Stress State Considerations for Resilient Modulus Testing of Pavement Subgrade

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The stress state imposed on subgrade materials during laboratory resilient modulus testing is compared with the anticipated stress state for in situ conditions during traffic loading. Revisions to AASHTO and the Strategic Highway Research Program resilient modulus testing procedures are under way; however, previously most resilient modulus tests have been performed according to the former AASHTO T274-82 specification. In this study, the stress state called for in AASHTO T274 was found to overstress subgrade specimens compared to traffic loading. The issue of stress state needs to be evaluated carefully in making revisions to the testing procedure. The probable effect of overstressing is discussed. Overstressing from shear and normal loading, which have opposite effects on the laboratory-measured resilient modulus, are both considered. Recommendations for resilient modulus testing of subgrade materials are made. The recommended procedure is designed to eliminate overstressing the test specimen. It is also designed to improve the degree to which preconditioning of the specimen removes plastic strains prior to obtaining measurements required for determining the resilient modulus. Laboratory tests on several subgrade materials are conducted using the modified procedure.

The resilient modulus has become a common parameter for characterization of pavement materials. Numerous state and federal agencies, as well as many engineering consulting companies, are developing the capability to perform the laboratory tests required for obtaining the resilient modulus. The resilient modulus is obtained by subjecting a specimen to repeated loading at a particular stress level and measuring the recoverable strain. Ideally, the specimen is exhibiting only elastic strains at the time the resilient modulus is measured. The resilient modulus can therefore be thought of as the secant Young's modulus of the material, which is typically different than the initial tangent value of Young's modulus, as can be seen in Figure 1.

The laboratory procedure being followed by most laboratories is AASHTO T274-82 (which is currently being revised as T292-91I). This laboratory procedure (*1*) includes specifications for preconditioning the soil specimen during testing. One of the intents of the preconditioning loading phase of the resilient modulus test is to induce any plastic strains that are prone to occur, so that mostly elastic strains remain during resilient modulus loading. It is best if the preconditioning loading phase of the test would use stress levels anticipated for in situ conditions, that is, stress levels comparable to those imposed by traffic loads and overburden. Overstressing a soil subgrade specimen in the laboratory can cause permanent changes in the material, thus decreasing the chance of obtaining a resilient modulus measurement that is indicative of in situ conditions. Investigation of the laboratory-imposed stress state on subgrade specimens compared to the in situ stress state is the subject of this paper.

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EFFECT OF STRESS OVERLOAD

It is a known fact that when stresses on a soil specimen are increased to a level higher than ever applied previously, plastic strains will occur (*2,3*). Therefore, the resilient modulus cannot be measured for such a cycle of loading. Stresses may be described broadly as either normal (spherical) stresses or shear (deviatoric) stresses. When discussing stress level, it is important to distinguish between normal stress level and shear stress level because normal and shear stresses produce somewhat differing effects on soil specimens (*4–6*). When a specimen is overstressed by normal stress, plastic strains occur and bonds between particles are broken. However, bonds are reformed at a higher normal stress, and the net effect of having been loaded to a higher normal stress is that the specimen is now denser, stiffer, and stronger than it was previously (*7*). By contrast, when shear stress is raised to a level higher than ever before, plastic strains result in bonds breaking; either these bonds do not reform, or new bonds are formed that are typically weaker than previous bonds (*7*). Therefore, the net effect of increasing the shear stress to a new higher value is to produce a specimen that is softer and weaker than before. Overloading by shear is generally more damaging than overloading by normal stress.

Thus the effect of shear stress elevation on the modulus is opposite to the effect of normal stress elevation (*4*). In the laboratory, separation of and distinction between shear and normal stresses are relatively easy. In the field, wheel loads produce both shear and normal stresses, and the predominant type of loading varies with the point of consideration within the pavement structure.

The measured modulus is sensitive to an increase in either normal or shear stress to levels higher than ever applied before because plastic strains are induced. However, when significant plastic strains occur, the resilient modulus cannot be measured in a straightforward manner because elastic and plastic strains must first be separated. Thus, the resilient modulus is most readily quantified when the following conditions are met:

1. The stresses applied (both shear and normal) are less than or equal to the maximum level of stress previously applied.

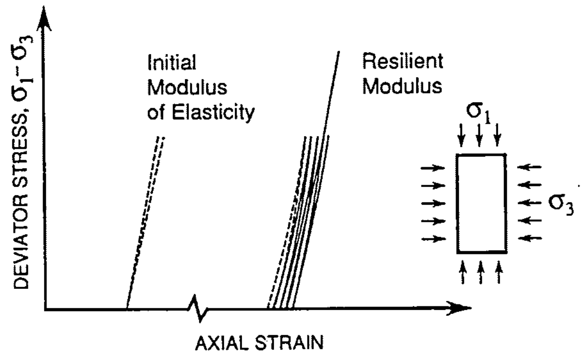

FIGURE 1 Definition of resilient modulus.

2. The stress has been applied for a sufficient number of times that the strains become essentially completely recoverable.

If the conditions of the laboratory test are such that the normal or shear stress imposed on the specimen is greater than that the specimen has ever been exposed to in situ, or if the stresses are greater than the stresses that the specimen will be exposed to in situ in the life of the pavement, then the laboratory modulus would be expected to differ from the field modulus, even if sampling were perfect and sample disturbance were absent. If the specimen is overstressed by normal stress loading, the effect on the modulus would be opposite to that for shear stress overloading.

As a part of the preconditioning, the former AASHTO T274 procedure calls for levels of both shear and normal stress that in most cases are well beyond those estimated to have been applied by in situ traffic stresses. For example, T274 calls for application of shear stresses to triaxial specimens of clayey soils when the confining pressure is zero, a condition that never exists for a subgrade in situ.

As noted above, it is also important for all plastic strains to have been removed by preconditioning before the resilient modulus is measured. The former AASHTO T274 procedure calls for preconditioning to only 200 cycles at each stress state. This number of cycles of loading is often insufficient to remove all significant plastic strains. Revisions to the AASHTO procedure and the Strategic Highway Research Program (SHRP) procedure (both under development at the time of this writing) call for additional conditioning of 1,000 repetitions. In the laboratory testing program conducted as part of this study, it was found that several thousand cycles of loading were often needed to remove the plastic strains, as noted by other researchers (*2,3,8,9*).

STRESS LEVEL

Because the subgrade material properties are generally stress dependent, the resilient modulus varies at different stress states. The moduli of subgrade materials change with changes in confining pressure and deviator stress (*6,10*). Changes in confinement correspond to changes in normal stress level, and changes in deviator stress correspond to changes in shear stress level. To determine the specific modulus in the laboratory that corresponds to the in situ condition, the state of stress of the sample in the laboratory has to match that anticipated for the field condition.

It is most convenient to represent the stress state of a soil specimen by stress invariants. Stress invariants are functions of the stress tensor that are independent of coordinate transformation. Functions of the principal stresses are probably the most-used stress invariants for describing the stress state for soil (*5,7,11*). It is common to use the octahedral normal and shear stresses, or other representations of the first and second stress tensor invariants, for describing the stress state of a material when it is important to consider normal and shear stress changes (*6,10,11*). For this purpose, the octahedral normal stress (σ_{oct}) and the octahedral shear stress (τ_{oct}) in the laboratory should be compared with the octahedral normal and shear stresses in the field. The octahedral normal and shear stresses are defined, respectively, as follows:

$$\sigma_{oct} = (\sigma_1 + \sigma_2 + \sigma_3)/3 \tag{1}$$

$$\tau_{oct} = \tfrac{1}{3}[(\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2]^{1/2} \tag{2}$$

Figure 2 shows the three-dimensional stress space. Figure 2(*a*) shows the view looking down the hydrostatic axis. The hydrostatic axis is the line along which the three principal stresses are all equal. Figure 2(*b*) shows a different perspective of the stress space, showing the octahedral shear stress is zero along the hydrostatic axis. As the octahedral normal stress increases, the point corresponding to the state of stress of the soil moves outward along the hydrostatic axis. Increasing octahedral shear stress is also indicated in Figure 2(*b*). Compressive stresses are positive for Figure 2.

A typical soil failure surface is shown in Figure 3. A projection of this failure surface in the more customary shear stress versus normal stress space would look like the Mohr Coulomb failure surface. Two perspectives of this failure surface are given in Figures 3(*a*) and 3(*b*), corresponding to the perspectives shown in Figures 2(*a*) and 2(*b*), respectively.

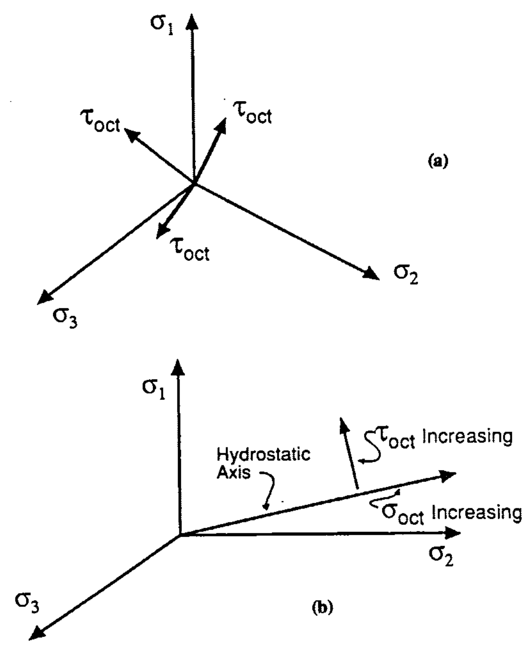

FIGURE 2 Three-dimensional stress space.

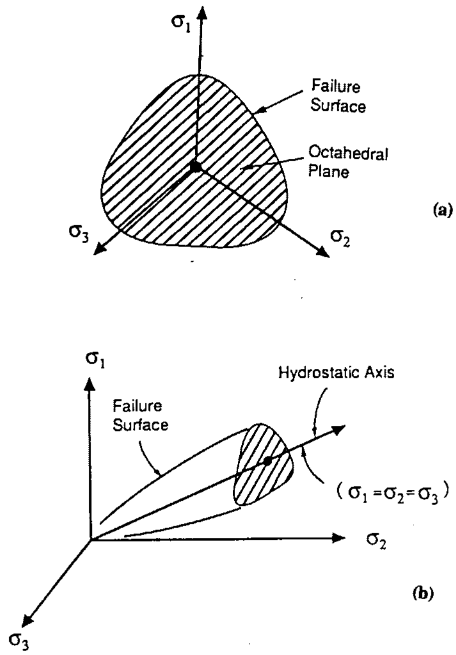

FIGURE 3 Typical soil failure surface.

It is possible to sketch a surface in stress space corresponding to the maximum stresses resulting from the maximum traffic loads plus the overburden stresses. A hypothetical surface representing the maximum in situ stress is shown in Figure 4, together with the soil failure surface. The surface of maximum in situ stresses due to traffic and overburden stress marks the desired limits for the laboratory testing program for subgrade materials.

The ELSYM5 multilayer elastic material computer program was used to compute the octahedral normal and shear stresses in the field under the pavement (*12*). An axle load of 100 kN (22,000 lb), to simulate an overloaded truck, was applied at the surface of each pavement section, and the stresses at the top of the subgrade were computed. Figure 5 shows results of the example computation of stress states for increasing wheel loads for three different depths. The dotted curve in Figure 5 represents the envelope of the maximum stresses, or the stress state associated with the 100 kN axle load. The

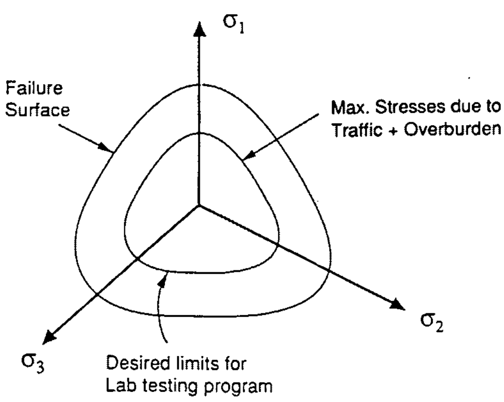

FIGURE 4 Failure surface and stress level.

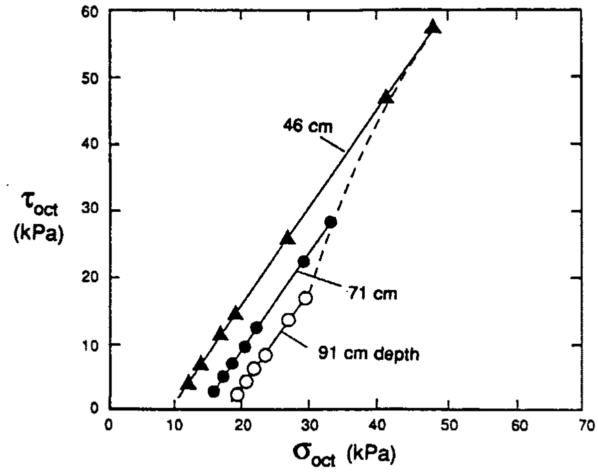

FIGURE 5 Stresses showing loading path for various depths of subgrade (1 kPa = 0.145 psi, 2.54 cm = 1 in.).

results of the computer analyses are given in terms of octahedral shear stress and octahedral normal stress for maximum generality.

Computation of in situ stresses requires the use of a layered elastic analysis computer program. The stress components from the analysis are required to compute the octahedral normal and octahedral shear stresses. Additional discussion on computation of in situ stresses is provided by Bush and Baladi (*13*). For laboratory triaxial conditions, σ_2 is equal to σ_3 and the deviator stress σ_d is $\sigma_1 - \sigma_3$. The octahedral shear and normal stresses for triaxial conditions become:

$$\sigma_{oct} = (\sigma_d/3) + \sigma_3 \tag{3}$$

$$\tau_{oct} = (\sqrt{2}/3)\sigma_d \tag{4}$$

Using these relationships, the deviator stress and confining pressure desirable for the laboratory testing program can be computed if the octahedral normal stress and the octahedral shear stress in the field are known.

Figure 6(*a*) shows the plane in which the triaxial stress conditions plot in principal stress space. Figure 6(*b*), which is given in terms of major and minor principal stresses, depicts a surface that envelopes all the stress states ever imposed by traffic plus overburden loading. This surface applies to only one point (depth) in the sublayer. Each point below the surface would have a different maximum stress surface.

To compare the stress state imposed by following the AASHTO T274 procedure for resilient modulus testing of subgrade materials to the maximum stress state that is likely to occur in situ, an example calculation was performed for a subgrade depth of 63.5 cm (25 in.) and a maximum axle load of 100 kN (22,000 lb). The resulting stress triangle, the set of octahedral shear and normal stresses enveloped by the loading path of Figure 5, is shown in Figure 7. The square data points show the prescribed stress states for the AASHTO T274 resilient modulus test procedure. Although this is only an example, it is typical, showing that the prescribed stress state for laboratory testing performed according to AASHTO T274 significantly exceeds the stress state due to traffic loading plus overburden stresses.

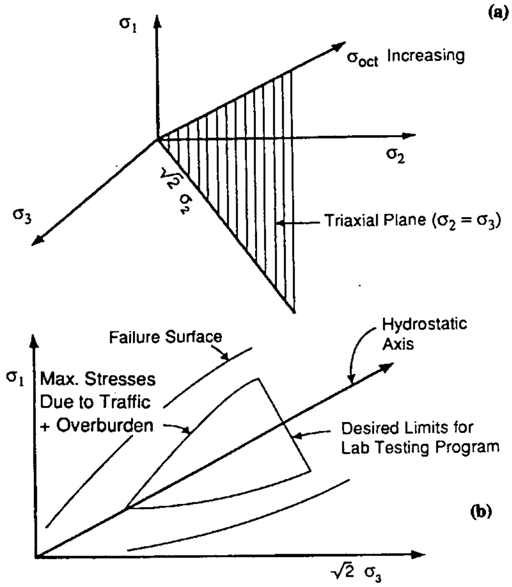

FIGURE 6 Stress states for failure, traffic loading, and laboratory testing.

SUGGESTIONS FOR RESILIENT MODULUS TESTING OF SUBGRADES

The following deviations from the AASHTO T274 procedure for resilient modulus testing appear to be justified on the basis of the preceding arguments and existing literature on the topic of resilient modulus testing of subgrade materials of varying types. It is the authors' understanding that some, though not all, of these suggestions are being considered in the new SHRP procedure and for AASHTO T292-91I.

Stress State

As part of preconditioning the specimen, the AASHTO T274 procedure called for levels of both shear and normal stresses that are in most cases greater than those estimated to have been applied by in situ traffic loading. For example, AASHTO T274 procedure called for application of shear stresses to triaxial specimens of clayey soils when the confining pressure is zero, a condition that never exists for subgrade in situ. Accordingly, a preconditioning program for each site could be selected in the following way, avoiding overloading the specimen in both shear and normal loading.

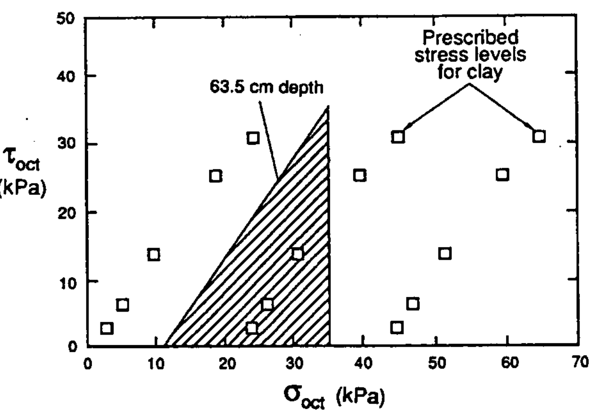

FIGURE 7 Stress triangle for element of subgrade at 63.5-cm depth (1 kPa = 0.145 psi, 2.54 cm = 1 in.).

1. Establish the pavement structure geometry for each site from boring logs and the existing data base.
2. Estimate the elastic moduli for the various layers using backcalculated values from data obtained from nondestructive testing (NDT) (*14*), or estimate a reasonable range in moduli from experience.
3. Estimate the maximum past stress state using an elastic multilayer pavement analysis program, such as ELSYM5 (*12*). An axle overload to 100 kN (22 kips) is likely to be a reasonable maximum loading for most cases.
4. Construct the "loading triangle" (see Figure 7), indicating the maximum past stress state for the subgrade.
5. Establish a preconditioning program and a testing procedure for each test specimen using the loading triangle. In general, each specimen should be loaded for 1,000 cycles at a low stress state, 1,000 cycles at a medium stress state, and 2,000 cycles at the maximum stress state (the apex of the triangle).
6. Load the specimen, after preconditioning, for 200 cycles at various lower stress states to measure the resilient modulus.

It may be possible to adopt an envelope of stress state, which would be conservative for all conceivable cases. If so, Steps 1 through 4 could be eliminated.

Preconditioning

If the sampling process were perfect and free of disturbance, then reapplication of traffic loads would produce no new plastic strains because plastic strains would have already occurred in situ. However, the sampling process is imperfect, and some plastic strains do occur during the preconditioning. Preconditioning is, in part, an attempt to erase the effects of sample disturbance.

The AASHTO T274 procedure called for preconditioning by cyclic loading to only 200 cycles at each stress state. The SHRP protocol P46 procedure (1991, unpublished) calls for 1,000 cycles of loading. In the laboratory testing conducted as a part of this study, it was consistently found that cyclic loading to several thousand cycles was needed to remove plastic strains. Other researchers have found that several thousand cycles of loading are needed to remove plastic strains (*2,9*). (This issue was addressed in Step 5 in the preceding section on stress state.)

Preparation of Specimen Ends

To ensure an intimate contact between the specimen ends and the end platens, a layer of a quick hardening cement, such as Burkstone, should be placed on the platens and allowed to set with the platens and the loading piston aligned and screwed into the top cap. If a bonding agent like this is not used, the interface between the specimen and the end platens might be compressible and produce a significant error in the measured modulus. An alternative to Burkstone is an epoxy, such as Bondo, which is used widely for automobile body repair. The advantage of the epoxy over the cement is that it produces no change whatsoever in water content of the specimen near the end platens.

LABORATORY TESTING PROGRAM

As part of a research project conducted for the Arizona Department of Transportation (*15,16*), a series of resilient modulus tests were conducted on subgrades from 20 locations throughout Arizona. The recommended procedure described in the preceding section of this paper was used in the laboratory testing program of subgrade materials.

Sampling

At each location, cores of asphalt concrete were obtained using a portable, electric-powered coring device. A 114-cm (4.5-in.) O.D. continuous flight auger was used to advance the hole after the asphalt core had been removed. Undisturbed samples of subgrade were obtained by pushing 76-mm (3-in.) O.D., 71-mm (2.8 in.) I.D. thin-walled stainless steel sample tubes hydraulically with the drill rig. In a few instances, the tube required driving with a 0.6-kN (140-lb) drop hammer.

Resilient Modulus Testing of Subgrade Materials

A microcomputer-controlled closed-loop testing system was used to conduct the resilient modulus testing of the subgrade materials (*15,16*). An outline of the sample preparation and triaxial test sequence used is given next.

A high-strength, fast-setting cement was used to ensure intimate contact between the specimen and the top and base platens. The cement was placed on a greased sample cap and then placed on the trimmed sample base. The cement was allowed to harden, and then the cap was removed. The location of the porous stone was marked in the cement, and a small hole was drilled for air communication. This air hole was for the purpose of allowing any pore air pressure caused by consolidation to dissipate.

Being careful of the air hole alignment, researchers then extruded the sample from the tube. After the specimen was extruded, weighed, and measured, the specimen base was placed onto the base of the triaxial cell. The top of the specimen was then mated to the top cap with cement. The top cap was first attached to the piston rod. Then a thin layer of cement was applied to the top cap. The top cap was brought into contact with the top of the specimen by easing the piston down into place by hand. The piston was then vibrated until the entire surface of the specimen top was covered with cement and there were no voids between the cap and the specimen. Then the cement was allowed to harden, which required less than 5 min.

The loading piston was unscrewed from the top cap, and the specimen was placed in a membrane and sealed with O-rings to isolate it from the confining fluid of the triaxial cell, in accordance with conventional triaxial procedure. O-rings were used to seal the membrane against the top and base caps. The triaxial cell apparatus was then assembled, and the loading pistons screwed back into the top cap.

Resilient Modulus Test Results

The average values of the subgrade resilient moduli from the laboratory testing program described previously are shown in Table 1. The last column indicates the soil type. The laboratory test specimens were subjected to a range of confining stress and deviator stress to assess sensitivity to both types of stress. The values reported in Table 1 are the average of two or more tests for the various levels of stress indicated. The laboratory specimens were undisturbed specimens obtained from existing subgrades, as previously mentioned. The data in Table 1 show that the average laboratory resilient moduli vary from about 44.2 to 110.4 MPa (4.8 to 16 ksi). These values are reasonable for moduli of the subgrade materials encountered in this study. A more detailed account of the resilient modulus test results is presented in Table 2. For each combination of confining stress and deviator stress, a best estimate value of modulus was determined. The best estimate moduli correspond to the average for the range of reasonable interpretations that could be applied in computing the resilient moduli from the hysteresis loops obtained.

DISCUSSION OF LABORATORY TEST RESULTS

An inspection of Tables 1 and 2 shows that the resilient modulus for the clayey soils decreased with increasing deviator stress level, but only slightly. Other researchers have reported decreased resilient modulus with increasing deviator stress, typically to a greater extent than those observed in this study (*4,5,17*). Likewise, the effect of confining pressure was only slight for the clayey soils. The results of the data given in Tables 1 and 2 for the clayey subgrades are attributed to the following three factors:

1. The preconditioning and loading procedures recommended herein were used for this test series. Therefore, overstressing with respect to previous traffic loading was not committed. That is, the stresses applied in the laboratory were no higher than those estimated to have been applied by traffic. In addition, preconditioning with several thousand cycles of stress was effective in removing most of the plastic strains and stabilizing the modulus (*15,16*).
2. Preconditioning to the highest stress level was done first. Then moduli were measured at lower values of deviator stress. This procedure also minimized plastic strains, contributing to constancy.
3. The stress level applied was in most cases only a small fraction of the shear strength. The high shear strength is attributed to the dry climate, high pore water suction, and high degree of cementation in the subgrade.

TABLE 1 Summary of Average Resilient Moduli of Soil Samples

Site/ Station	Sample Depth (cm)	Dry Unit Weight (kN/m^3)	Water Content (%)	Confining Stress (kPa)	Deviator Stress (kPa)	Resilient Modulus (ksi)	Unified Soil Classification
1/1	63-81	19.2	5.28	14-31	18-93	10.19	SM-SC
1/4	63-81	18.9	4.51	25-35	18-76	11.96	SM
2/1	48-63	18.6	7.09	12-30	18-69	13.10	SM
2/7	96-114	17.5	7.83	20-27	18-38	15.20	SM
3/7	68-86	17.7	12.4	14-31	18-86	6.44	SM
4/1	63-81	17.6	10.4	17-41	20-86	9.76	SM
5/4	51-68	18.8	12.4	20-33	19-62	12.29	SM
7/1	68-86	18.6	10.6	15-35	19-75	12.10	SM
7/4	68-86	18.9	9.23	15-35	19-77	11.36	SM
8/1	79-96	17.7	11.1	21-29	19-47	7.99	SM
9/1	127-145	16.4	22.8	26-31	19-71	16.14	CL-CH
10/4	112-130	15.2	25.9	25-33	21-49	12.48	CH
11/1	30-48	19.3	2.21	16-48	19-80	13.33	SM
12/1	81-99	18.9	8.56	15-25	18-58	7.41	SC-SM
13/4	33-51	17.4	8.81	12-25	20-65	14.35	SC
14/4	30-48	16.0	15.4	9-22	19-58	10.42	SC-CH
16/1	43-61	18.5	7.90	12-25	20-61	9.83	SM
17/1	51-66	16.5	17.8	12-25	20-57	4.82	ML
19/1	58-76	16.4	22.7	15-27	20-55	12.01	SC
19/4	79-97	15.1	28.9	15-27	19-53	15.64	CL

Note: 1 MPa = 0.145 ksi
1 kPa = 0.145 psi
62.4 pcf = 9.807 kN/m^3
1 in. = 2.54 cm

The more granular subgrade materials showed a rather consistent trend of increasing resilient modulus with increasing confining pressure. This trend is as anticipated because, in general, cohesionless (granular) materials are more sensitive to confining stress changes than clayey materials. Increasing the resilient modulus of granular soils with increasing confinement has also been reported by numerous researchers (*8–10,17,18*). Although the three factors listed for the clayey soils were also largely present for the granular soils, the tendency of the modulus to increase with confining pressure for granular soils is too strong to be masked by the high strength of the specimens.

SUMMARY AND RECOMMENDATIONS

It is well known that subgrade materials have a nonlinear response to a load. However, if the load is repeated thousands of times, the effect of nonlinearity is reduced. A typical stress-strain relationship for a soil specimen subjected to a triaxial state of stress, where the axial stress is varied in a pulsating form while the confining pressure remains constant, will show that nonlinearity is large when the load is applied for the first time. After many applications of load, however, the response is essentially elastic and linear.

Based on the observation of many resilient modulus tests (*15,16*), it has been found that the preconditioning specified by the former AASHTO T274 procedure for resilient modulus testing was generally inadequate to remove the plastic strains from subgrade materials. The specified number of preconditioning loading cycles in the AASHTO T274 procedure was 200. As part of the laboratory testing conducted in this study, it was found that 1,000 to 2,000 cycles of a preconditioning load were required to eliminate most of the plastic deformations. The SHRP protocol P46 procedure calls for 1,000 cycles of preconditioning.

Because it is desirable to have essentially a linear elastic response of the material when the measurements are made for resilient modulus computation, a modification to most current resilient modulus testing procedures is recommended. The recommended modification is to use 1,000 cycles of loading for preconditioning samples at low to moderate stress levels, and 2,000 cycles for higher stress levels.

The modulus can be affected by the state of stress of the material. Differences in both confining pressure and deviator stress must be considered. The octahedral shear stress and normal stress have been proposed in this study as the parameters for comparing the stress state between laboratory tests and the in situ condition. It has been found that the normal and shear stresses prescribed in the AASHTO T274 procedure

TABLE 2 Laboratory Resilient Modulus Data of Subgrade Materials

Site/ Station	Sample Depth (cm)	Dry Unit Weight (kN/m³)	Water Content (%)	Confining Pressure (kPa)	Deviator Stress (kPa)	Resilient Modulus (MPa)	Resilient Modulus (ksi)
1/1	63-81	19.2	5.28	14	93	72.4	10.5
				22	56	68.7	9.95
				31	28	91.8	13.3
				14	50	59.0	8.55
				22	26	72.1	10.45
				14	18	57.95	8.4
1/4	63-81	18.9	4.51	25	18	72.1	10.45
				25	25	77.3	11.2
				25	42	75.2	10.9
				35	25	90.4	13.1
				35	43	90.7	13.15
				35	76	89.4	12.95
2/1	48-63	18.6	7.09	17	69	80.7	11.7
				23	48	83.1	12.05
				30	22	104.9	15.2
				17	45	81.4	11.8
				20	31	83.8	12.15
				23	18	105.9	15.35
				12	21	92.5	13.4
2/7	96-114	17.5	7.83	23	27	92.1	13.35
				21	20	116.6	16.9
				20	38	86.6	12.55
				27	18	124.2	18.0
3/7	68-86	17.7	12.4	14	86	39.0	5.65
				22	53	40.0	5.8
				31	26	64.2	9.3
				14	46	36.9	5.35
				22	24	47.6	6.9
				14	18	39.0	5.65
4/1	63-81	17.6	10.4	24	84	63.1	9.15
				32	55	65.9	9.55
				41	23	86.25	12.5
				21	50	57.6	8.35
				31	24	69.35	10.05
				17	31	54.5	7.9
				17	21	64.2	9.3
				22	20	68.3	9.9
				40	86	76.9	11.15
5/4	51-68	18.8	12.4	20	62	58.0	8.4
				27	39	85.9	12.45
				33	21	93.8	13.6
				20	38	70.4	10.2
				25	21	96.3	13.95
				20	19	104.5	15.15
7/1	68-86	18.6	10.6	20	75	64.8	9.4
				15	45	53.1	7.7
				27	45	69.7	10.1
				35	19	122.9	17.8
				25	19	111.1	16.1
				15	19	79.4	11.5
7/4	68-86	18.9	9.23	21	77	71.7	10.4
				27	48	76.5	11.1
				35	21	112.4	16.3
				15	48	56.9	8.25
				26	21	87.9	12.75
				16	19	64.5	13.5
8/1	79-96	17.7	11.1	21	47	48.3	7.0
				25	35	58.3	8.45
				29	19	61.4	8.9
				21	19	48.3	7.0
				21	29	53.1	7.7
				26	19	61.4	8.9

(continued on next page)

TABLE 2 *(continued)*

Site/ Station	Sample Depth (cm)	Dry Unit Weight (kN/m³)	Water Content (%)	Confining Pressure (kPa)	Deviator Stress (kPa)	Resilient Modulus (MPa)	Resilient Modulus (ksi)
9/1	127-145	16.4	22.8	26	71	103.5	15.0
				31	42	109.7	15.9
				31	19	124.5	18.05
				26	30	112.5	16.3
				26	19	109.4	15.85
10/4	112-130	15.2	25.9	25	49	73.5	10.65
				29	33	81.8	11.85
				33	21	88.0	12.75
				25	31	84.2	12.2
				29	21	94.5	13.7
				25	22	92.1	13.35
11/1	30-48	19.3	2.21	31	80	94.5	13.7
				37	55	97.3	14.1
				48	23	123.9	17.95
				26	57	90.0	13.05
				34	25	92.5	13.4
				20	30	77.6	11.25
				24	19	90.0	13.05
				16	19	70.0	10.15
12/1	81-99	18.9	8.56	15	58	46.6	6.75
				16	49	50.0	7.25
				21	31	50.7	7.35
				21	18	48.6	7.05
				25	19	59.7	8.65
13/4	33-51	17.4	8.81	15	65	97.3	14.1
				20	46	100.4	14.55
				25	31	123.9	17.95
				18	33	91.4	13.25
				13	55	90.0	13.05
				22	20	108.7	15.75
				12	31	81.4	11.8
14/4	30-48	16.0	15.4	12	58	82.5	11.95
				17	42	88.7	12.85
				22	22	82.1	11.9
				11	40	65.6	9.5
				16	21	64.9	9.4
				9	19	47.6	6.9
16/1	43-61	18.5	7.90	15	61	61.6	8.9
				20	40	64.35	9.35
				25	26	77.3	11.2
				13	52	56.65	8.2
				18	31	68.3	9.9
				22	20	92.5	13.4
				12	29	54.1	7.85
17/1	51-66	16.5	17.8	15	57	28.85	4.2
				25	21	43.65	6.35
				17	43	28.35	4.1
				20	31	33.05	4.8
				20	20	37.4	5.4
				12	26	27.9	4.05
19/1	58-76	16.4	22.7	15	55	66.15	9.6
				27	20	98.7	14.3
				17	41	73.1	10.6
				20	29	81.6	11.8
				20	20	94.8	13.75
19/4	79-97	15.1	28.9	15	53	111.4	16.15
				27	19	113.8	16.5
				17	39	90.05	13.05
				20	28	106.0	15.2
				15	28	119.2	17.3

Note: 1 MPa = 0.145 ksi   62.4 pcf = 9.807 kN/m³
1 kPa = 0.145 psi   1 in. = 2.54 cm

for resilient modulus testing typically exceed those expected for in situ conditions, even considering loading by a heavily overloaded truck.

It is proposed that the stress state imposed in the laboratory during resilient modulus testing should not exceed the greatest loading expected in situ because of possible modification of subsequently measured modulus. It is important to avoid overloading the laboratory specimen in both normal and shear stresses. Therefore, it is recommended that the octahedral shear stress and octahedral normal stress be less than or equal to the maximum values anticipated for the field loading. The maximum octahedral normal stress and maximum octahedral shear stress can be estimated by using a linear elastic, multilayer pavement system analysis program. This study used falling weight deflectometer test results for estimating the moduli of the layers and the ELSYM5 program for the analysis. In the absence of NDT results, experience can usually be used to estimate layer moduli with an accuracy sufficient for calculating reasonably expectable maximum stress states in the prototype.

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