative "time-of-year" conditions. Limited analyses suggest that late spring conditions should be reasonable for most areas of the United States and probably no worse an approximation than the seasonal moisture variation estimate required by the AASHTO method. The advantage of this approach would be a significant reduction in the amount of testing needed for an individual soil

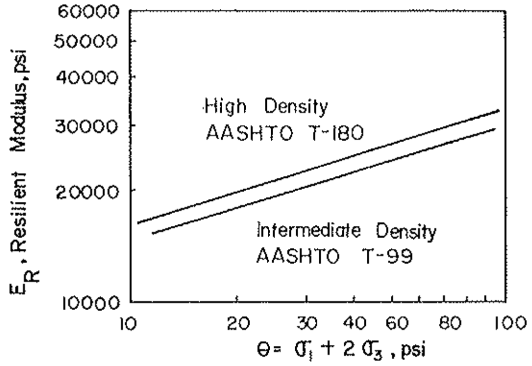


FIGURE 17 Effect of density on resilient modulus of a granular base material (*13*).

sample. This would permit testing more soils for the same testing effort.

RESILIENT MODULUS IN PERSPECTIVE

Resilient modulus is a significant and rational material property that needs to be included in the pavement design process. However, the resilient modulus does not represent all properties of a subgrade or granular layer that can affect the performance of a pavement.

The most direct evidence that other properties are also significant comes from the AASHO Road Test (*4*). Two granular materials were used—crushed stone and gravel. Of these, the gravel base sections deflected less. Inch for inch, the gravel was more effective in reducing the deflections. This suggests that the gravel possessed the higher resilient modulus. Nevertheless, the crushed stone sections had the superior performance. As stated in the Road Test report: "Perhaps the gravel possessed less internal stability than the stone; yet it may have been somewhat less resilient (i.e., higher resilient modulus)."

Similarly, Figure 17 indicates that density has only a limited effect on resilient modulus of a granular material. This could lead one to conclude that density is not significant. However, Figure 18 shows that density is quite significant relative to permanent deformation (strain).

Resilient modulus reflects only the rebound or resilient deformation behavior of the material. In so far as this relates to the load-induced stresses, strains, and deflections, resilient modulus is important and significant. However, the resilient modulus is not a good indicator of rutting potential. For many materials, the permanent deformation (rutting) behavior may well be the factor controlling pavement life. Therefore, resilient modulus must not be the only property considered in designing and selecting materials for a flexible pavement; layer coefficients based solely on resilient modulus can be misleading.

CONCLUSIONS

1. Resilient modulus is a fundamental material property. It relates to pavement design and performance for the same reason that surface deflection relates. It provides a measure of the load-induced stress-strain behavior of the soil and granular base layers which in turn governs the load response of the pavement system.
2. Resilient modulus should not be the only property considered in judging the acceptability of a soil or granular material. Because resilient modulus provides no measure of the permanent deformation (rutting) behavior, the selection of a granular material and assignment of layer coefficients based solely on resilient modulus can be misleading.
3. Many factors affect the resilient modulus causing it to vary seasonally throughout the life of the pavement. Conse-

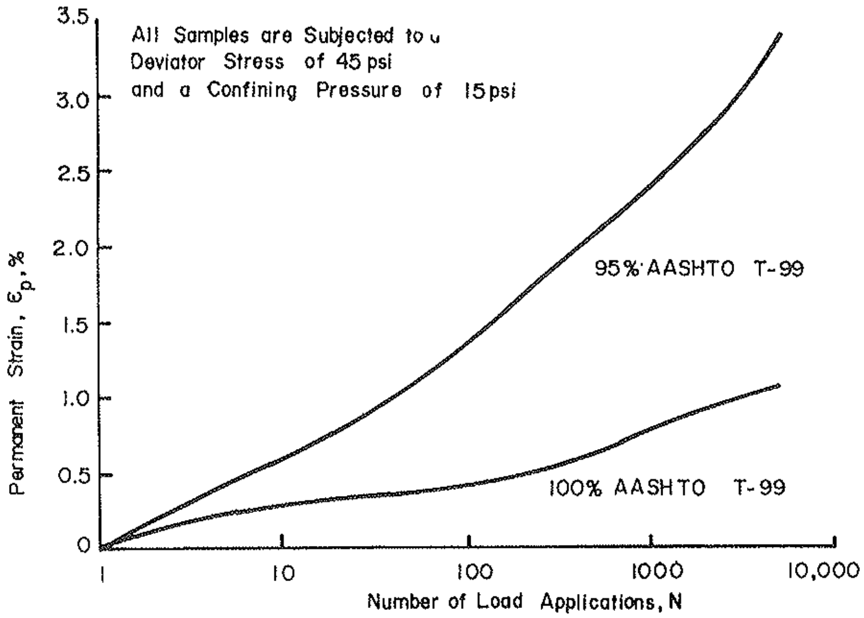


FIGURE 18 Effect of density on permanent deformation behavior of a granular base material (*13*).

quently, the selection of a single soil resilient modulus for use in design can be complicated.

4. While on paper the AASHTO Guide selection procedure is rational and straightforward, the estimation of seasonal moisture variation can be quite nebulous and the amount of testing required very time consuming. Consequently, a more practical approach is to test under a single, representative time-of-year condition. Late spring is a reasonable first approximation of the appropriate time of year for most of the United States.

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