

Modifications to Resilient Modulus Testing Procedure and Use of Synthetic Samples for Equipment Calibration

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Modifications to the resilient modulus testing procedure (AASHTO T-274) and the use of synthetic samples for equipment evaluation and calibration are described. The modifications to the AASHTO T-274 were carried out to produce a testing protocol for use in the testing program of the Strategic Highway Research Program. The modifications were aimed at producing a more repeatable and less complicated test procedure. The main changes are the use of external linear variable differential transformers (LVDTs) for deformation measurements of all soil types and complete modification of the loading sequence and eliminating low deviator stresses, which produce high variability and high deviator stresses, which produce sample failure. The use of synthetic samples (polyurethane) with well-known properties to calibrate and evaluate resilient modulus equipment is also described. Synthetic samples could be an excellent choice in the development of a standard procedure for calibration of resilient modulus equipment.

The resilient modulus test for soils was originally developed by Seed et al. (1) and was initially formulated for highway applications. Later, the test was applied to earthquake research.

The resilient modulus is a measure of the "elastic" behavior (load-unload response) of the soil layer that may be in the nonlinear range. The resilient modulus can be used directly for the design of flexible pavements but must be converted to a modulus of subgrade reaction (k -value) for the design of rigid or composite pavements.

Traditionally, this test measures the elastic properties of the unbound soils and requires specialized, and expensive, equipment. The test is also fairly difficult to perform. While the test is considered the state of the art, it is not widely accepted for routine application by state transportation departments. It was not until 1986 that the resilient modulus was formally accepted and included in the AASHTO *Guide for Design of Pavement Structures* (1986).

The resilient modulus was selected to replace the soil support value used in previous editions of the AASHTO design guide for the following reasons:

1. It indicates a basic material property, which can be used in mechanistic analysis of multilayered systems for predicting pavement distresses such as cracking, roughness, rutting, and faulting.
2. It has been internationally recognized as a method for characterizing materials for use in pavement design and evaluation.

3. Techniques are available for estimating the resilient modulus of various in-place materials from nondestructive tests.

The resilient modulus of cohesive subgrade materials or unbound base materials is determined in a repeated load triaxial compression test, such as the one in Figure 1. The load is applied with any device capable of providing a variable load of fixed cycle and load duration. The test is conducted by placing a specimen in the triaxial cell. The specimen is subject to all-around confining pressure (σ_3), and a repeated axial stress, σ_d ($\sigma_d = \sigma_1 - \sigma_3$), is applied to the sample. During the test the recoverable axial strain ϵ_r is determined by measuring the recoverable deformation across a known gauge length or the total sample height. The resilient modulus is calculated by using the following expression:

$$M_R = \frac{\sigma_d}{\epsilon_r}$$

where σ_d is cyclic deviation stress and ϵ_r is resilient strain.

The test procedure for estimating the resilient modulus of a particular material depends on the material type. Materials with relatively low stiffnesses, such as natural soils, unbound granular layers, and even slightly stabilized layers, should be tested by using the resilient modulus test method (AASHTO T-274). Alternatively, the stiff materials, such as stabilized bases and asphalt concrete, may be tested by using the repeated-load indirect tensile test (ASTM D4123).

The focus of this paper is the analysis of changes made to the testing procedure (AASHTO T-274) for determining the resilient modulus (M_R) of soils and unbound granular layers for use in the Strategic Highway Research Program (SHRP). The use of synthetic samples with known moduli to test and calibrate M_R equipment is also included. A calibration procedure for M_R equipment may be very important in SHRP, because several laboratories perform the resilient modulus testing. Uniformity of equipment and testing techniques is essential to obtain comparable data.

CHANGES IN THE AASHTO T-274 TEST PROCEDURE

The resilient modulus of soils and unbound granular materials is commonly measured by using the AASHTO T-274 procedure (2), although, unfortunately, some researchers have

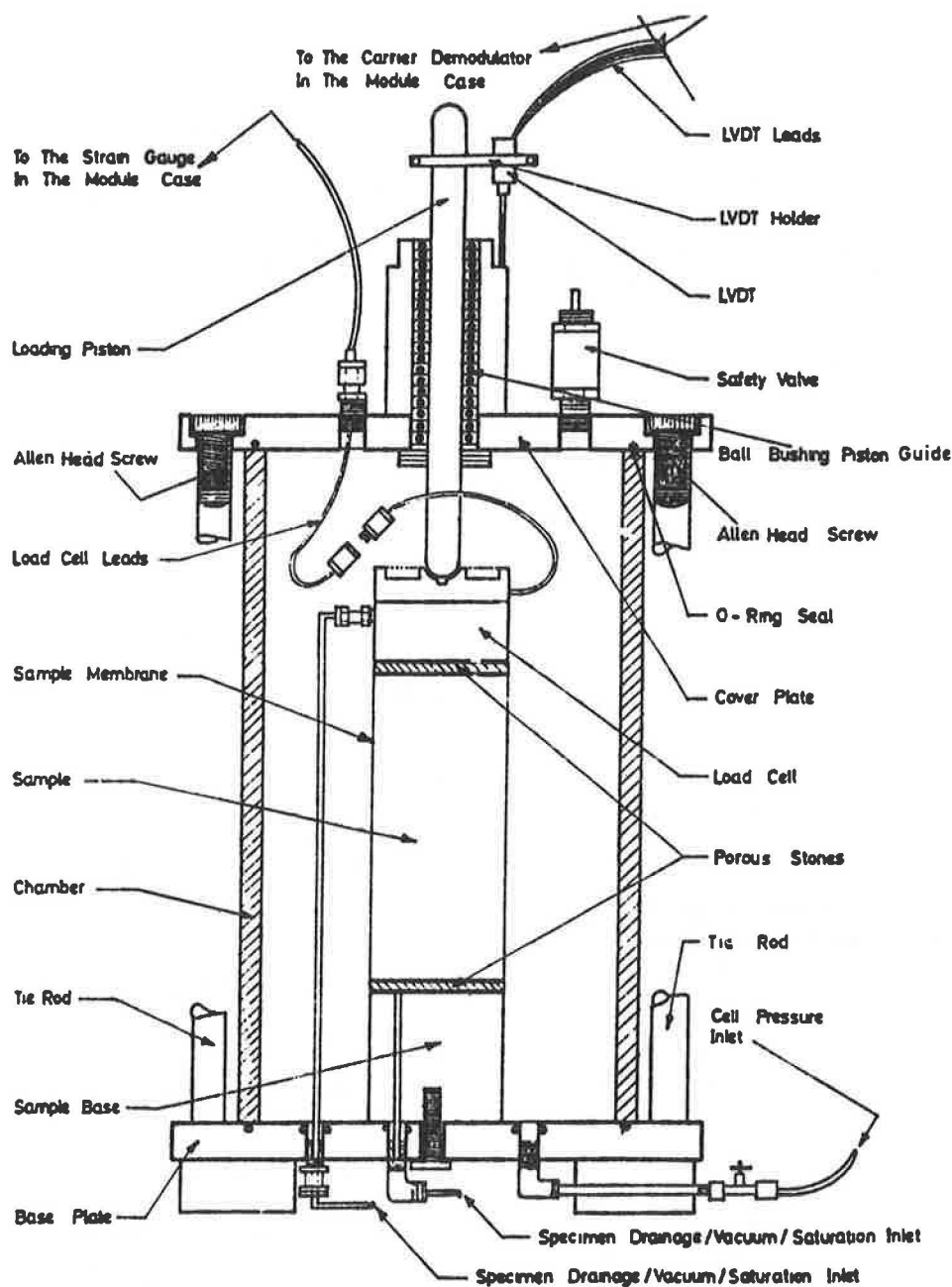


FIGURE 1 Triaxial test cell with test specimen in place.

used variations of this test procedure, which has led to non-uniform results. Even if this test procedure were to be followed, different results could occur, given the very open nature of this test, which would allow the researcher to choose from various options in the procedure. Some experts in this area have pointed out that the T-274 procedure is not a "mature" test. Few state highway agencies or commercial testing laboratories routinely conduct resilient modulus testing. Therefore, most of the available data on the resilient modulus of soils and granular materials have been developed from research-oriented activities. Unfortunately, there are no widely used and accepted test procedures, and many agencies have expressed considerable dissatisfaction with the AASHTO T-274 procedure.

To fulfill the testing needs of SHRP, experts were assembled in Austin, Texas in early April 1989. The AASHTO T-274 procedure and the draft version of the ASTM (Committee D18.09) procedures were used as the base documents for SHRP protocol P-46, which was the most important modification to AASHTO T-274 made by the Austin group.

Equipment

The triaxial pressure chamber for AASHTO T-274 has two different layouts that allow the measurement of the resilient deformation using internal or externally mounted linear variable differential transformers (LVDTs). The use of internal

LVDTs on stiff samples increases the variability of results because it is very difficult to secure the clamps on the specimen to ensure that there is no movement. The sample also has an outer membrane, which can slip, inducing small clamp movements. A movement of 0.05×10^{-3} in. in the clamps can change by 50 percent the resilient modulus of a sample with a 40,000 psi modulus when tested under a 2-psi deviator stress. On the other hand, fine plastic soils have much permanent deformation, which make the internal LVDTs slip out of range, forcing the test to be stopped, the triaxial chamber to be opened, and the LVDTs to be readjusted. The use of voltage suppressor knobs is not recommended because the core position in the LVDTs is physically out of the range of calibration. On the basis of this fact, the SHRP protocol uses an externally mounted LVDT, which measures the resilient deformation of the total sample height for all soil types and granular unbounded materials. The layout of the triaxial chamber for the SHRP protocol, presented in Figure 1, includes an internal load cell to eliminate the piston friction.

The external loading source for the P-46 protocol is a closed-loop electrohydraulic system. Other systems, such as open-loop air or static weights, are not acceptable. The load duration is 0.1 sec, and the cycle duration is 1 sec. This short load duration can not be achieved with an open-loop air system or static weights. The recently developed closed-loop air system has the capability to apply a 0.1-sec load duration if the resilient deformation is not very large. This type of system can be an alternative to the more complex electrohydraulic systems.

A haversine stress pulse was chosen for protocol P-46 because it better represents the shape of a truck load on pavement (3) and is also similar to the load pulse applied by a nondestructive testing device, such as the Falling Weight Deflectometer. The triaxial chamber fluid for the protocol is air, and the chamber pressure should be monitored with pressure gauges, manometers, or pressure transducers with an accuracy of 0.1 psi. The load cell and LVDTs to be used in this test are specified and depend on the sample diameter. This may ensure uniform accuracy of the load and deformation measuring devices. Recommended load cells and LVDTs are included in Table 1. The use of suitable recording devices, which allow simultaneous recording of axial load and deformation, is recommended. The signal for the transducer should be free of noise. If filters are used, they should have a frequency that cannot attenuate the transducer signal.

TABLE 1 RECOMMENDED LOAD CELLS AND LVDTS FOR M_R TESTING

Sample Diameter (inches)	Load Cell Capacity (lb)	LVDT Range (inches)
2.8	100	± 0.05
4.0	600	± 0.10
6.0	1,400	± 0.25

Preparation of Test Specimens

Specimen length should not be less than two times the diameter. The minimum specimen diameter is 2.8 in., or five times the nominal size. The compaction of fine plastic soils uses the AASHTO T-99 method. A partial face hammer (with 30 percent of the specimen area) is recommended. The number of blows per layer should be adjusted to reproduce the field dry density. Granular soils are compacted by using AASHTO T-180. Manually operated vibrators (electric or air-driven) are an option for this type of soil. For fine nonplastic soils, a full face plate with a vibrating system can be used to obtain the desired dry density.

Testing Procedure

The load sequence during the test procedure depends on the type of soil to be tested. Two criteria were used for soil Types 1 and 2:

1. Soil Type 1 is all unbound granular base and subbase materials. Unbound subgrade soil has the following criteria: (a) less than 70 percent passing the No. 10 sieve and (b) a maximum of 20 percent passing the No. 200 sieve.
2. Soil Type 2 is all unbound subgrade soil not meeting criterion 1.

Because it is important to test soils at the levels of stress to which they will be subjected in a pavement structure, these soil definitions are different from those in AASHTO T-274. Subgrade soils, whether granular or fine cohesive, will be subjected to much lower stresses than the subbase and base materials. Therefore, the soils should be tested at lower stress levels.

The loading sequence for soil Type 1 is presented in Table 2. The σ_1/σ_3 ratio has a maximum value of 3 to prevent the

TABLE 2 SOIL TYPE 1 TESTING SEQUENCE

Sequence Number	Confining Pressure σ_3 (psi)	Deviator Stress σ_d (psi)	Number of Load Applications
1	3	3	100
2	3	6	100
3	3	9	100
4	5	5	100
5	5	10	100
6	5	15	100
7	10	10	100
8	10	20	100
9	10	30	100
10	15	10	100
11	15	15	100
12	15	30	100
13	20	15	100
14	20	20	100
15	20	40	100

sample from failing. This condition was never followed in AASHTO T-274, and samples failed many times before the test was completed. The number of load applications after conditioning was reduced to 100 repetitions per each sequence. There is no change in the size of the deformation after the conditioning, and it is not necessary to wait for 200 load repetitions before recording deformations as is recommended in AASHTO T-274.

The loading sequence for soil Type 2 (subgrade soils) is presented in Table 3. It can be seen that the test at zero confining pressure ($\sigma_3 = 0$) was eliminated because there is no realistic state of stress for a subgrade in a pavement structure. The deviator stresses applied to the sample are 2, 4, 6, 8, and 10 psi. The deviator stress of 1 psi was eliminated because experience has shown that the major dispersion of results is at this stress level. The high dispersion is the product of the small resilient deformation, which cannot be measured accurately and sometimes is not bigger than the noise of the signal.

The number of load repetitions was reduced to 100 for each load sequence, as for soil Type 1. This also allows the testing to be shortened. A failure criterion was included in the test to eliminate samples with large permanent deformations. A specimen is considered failed if the permanent deformation (vertical strain) exceeds 10 percent.

The deviator stress and the resilient deformation are recorded for the calculation of the resilient modulus during the last five loading cycles for soil Types 1 and 2. The forms in Figures 2 and 3 are recommended for this purpose.

Calculations of the Test

Calculations are performed by using the tabular arrangement forms in Figures 2 and 3. The mean and standard deviation

of the applied load and the recoverable deformation are calculated. The mean values are used to compute the deviator stress and the resilient strain.

Test Report

A report of the resilient modulus test should include the data forms (Figures 2 and 3) and a simple linear regression predicting M_R as a function of bulk stresses ($\theta = \sigma_1 + 2\sigma_3$). For soil Type 1, the regression equation has the following form:

$$M_R = K_2 \theta^{n_2}$$

or

$$\log M_R = \log K_2 + n_2 \log \theta$$

For soil Type 2, the regression equation of M_R should be expressed as a function of deviator stress ($\sigma_d = \sigma_1 - \sigma_3$) in the following form:

$$M_R = K_1 \sigma_d^{n_1}$$

or

$$\log M_R = \log K_1 + n_1 \log \sigma_d$$

The coefficient of determination (R^2) is reported, and this value can be used to judge the quality of the test. Outlier points could be eliminated by using a statistical test for outliers.

Limitation of the New Testing Procedure

The modifications made to AASHTO T-274 to produce protocol P-46 make this test more repeatable, but there are some problems still to be resolved. A summary of those problems follows.

1. The measurement of the resilient deformation, using the external LVDT, assumes that the strain distribution in the sample is uniform, which is not correct as some researchers have found (4). Unfortunately, the measurements of strains in the middle portion of the sample are not reliable owing to the slight movement of the clamps, as was previously mentioned. The only possibility is to use some type of noncontact transducer to make those measurements. Researchers at The University of Texas at Austin are experimenting with an electro-optical biaxial tracking system that will allow the measurement of deformation in the sample without contact. Because the strain distribution depends on the sample stiffness, a series of correction factors can be obtained by using an optical-tracking device to correct the resilient modulus obtained with external LVDTs. This correction is also dependent on sample stiffness.

2. The test procedure has two loading sequences. The criterion for use is the type of soil to be tested. This criterion is incorrect because the most important factor should be the position of the soil in the pavement (subgrade, subbase, or

TABLE 3 SOIL TYPE 2 TESTING SEQUENCE

Sequence Number	Confining Pressure σ_3 (psi)	Deviator Stress σ_d (psi)	Number of Load Applications
1	6	2	100
2	6	4	100
3	6	6	100
4	6	8	100
5	6	10	100
6	4	2	100
7	4	4	100
8	4	6	100
9	4	8	100
10	4	10	100
11	2	2	100
12	2	4	100
13	2	6	100
14	2	8	100
15	2	10	100

Soil Sample _____
 Location _____
 Sample No. _____
 Specific Gravity _____
 Soil Specimen Measurements:
 Top _____
 Diameter Middle _____
 Bottom _____
 Average _____
 Membrane Thickness _____
 Net Diameter _____
 Ht Specimen + Cap + Base _____
 Ht Cap + Base _____
 Initial Length, Lo _____
 Inside Diameter of Mold _____

Soil Specimen Weight:
 Initial Weight of Container _____
 * Wet Soil gms _____
 Final Weight of Container _____
 * Wet Soil gms _____
 Weight Wet Soil Used _____
 Soil Specimen Volume:
 Initial Area, Ao _____
 In2 (cm2) _____
 Initial Volume, Ao Lo _____
 In3 (cm3) _____
 Wet Density.pcf (kn/m3) _____
 Compaction Water Content, Wc % _____
 % Saturation _____
 Dry Density.pcf (kn/m3) _____

Date _____
 Compaction Method _____
 Constants
 Vertical LVDT _____
 Load Cell _____
 Water Content After
 Resilience Testing % _____
 Comments _____

Pressure Chamber	Nominal Deviator Stress (in PSI)	Load Cell Reading	Deviator Load (lb)	Mean Deviator Load (lb)	Standard Deviation of Load (lb)	Applied Deviator Stress (in psi)	Recoverable Deformation LVDT Reading	Recoverable Deformation (inches)	Mean Recoverable Deformation (inches)	Std. Dev. of Recoverable Deformation (inches)	Resilient Strain	MR	Bulk Stress
3	3												
3	6												
3	9												
5	5												
5	10												
5	15												
10	10												
10	20												
10	30												
15	10												
15	15												
15	30												
20	15												
20	20												
20	40												

FIGURE 2 Form for resilient modulus test on soil Type 1.

Soil Sample _____	Soil Specimen Weight:	Date _____
Location _____	Initial Weight of Container _____	Compaction Method _____
Sample No. _____	* Wet Soil gms _____	
Specific Gravity _____	Final Weight of Container _____	Constants
Soil Specimen Measurements:	* Wet Soil gms _____	Vertical LVDT _____
Top _____	Weight Wet Soil Used _____	Load Cell _____
Diameter Middle _____	Soil Specimen Volume:	Water Content After
Bottom _____	Initial Area, A _o _____	Resilience Testing % _____
Average _____	in2 (cm2) _____	Comments _____
Membrane Thickness _____	Initial Volume, A _o L _o _____	_____
Net Diameter _____	in3 (cm3) _____	_____
Ht Specimen + Cap + Base _____	Wet Density.pcf (kN/m3) _____	
Ht Cap + Base _____	Compaction Water Content, W _c % _____	
Initial Length, L _o _____	% Saturation _____	
Inside Diameter of Mold _____	Dry Density.pcf (kN/m3) _____	

Pressure Chamber	Nominal Deviator Stress (in PSI)	Load Cell Reading	Deviator Load (lb)	Mean Deviator Load (lb)	Standard Deviation of Load (lb)	Applied Deviator Stress (in psi)	Recoverable Deformation LVDT Reading	Recoverable Deformation (inches)	Mean Recoverable Deformation (inches)	Std. Dev. of Recoverable Deformation (inches)	Resilient Strain	Resilient Modulus MR=
6	2											
6	4											
6	6											
6	8											
6	10											
4	2											
4	4											
4	6											
4	8											
4	10											
2	2											
2	4											
2	6											
2	8											
2	10											

FIGURE 3 Form for resilient modulus test on soil Type 2.

base) and not the type. A more rational approach would be to have loading sequences for testing subgrades, subbases, and bases based on average pavement structures.

3. The stress levels of the loading sequences were reduced to reflect a more realistic state of stresses in pavement layers, but they are still fairly large. Those stresses applied to soils produce a wide range of strains, as is indicated in Figure 4. For example, soil A-2-6 can have strains going from 3×10^{-3} to 3×10^{-2} percent when tested as soil Type 2. The wide variation on the slope of the relationship E versus strain observed in Figure 4 makes the characterization of this soil more imprecise if the secant slope is calculated. If the testing stress levels were reduced to comparable stresses in the pavement structure, then the strain range will be smaller and the characterization will be more accurate. The same analysis is true for soil A-7-5.

4. The linear regression models used to predict the resilient modulus have deviator stress (σ_d) and bulk stresses (θ) as independent variables for soil Types 1 and 2, respectively. Those independent variables are not the best predictors of the resilient modulus. Other variables, such as resilient strain (ϵ_r) and confining pressure (σ_3), have coefficients with a higher correlation with M_R . As an example, the following regression models were tested for the same set of data (A-2-6 soil):

Model 1:

$$M_R = K_1 \sigma_d^{n_1}$$

$$M_R = 65629 \sigma_d^{-0.552} \quad R^2 = 0.61$$

Model 2:

$$M_R = K_2 \epsilon_r^{n_2}$$

$$M_R = 882 \epsilon_r^{-0.3990} \quad R^2 = 0.85$$

Model 3:

$$M_R = K_3 \sigma_3^{n_3} \epsilon_r^{n_4}$$

$$M_R = 906.6 \sigma_3^{0.1252} / \epsilon_r^{0.3756} \quad R^2 = 0.87$$

Models 2 and 3 give the highest coefficient of correlation (R^2) for the same set of data, and therefore, those independent variables are better predictors of M_R .

CALIBRATION OF RESILIENT MODULUS EQUIPMENT USING SYNTHETIC SAMPLES

If accurate results are desired, the resilient modulus test requires very good calibrations of each one of the transducers and the complete device. Calibrations of the load cell and the LVDTs are standard procedures, but those calibrations do not test the complete equipment. A multilaboratory calibration will be necessary for SHRP if comparable data results are expected. To test the complete M_R equipment and to be able to compare results between laboratories, some kind of standard material is required. Some researchers have used standard sands for this purpose, but the sample preparation could be another factor in the variation between laboratories.

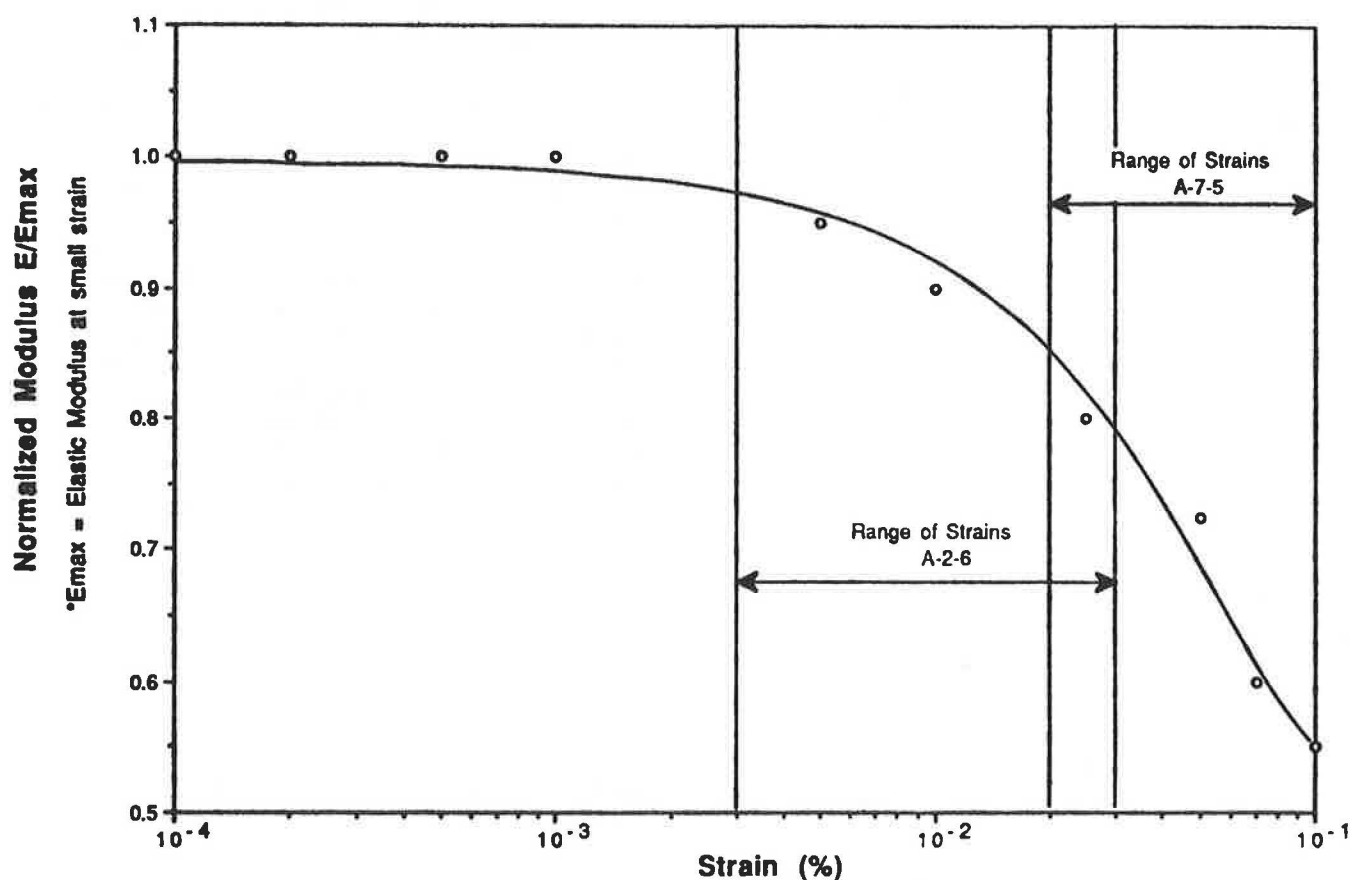


FIGURE 4 Normalized Young's modulus: vertical strain general relationship.

The authors have been developing polyurethane specimens for equipment calibration. The complete characteristics of these sample are presented in a companion paper in this Record. Typical shear-modulus versus shear-strain and shear-modulus versus confining-pressure curves for one specimen are indicated in Figures 5 and 6, respectively.

The use of those specimens for equipment calibration has the following benefits:

1. The properties can be accurately determined by independent methods, such as the resonant column test, the torsional shear test.
2. Specimens with any reasonable subgrade stiffness (from about 2,500 to 100,000 psi, Young's modulus) can be manufactured.
3. Identical specimens can be manufactured for testing by different laboratories.
4. The properties are essentially independent of stress and strain so that flaws or limitations or both in the measurement systems can be evaluated.
5. Test procedures can be developed and evaluated because the properties of the specimens are known and constant with time.

It is the fifth benefit that makes the use of those specimens so important in the evaluation and calibration of equipment. The specimens will permit a systematic evaluation of the stress and strain measurement procedures to be evaluated so the most appropriate procedures can be logically selected and their limitations determined.

Synthetic samples (polyurethane) with three levels of stiffness were cast for calibration of the resilient modulus equipment at The University of Texas at Austin and at The University of Texas at El Paso, as part of Research Study 2/3-10-8-89/0-1177, sponsored by the Texas State Department of Highways and Public Transportation. The samples were named synthetic 1 (TU960), with Young's modulus of approximately

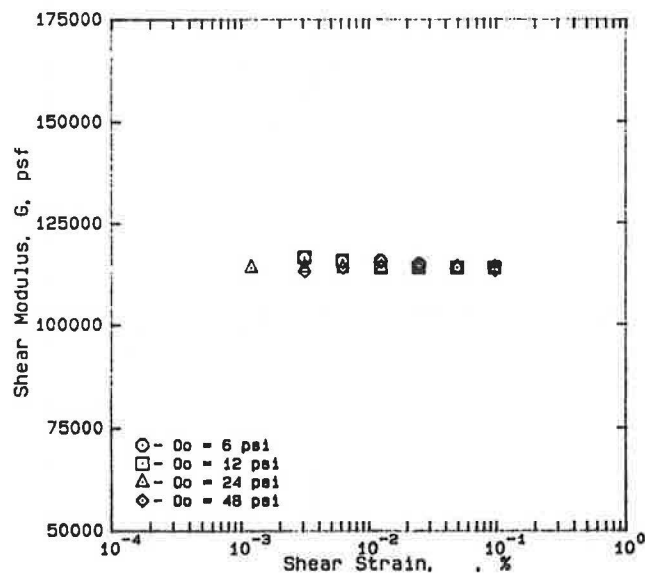


FIGURE 5 Shear modulus versus shear strain for synthetic 3 (TU700).

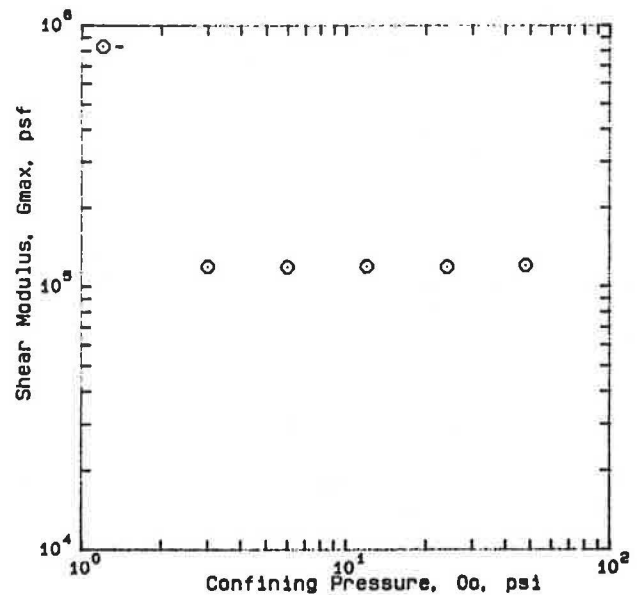


FIGURE 6 Shear strain versus confining pressure for synthetic 3 (TU700).

40,000 psi; synthetic 2 (TU900), with a modulus of 8,000 psi; and synthetic 3 (TU700), with a modulus of 2,500 psi.

Sample Testing Using Resonant Column and M_R Test

These samples were tested for preliminary comparison by using the resonant column and the M_R equipment. The moduli obtained by each of the testing devices were then compared. The resilient modulus for synthetic 1 (the stiffest) showed a much lower modulus (around 50 percent) than the one obtained in the resonant column. The resilient modulus for samples 2 and 3 were also somewhat lower (around 10 to 15 percent). Those resilient moduli were calculated without considering that the internal load cell also deflects under load. Those small deformations need to be subtracted from the deformation measured by the external LVDTs. A calibration of the load cell deflection was obtained for three seating pressures and is shown in Figure 7. By using this calibration, the resilient modulus values were corrected and plotted in Figures 8–10 for samples 1, 2, and 3. Because the resonant column measures shear modulus, those values were transformed to Young's modulus values by using the elastic relationship between E and G .

$$E = 2G(1 + \mu)$$

where

E = Young's modulus,
 G = shear modulus, and
 μ = Poisson's ratio.

The Poisson's ratios of the synthetic samples were measured statically (5) and their values are as follows: Sample 1, $\mu = 0.39$, and Samples 2 and 3, $\mu = 0.5$.

Figures 8–10 indicate that the moduli obtained with the resonant column and the M_R equipment are comparable, but

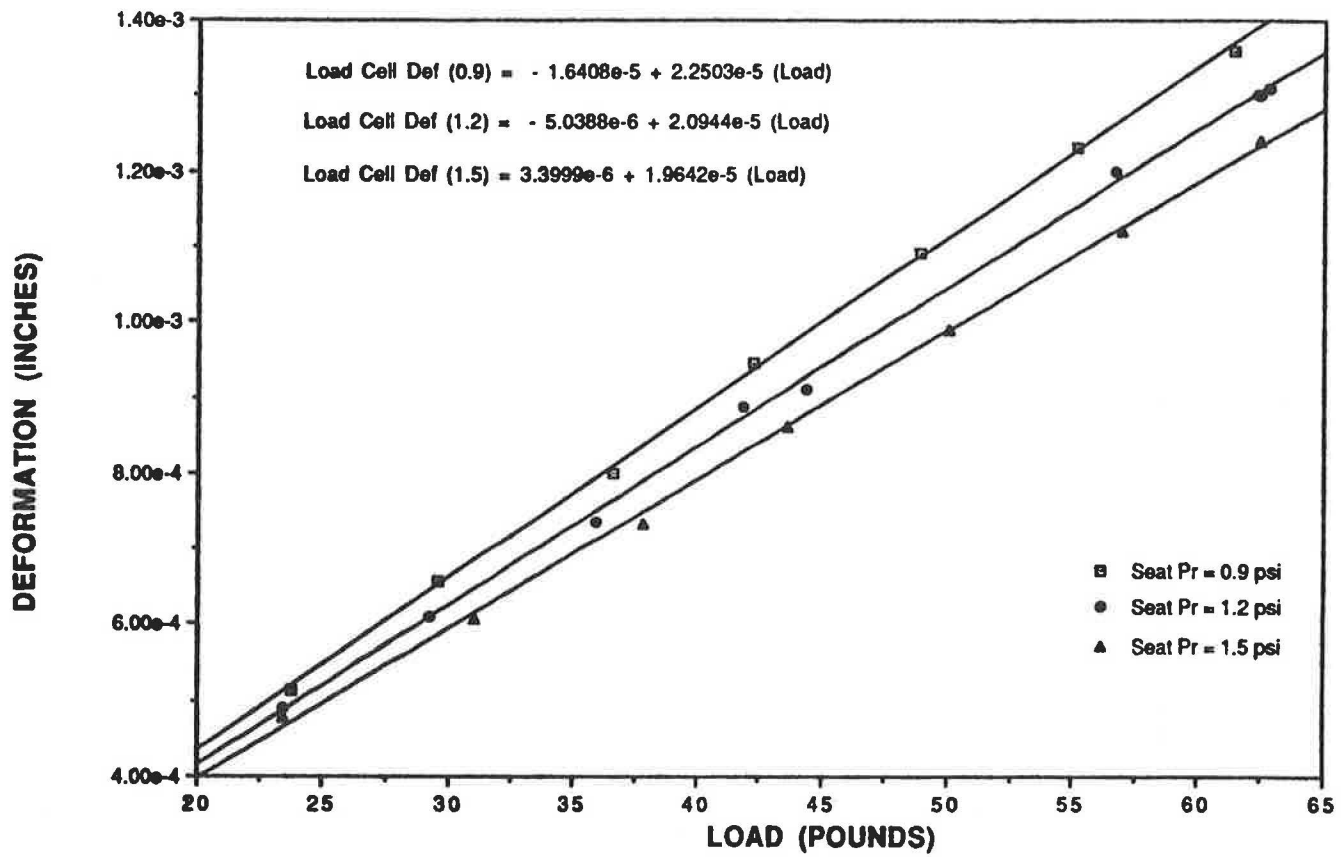


FIGURE 7 Calibration of load cell deformation.

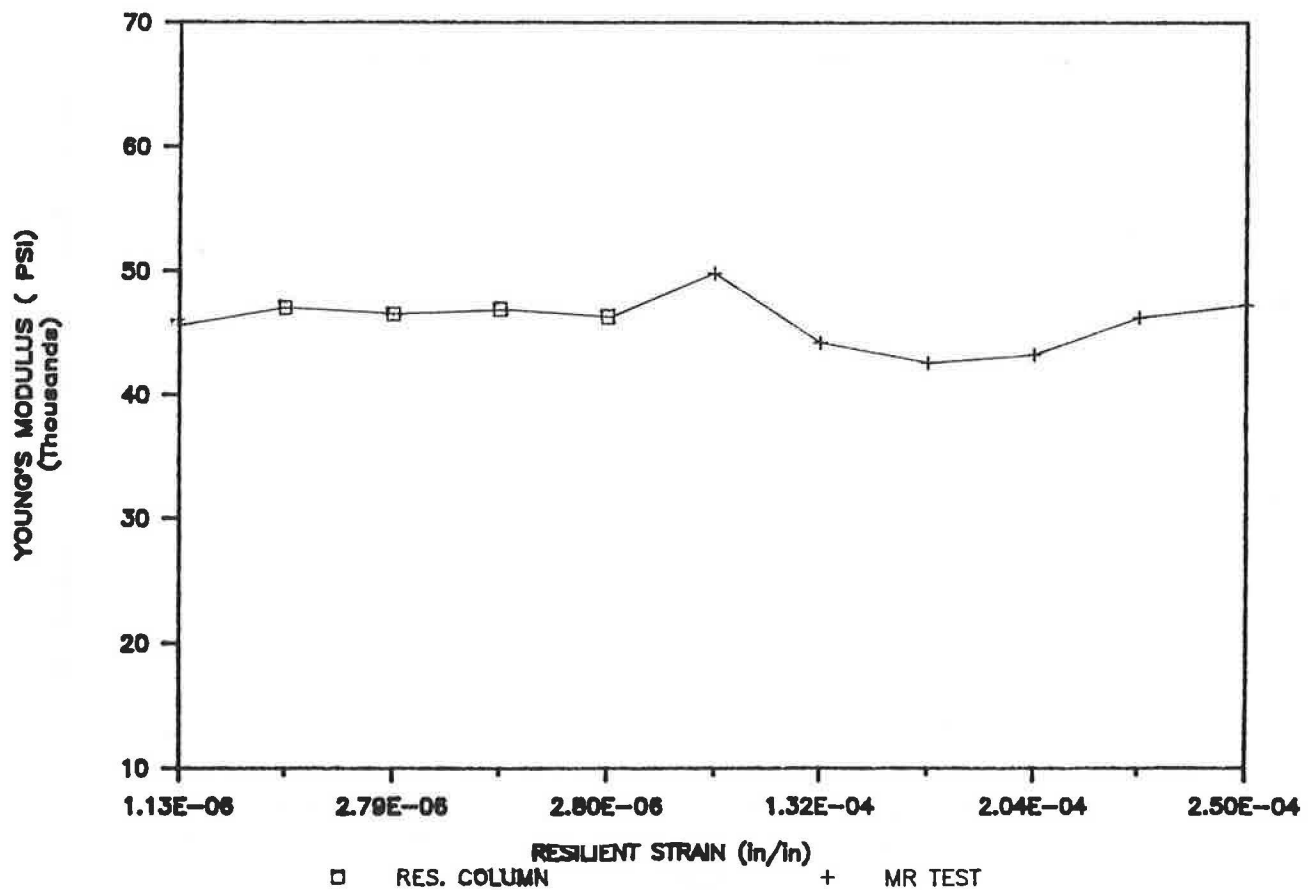


FIGURE 8 Comparison of modulus values for synthetic 1.

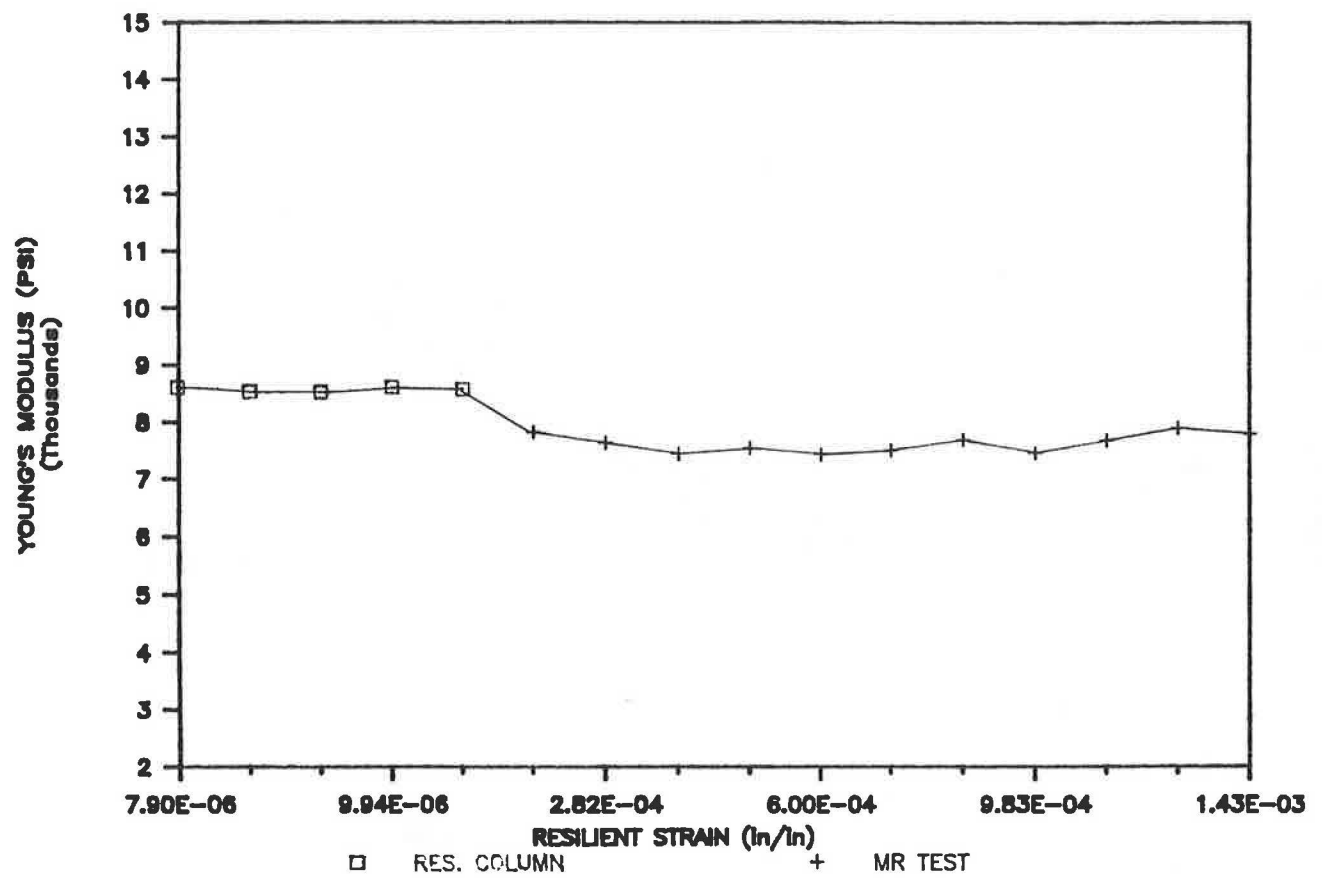


FIGURE 9 Comparison of modulus values for synthetic 2.

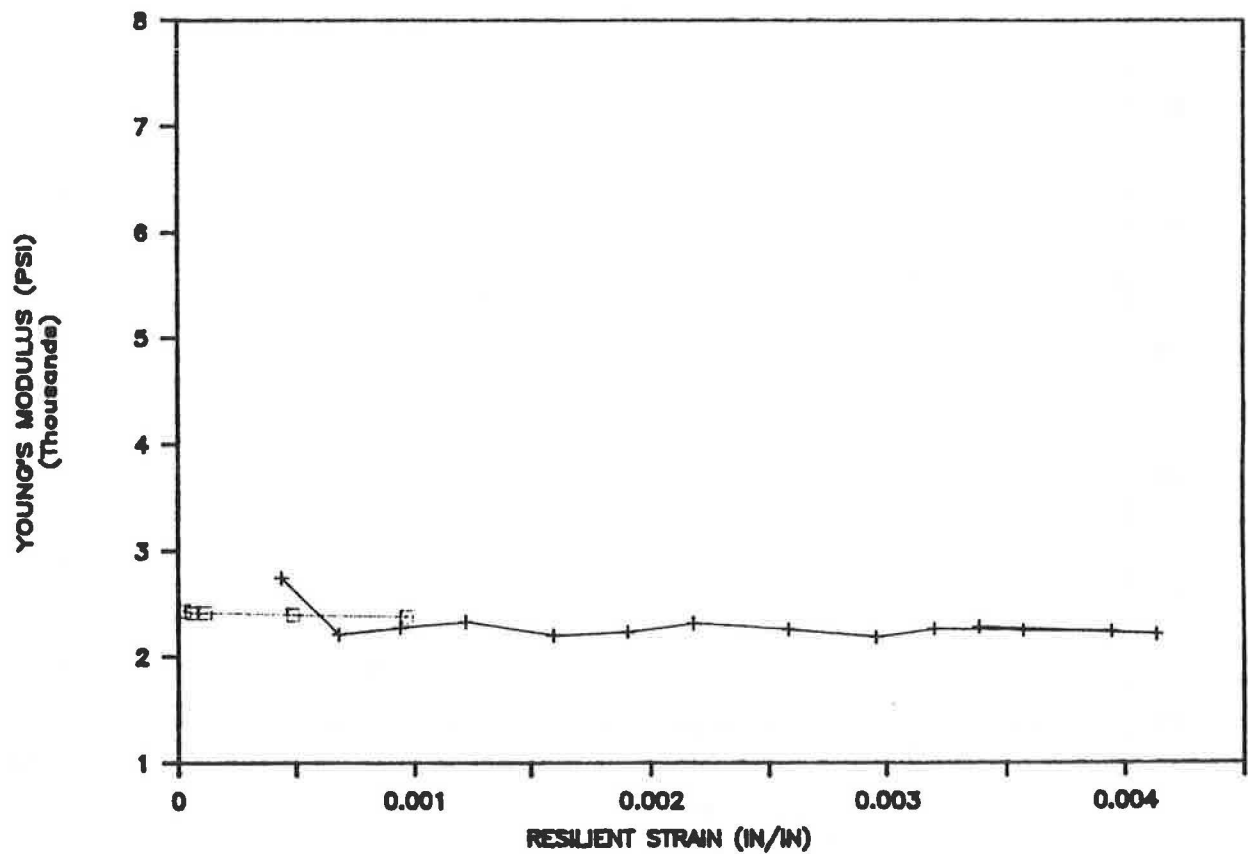


FIGURE 10 Comparison of modulus value for synthetic 3.

samples 1 and 2, when compared with those shown in sample 3, indicate a greater disparity between modulus values. The modulus variation in sample 1 obtained with the M_R equipment is also greater than the moduli in the outer two samples. This difference results because the resilient deformation in sample 1 is very small and is very difficult to measure.

Sample Testing Using Torsional Shear

To investigate further the influence of loading frequency on the synthetic samples, a series of torsional shear tests was performed (5).

The results of those tests show that the moduli of those samples are frequency dependent, as is shown in Figure 11 for synthetic 3. This plot shows the low frequency for the torsional shear and the high frequency for the resonant column. The resilient modulus has a load duration of 0.1 sec, which leads to a frequency of 5 Hz if half the period is considered.

The shear moduli of those samples, using the torsional shear test, depend on the frequency of loading at fixed shear strain amplitude. On the other hand, the resilient moduli depend on the deformation amplitude at loading (resilient strain), because the loading frequency for the M_R test is fixed to 5

Hz for a load duration of 0.1 sec. To compare both tests, a series of repeated modulus determinations was performed at the same deformation amplitude and frequency (5 Hz). The results of those tests and the descriptive statistics are included in Table 4. The shear strain (γ) was transformed to axial strain (ϵ_a) for comparison with the M_R test, using the expression

$$\epsilon_a = \frac{\gamma}{(1 + \mu)}$$

where

ϵ_a = axial strain,
 γ = shear strain, and
 μ = Poisson's ratio.

The test results in Table 4 indicate that sample 1 (TU960) measured modulus had a 2.5 percent difference by using those tests, which in practice is very small. A statistical test (two-sample test) shows a significant difference between the means, indicating that the two sets of data are different, but for all practical purposes a 2.5 percent difference is not significant.

The moduli obtained for sample 2 (TU900) with both tests show that there is a larger discrepancy in the results (about 12 percent difference). This discrepancy may be explained by the fact that the load cell deflection calibration was done for

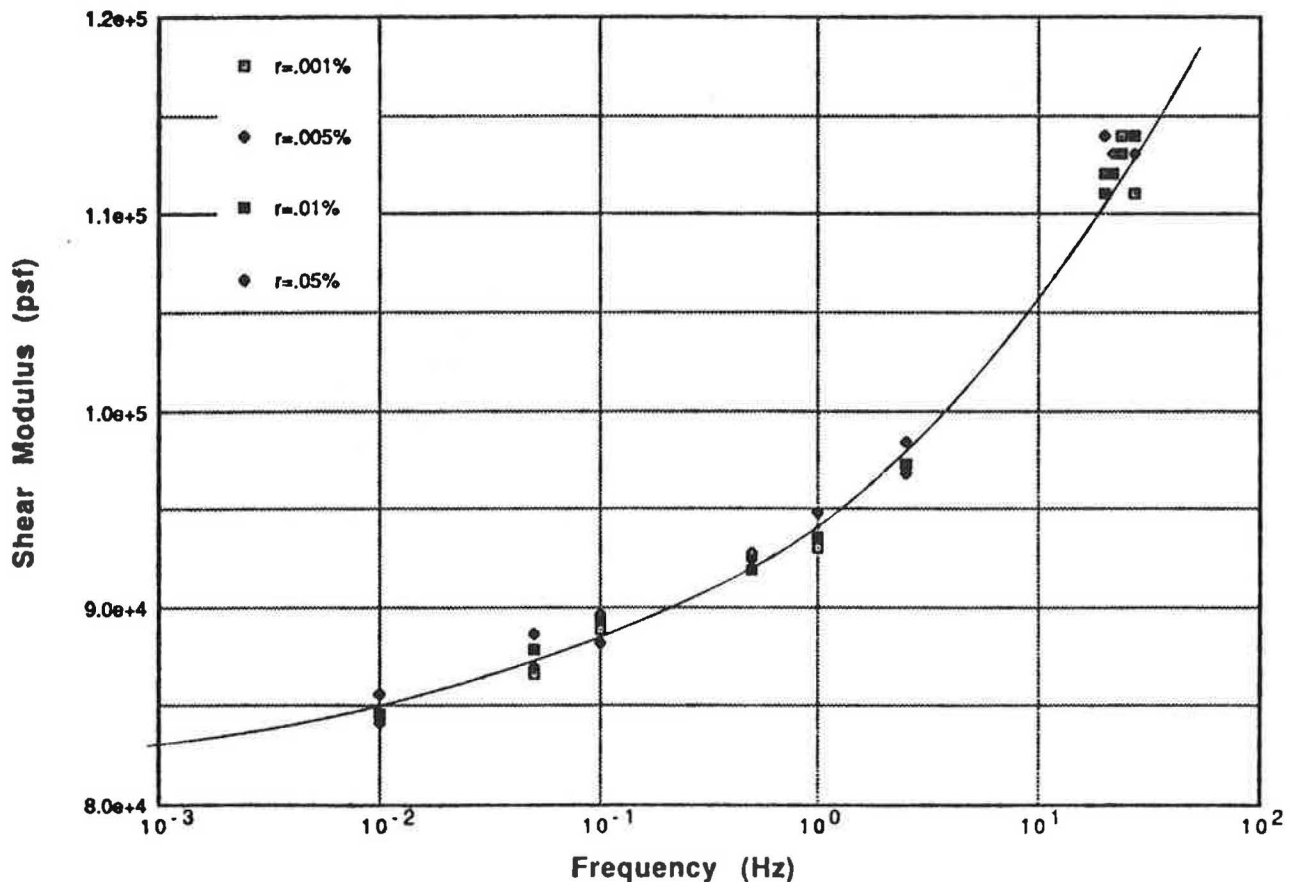


FIGURE 11 Shear modulus versus loading frequency for synthetic 3 (TU700).

TABLE 4 MULTIPLE TEST RESULTS FOR SYNTHETIC SAMPLES

Sample	Resilient Modulus Test				Torsional Shear Test			
	Number of Tests	Mean (psi)	Standard Deviation	Coefficient of Variation (percent)	Number of Tests	Mean (psi)	Standard Deviation	Coefficient of Variation (percent)
Sample 1 (TU960)	25	40,630	144.5	0.35	5	39,070	323.2	0.82
Sample 2 (TU900)	45	7,288	178.5	2.4	5	8,266	17.09	0.2
Sample 3 (TU700)	25	2,388	12.4	0.5	1	2,145	—	—

sample 1, the stiffness of which is higher than that of sample 2. Because the M_R is a dynamic test, the static solution to subtract the load cell deflection from the total deflection measured by the external LVDT may not be applicable. The authors are currently studying, through the use of accelerometers, the displacements of different parts of the M_R device during testing to locate the best reference point for measuring sample deformations that eliminate the load cell deflections.

Repeated torsional shear tests for sample 3 are not available because of limitations in the torsional shear equipment that induce large deformations in soft specimens. A shear modulus value for sample 3 can be obtained from Figure 11 at a 5-Hz frequency. This value is approximately 103,000 psf, or a Young's modulus of 2,145 psi, for a Poisson's ratio of 0.50. If this value were to be compared to the modulus value obtained by using the M_R equipment (2,388 psi), then an 11 percent difference would be observed. Again, this discrepancy is explained because the load cell deflections are not corrected properly.

There is a general tendency to make a static analysis of a dynamic test, as is the case of the M_R test. The M_R test needs to be analyzed dynamically to understand better the limitations of the test and the equipment used.

CONCLUSIONS

The following conclusions can be drawn:

1. The modifications to the AASHTO T-274 procedure are moving in the right direction, although further improvements are necessary.

2. The test procedure in protocol P-46 is repeatable and easy to perform and could be adopted as the standard procedure because it is specific. Perhaps it is still not the ideal test, but it is a base for further development.

3. Polyurethane samples with a range of stiffness are very useful in calibration and for familiarization with M_R equipment.

4. Synthetic samples have the potential to become standard in the procedure for M_R equipment calibration.

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