Development of Synthetic Specimens for Calibration and Evaluation of M_R Equipment

KENNETH H. STOKOE II, DONG-SOO KIM, AND RONALD D. ANDRUS

Laboratory measurement of the deformational characteristics of subgrade materials can be quite difficult because of the small values of stress and strain typically involved and the need to eliminate equipment compliance. Measurement of resilient modulus (M_R) of subgrades falls into this category. Therefore, synthetic specimens with known stiffness characteristics would be beneficial in evaluating and calibrating M_R equipment as well as training personnel. Two-component urethane elastomer resins are shown to make good candidates for calibration specimens. They can be made with a wide range of stiffnesses that vary from soft subgrades to stiff uncemented bases. Urethane can be modeled as a linear, viscoelastic material with stiffness characteristics essentially independent of confining pressure, strain amplitude, and stress history for the type of cyclic loading used in M_R testing. Urethane stiffness is, however, dependent on loading frequency and temperature. Therefore, values of Young's modulus used to equate to M_R have to be selected at the appropriate frequency and temperature.

Laboratory measurement of the deformational characteristics of subgrade materials in the linear and nonlinear ranges can be performed by various cyclic and dynamic methods. Acceptance of the resilient modulus (M_R) as a measure of the deformational characteristics of subgrades (*1*) has resulted in the use of a number of different systems to perform such measurements. The strengths and weaknesses of those systems deserve further study for optimum use. Experience gained in applying the cyclic triaxial test in geotechnical earthquake engineering has shown that great care must be exercised in evaluating the deformational characteristics of geotechnical materials at small ($\varepsilon < 0.001$ percent) to intermediate (0.001 percent $< \varepsilon < 0.1$ percent) strains or significant inaccuracies can occur (*2–4*).

One means of evaluating the performance of M_R equipment is to use the equipment to test specimens with known stiffness characteristics. (Such specimens are referred to as calibration specimens.) Values of M_R determined with the equipment can then be compared with stiffnesses of the calibration specimens that have been established by independent tests. If there are differences between the measured and calibration stiffnesses, then modifications to the equipment or procedures or both can be undertaken.

The purpose of this paper is to discuss the development of calibration specimens. Synthetic materials, rather than real soils, are used to construct such specimens. The stiffnesses are conveniently evaluated in terms of Young's modulus, E, which is taken to be equal to M_R for this material. Use of the calibration specimens with M_R equipment is discussed in a companion paper in this Record. Synthetic specimens have advantages: (a) They are easy to construct in the appropriate sizes for M_R equipment, (b) have physical characteristics that remain constant with time, and (c) have stiffness properties that can be determined by independent tests, and (d) can be repeatedly tested as desired by different personnel and laboratories or both. Specimens made from urethane elastomers have those characteristics.

Department of Civil Engineering, The University of Texas at Austin, Austin, Tex. 78712.

CALIBRATION SPECIMENS

Calibration specimens were constructed by using a two-component urethane elastomer resin system manufactured by Conap, Inc., of Olean, New York. The first component consisted of dicyclohexylmethane-4,4′-diisocyanate for all specimens. The second component consisted of diethyltoluene diamine for specimens TU-700 and TU-900 and 4,4′-methylenedianiline for specimen TU-960. One key characteristic of urethane elastomers, also called polyurethanes, is their very broad hardness range. Specimens can be formed with hardnesses (stiffnesses) ranging from that approximating a very soft subgrade to that approximating a stiff, uncemented base. Unlike other plastics, the hardness of polyurethane is governed by the molecular structure of the prepolymer (*5*) and not by the addition of plasticizers and fillers. As a result, constructing specimens of a preselected stiffness is straightforward, a task that can be difficult with other synthetic materials. Urethanes are also tough, durable, and have a high resistance to abrasion, weather, ozone, oxygen, and radiation.

Three individual mixtures were used to create synthetic specimens (Conathane® TU-700, TU-900, and TU-960) for this study. Casting procedures outlined by the manufacturer were followed. Each component was measured according to the specified accuracy and mix ratio. Disposable plastic containers were used for both weighing and mixing for ease in handling and cleanup. The two components were mixed thoroughly and then degassed for about 5 min to remove entrapped air caused by mixing. For effective degassing, the manufacturer recommended a vacuum of 28 to 29 in. of mercury (14 psi), a factor the authors found to be important. The working life of the mixture was about 20 min so that once mixing was started, construction progressed quickly.

Before pouring, a mold release (Conap® MR-5002) was applied to the inner surface of the cylindrical mold. The degassed mixture was then carefully poured into the mold in a manner that attempted to minimize the trapping of air bubbles. Nevertheless, several tiny air bubbles would always become trapped during the pour. The trapped air bubbles would slowly move upward in the mixture and collect at the top. As the mixture cured, 1 to 1.5 percent shrinkage occurred. When a closed mold was used, even if vent holes were added at the top, the effects from the bubbles and shrinkage were unfavorable. These unfavorable effects were eliminated by (a) using a mold that was completely open at the top and (b) warming the mold and freshly poured urethane with a hair dryer, heating tape, or oven.

A curing time of 7 days was recommended by the manufacturer. However, the specimen could be removed from the mold after 1 day. As with most polyurethanes, it was necessary to wear gloves and work in a well-ventilated area when handling unmixed and uncured materials.

Both acrylic split molds and metal pipe molds were tried. The metal pipe mold was the simplest to use. However, a pipe of the proper dimensions may require special ordering, and an extruder is needed to push the cured specimens out of the pipe. Molds having diameters of 1.4, 2.0, and 2.8 in. and lengths of 2 to 3 times the diameter were used. The top inch of the cured urethane specimens was cut off, and the end was machined flat and perpendicular to the cylindrical axis by a surface grinder. Removal of the top inch of the specimen also had the beneficial effect of eliminating material with bubbles in it because bubbles tended to collect there.

The majority of the specimens used in this initial study were 2.8 in. in diameter and 5.6 in. long. Unit weights for those specimens ranged from 65 to 67 pcf.

Since completion of the initial study, the authors have constructed additional specimens not presented here. The urethane material was purchased locally in 2- to 3-ft long rods of specified hardnesses (hardness and stiffness are related in Figure 13). The rods were then cut in desired lengths, and the specimens were machined to their final dimensions. Happily, this approach eliminated the rather messy casting process used initially. The main hurdle in machining precise circular cylinders is the tendency of soft urethane to bend away from the cutting tool. This problem has been overcome through the use of a surface grinder.

TEST EQUIPMENT AND PROCEDURES

Once the calibration specimens were constructed, the deformational characteristics of each had to be measured by several independent methods to establish the stiffness characteristics of the material. The specimens became reference specimens with known stiffnesses for use in evaluation of M_R equipment and test procedures. Static compression, torsional resonant column, and slow cyclic torsional tests were used to establish the stiffness characteristics and to evaluate variables affecting them.

Static Compression Testing

Static measurements of Young's modulus and Poisson's ratio were determined by using the test setup shown in Figure 1. Axial loads were applied by placing known weights concentrically on top of each urethane specimen. A special top cap

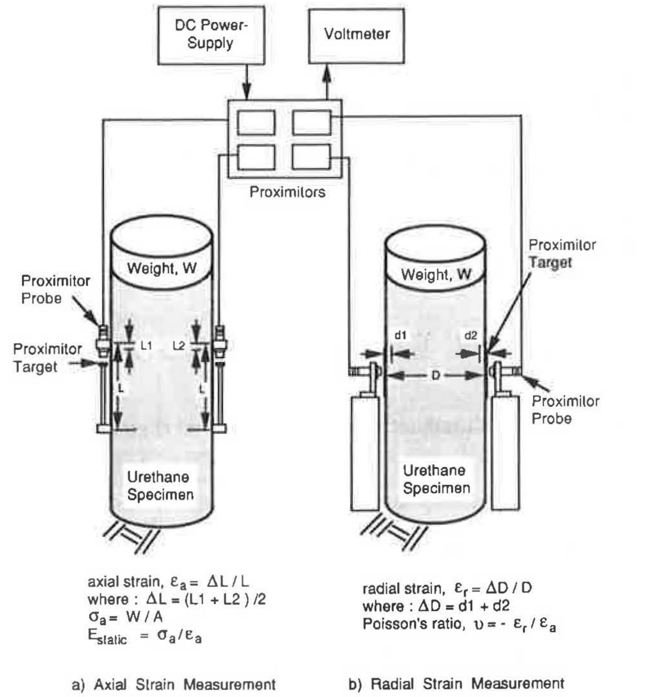


FIGURE 1 Configuration of equipment used to perform static compression measurements.

was used to align the weights concentrically. Proximitor probes and targets positioned near the middle of the specimen measured the axial and radial deformations. Those proximitors (MicroProx® Proximity Transducer System manufactured by Bently Nevada, Minden, Nevada) were capable of measuring displacements to within an accuracy of 0.000005 in. To ensure concentric loading, proximitors were located on opposite sides of the specimen, and their outputs had to exhibit deformations within 5 percent of each other for measurements to be accepted.

By using the relationships given in Figure 1, axial and radial strains were determined. Static Young's modulus or modulus of elasticity, E, was then calculated from

$$E = \sigma_a / \varepsilon_a \quad (1)$$

where σ_a is axial stress and ε_a is axial strain.

Poisson's ratio, ν, was determined from the ratio of radial strain to axial strain:

$$\nu = -\varepsilon_r / \varepsilon_a \quad (2)$$

where ε_r is radial strain.

The testing procedure was simply to add a load and then measure the resulting deformation. Measurements were made about 1 min after application of each load when the proximeter signal had stabilized.

Torsional Resonant Column Testing

Resonant column equipment of the torsional fixed-free type was used. A simplified diagram of a fixed-free resonant column is supplied in Figure 2. In this configuration, the bottom of the test specimen is fixed to the base with a hard epoxy glue. The top (free end) is connected to a drive system used to excite and monitor torsional motion. The basic operational principle is to vibrate the cylindrical specimen in first-mode torsional motion. Once first mode is established, measurements of the resonant frequency and amplitude of vibration are made. Those measurements are then combined with equipment characteristics and specimen size to calculate shear wave velocity, shear modulus, and shearing strain amplitude (*6,7*).

By using the wave equation, the basic data-reduction equation can be expressed as (*8*)

$$I/I_0 = (\omega_r L/V_s) \tan (\omega_r L/V_s) \tag{3}$$

where

- I = mass moment of inertia of test specimen,
- I_0 = mass moment of inertia of drive plate,
- 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

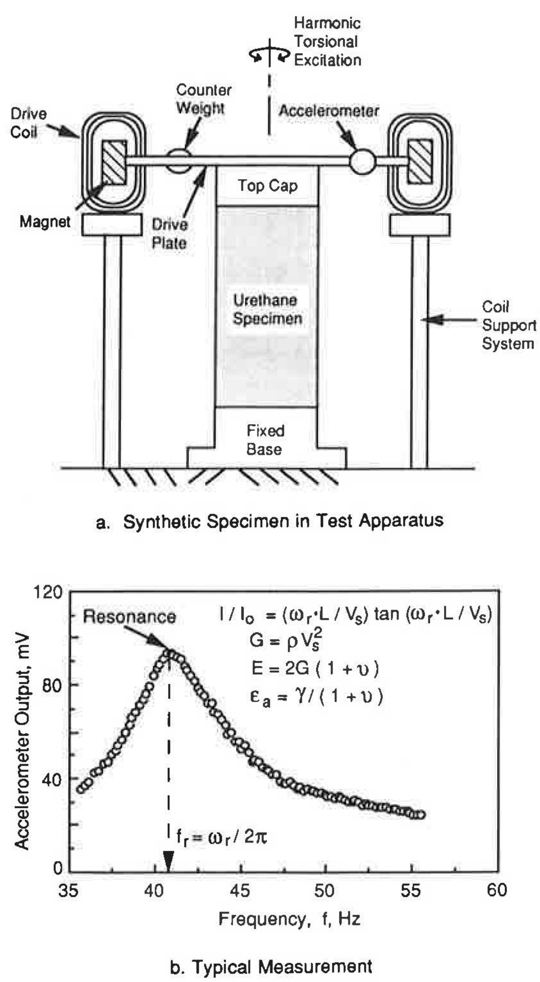


FIGURE 2 Configuration of fixed-free resonant column test and typical test results.

Equation 3, shear modulus G and Young's modulus E are calculated from

$$G = \rho V_s^2 \tag{4}$$

$$E = 2G (1 + \nu) \tag{5}$$

where ρ is mass density of the urethane. The value of Poisson's ratio was taken from the static compression tests.

Shearing strain γ is calculated from the peak rotation of the top of the specimen at 0.67 times the radius (*6,7*). By following standard procedures in relating cyclic triaxial and resonant column results, the axial strain compatible with this shearing strain is then (*9*)

$$\varepsilon_a = \gamma/(1 + \nu) \tag{6}$$

In applying Equation 6, the material is assumed to be homogeneous and isotropic.

Torsional Shear Testing

The torsional shear test is another method of determining shear and Young's moduli, using the same resonant column equipment but operating it in a different manner. In this test, a cyclic torsional force with a given frequency, generally below 10 Hz, is applied at the top of the specimen. Instead of determining a resonant frequency, the stress-strain hysteresis loop is determined from measuring the torque-twist response of the specimen. Proximitors are used to measure twist, and 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 indicated in Figure 3 and is calculated from

$$G = \tau/\gamma \tag{7}$$

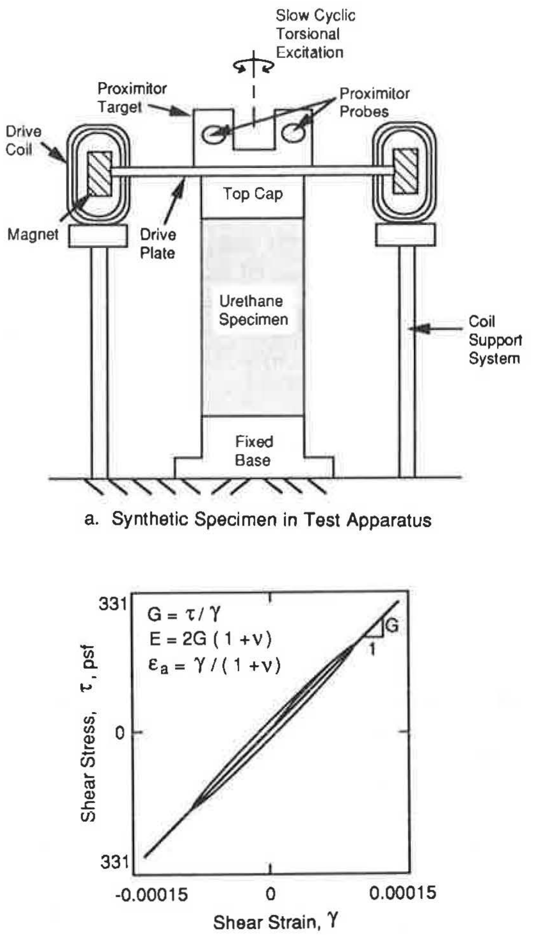
where τ is shearing stress and γ is shearing strain.

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 resonant column tests. When the torsional shear test is performed at low frequencies, 0.01 to about 1 Hz, the inertial effect can be ignored. However, at higher frequencies, inertia significantly magnifies the amount of strain. The amount of strain caused by inertia can be estimated by using the dynamic magnification factor equation for a viscously damped single-degree-of-freedom system (*8*). This approach was followed in the calculations of shear modulus above 2 Hz but well below the resonant frequency.

Once G and γ were determined, Young's modulus and axial strain were calculated from Equations 5 and 6, using a value of Poisson's ratio from the static compression tests.

Torsional Testing Procedures

Before testing in either the resonant or the torsional shear mode, each specimen was glued to the base pedestal and top cap by using a hard, 5-min epoxy. The glue was allowed to cure overnight. This approach, which had worked well in testing other materials, eliminated any seating problems in



b. Typical Measurement

FIGURE 3 Configuration of torsional shear test and typical test results.

the tests. Each specimen was then tested under isotropic confining pressures of 0, 2, 4, 8, 16, 32, and 64 psi. Low-amplitude resonant column tests ($\gamma < 0.001$ percent) were performed at about 10-min time intervals at each pressure level. The tests are low-amplitude because the specimens exhibit linear behavior in this range (as well as at higher strains, as will be seen later). A series of those measurements at an isotropic confining pressure of 64 psi for each specimen stiffness is presented in Figure 4. The small-strain shear moduli reported for each specimen in subsequent figures and tables are the values calculated from measurements made 50 min after applying each confining pressure, even though the values were essentially independent of confinement time, as presented in Figure 4.

A series of torsional shear tests was performed after finishing low-amplitude resonant column tests at each confining pressure. The loading frequency and strain amplitude were varied in the torsional shear tests. Loading frequencies between 0.01 and 40 Hz were used, and shearing strain amplitudes ranging from 0.0005 to 0.05 percent (single amplitude) were generated at each frequency. High-amplitude resonant column tests were then performed at the same strain amplitudes as was the torsional shear tests. Finally, low-amplitude resonant column tests were again performed to see if any

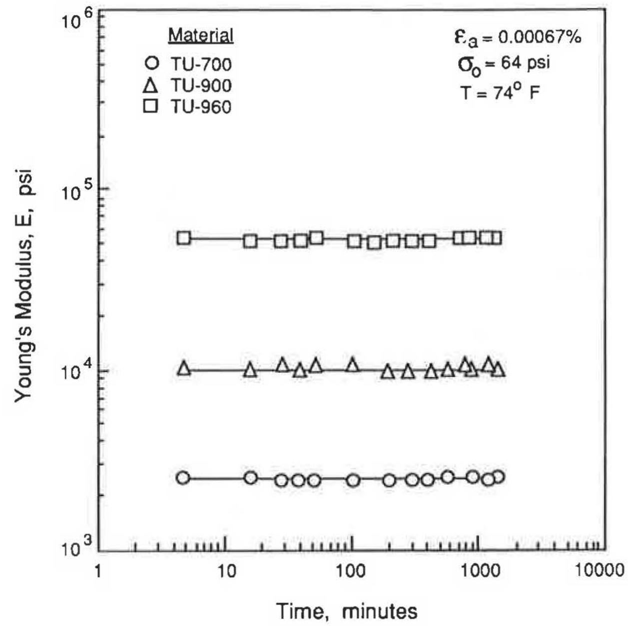


FIGURE 4 Variation in small-strain Young's modulus with time of confinement determined by resonant column tests with specimens confined at an isotropic pressure of 64 psi.

changes had occurred in the low-amplitude modulus. Variations in the low-amplitude moduli measured before and after high-amplitude testing were less than 3 percent and were considered to be within experimental scatter.

A typical series of measurements at one confining pressure is listed in Table 1. One specimen was tested at two different times to study the repeatability of the measurements. The specimen was removed from the apparatus and then reglued to the top cap and base between testing. As is indicated in the table, values of modulus for the two test series are within 3 percent, which indicates the high degree of repeatability. Smaller variations in modulus were observed if the specimen did not need to be reglued to the top cap and fixed base.

CALIBRATION TEST RESULTS

Factors involving material characteristics, specimen characteristics, and testing procedures need to be considered when developing calibration specimens. Material characteristics include the effect of the following factors: confining pressure (isotropic and anisotropic), strain amplitude, loading frequency, temperature, moisture, and time (e.g., changes with time of curing, ultraviolet radiation, as well as "creep" under load). Specimen characteristics include specimen length, diameter, uniformity, and end conditions. Test procedures include load history, seating load, rest times, equipment stiffness, and reproducibility.

This study started the initial steps in understanding the material and specimen characteristics of urethane calibration specimens. The effects of isotropic confining pressure, time under confinement, strain amplitude, loading frequency, and temperature have been evaluated. Specimen characteristics and the repeatability of the test results also have been studied. Testing procedures in terms of M_R tests are addressed in a companion paper in this Record.

TABLE 1 TYPICAL SERIES OF MEASUREMENTS ON ONE SPECIMEN* FROM COMBINED RESONANT COLUMN/ TORSIONAL SHEAR TESTS AT ONE CONFINING PRESSURE

Type of Test	Time,▽ minutes	Shearing Strain γ,%	Shear Modulus, G, ksi Trial 1			Trial 2 (reglued)△		
			@56Hz			@56Hz		
Low-Amplitude	4	1×10^{-3}	501			494		
Resonant Column	15	1×10^{-3}	496			499		
	25	1×10^{-3}	503			493		
	35	1×10^{-3}	501			497		
	45	1×10^{-3}	497			495		
	55	1×10^{-3}	503			497		
	65	1×10^{-3}	501			497		
			@0.01Hz	0.1Hz	1 Hz	0.01Hz	0.1Hz	1Hz
Torsional Shear	90	5×10^{-4}	332	351	382	330	355	392
	115	1×10^{-3}	336	354	385	335	352	386
	140	5×10^{-3}	333	357	390	335	354	389
	165	1×10^{-2}	337	356	388	335	356	388
	190	5×10^{-2}	341	361	392	340	361	394
			@18Hz			@18Hz		
High-Amplitude	195	5×10^{-4}	501			501		
Resonant Column	200	1×10^{-3}	499			494		
	205	5×10^{-3}	492			497		
	210	1×10^{-2}	499			495		
	215	5×10^{-2}	498			494		

* Specimen: TU-900, Diameter = 2.8 in., Length = 5.6 in.; σ_o = 8 psi, T = 74° F
▽ Time since application of isotropic confining pressure
△ Trial 2 was performed two days after trial 1

TABLE 2 SUMMARY OF YOUNG'S MODULUS AND POISSON'S RATIO MEASUREMENTS PERFORMED STATICALLY

Material	Axial Stress σ_a (psi)	Axial Strain* ε_a (10^{-3}%)	Young's Modulus E (psi)	Poisson's Ratio ν
TU-700	0.10	6.1	1698	0.47
	0.22	13.1	1672	0.48
	0.33	20.1	1666	0.48
	0.84	50.2	1680	0.48
	1.35	81.0	1672	0.48
	1.86	111.0	1677	0.48
	2.37	142.0	1671	0.48
	2.88	172.0	1668	0.48
	3.39	204.0	1666	0.48
	3.90	235.0	1664	0.48
TU-900	0.23	3.5	6562	0.48
	0.74	11.3	6544	0.49
	1.25	19.1	6549	0.50
	1.76	26.9	6546	0.50
	2.27	34.7	6539	0.50
	2.78	42.6	6526	0.50
	3.29	50.6	6512	0.50
	3.80	58.5	6498	0.50
	4.31	66.5	6485	0.50
	4.82	74.5	6473	0.50
	5.45	84.5	6454	0.50
	6.08	94.2	6454	0.50
	6.71	104.0	6458	0.49
	7.34	114.0	6452	0.49
TU-960	0.51	1.6	32903	0.48
	1.02	3.1	32983	0.47
	1.53	4.6	32992	0.48
	2.04	6.2	32771	0.48
	2.55	7.8	32661	0.47
	3.06	9.4	32458	0.47
	3.57	11.1	32242	0.47
	4.08	12.7	32145	0.47
	4.59	14.3	32104	0.47
	5.22	16.3	32015	0.47
	5.85	18.3	31880	0.47
	6.48	20.3	31882	0.47
	7.11	22.4	31759	0.46

* Measurements were performed about 1 minute after applying each load
Tested at 74° F

Static Material Properties

Axial stresses ranging from 0.10 to 7.34 psi were applied to each unconfined specimen. Axial and radial deformations were measured for each load. Static Young's moduli and Poisson's ratio were determined on the basis of those measurements. The results are given in Table 2 and Figure 5. Static values of Young's modulus at small strains for the soft, medium, and hard specimens are 1,670, 6,550, and 32,300 psi, respectively. Less than a 2 percent decrease in modulus for the soft and medium specimens (TU-700 and TU-900) was found, and less than a 4 percent decrease in modulus for the hard specimen (TU-960) also was found over the time and strain ranges in the tests. The small decreases in modulus may be due to creep and nonlinear behavior or both. However, the small decrease is inconsequential for the cyclic M_R testing, as will be discussed in the next sections. Average values of Poisson's ratio for the soft, medium, and hard specimens are 0.48, 0.50, and 0.47, respectively. Only small variations exist between values of Poisson's ratio determined at the different loads. Those results show that the urethane behaves fairly linearly at small static strains (axial strains less than about 0.3 percent). Stress-strain properties of various urethanes cited in the literature (*5*) are based on large strain elongation tests. Plastic deformation in those elongation tests occurs above strains of 1 percent.

Effect of Isotropic Confining Pressure

As was outlined earlier, shear modulus was determined with resonant column and torsional shear tests at several confining pressures. Young's modulus E was then derived from Equation 5. The influence of isotropic confining pressure on small-strain Young's modulus for the three urethane specimens is shown in Figure 6. All moduli measurements were performed at an equivalent axial strain of about 6.7×10^{-4} percent after 50 min at each pressure. Moduli corresponding to zero confining pressure are not presented owing to the use of the log-log plot. However, essentially the same moduli were measured at zero confining pressure.

Average Young's moduli determined by the resonant column method for the soft, medium, and hard specimens are 2,430, 10,070, and 52,000 psi, respectively. Note that Young's moduli determined by the resonant column method are greater than those determined by static testing. This difference is due to the effect of loading frequency, which will be discussed.

Moduli measured at different confining pressures varied by less than 3 percent for each specimen. On the basis of those

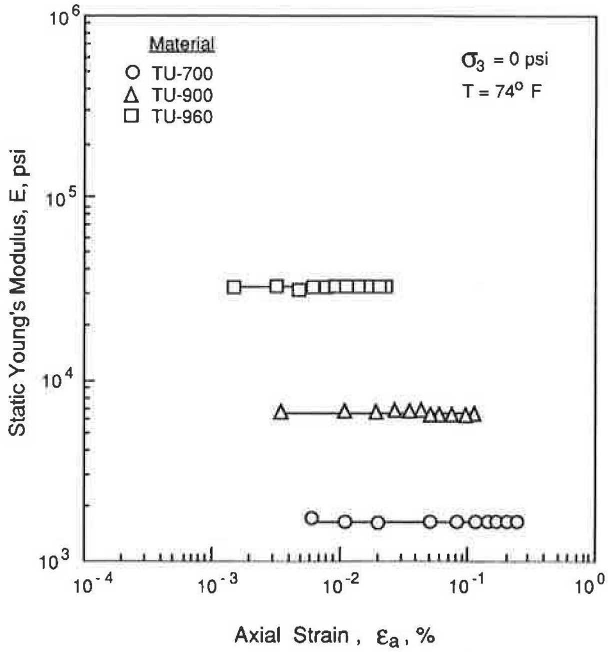


FIGURE 5 Variation in static Young's modulus with axial strain from unconfined compression tests.

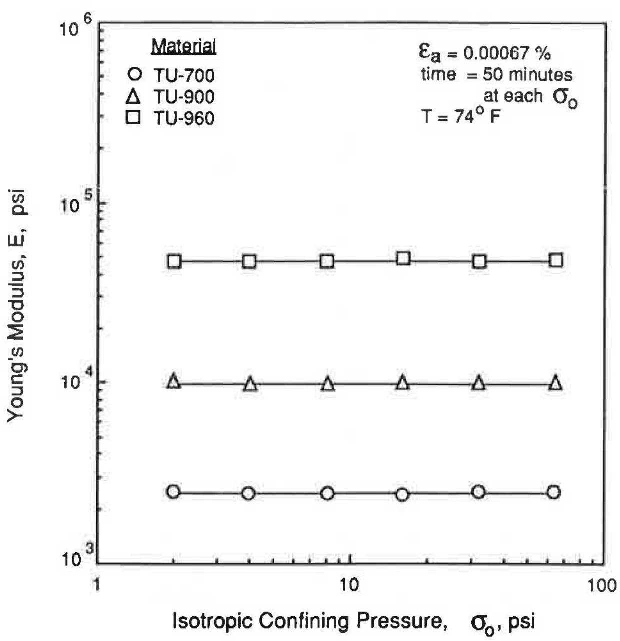


FIGURE 6 Variation in small-strain Young's modulus with isotropic confining pressure determined by resonant column tests.

results and similar results obtained with the torsional shear method, the stiffness of the urethane specimens can be assumed to be independent of confining pressure, at least for pressures between 0 and 64 psi and for measurements performed at room temperature (~ 74°F).

Effect of Strain Amplitude

Resonant column tests were performed at shearing strain amplitudes ranging from 0.0005 to 0.3 percent. Shearing strains were converted to equivalent axial strains, using Equation 6. Poisson's ratios determined from static testing were used. Figure 7 presents the resonant column test results performed at zero confining pressure with the three specimens. As is seen in the figure, the modulus is essentially constant over the range of strains tested. The small amount of creep and nonlinear behavior or both observed under static loading had no effect on the modulus measured dynamically.

To obtain a perspective on how the strains used in those tests compare with those generated in M_R testing, the range in strains in the M_R test are presented in Figure 8 for materials with stiffnesses ranging from 1,000 to 100,000 psi. In this figure, a range in cyclic axial stress of 1 to 20 psi has been used to calculate the strains. The data presented in Figure 7 for the synthetic specimens have also been included. The strains used in resonant column testing of the medium and stiff urethane specimens completely extend over the strain range generated by following the AASHTO T274-82 M_R testing procedure. The strains used in resonant column testing of the soft urethane specimen extend over about half of the strain range in M_R testing. Therefore, the specimens have been calibrated over the proper strain range.

Note that the wide range in strains generated in the M_R test as the material changes from a stiff to a soft soil, as is shown in Figure 8. Strain is a key variable in predicting soil (subgrade) behavior (*10*), and a very stiff subgrade loaded with $\Delta\sigma$ = 1 psi should be expected to behave essentially linearly if $\varepsilon_a \sim 0.001$ percent. A very soft subgrade will behave very nonlinearly under the same cyclic stress because the strain will be on the order of 20 to 50 times greater.

Torsional shear tests were also performed at similar strain amplitudes to demonstrate the effect of strain amplitude at frequencies other than resonance. Those data are shown in Figure 9 for one specimen with the resonant column data also included. As is seen in the figure, Young's modulus of ure-

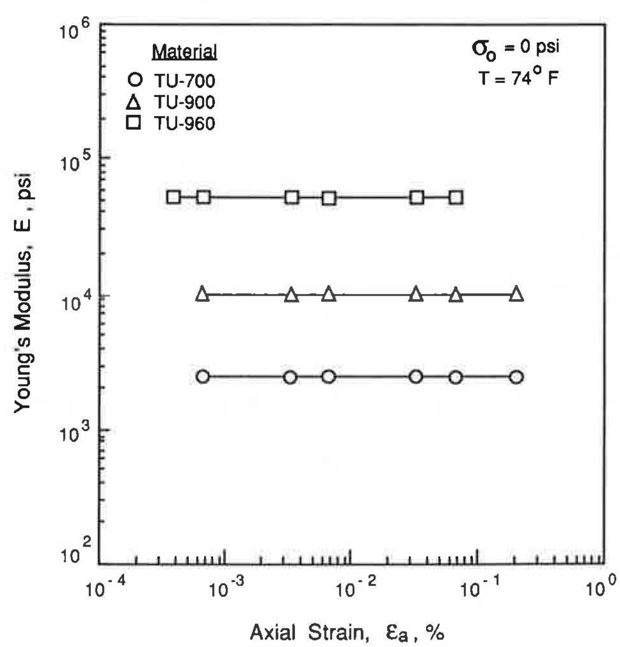


FIGURE 7 Variation in Young's modulus with axial strain as determined by resonant column testing at zero confining pressure.

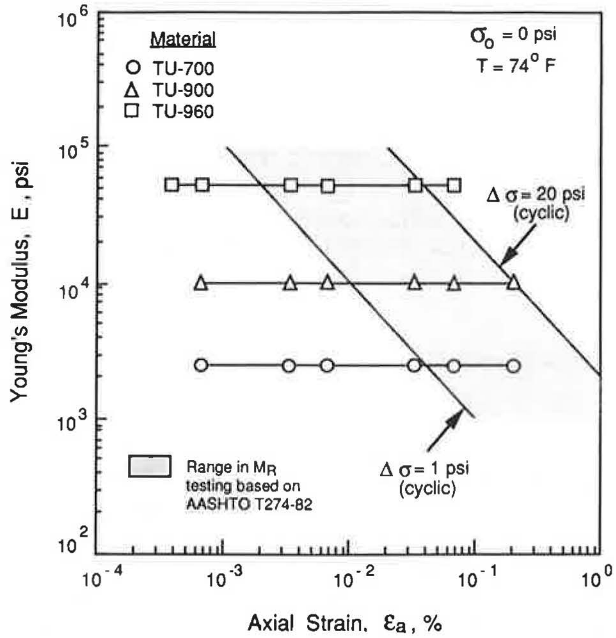


FIGURE 8 Comparison of axial strains generated in M_R testing with those generated in calibrating the synthetic specimens.

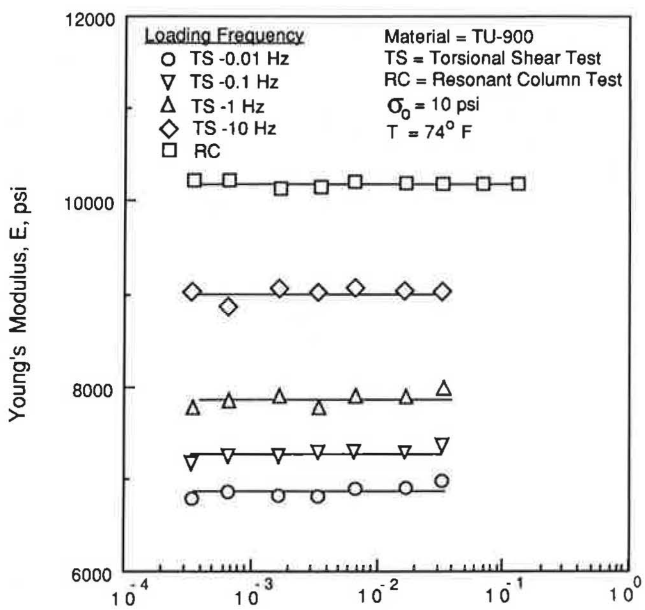


FIGURE 9 Variation in Young's modulus with axial strain for specimen TU-900 tested at various loading frequencies.

thane is independent of strain amplitude at a given excitation frequency. However, it is dependent on loading frequency.

Effect of Loading Frequency

The effect of frequency can be easily evaluated by using a combination of resonant column and torsional shear tests. Moduli determined by the resonant column test are based on first-made resonant frequency, which depends on the stiffness of the specimen and the mass moment of inertia of the drive plate. For the soft, medium, and stiff specimens, resonant frequencies were 27, 56, and 127 Hz, respectively. Loading frequency in the torsional shear test can be easily varied by changing the input frequency.

Moduli determined by the resonant column and torsional shear tests at various loading frequencies and strain amplitudes are plotted in Figure 10. Note that Young's modulus increases with increasing loading frequency but is independent of strain amplitude. Values of static Young's modulus are also shown in Figure 10. Static moduli are very close to the moduli determined at a loading frequency of 0.01 Hz. This comparison shows the consistency between Young's modulus derived from static measurements and from the torsional shear test, also suggesting that appropriate values of Poisson's ratio were measured.

All moduli shown in Figure 10 are presented in a normalized fashion in Figure 11 by using the modulus of each specimen determined at 0.01 Hz as the basis for normalization. Note that the effect of frequency on modulus is essentially the same for each specimen.

Effect of Temperature

The effect of temperature on the urethane specimens is presently under investigation. To date, only one specimen has been tested at temperatures other than room temperature, 74°F. Moduli determined for this specimen (TU-900, 2.0-in. diameter) at three temperatures, various loading frequencies, and four strain amplitudes are plotted in Figure 12. Average Young's moduli determined by the resonant column method for temperatures of 61°, 74°, and 85°F are 10,400, 9,770, and

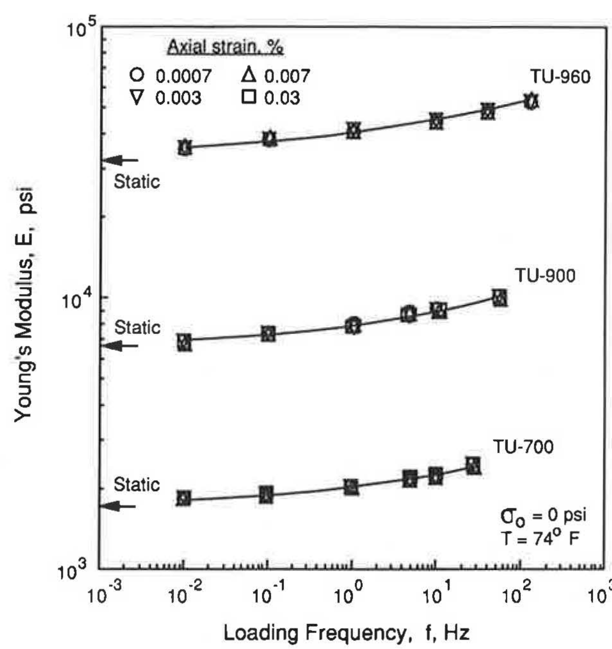


FIGURE 10 Variation in Young's modulus with axial strain amplitude and loading frequency as determined by cyclic torsional and resonant column tests at zero confining pressure.

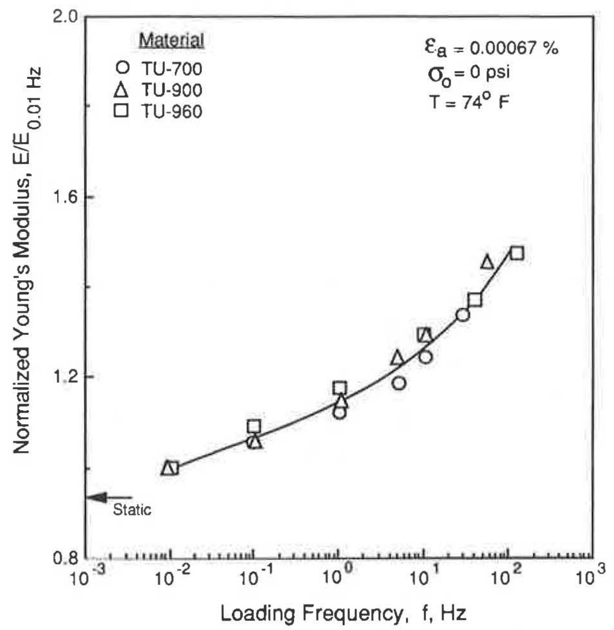


FIGURE 11 Variation in normalized Young's modulus with loading frequency as determined by cyclic torsional tests.

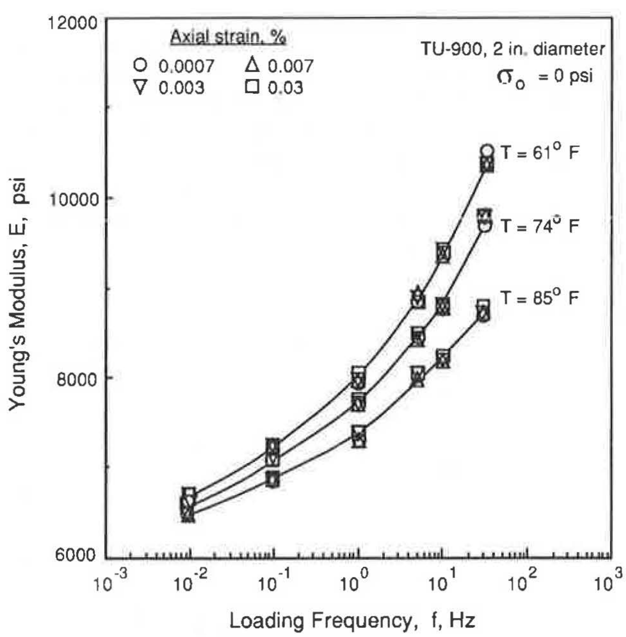


FIGURE 12 Variation in Young's modulus with temperature for specimen TU-900 tested at various loading frequencies.

8,720 psi, respectively, which reflects about an 0.8 percent change in modulus for each degree (1°F) change. The resonant frequency of the test specimen for this temperature range varied from 29.5 to 32 Hz. The effect of temperature decreased with slower loading frequencies. The change in modulus was less than 0.2 percent per degree (1°F) change at a loading frequency of 0.01 Hz. Those results provide a preliminary temperature correction factor that should be applied when using the specimens to calibrate M_R equipment at temperatures other than 74°F.

The rate at which the urethane specimens regain strength after being heated and then cooled has yet to be studied. Studies on polyurethane (*5*) have shown the rate at which strength is to be regained will depend on the temperature, chemistry, and molecular structure. When the synthetic specimen was heated to 85°F and then was allowed to return to room temperature, after 2 days the modulus had only returned to 96 percent of its original strength. This suggests that exposing the specimens to large temperature changes, especially after calibration, should be avoided.

Relationship Between Material Stiffness and Hardness

A common index test used when selecting synthetic elastomers is durometer hardness. The soft, medium, and hard specimens calibrated in this study have durometer hardnesses of A72.5, A90.5, and D60, respectively. Those hardness values and corresponding static Young's modulus are plotted in Figure 13. The range in moduli shown in this plot is typical for uncemented highway subgrades. Thus, the relationship shown in Figure 13 could be very useful in the selection of future elastomeric calibration materials.

CONCLUSIONS

Cylindrical urethane specimens can be constructed with stiffnesses ranging from very soft subgrade to stiff uncemented base. Three representative materials have been tested, using axial compression, torsional resonant column, and torsional shear testing techniques. On the basis of initial laboratory tests, urethane can be considered to be a linear, viscoelastic material with stiffness characteristics independent of confining pressure, strain amplitude, and stress history. Those prop-

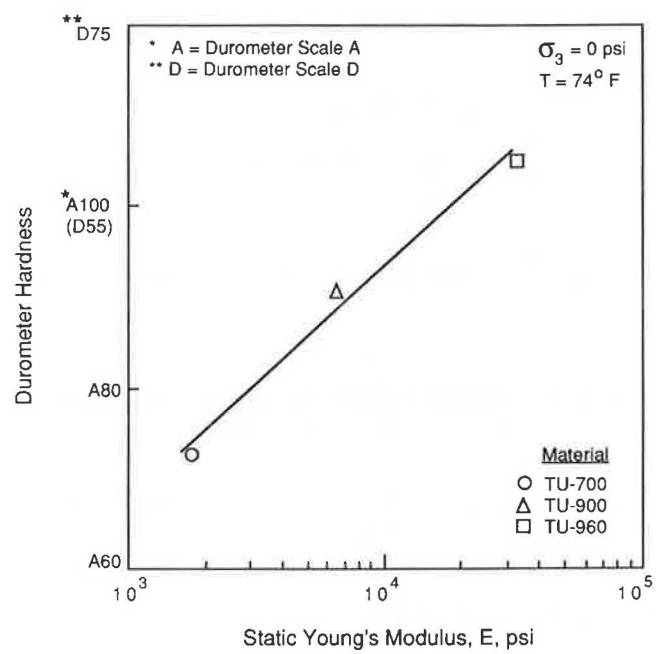


FIGURE 13 Relationship between static Young's modulus and durometer hardness.

erties make urethane a good material to construct calibration specimens that can be used in the evaluation of M_R equipment. Urethane stiffness is, however, dependent on loading frequency and temperature. Therefore, values of Young's modulus used to equate to M_R have to be selected at the appropriate frequency and temperature. Interestingly, the effect of loading frequency is similar for specimens of different stiffnesses and can be normalized to form a single curve.

Testing is presently underway that will characterize the urethane specimens further. Those investigations include the effects of large strains, long-term creep, biaxial and triaxial loading conditions, temperature, moisture, curing time, ultraviolet radiation, and specimen length and diameter. However, use of those has already been very beneficial in evaluations of M_R equipment (see paper by Claros et al. in this Record).

ACKNOWLEDGMENT

This work was supported by the Texas State Department of Highways and Public Transportation. The authors wish to express their appreciation for this support.

REFERENCES

1. *Resilient Modulus of Subgrade Soils*. AASHTO T274-82. American Association of State Highway and Transportation Officials, Aug. 1986, pp. 1157–1177.
2. R. S. Ladd, and P. Dutko. Small-Strain Measurements Using Triaxial Apparatus. *Proc., Advances in the Art of Testing Soils Under Cyclic Conditions*, ASCE, Detroit, Mich., Oct. 1985, pp. 148–165.
3. F. I. Makdisi, H. B. Seed, and I. M. Idriss. Analysis of Chabot Dam During the 1906 Earthquake. *Proc., Earthquake Engineering and Soil Dynamics*, ASCE, Geotechnical Engineering Division, Pasadena, Calif., Vol 2, June 1978, pp. 569–587.
4. T. S. Vinson. Fundamentals of Resilient Modulus Testing. Presented at the Workshop on Resilient Modulus Testing, Oregon State University, Corvallis, March 1989.
5. J. Bhattacharyya. Physical and Chemical Crosslinking of Polyurethane. In *Handbook of Polymer Science and Technology* (N.P. Cheremisinoff, ed.), Vol. 2, 1989, pp. 557–598.
6. V. P. Drnevich, B. O. Hardin, and D. J. Shippy. Modulus and Damping of Soils by the Resonant-Column Method. In *Dynamic Geotechnical Testing*, ASTM STP 654, American Society for Testing and Materials, Philadelphia, Pa., 1978, pp. 91–125.
7. Standard Test Methods for Modulus and Damping of Soils by the Resonant-Column Method. In *1987 Annual Book of Standards*, Vol. 04.08, ASTM D4015-87. American Society for Testing and Materials, pp. 507–525.
8. F. E. Richart, Jr., J. R. Hall, Jr., and R. D. Woods. *Vibrations of Soils and Foundations*, Prentice Hall, Englewood Cliffs, N.J., 1970.
9. M. L. Silver and T. K. Park. Testing Procedure Effects on Dynamic Soil Behavior. *Journal of the Geotechnical Engineering Division*, ASCE, Vol. 101, No. GT10, Oct. 1975, pp. 1061–1083.
10. B. O. Hardin and V. P. Drnevich. Shear Modulus and Damping in Soils: Measurement and Parameter Effects. *Journal of the Soil Mechanics and Foundations Division*, ASCE, Vol. 98, No. SM6, June 1972, pp. 603–624.

Publication of this paper sponsored by Committee on Soil and Rock Properties.