Accuracy Improvement of External Resilient Modulus Measurements Using Specimen Grouting to End Platens

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To eliminate the source of errors in deformational measurements at small to intermediate strains (0.01 percent to 1.0 percent), a local strain measurement system inside the triaxial cell has been adopted in the resilient modulus (M_R) test. However because of complexities inherent in the local measurement, there are difficulties in using this technique in routine tests. As an alternative solution, external M_R measurement with the specimen grouted to the end platens with hydrostone paste was used. The effects of specimen grouting and the stiffness range on reliable external M_R measurements were investigated using six synthetic specimens of known stiffnesses ranging from that approximating a soft subgrade to that approximating stiff base material [from 20.7 MPa (3 ksi) to 552 MPa (80 ksi)]. For stiffness below about 345 MPa (50,000 psi), M_R values determined by external measurements with grouted specimens are identical to the known values from torsional testing. However for the stiffer specimens, M_R values of the grouted specimens are less than those from torsional testing, and the deviation increases with the increasing stiffness of the specimen. The secant static moduli determined by both loading and unloading curves closely matched the cyclic M_R at the same strain rate (or loading frequency), proving the feasibility of using the static testing scheme instead of the more expensive cyclic test. Finally the effects of specimen grouting were investigated using compacted subgrade soils.

AASHTO has adopted the use of resilient modulus (M_R) in pavement design to represent the deformational characteristics of pavement materials (*1*). Standard testing procedures for determining M_R were updated in AASHTO T-294-92I (*2*). However experience gained in applying these testing procedures has shown that great care must be exercised in evaluating resilient modulus at small to intermediate strains (0.01 percent to 1.0 percent) where the soil-pavement system is subjected to traffic loading, or significant inaccuracies can occur.

The axial strain is usually overestimated when the axial deformation is measured externally from the movement of the loading piston outside the triaxial cell (*3,4*). When stiffer specimens are tested at smaller strain amplitude under lower confining pressures, the degree of error is more pronounced. To eliminate the source of errors many local strain measurement systems inside the triaxial cell have been developed (*3–5*). However because of complexities inherent in the local measurement, there are difficulties using local measurement techniques in routine testing. Either compressed air or silicone oil, which is inert to a linear variable differential transformer, should be used as a confining fluid to accommodate the equipment inside the triaxial cell (*6*). Furthermore, even with on-specimen local deformation measurement, errors can still occur as a result of movement of the membrane relative to the specimen during a high-frequency cyclic test such as an M_R test.

As an alternative solution, external M_R measurement with the specimen grouted to the end platens with hydrostone paste can be used without introducing the technical difficulties involved in internal measurement. Moduli of the grouted specimens determined by cyclic triaxial testing have been compared closely with those obtained by resonant column and torsional shear tests (*7–9*). Specimen grouting improves the contact between the specimen and the top cap and bottom plate, eliminating bedding errors. Use of hydrostone paste also has beneficial results because the evenness of the top cap can be adjusted to accommodate unevenness in the specimen end. However the reliability of external measurement depends on the stiffness of the specimen. Consequently before application for routine M_R testing, the effects of specimen grouting and stiffness range on reliable external M_R measurements should be investigated.

In this study, the effects of specimen grouting on external M_R measurements were investigated and quantified using six synthetic specimens of known stiffnesses. Both static modulus and cyclic M_R measurements were performed on the same specimen to investigate the feasibility of using the static testing scheme instead of the more expensive cyclic test. Static secant moduli determined by both loading and unloading curves were compared with cyclic M_R values. To investigate the reliability of external M_R measurements, both static modulus and cyclic M_R values of grouted specimens were compared with the known stiffness determined by torsional testing for a wide range of stiffness. Finally the effects of specimen grouting were investigated using compacted subgrade soils.

METHOD OF ANALYSIS

In the cyclic M_R test the modulus becomes nearly constant and the response can be assumed to be approximately elastic after about 100 cycles of loading for soil specimens (*2,10*). M_R values of soil specimens were determined using the average value of the last five cycles about the 100th cycle. M_R values of synthetic specimens were determined using the average value of three cycles about the 10th cycle because M_R values of synthetic specimens are independent of the number of loading cycles (*11*). The resilient strain and the deviator stress are measured as shown in Figure 1 (top), and the modulus is calculated from

$$M_R = (\sigma_1 - \sigma_3) / \epsilon_a = \sigma_d / \epsilon_a \quad (1)$$

where σ_1 is the major principal stress, σ_3 is the minor principal stress, σ_d is the deviator stress, and ϵ_a is the resilient axial strain.

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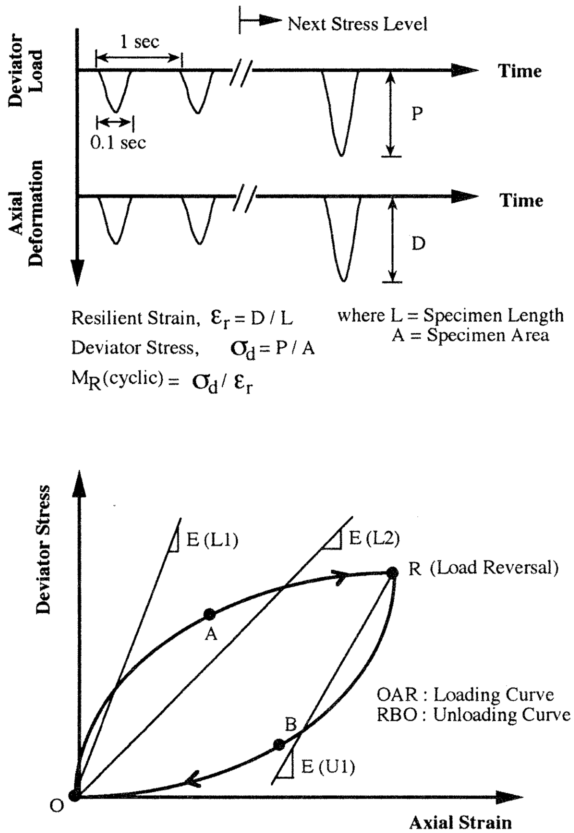

FIGURE 1 Determination of cyclic resilient modulus *(top)* and static secant modulus *(bottom).*

In the static test the stress amplitudes increased linearly up to the maximum stress level used in the series of cyclic tests and decreased linearly to the zero level. The corresponding stress-strain relationships under loading and unloading conditions were determined as shown in Figure 1 (bottom). The secant moduli were calculated from the slope of a line connected from the origin to the stress-strain curve at various strain amplitudes. When the secant moduli were determined from the unloading curve the origin was translated to the reversal point as shown in Figure 1 (bottom). Variation in static modulus with strain amplitude can be obtained by performing only one static test, whereas more than one cyclic test would be required.

TEST MATERIALS

Six synthetic specimens with M_R values ranging from that approximating a soft subgrade to that approximating stiff base material [from 20.7 MPa (3 ksi) to 552 MPa (80 ksi)] were constructed at The University of Texas at Austin. The construction procedures and stiffness characteristics of synthetic specimens were well documented by Stokoe et al. (*11*). Synthetic specimens have physical characteristics that remain constant with time and thereby can be repeatedly tested using different testing schemes. The stiffness of synthetic specimens is essentially independent of strain amplitude and confining pressure in the range of M_R tests. The shear moduli of synthetic specimens were determined by torsional testing, and the measured shear modulus (G) was converted to Young's modulus (E) using the elastic equation.

$$E = 2\,G\,(1 + \upsilon) \qquad (2)$$

where υ is Poisson's ratio. In M_R testing, E and M_R are assumed equal because the stiffness of the synthetic specimen is independent of loading history.

Two compacted subgrade soils were prepared and compacted at the optimum moisture content by dropping a hammer weighing 2.5 kg (5.5 lb) from a height of 30 cm (12 in.) with compaction energy based on the AASHTO T99 compaction method. Specimens were trimmed to approximately 10 cm (4 in.) in diameter and 20 cm (8 in.) in height. Table 1 presents the basic engineering properties of the test soils.

PROPERTIES OF HYDROSTONE PASTE

Hydrostone is a white, plaster-like material that is mixed with water and gains stiffness during the curing process. Because hydrostone paste is highly workable and has a rapid setting time, it is an appropriate material with which to grout the specimen to end platens. In addition, once cured, it is quite stiff. After the workability and setting time were checked, the water-hydrostone cement (W/C) ratio by weight was determined as 0.4.

In order to investigate the properties of hydrostone paste, a specimen with a W/C ratio of 0.4 was constructed with dimensions of 7.1 cm (2.8 in.) in diameter and 14.2 cm (5.6 in.) in height. Resilient modulus tests were performed at various curing times, then an unconfined compression test was performed at a curing time of 270 min. (*10*). The stiffness of the hydrostone paste increased from 1.04 GPa (150 ksi) to 1.73 GPa (250 ksi) at curing times of 50 min and 250 min, respectively. Pezo (*10*) recommended 120 min of curing time because the stiffness of hydrostone grout is strong enough [M_R of hydrostone grout is 1.38 GPa (200 ksi)] not to introduce problems on the M_R measurement of compacted subgrade soils with stiffnesses ranges up to about 345 MPa (50 ksi). The stress-strain curve of hydrostone paste obtained from the unconfined compression test showed the linear relationship up to a strain amplitude of 0.6 percent, within the range of most M_R tests.

TEST PROCEDURES

Synthetic Specimens

Synthetic specimens were tested under three different end conditions: grouted, ungrouted without seating pressure, and ungrouted with seating pressure. A seating pressure (static deviator pressure) of 69 kPa (10 psi) was used for ungrouted specimens to achieve bet-

TABLE 1 Basic Properties of Compacted Subgrade Soils

Soil ID	AASHTO Class.	Passing No. 200 (%)	Liquid Limit	Plasticity Index	Optimum Moisture Content (%)	Sample Moisture Content (%)	Wet Unit Wt. (pcf)
1	A-7-6	87.3	56	29	19.3	19.3	112.7
2	A-4	34.9	25	10	10.6	10.5	129.8

ter contact between the specimen and the end platens and to simulate the conditioning effect for the soil specimen. All of the tests were performed at zero confinement.

Both cyclic and static tests were performed on the same specimen. The cyclic tests were performed with increasing deviator stress amplitude up to approximately 207 kPa (30 psi). A harversine waveform was used with a load duration and cycle duration of 0.1 sec and 1.0 sec, respectively. Once the cyclic tests were completed, static tests were performed. The deviator stress was loaded linearly to the maximum stress level [207 kPa (30 psi)] during cyclic tests and unloaded to the original stress level, with a typical load duration of 10 sec.

Compacted Subgrade Soil

The compacted clay specimens were tested under three different end conditions: grouted, ungrouted without conditioning, and ungrouted with conditioning. Both cyclic and static tests were performed on the same specimen. The specimen was tested at a confining pressure of 41.4 kPa (6 psi). The cyclic tests were performed with increasing deviator stress from 6.9 kPa to 83 kPa (1 psi to 12 psi). After completion of the cyclic test at the highest stress amplitude, a low stress modulus was measured again and compared with the previous value to ensure that the specimen was not damaged. If the specimen was not damaged during cyclic tests (the moduli difference was within 5 percent), which was true for most cases, static tests were performed using the same waveform used on synthetic specimens.

After M_R tests with a grouted specimen were finished the specimen was carefully detached from the end platens. Both ends of the specimen were trimmed flat and the specimen was placed without grouting. At first the specimen was tested under cyclic and static loadings at 41.4 kPa (6 psi) of confining pressure without any conditioning. During the test the specimen was subjected to numerous load repetitions of various amplitudes more than specified in current conditioning stage (*2*). Conditioning was considered achieved during the first set of tests. The specimen was then tested following the same procedures used on the grouted specimen.

EFFECTS OF GROUTING ON SYNTHETIC SPECIMENS

Cyclic Resilient Modulus

The typical variation in cyclic resilient modulus with axial strain is shown in Figure 2 at three different end conditions. The moduli measured in the cyclic tests are almost independent of strain amplitude, but are substantially affected by the end conditions. The moduli of the grouted specimen are larger than those of the ungrouted one, and for the ungrouted specimen the moduli with seating pressure are larger than those without seating pressure. M_R values obtained from torsional testing are also plotted for comparison purposes and closely match the moduli of the grouted specimen.

It is difficult to make the specimen ends perfectly flat, hence an irregular air gap exists between the specimen and the end platens when placing the specimen without grouting. Because of these irregular gaps and nonuniform distribution of contact pressures (bedding errors), excessive deformation was monitored during the testing. Even if this measured erratic deformation is small, it can destroy

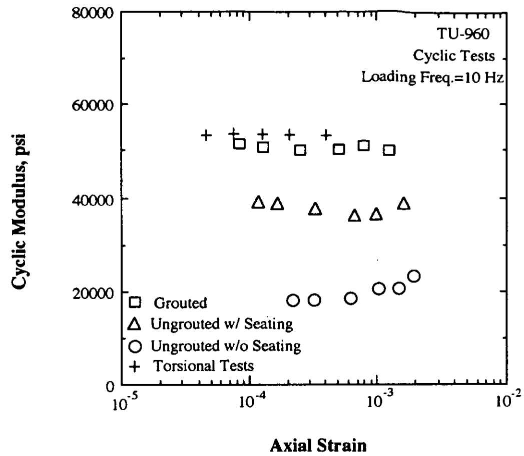

FIGURE 2 Typical variations in cyclic resilient moduli of synthetic specimens with axial strain determined at different end conditions.

the M_R measurements for relatively stiff specimens. For example, an error of approximately 2 thousandths of an inch (0.005 cm) in the deformation measurement (assuming the load is properly measured) provides a 0.025 percent error in strain measurement of a specimen 20 cm (8 in.) in height. If the real stiffness of this specimen is 345 MPa (50 ksi), only the M_R value of 112 MPa (16.2 ksi) would be measured when applying deviator stress of 41.4 KPa (6 psi).

Once the specimen ends are grouted to the end platens with hydrostone paste, the air gap is filled with hydrostone and uniform contact between specimen and end caps can be achieved. Because the erratic measurement of deformation is eliminated by specimen grouting, the moduli determined by a grouted specimen are much more reliable than those of an ungrouted one. The bedding error can also be reduced by applying seating pressure, but the improvement in the M_R measurement due to seating pressure is much less than the improvement due to grouting, as shown in Figure 2. Moreover, excessive seating pressure applied to the soil specimen may cause changes in the stress history of the specimen.

Cyclic M_R values of synthetic specimens measured at a strain amplitude of about 0.02 percent are summarized in Table 2; cyclic moduli obtained from torsional testings are included. To quantify the effect of specimen grouting on stiffness measurements, the moduli of the ungrouted specimen were normalized by the value of the grouted one. Figure 3 shows the variations in normalized modulus, M_R(ungrouted)/M_R(grouted), with the stiffness of the grouted specimen. The normalized moduli of ungrouted specimens varied from 100 percent to 25 percent of those of grouted specimens without seating pressure and from 100 percent to 50 percent of those of grouted specimens with seating pressure when the grouted M_R values varied from 21.4 MPa (3.1 ksi) to 497 MPa (72 ksi). Specimen grouting improves the M_R measurement significantly, and the amount of improvement increases as the stiffness of the specimen increases.

To investigate the effects of the stiffness range on reliable external M_R measurements with specimen grouting, moduli obtained from M_R tests were compared with moduli obtained from torsional testing, as shown in Figure 4. Within the range of stiffness below about 345 MPa (50 ksi), M_R values determined by external measurements with grouted specimens were identical with the cyclic

TABLE 2 Cyclic Moduli of Synthetic Specimens Determined at Different End Conditions

Specimen ID	Cyclic Modulus[1] (psi)			Cyclic Modulus by RCTS (psi)[2]
	Grouted	Ungrouted with Preload	Ungrouted without Preload	
TU 700	3100	2970	2950	3060
TU 900	10200	8900	5500	10100
TU960	50700	39800	16000	53500
D50	20100	18100	11300	20200
D60	50300	27100	15400	58600
D70	71900	37000	16800	89800

[1] Determined at a load duration of 0.1 sec and cycle duration of 1.0 sec, and at a strain amplitude of about 0.02%.

[2] Determined by resonant column and torsional shear test at a loading frequency of 10 Hz

moduli from torsional testing. The typical range of the resilient modulus of subgrade soils and unbound granular materials used in pavement design is less than 310 MPa (45 ksi) (*1*). Therefore the resilient modulus can be reliably determined for pavement design using external measurements of the axial strains of the grouted specimen. However in the stiffness ranges above about 345 MPa (50 ksi), M_R values of the grouted specimen are less than those from torsional testing, and the deviation increases with the increasing stiffness of the specimen.

Static Modulus

Typical stress-strain relationships obtained by static loading are shown in Figure 5 (top). The stress-strain behaviors of synthetic specimens are linear regardless of end condition. However the slopes of the stress-strain curves are substantially different depending on the end conditions. The slope for the grouted specimen is much steeper than those for ungrouted specimens. For the ungrouted specimens, the slope for the specimen with seating pressure is steeper than the slope for the specimen without seating pressure. It is interesting to note that strain amplitudes are different at the same corresponding deviator stress depending on the end conditions. The deformation of ungrouted specimens is overestimated because of the irregular gap that exists between the specimen ends and end platens. These erratic deformation measurements adversely influence the stress-strain behavior.

Typical stress-strain relationships measured from static unloading are shown in Figure 5 (bottom). The stress-strain behavior of the

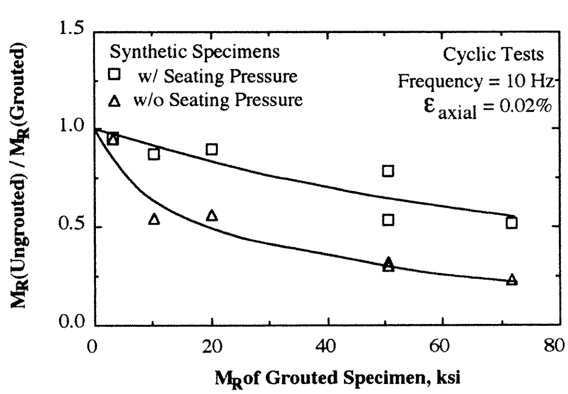

FIGURE 3 Variation in normalized moduli of synthetic specimens, M_R (ungrouted)/M_R (grouted), with stiffness of grouted specimen.

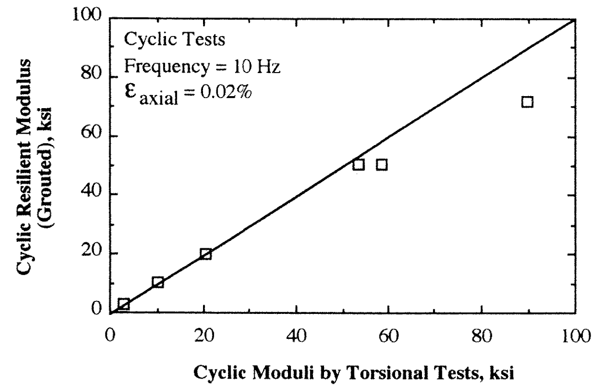

FIGURE 4 Comparison of resilient modulus of synthetic specimens determined by external measurement with specimen grouting and cyclic moduli determined by torsional testing.

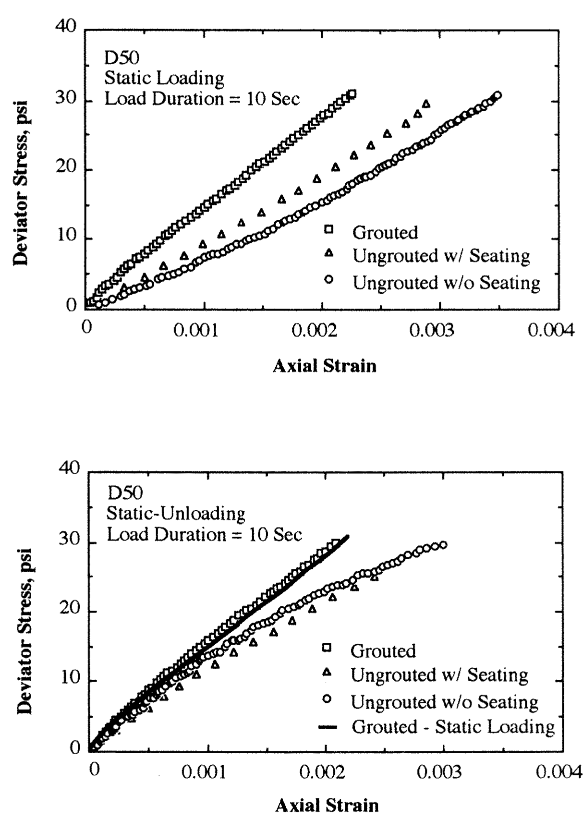

FIGURE 5 Typical stress-strain relationships of synthetic specimens under static loading (*top*) and unloading determined at different end conditions (*bottom*).

grouted specimen obtained from static loading is also included for comparison. The behaviors of grouted specimens measured from static loading and unloading tests are almost identical; however, the behaviors of the ungrouted specimens are quite different from those determined by static loadings. At strains below about 0.0005, all stress-strain curves match well. At higher strains, however, the strain amplitudes determined by ungrouted specimens are overestimated compared with those of the grouted specimen, and the difference increases with strain amplitude. This indicates that an irregular gap between the specimen ends and platens was closed during the static loading, and uniform contact was achieved before unloading. In the early stage of unloading, uniform contact remained even for ungrouted specimens, but at higher strains the irregular gap occurred again and influenced the measurements.

Static moduli of synthetic specimens determined by both loading and unloading tests under different end conditions are summarized in Table 3. Static moduli are determined at a load duration of 10 sec and at a strain amplitude of about 0.02 percent. To quantify the effect of specimen grouting on the static measurement, the moduli of the ungrouted specimen were normalized by the value of grouted specimen, and the variation in the normalized modulus with the stiffness of the grouted specimen is shown in Figure 6. The static modulus determined from loading tests is substantially affected by end conditions: the normalized values of ungrouted specimens without seating pressures varied from 98 percent to 26 percent of grouted specimen values, and values of ungrouted specimens with seating pressures varied from 102 percent to 46 percent of grouted specimen values when those values varied from 18.6 MPa (2.7 ksi) to 308 MPa (44.7 ksi), respectively. Specimen grouting significantly improves the accuracy of measurements, and the higher improvement rate is achieved for the stiffer specimens. The improvement rate achieved in the static loading test is similar to that in cyclic M_R tests at a given stiffness. However the static modulus determined from unloading tests is much less affected by the end conditions than that determined from static loading tests: the maximum difference of moduli between grouted and ungrouted specimens is less than 30 percent.

To investigate the reliability of static measurements, the moduli of grouted specimens determined by loading and unloading tests are compared with moduli determined by torsional testing, as shown in Figure 7. Because the stiffness of the synthetic specimen is affected by the loading rate (*11*), M_R values are compared at a similar loading rate: torsional testing was performed at a loading frequency of 0.05 Hz and static testing was performed using a load duration (equivalent to a half period in the cyclic test) of 10 sec. Within the ranges of stiffness below about 290 MPa (42 ksi), static moduli obtained from both loading and unloading curves were almost identical to the values obtained from torsional testing. This indicates an interesting feature: a reliable moduli can be measured using a static testing scheme if the M_R values are corrected to consider the loading rate. More important, if the specimen ends are grouted to the end platens using hydrostone paste, a static triaxial loading scheme with external measurement, which is common for conventional triaxial testing, provides an alternative M_R testing method without introducing the technical difficulties involved in internal measurement. In addition, the need for expensive cyclic testing equipment is avoided. At higher stiffness ranges, however, static moduli of grouted specimens are less than the values from torsional testing.

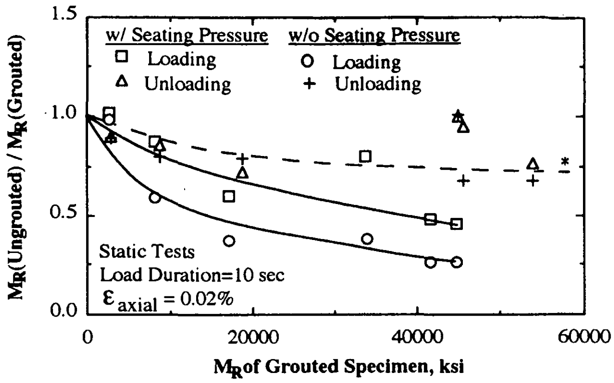

FIGURE 6 Variation in normalized static moduli of synthetic specimens, M_R (ungrouted)/M_R (grouted), with stiffness of grouted specimen.

TABLE 3 Static Moduli of Synthetic Specimens Determined at Different End Conditions

End Condition / Loading Condition / Specimen ID	Static Modulus[1] (psi) Grouted Load	Grouted Unload	Ungrouted with Preload Load	Ungrouted with Preload Unload	Ungrouted without Preload Load	Ungrouted without Preload Unload	Cyclic[2] Modulus by RCTS (psi)
TU 700	2700	3020	2750	2720	2650	2700	2650
TU 900	8150	8800	7120	7550	4820	7030	8800
TU960	33900	45000	26500	45100	12800	42700	32700
D50	17100	18800	10200	13500	6300	14800	17300
D60	41600	45600	20100	43500	10700	31200	42100
D70	44700	53900	20400	40900	11700	36800	69600

[1] Determined by loading and unloading curves at load duration of 10 sec.
[2] Determined by resonant column and torsional shear test at a loading frequency of 0.05 Hz

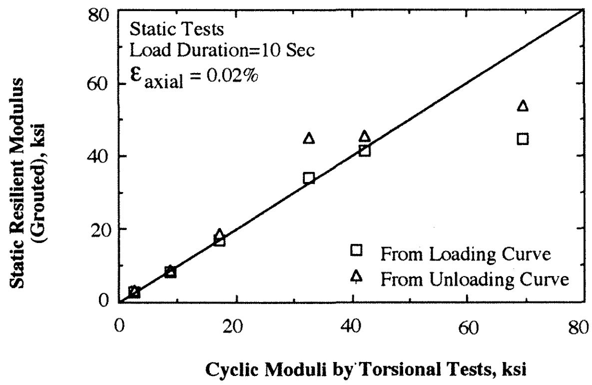

FIGURE 7 Comparison of static modulus of synthetic specimens determined by external measurement with specimen grouting and cyclic moduli determined by torsional testing (0.05 Hz).

EFFECTS OF GROUTING ON COMPACTED SUBGRADE SOILS

Cyclic Resilient Modulus

The variations in cyclic resilient moduli of two compacted subgrade soils with their strain amplitudes are shown in Figure 8. M_R values of grouted specimens are generally larger than those of ungrouted specimens. Modulus difference between the grouted and ungrouted specimens is greater for higher values of M_R and decreases as M_R decreases. At M_R values below about 69 MPa (10 ksi), both the moduli of the grouted and of the ungrouted specimens are almost identical regardless of end conditions. This behavior indicates that improvements in the cyclic M_R measurements due to specimen grouting are greater when the stiffness of the specimen is higher.

To show the effect of conditioning on M_R measurements, moduli of Sample 2 determined without conditioning are included in Figure 8. Moduli without conditioning are significantly lower than the grouted values, whereas moduli determined after conditioning are much closer to the grouted values, indicating that conditioning significantly improves the test results, particularly at low strain measurements, by making better contacts between the specimen and end platens. After conditioning the normalized moduli of compacted subgrade soils, M_R (ungrouted)/M_R (grouted), are approximately from 80 percent to 85 percent when M_R values vary from 207 MPa (30 ksi) to 138 MPa (20 ksi). These values are considerably higher than those on synthetic specimens without seating pressure (45 percent to 50 percent) and similar to those with seating pressures (76 percent to 83 percent) as shown in Figure 3. Specimen conditioning improves M_R measurements on compacted subgrade soils by reducing bedding errors, but it does not provide the same level of improvement achieved by specimen grouting.

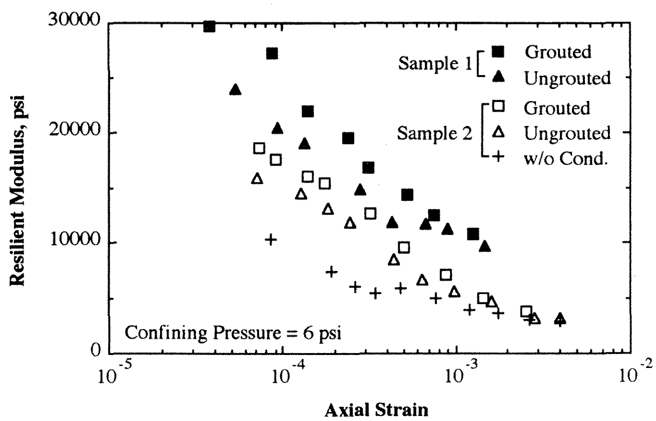

FIGURE 8 Variations in cyclic resilient modulus of two compacted subgrade soils with axial strain under different end conditions.

Static Modulus

Typical variations in static moduli with strain amplitude determined by loading and unloading tests are shown in Figure 9. Static moduli determined by loading tests are affected by end conditions as shown in the top portion of Figure 9: moduli of grouted specimens are greater than the values of ungrouted specimens. However specimen end condition does not influence the static modulus determined by unloading tests, as shown in the bottom portion of Figure 9, where the moduli of grouted and ungrouted specimens are almost identical.

For comparison of the M_R values determined by static and cyclic tests, cyclic moduli of grouted specimen are included in Figure 9.

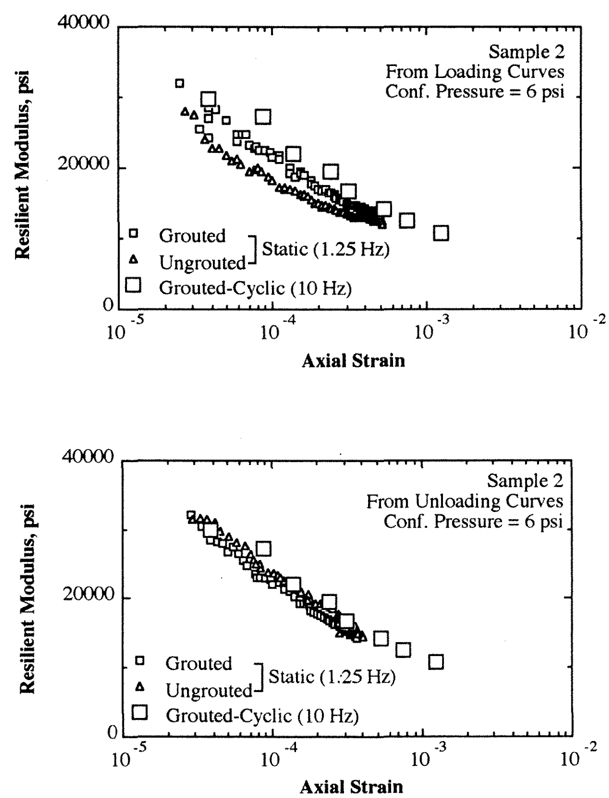

FIGURE 9 Typical variation in static modulus of compacted subgrade soil with strain amplitude determined by static loading (*top*) and unloading (*bottom*) curves at different end conditions.

With an identical specimen, the static modulus is determined at a load duration of 0.4 sec (equivalent of 1.25 Hz) and a cyclic modulus is determined at a loading frequency of 10 Hz. All static moduli match fairly well except for those of the ungrouted specimen measured by the loading curve but they are somewhat smaller than the cyclic moduli. This difference can be explained by the difference in loading frequency between both tests, because the resilient modulus of compacted subgrade soil is affected by the loading frequency (*12*). This suggests the feasibility of using an alternative static loading scheme for a resilient modulus measurement if the measured value is properly corrected to consider the loading frequency. Further study is being conducted by the authors.

CONCLUSIONS

The reliability of external M_R measurements with specimens grouted to end platens was investigated using synthetic specimens of known stiffness and compacted subgrade soils. Both static and cyclic tests were performed on the same specimens. The following conclusions were drawn:

1. Specimen grouting provides better contact between the specimen and end platens and improves the external M_R measurements by eliminating bedding errors. The amount of improvement increases as the stiffness of the specimen increases. For synthetic specimens, the moduli of ungrouted specimens varied from 100 percent to 25 percent of grouted specimen values without seating pressure and from 100 percent to 50 percent of grouted specimen values with seating pressure when the grouted specimen M_R values varied from 21.4 MPa (3.1 ksi) to 497 MPa (72 ksi).
2. Static secant moduli are obtained from both static loading and unloading curves. The improvement achieved in static loading tests due to specimen grouting was similar to that in the cyclic M_R tests at a given stiffness. However static modulus obtained from the unloading curve was much less affected by the end conditions.
3. Reliable M_R can be determined for pavement design by external M_R measurements with specimen grouting in the range of stiffness below about 290 MPa (42 ksi) for static tests and below about 345 MPa (50 ksi) for cyclic tests. However at higher stiffness ranges, external M_R measurements underestimate the M_R values and the deviation increases with the increasing stiffness of the specimen.
4. Static moduli of synthetic specimens and compacted subgrade soils determined by external measurements match fairly well with the cyclic M_R values at a corresponding strain amplitude if the loading rate is considered in the comparison. A static triaxial loading scheme with an external measurement may provide an alternative M_R testing method without introducing the technical difficulties involved in internal measurement and without the need for expensive cyclic testing equipment.

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REFERENCES

1. *AASHTO Guide for Design of Pavement Structures.* AASHTO, Washington, D.C., 1986.
2. *Resilient Modulus of Unbound Base/Subbase Materials and Subgrade Soils*—SHRP Protocol P46 AASHTO, T-294-92I. AASHTO, Washington, D.C., 1992, pp. 52–65.
3. Burland, J. B. Ninth Lauritis Bjerrum Memorial Lecture: Small is Beautiful—The Stiffness of Soils at Small Strains. *Canadian Geotechnical Journal,* 26, 1989, pp. 499–516.
4. Tatsuoka, F., S. Shibuya, S. Goto, T. Sato, and X. J. Kong. Discussion on the Paper by Clayton et al. *Geotechnical Testing Journal,* Vol. 13, No. 1, 1990, pp. 63–67.
5. Goto, S., F. Tatsuoka, S. Shibuya, Y. S. Kim, and T. Sato. A Simple Gauge for Local Small Strain Measurement in the Laboratory. *Soils and Foundations,* Vol. 31, No.1, March 1991, pp. 169–180.
6. Nataatmadja, A., and A. K. Parkin. Axial Deformation Measurement in Repeated Load Triaxial Testing. *Geotechnical Testing Journal,* Vol. 13, No. 1, March 1990, pp. 45–48.
7. Ladd, R. S., and P. Dutko. Small-Strain Measurements Using Triaxial Apparatus. *Proc., Advances in the Art of Testing Soils Under Cyclic Conditions,* Detroit, Mich. ASCE, 1985, pp. 148–165,
8. Pezo, R. F., D. S. Kim, K. H. Stokoe, and W. R. Hudson. Developing a Reliable Resilient Modulus Testing System. In *Transportation Research Record 1307,* TRB, National Research Council, Washington, D.C., 1991, pp. 90–98.
9. Kim, D. S. *Deformational Characteristics of Soils at Small to Intermediate Strain From Cyclic Tests.* Ph.D dissertation. The University of Texas at Austin, 1991.
10. Pezo, R. F. *Development of Reliable Resilient Modulus Test for Subgrade and Subbase Materials for Use in Routine Pavement Design.* Ph.D dissertation. The University of Texas at Austin, 1991.
11. Stokoe, K. H., D. S. Kim, and R. Andrus. Development of Synthetic Specimens for Calibration and Evaluation of M_R Equipment. In *Transportation Research Record 1278,* TRB, National Research Council, Washington, D.C., 1990, pp 63–71.
12. Kim, D. S., and K. H. Stokoe. Characterization of Resilient Modulus of Compacted Subgrade Soils Using Resonant Column and Torsional Shear Tests. In *Transportation Research Record 1369,* TRB, National Research Council, Washington, D.C., 1992, pp 83–91.

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