

A Reliable Resilient Modulus Testing System

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In 1986 AASHTO adopted the resilient modulus test for use in the design of pavement structures to determine properties of roadbed soil and pavement components (AASHTO T274-82). The criticism that followed this adoption has resulted in the publication of several papers aimed at resolving the problems generated by the test method. The Strategic Highway Research Program's published modifications to the test procedure are examined, in particular. In addition, the experience gained in calibrating a resilient modulus testing system—as well as the results obtained from a pilot test program with cohesive soil—is presented. Finally, the comparison results obtained from testing companion cohesive specimens using the resilient modulus test and torsional testing techniques are reported. The results indicate that (a) strong uniform contact between the specimen and the top and bottom caps of the triaxial cell is required for accurate measurement of modulus; (b) synthetic samples of known properties can be useful for the detection of equipment compliances, as well as for assessing a reliable system; and (c) the resonant column and torsional shear apparatus provides a basic approach to characterizing pavement materials—an approach that was useful for comparison with the resilient modulus test.

In 1986 AASHTO (1) began using the resilient modulus (M_R) test in the design of flexible, rigid, and composite pavements. The M_R test is used to determine roadbed soil and pavement component properties, with the standard testing method determined by AASHTO T274-82.

Laboratory measurements of the deformational characteristics of subgrade materials can be complex because of the small strains that are typically involved in such pavement components. Moreover, experience in applying the cyclic triaxial test in geotechnical earthquake engineering has indicated that extreme care must be exercised when evaluating the deformational characteristics of soils, particularly at small to intermediate strain levels (10^{-3} to 10^{-1} percent). These strain levels are also the strain levels at which M_R testing is used. Other popular techniques used to characterize soil properties in this strain range include the torsional shear test and the resonant column test.

TESTING EQUIPMENT

M_R Testing Equipment

In general, the resilient moduli of cohesive and cohesionless materials are determined in a repeated-load triaxial compres-

sion test known as the M_R test. The equipment used in this test is similar to that used in common triaxial testing, although in this case some modification was required to facilitate the internally mounted load and deformation transducers. Because transducers are located inside the triaxial chamber, air is generally used as the cell fluid to provide confinement to the test samples. The external loading source, in most cases, is a closed-loop electrohydraulic system capable of providing a variable load of fixed cycle and load duration.

During the M_R test, specimens are subjected to testing sequences that consist of the application of different repeated axial deviator stresses (σ_d) under different confining pressures (σ_3). Also during the test, the recoverable axial strain (ϵ_a) is determined by measuring the resilient deformation of the sample across a known gauge length. M_R is thus defined as follows:

$$M_R = \sigma_d / \epsilon_a \quad (1)$$

Applying the deviator stress results in an immediate axial deformation followed by a plastic deformation while the load is sustained, with a rebound occurring once the load is removed. The rebound, called the "resilient deformation," remains approximately constant throughout a large number of applications of a given load. Axial deviator stress is defined as the applied axial load (P) over the cross-sectional area of the sample (A):

$$\sigma_d = P/A \quad (2)$$

It is generally recommended that a load cell be used inside the test cell to offset the effect of friction on the loading piston. Deformation measurements may be taken with external or internal linear variable deformation transformers (LVDTs) fixed to the triaxial chamber. Axial strain is defined as the axial deformation (Δ) over the gauge length (Lg):

$$\epsilon_a = \Delta / Lg \quad (3)$$

Vinson (2) states that, during the load application, it is possible for deformations in the load train to be present; if an external LVDT is used, such deformations will be included and the results will have unacceptable errors. In order to avoid this problem, it is usually recommended that the displacement transducers be mounted inside the triaxial chamber.

The standard test for M_R of subgrade soils was specified in 1982 by AASHTO (AASHTO T274-82). The test method, which is generally accepted as fundamentally sound, requires

an evaluation of resilient moduli under a number of stress states for cohesive and cohesionless soils.

For cohesionless and cohesive soils, the M_R is expressed by Equations 4 and 5, respectively:

$$M_R = K_1 \theta^{K_2} \quad (4)$$

$$M_R = K_1 \sigma_d^{K_2} \quad (5)$$

where K_1 and K_2 are experimental constants determined from a set of test results with the use of statistical regression tools, and θ is the sum of principal stresses.

However, in recent years this test method has increasingly been criticized (3-5). Hence, in 1989 the Strategic Highway Research Program (SHRP) (6) published the laboratory testing procedure for determination of the M_R of unbound granular base and subbase materials and subgrade soils (SHRP Protocol P-46), which was essentially a modification of AASHTO T274-82.

At The University of Texas at Austin, M_R testing equipment has been implemented following the recommendations published by SHRP (6). This testing equipment included the following characteristics:

- A hydraulic loading system capable of applying repeated dynamic loads controlled under an MTS Systems Corp. closed-loop system. The shape and amplitude of the cyclic loading waveform are set by the use of a function generator, with the loading function continuously monitored by an oscilloscope and a plot strip chart. As specified by SHRP P-46 (6), the load pulse duration and cyclic loading are set at 0.10 and 1.00 sec, respectively, with a Haversine loading waveform.
- Two LVDTs, with a calibration range of 0.02 in. and mounted inside the triaxial chamber diametrically opposite each other, are used to monitor axial deformations for the

whole length of the specimen (located at the top of the samples). All measurements from the LVDTs are referred to the base of the triaxial chamber, and the average of the two signals is used to estimate the strain value that is used for computing the M_R of the specimen.

- A 100-lb load cell mounted inside the triaxial chamber and centered on the top of the soil sample was used to monitor the actual deviator stress applied during the testing process.

- A data acquisition system was developed to record the signals emitted by the transducers. A data acquisition board was mounted inside an IBM XT personal computer; software was developed for acquiring, plotting, storing, and computing the M_R values of the test samples.

The M_R testing equipment used cannot accurately measure axial strains smaller than about 10^{-2} percent (because of the resolution of the transducers installed and the compliance of the system itself). Generally, this is a limitation common to all M_R testing equipment: when the sample undergoes smaller strains, erratic M_R values are calculated. Figure 1 shows the system assembled and used in the laboratories of the Department of Civil Engineering at The University of Texas at Austin.

Torsional Testing Equipment

Torsional RC

Torsional resonant column (RC) equipment of the fixed-free type was used in these tests. In the fixed-free configuration, the bottom of the test specimen is held fixed while the top (free end) is connected to a drive system used to excite and monitor torsional motion, as illustrated in Figure 2a.

The basic operational principle is to vibrate the cylindrical specimen in first-mode torsional motion. Once first mode is

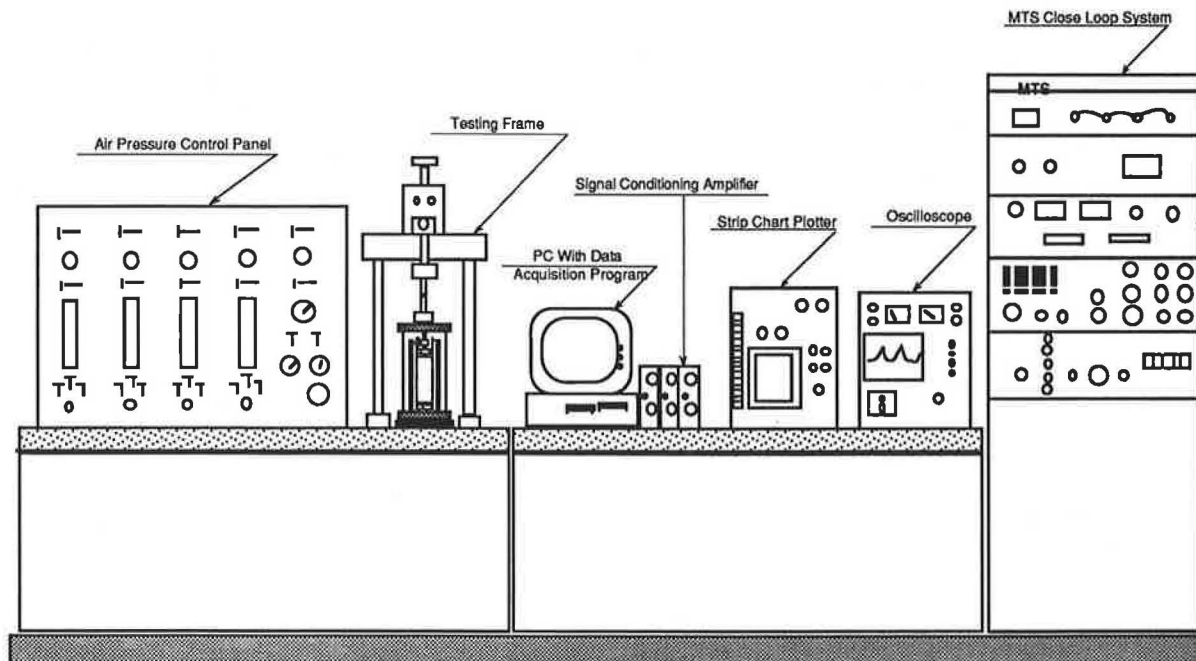
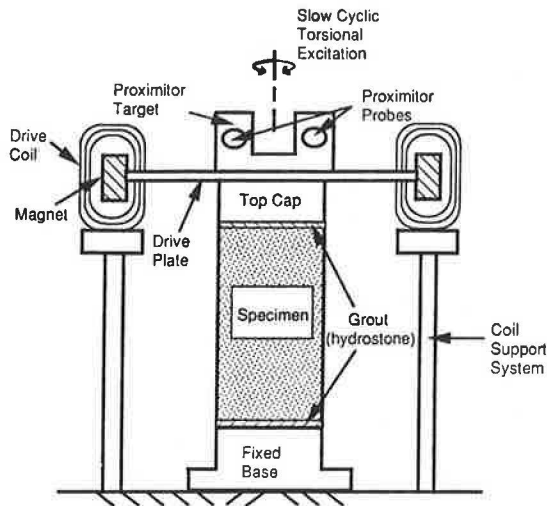
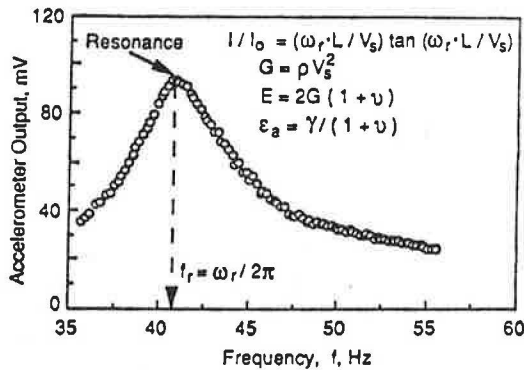


FIGURE 1 Sketch of M_R testing equipment developed at The University of Texas at Austin.



a. Specimen in Test Apparatus



b. Typical Measurement

FIGURE 2 Configuration of fixed-free RC test and typical test results.

established, measurements of the resonant frequency and amplitude of vibration are made, as shown in Figure 2b. These measurements are then combined with equipment characteristics and specimen size to calculate shear wave velocity (V_s), shear modulus (G), and shearing strain amplitude (γ) (ASTM D4015-87).

One-dimensional wave propagation in a circular rod is used to analyze the dynamic response of the specimen. The basic data reduction equation is expressed as follows:

$$I/I_0 = \omega_r L / V_s \tan(\omega_r L / V_s) \tag{6}$$

where

- I = mass moment of inertia of the specimen,
- I_0 = mass moment of inertia of drive system,
- ω_r = resonant circular frequency,
- L = length of the specimen, and
- V_s = shear wave velocity.

Once the value of shear wave velocity is determined from Equation 6, shear modulus (G) and Young's modulus (E) of the specimen can be calculated from the following:

$$G = \rho V_s^2 \tag{7}$$

$$E = 2G(1 + \nu) \tag{8}$$

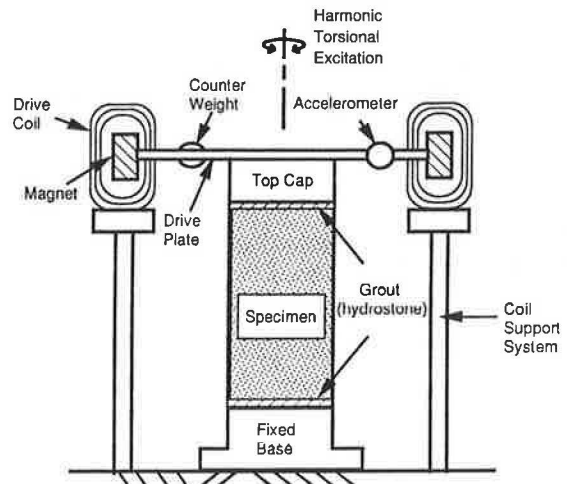
where ρ is the mass density and ν is Poisson's ratio of the specimen.

The shearing strain (γ) is calculated from the peak rotation of the top of the specimen at 0.67 times the radius of the solid sample (ASTM D4015-87). By following standard procedures in relating cyclic triaxial and RC results and by assuming that the material is homogeneous and isotropic, the axial strain is obtained compatible with this shearing strain:

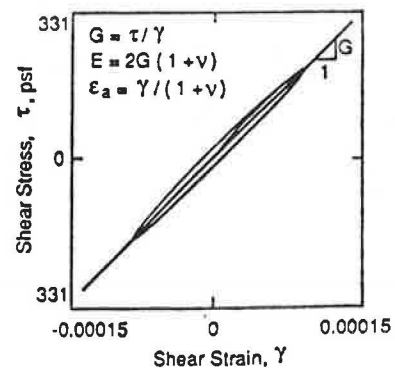
$$\epsilon_a = \gamma / (1 + \nu) \tag{9}$$

TS Test

The torsional shear (TS) test is another method for determining shear and Young's moduli using the same RC equipment but operating it in a different fashion. In this test a cyclic torsional force with a given frequency, generally below 10 Hz, is applied at the top of the specimen while the bottom is held fixed, as shown in Figure 3a. Instead of determining a resonant frequency, the stress-strain hysteresis loop is determined from measuring the torque-twist response of the specimen.



a. Specimen in Test Apparatus



b. Typical Measurement

FIGURE 3 Configuration of TS test and typical test results.

Proximeters are used to measure twist while the current applied to the coils is calibrated to yield torque. Shear modulus (G) corresponds to the slope of a line through the end points of the hysteresis loop, as shown in Figure 3b. Using this technique, the shear modulus, defined as the ratio of shearing stress to shearing strain, is calculated from the following:

$$G = \tau/\gamma \quad (10)$$

Values of shearing strain are presented as single-amplitude values and are calculated at 0.67 times the radius of the specimen, just as in RC tests. Once G and γ are determined, Young's modulus and axial strain can be determined using Equations 8 and 9.

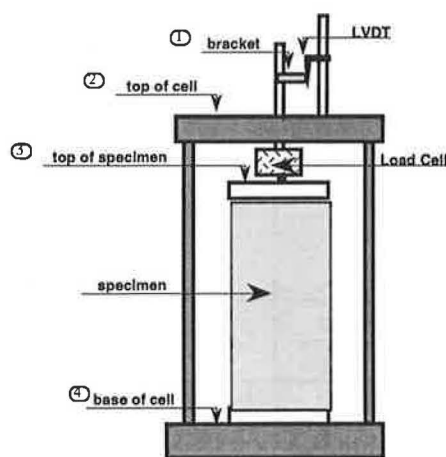
CALIBRATION OF M_R EQUIPMENT

As with all cyclic loading equipment, M_R equipment requires careful calibration of each of the deformational and loading transducers. In addition, calibration of the complete system is advisable if accurate results are to be determined for stiff specimens or for small-strain measurements. Calibrations of the individual transducers are standard procedures, but calibration of the whole system requires more than routine adjustments of its individual parts. To calibrate the entire M_R system, three synthetic samples of known stiffness properties (7) were used.

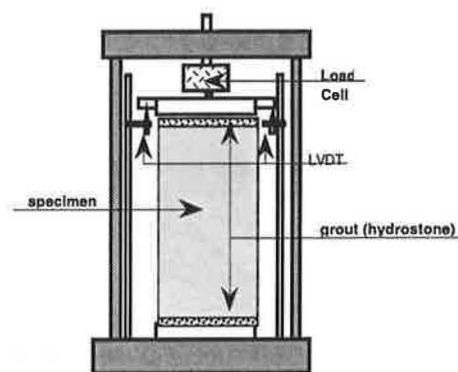
Calibration of the complete M_R system turned out to be an involved task, with several problems having to be overcome before a satisfactory state was achieved. Claros et al. (8) pointed out the necessity of changing the location of the LVDT used to record the axial deformation of the sample. At that time they were using an external LVDT that recorded the movement of a bracket attached to the loading piston, as shown in Figure 4a.

To find the best location for monitoring axial deformations, the relative movements of four points in the triaxial chamber were measured while performing the M_R test on synthetic samples. Figure 4a also shows the four points monitored in this inspection: the base and top of the triaxial chamber, the top of the specimen, and the external bracket. Microproximeters, placed on each of the chosen points, were hooked onto a computerized analyzer that recorded the voltage signal emitted by the transducers. In general, measuring the relative movements of those points at different levels of deviator stress revealed that (a) the base of the triaxial chamber is a good reference point for these measurements because it moves the least at any level of deviator stress and (b) a better position for monitoring axial deformations is the top of the specimen rather than the external bracket (used previously). In addition, the decision was made to use two LVDTs (instead of only one), located diametrically opposite at the top of the specimen. Each LVDT was supported by a steel bar attached to the base of the triaxial chamber. Modifications in the geometry of the top cap were also made to facilitate operation of the transducers. Figure 4b shows the final setup of the triaxial cell.

Once the final arrangement was selected, more testing with synthetic samples was performed. The new results, although closer to the moduli than those previously obtained by Claros et al. (8), were not close enough. In particular, values for the



a. Initial Set-Up as used by Claros et al. (8).



b. Final Set-Up.

FIGURE 4 Configuration of M_R test.

TU-960 specimen (the stiffest sample) were still lower by 50 percent. At this point, hydrostone paste was used to improve the connections between the specimen and the top and bottom platens. The connections were grouted in such a way that an even contact surface—and a good continuous connection—was achieved between the top and bottom steel platens and the synthetic samples. Then, the three synthetic samples were tested again. Testing consisted of applying various levels of deviator stresses at 10 Hz under no confining pressure and a temperature of 70°F. Several repetitions were performed to gain a better statistical representation of the values. Finally, new M_R values close to those published by Stokoe et al. (7) were obtained for the three synthetic samples. Table 1 presents the comparison of moduli of synthetic samples determined by M_R and torsional testing techniques. Figure 5 shows this comparison, as well as the deviation in the M_R obtained from not grouting the samples to the end platens. The deviations in the moduli caused by not grouting the samples to the end platens are significant for materials with an M_R value greater than 9,000 psi.

With this calibration, it was believed that there were no significant discrepancies in the comparisons of the M_R with the torsional testing techniques for the synthetic samples and that the final arrangement of the M_R testing equipment was capable of providing accurate measurements. It was obvious in this work that all measurements in the M_R testing equipment are sensitive both to specimen preparation and to the

TABLE 1 COMPARISON OF MODULI OF SYNTHETIC SAMPLES DETERMINED BY RESILIENT MODULUS AND TORSIONAL TESTING TECHNIQUES

SYNTHETIC SAMPLE	GROUTING	RESILIENT MODULUS	RESONANT COLUMN & TORSIONAL SHEAR	MR / E	DEVIATION (%)
		MR, psi	E, psi		
TU-700	NO	1888	2220 *	0.850	-15.00
	YES	2252		1.014	+ 1.40
TU-900	NO	6550	8921 *	0.734	-26.58
	YES	8880		0.995	-0.45
TU-960	NO	22410	45735 *	0.490	-51.00
	YES	44197		0.966	-3.40

Note: (*) All moduli adjusted to a frequency of 10 Hz.

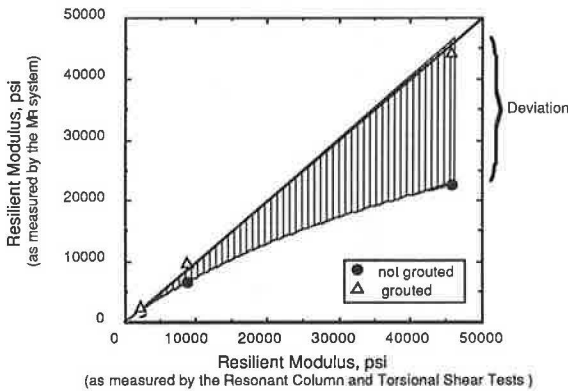


FIGURE 5 Variation of MR for synthetic samples tested by the MR system.

top and bottom cap connections. Extreme care must be taken to eliminate any compliance in the specimen-platen connections before testing.

TESTING MATERIAL AND TESTING PROGRAM

Once the MR testing equipment was understood and calibrated, a pilot program of soil testing was initiated to determine, in depth, how the MR is affected by the following parameters: soil type, water content, soil density, sample age, and the testing equipment itself.

Two different types of soils, one plastic (cohesive) and one nonplastic, were collected from the Austin, Texas, area. The analysis and evaluation of the results for the cohesive soil are nearly completed and are presented in the following paragraphs. Testing with the cohesionless soil is under way, and these results will be presented at a later date.

Material Properties of Cohesive Soil

Samples of cohesive soil were gathered from the intersection of MoPac and SH-183 in Austin. Preliminary tests were per-

formed to establish the index properties of this disturbed soil following the guidelines presented by the state of Texas (9). The soil classifies as an A-7-6 soil, Type 2 (according to SHRP P-46), with 87.3 percent of finer, a liquid limit (LL) of 56 percent, and a plasticity index (PI) of 27 percent. To obtain a characteristic compaction curve, Test Method Tex-113E was followed. Figure 6 illustrates the compaction curve of this soil, in which the maximum dry density of 93.9 pcf was determined at 19.3 percent of moisture content.

Testing Program

To define the effect of water content and dry density of the soil on the MR, samples were built with the same compacting effort of 6.64 ft-lb/in.³ with different water contents and dry densities. Four different levels of moisture content were selected for this experiment: one sample on the dry side of optimum, one at the optimum moisture content, and two samples on the wet side of optimum. Figure 6 shows these four points on the compaction curve. Each numbered point represents one specific condition of the soil in this testing program.

To determine the effect of sample age (age hardening or thixotropy), samples were tested at 2 days and 6 days after compaction. To compare MR values from different testing equipment, companion specimens (two samples with identical characteristics) were prepared so that they could be tested at the same time: one with the MR equipment and the other with the RC/TS testing apparatus.

The characteristics of the four pairs of soil samples included the following: (a) Companion Sample 1 had a moisture content of 17.3 percent (dry of optimum) and a dry density of 92.3 pcf; (b) Companion Sample 2 had a moisture content of 19.3 percent (optimum) and a dry density of 93.9 pcf (maximum); (c) Companion Sample 3 had a moisture content of 25.8 percent (wet of optimum) and a dry density of 89.2 pcf; and (d) Companion Sample 4 had a moisture content of 39.1 percent (wet of optimum) and a dry density of 77.9 pcf.

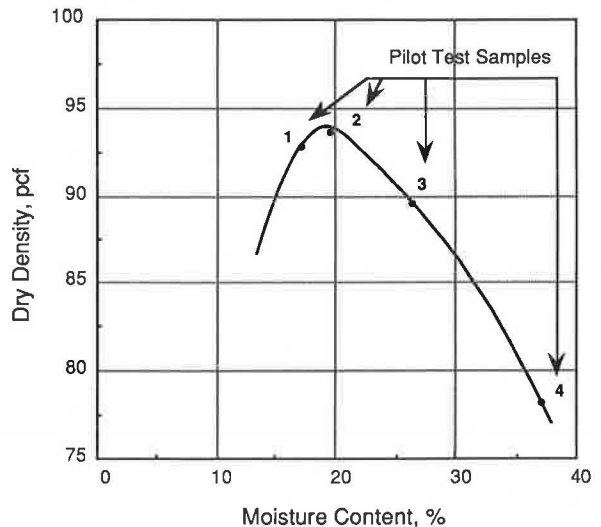


FIGURE 6 Compaction curve for cohesive soil compacted according to Test Method Tex-113E.

Sample Preparation

Specimens 2.8 in. in diameter and 5.60 in. in height were tested. The compacting effort for all specimens remained constant, with the compaction process based on Test Method Tex-113E, which is a modification of ASTM D1557 and AASHTO T180 methods. Once the samples were molded and well wrapped, they were stored in a constant temperature and humidity chamber for 1 day. After that, the companion samples were placed in each piece of testing equipment.

M_R Testing Procedure

In general, the cyclic triaxial tests (M_R) were run in accordance with SHRP Protocol P-46 (6). Details of this procedure follow.

Initially, each specimen was grouted to the top cap and base pedestal of the triaxial cell using a hydrostone paste. This procedure was used because, with the synthetic samples, it was found that those connections are important factors in evaluating M_R . Hydrostone paste has also proved useful in these tests because the levelness of the top cap can be easily adjusted to accommodate any unevenness in the ends. Two rubber membranes were placed around each specimen to prevent moisture loss or air migration during testing. After the sample was installed and its ends secured, it was allowed to cure overnight to ensure that the hydrostone reached its full strength and stiffness.

Testing of the sample began on the second day following compaction. First, the sample was subjected to a conditioning stage. For cohesive soil, SHRP Protocol P-46 (6) recommends the application of 200 loading repetitions of a 4-psi deviator stress under a 6-psi confining pressure. After this conditioning stage was completed, the testing sequence was followed. This testing sequence for cohesive soils consisted of applying 100 repetitions of each one of the following deviator stresses: 2, 4, 6, 8, and 10 psi (in ascending order) at each one of the confining pressures of 6, 4, and 2 psi (in descending order). To report the M_R values at different stress states, the strain values of the last five cycles of a particular testing sequence were recorded and averaged. In this way, M_R values were computed for a given level of deviator stress and axial strain. Then, by using all testing data recorded, simple linear regressions were developed and used to express M_R of the specimen in terms of the deviator stress, as expressed in Equation 5.

Over the following 4 days, the sample remained in the triaxial cell at atmospheric pressure. Six days after compaction the same sample was again tested using the same procedure. Following the testing, the specimen was taken out and destroyed to measure its final water content. This exercise confirmed that the samples, in general, did not experience any loss of moisture content.

Torsional Testing Procedures

Before testing in either the resonant or torsional shear mode, each specimen was fixed to the base pedestal and top cap (using hydrostone paste) and allowed to cure overnight, as in the M_R tests. This approach was meant to eliminate any slip-page problem that might occur at low confining pressures. A

rubber membrane was placed around each specimen to prevent moisture loss or air migration during testing.

Two days after compaction, a 2.8-in.-diameter specimen was tested under isotropic confining pressures of 2, 4, 6, 4, and 2 psi. At each pressure level, low-amplitude RC tests ($\gamma < 10^{-3}$ percent) were performed at 10-min intervals for 1 hour. Upon completing the low-amplitude RC tests, a series of TS tests was also performed at the unloading stages of 6, 4, and 2 psi. TS tests were performed mainly at a loading frequency of 0.5 Hz, with varying shearing strain amplitudes. To check the effect of frequency on stiffness, loading frequencies were changed at shearing strain amplitudes of about 10^{-3} and 10^{-2} percent. Loading frequencies of 0.05, 0.1, 0.5, 1, and 5 Hz were used. High-amplitude RC tests were then performed at each unloading pressure, changing the strain amplitude. Finally, low-amplitude RC tests were again performed to determine if any changes had occurred in the low-amplitude modulus from the TS and high-amplitude RC tests. Variation in the low-amplitude moduli measured before and after high-amplitude testing was less than 5 percent. Thus, it was determined that any changes in the soil skeleton caused by high-amplitude testing were negligible.

After completing the tests using the 2.8-in.-diameter sample, the same sample was trimmed to 1.5 in. in diameter and tested 6 days after compaction using the same procedures as used with the 2.8-in.-diameter sample. With the smaller-diameter sample, moduli at higher shearing strains, up to 10^{-1} percent, could be obtained, and moduli between torsional and M_R testing were more easily compared.

TEST RESULTS, DISCUSSION, AND COMPARISONS

Results from M_R Equipment

Results obtained from testing the four companion specimens using the M_R equipment were plotted and analyzed as suggested by SHRP Protocol P-46 (6). A typical result obtained in this pilot testing is shown in Figure 7, which shows plots of the results of Sample 2 tested at 2 and 6 days after compaction. Sample 2 exhibited the typical tendency of soils, which is that the modulus generally decreases with increasing deviator stresses and increasing axial strain amplitudes.

A summary of the M_R testing results obtained from the four companion specimens in terms of M_R coefficients, as expressed in Equation 5, is presented in Table 2 for the tests at 2 and 6 days.

The influence of age hardening on the two parameters, K_1 and K_2 , is also presented in Table 2. As seen in the table, the age of the sample significantly affects these results. This phenomenon is not addressed in current M_R testing procedures—although it should be, at least for cohesive soils, if consistent and repeatable results are desired.

Comparison Between RC and TS Results

One advantage of the RC and TS device is that both tests can be performed on the same soil specimen over a large range

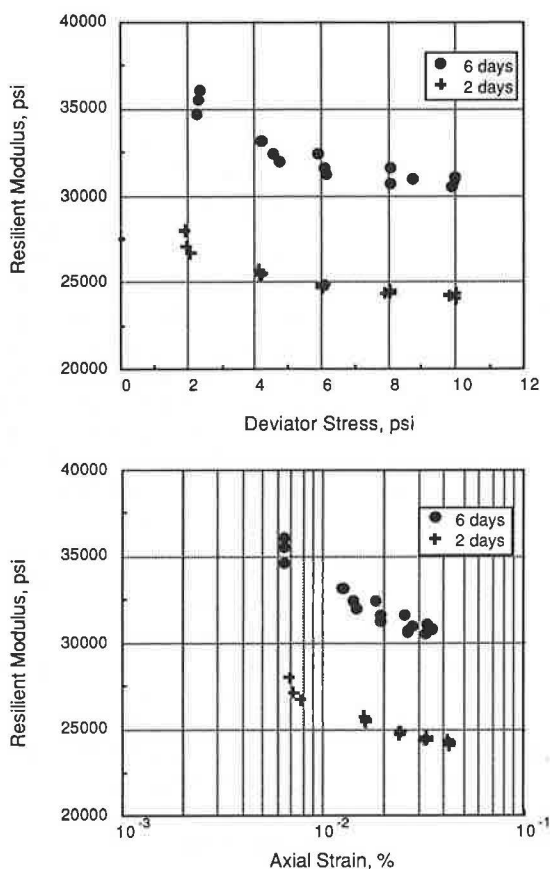


FIGURE 7 Influence on M_R of deviator stress and axial strain for Sample 2 tested 2 and 6 days after compaction.

of shearing strain amplitudes (10^{-4} to 10^{-1} percent). Values of shear moduli obtained from both tests were converted to the equivalent Young's modulus, E , using Equation 8. Typical results of a compacted clay specimen showing the variation of Young's modulus with equivalent axial strain are presented in Figure 8. At strain amplitudes below about 10^{-2} percent, moduli from RC and TS tests are independent of strain amplitude, and moduli from TS tests fall somewhat below the corresponding RC values at the same strain amplitude. This difference can be explained by the difference in loading frequencies between the two modes of testing, as discussed in the next subsection. At strains above 10^{-2} percent, it is shown that modulus decreases as strain amplitude increases in both tests.

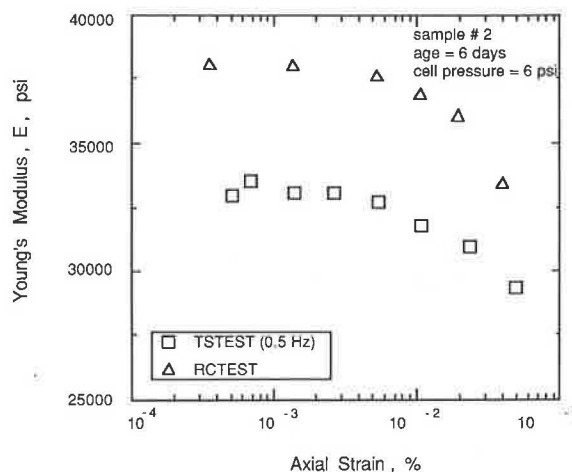


FIGURE 8 Variation in Young's modulus with axial strain for cohesive soil as determined by RC and TS tests.

Effect of Loading Frequencies

The effect of frequency can be determined by using a combination of RC and TS tests. Moduli determined by the RC test are based on first-mode resonant frequency, which depends on the stiffness of the specimen and on the mass moment of inertia of the drive plate. Loading frequency in the TS test can be varied by changing the input frequency.

Moduli determined by the RC and TS tests at various loading frequencies are plotted at axial strain amplitudes of 0.00067 and 0.02 percent in Figure 9. Modulus increases linearly as a function of the logarithm of loading frequency.

To quantify the influence of loading frequency on Young's modulus, E was normalized by the value of Young's modulus at a loading frequency of 0.5 Hz (at which high-amplitude TS tests were performed). Typical results are shown in Figure 10. Performing a least-square curve fitting on these data, the fitting curve yielded the effect of loading frequency on modulus, which was 5.78 percent per log cycle of loading frequency. Effects of loading frequencies on Samples 1, 2, 3, and 4 were 7.12, 5.78, 6.03, and 6.75 percent per log cycle of loading frequency, respectively.

Normalized Modulus

A more convenient way of presenting the change in modulus with strain amplitude is with a plot of normalized Young's

TABLE 2 RESILIENT MODULUS COEFFICIENTS FOR FOUR COMPANION SPECIMENS

SAMPLE	MOISTURE CONTENT (%)	RESULTS AT 2 DAYS AFTER COMPACTION		RESULTS AT 6 DAYS AFTER COMPACTION		AGING EFFECT ON MR COEFFICIENTS	
		K1	K2	K1	K2	K1 (6 days) K1 (2 days)	K2 (6 days) K2 (2 days)
1	17.30	46925	- 0.080	54677	- 0.038	1.165	0.467
2	19.20	28523	- 0.075	37949	- 0.095	1.333	1.267
3	25.80	29675	- 0.029	35768	- 0.045	1.205	1.551
4	39.10	6058	- 0.337	10273	- 0.261	1.696	0.774

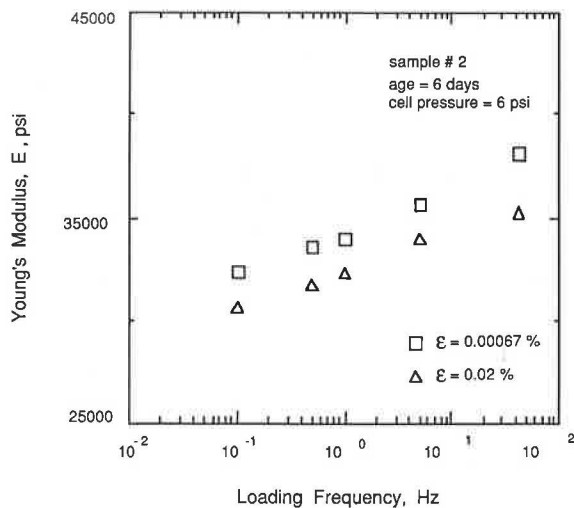


FIGURE 9 Variation in Young's modulus with frequency for cohesive soil as determined by RC and TS tests.

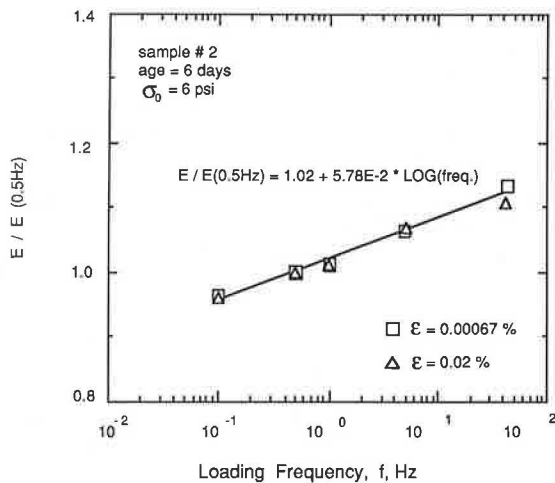


FIGURE 10 Normalization of Young's modulus with frequency for cohesive soil as determined by RC and TS tests.

modulus, E/E_{max} , versus the logarithm of axial strain. The high-amplitude data obtained by RC and TS tests at a confining pressure of 6 psi for four different samples are plotted with variations in the axial strain in Figure 11. Although the general tendency of samples with different moisture contents is almost the same (except Sample 1, which shows more brittle behavior), the samples have very different values of modulus. With this normalized curve and small-strain modulus values from field seismic tests, it is easy to predict the strain-dependent behavior of any subgrade material using the approach applied in geotechnical earthquake engineering.

Comparisons Between M_R and Torsional Testing Results

To determine the capability of the testing equipment, results obtained from the M_R and the RC and TS tests were compared. As previously mentioned in the section on M_R testing

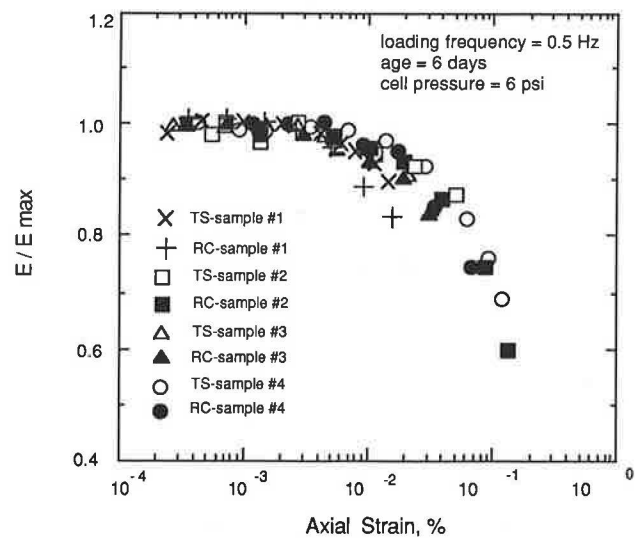


FIGURE 11 Variation in normalized Young's modulus with axial strain as determined by RC and TS tests.

with synthetic samples, good agreement was found between the moduli of the synthetic samples determined by both types of equipment. The synthetic specimens were easy to handle and test because their properties remained constant with time, were independent of strain amplitude and confining pressure, and could be repeatedly tested. In contrast, the comparison of the testing results for actual subgrade soils was more complicated.

In making that comparison, moduli obtained under RC and TS tests were converted to equivalent resilient moduli using Equations 8 and 9. In addition, the moduli were finally adjusted to an excitation frequency value of 10 Hz, which is the loading frequency of the M_R measurement.

Typical comparisons are shown in Figures 12 and 13. Figure 12 shows the variation in M_R with axial strain amplitude as determined by the three different testing methods for Sample 2. Overlapping the moduli obtained from M_R tests with the values from RC and TS tests provided sufficient evidence that a reliable system for measuring the elastic properties of subgrade materials had been developed. Figure 13, for Sample 4, shows an additionally encouraging overlap of moduli tested at 6 days and with a confining pressure of 6 psi.

CONCLUSIONS

M_R test equipment was evaluated using synthetic specimens and by performing pilot tests with cohesive soil. Torsional RC and TS tests were also used, with the moduli obtained from these tests comparing well with the values for the M_R test. The following conclusions can be drawn:

1. From the calibration of M_R equipment with synthetic specimens, it was found that strong contact between the specimen and top and bottom caps is important. For stiff materials, this factor is particularly crucial and can lead to erroneous estimates of modulus. The use of hydrostone paste provides a uniform contact between the specimen and end caps and eliminates additional movement at these points.

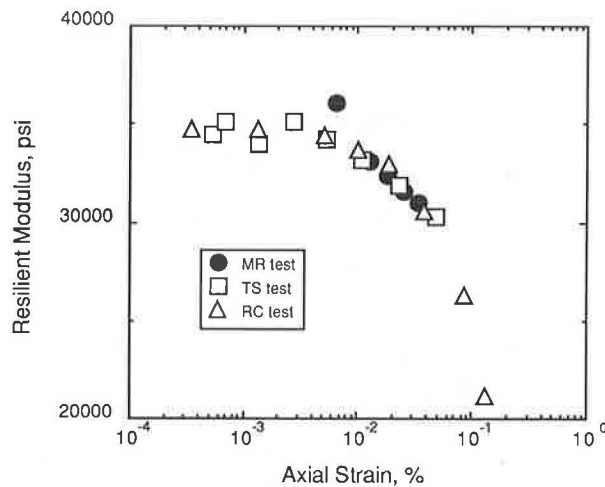


FIGURE 12 Comparison of M_R versus log (axial strain) and E versus log (axial strain) for cohesive Sample 2 tested at a confining pressure of 6 psi at 6 days after compaction.

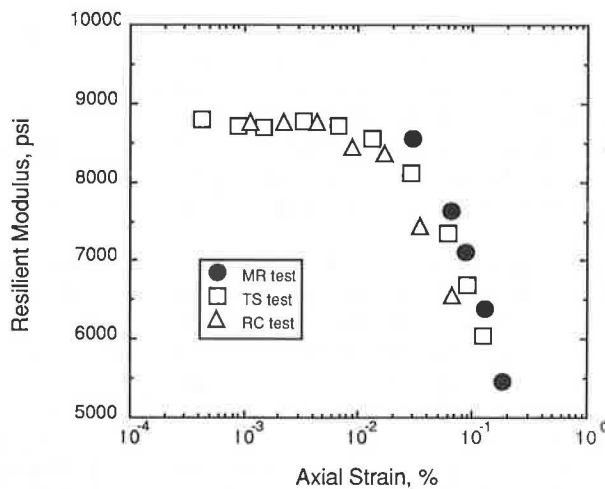


FIGURE 13 Comparison of M_R versus log (axial strain) and E versus log (axial strain) for cohesive Sample 4 tested at a confining pressure of 6 psi at 6 days after compaction.

2. Once the synthetic specimens were grouted in both the M_R and torsional devices, good agreement between moduli obtained from both tests was found.

3. In M_R testing the entire system requires calibration, not merely the individual transducers. To do this, testing synthetic samples of known properties can be used for the detection of equipment compliances, as well as for the assessment of a reliable system.

4. The pilot study with cohesive soil indicated that aging is an important factor in M_R measurements when no loss in water content is affected. Unfortunately, this factor is not taken into account in current M_R testing procedures.

5. Good comparisons were found between the moduli of cohesive soil measured with M_R and TS equipment. Two important points in the comparisons were that moduli had to be compared at both the same frequency and the same strain amplitude.

6. The RC and TS apparatus provides a powerful approach to the characterization of pavement materials over a wide range of strain amplitudes (10^{-4} to 10^{-1} percent) and can be considered an alternative technique to M_R testing.

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