Determination of Resilient Modulus of Subgrades Using Bender Elements

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Resilient moduli of subgrades are becoming important input parameters in mechanistic pavement design. As such, test methodologies have been introduced by many highway agencies to estimate this parameter. These tests require several hours to perform. Therefore, only a small number of specimens can be tested for a given project. An alternative for rapidly determining the resilient modulus of subgrade soils—bender elements—is presented. Bender elements are thin sheets of piezo-ceramic material which are inserted in a specimen. When subjected to appropriate electric current, a Bender element bends and couples seismic energy to the specimen. A bender element can also be used to detect the coupled energy since it converts movement to voltage. For convenience, the end caps of a regular static triaxial test set-up can be retrofitted with a set of transmitting and receiving bender elements. The data reduction, which comprises of determining the arrival time of the seismic energy, is simple and can be carried out during the test. The limitation of the device is that the deviatoric stress cannot be varied and as such moduli at low strain levels are measured. Therefore, this method can be utilized parallel to resilient modulus tests when a large number of specimens of a similar subgrades has to be tested. Based on tests on over 30 different specimens, the bender elements can feasibly provide resilient moduli of subgrade materials at a fraction of time and at significantly lower investment in initial equipment costs. The bender element tests can be a compliment to the resilient modulus test systems.

In recent years, resilient modulus testing has gained tremendous popularity. This increased interest has been attributed to the American Association of State Highways and Transportation Officials (AASHTO) design procedure adopted in 1986. In the design procedure, the resilient modulus of subgrade soil is considered as one of the most important design parameters.

In general, the actual testing consists of more than a dozen loading steps. At each step either the confining pressure and/or the deviatoric stress is changed. The procedure requires tests at several confining pressures (ranging from 21 to 140 kPa for AASHTO) and several deviatoric stresses (ranging from 21 to 280 kPa for AASHTO). At each step, the specimen is subjected to a large number of cycles (100 cycles for AASHTO). The applied load, F, and the resulting resilient deformation of the specimen, δ, are measured for the last five cycles. Knowing these two parameters as well as the cross-sectional area, A, and the height of the specimen, L, the resilient modulus, M_R, can be determined from

$$M_R = (F/A)/(\delta/L) \quad (1)$$

The test period for one specimen is approximately 3 hr. In addition the specimen preparation requires another 30–60 min.

The required equipment to perform resilient modulus tests is quite sophisticated and costly to acquire. A typical testing system consists of a closed-loop servo-valve system retrofitted with a triaxial cell, accurate load cells and linear variable differential transformers.

The use of piezo-ceramic bender elements in determining the dynamic properties of soil specimens in the geotechnical engineering area is becoming more popular (*1–4*). To respond to the level of interest, an ASTM subcommittee is developing standard procedure for this tests. Testing with the device is free from complicated data reduction procedures, is cost effective as well as rapid to perform.

The main limitation of the bender elements is that they yield moduli at low strain levels (less than 0.001 percent). Therefore, resilient modulus tests should still be carried out on the new subgrade specimens to determine their constitutive models. As done in the geotechnical engineering field, once the constitutive model for a given subgrade is developed, one can test similar subgrade soils with the bender elements as a rapid method for characterizing the variation in the moduli along a pavement or a highway.

Extrapolating the low-strain moduli from the bender elements to higher strain levels induced in the pavement is rather challenging. The study presented here is a feasibility study and as such does not address this important matter. However, this challenge with reasonable level of success has been addressed in geotechnical earthquake engineering [see Academy of Sciences (*5*) for an overview]. In that approach for a given soil, the variation in modulus with strain is normalized with respect to the modulus at a reference strain through comprehensive laboratory tests (resilient modulus in our case). This normalized curve, along with moduli from other test methods (bender elements in our case), are then combined during the analysis stages of the mechanistic pavement design.

DESCRIPTION OF BENDER ELEMENT DEVICE

The bender elements have been mounted and used in various laboratory apparatus to measure shear or Young's modulus of soils (*1–3*).

Dyvik and Madshus (*4*) determined the shear modulus of five different offshore clays. They found that shear moduli obtained from bender elements and a resonant column device were practically identical for a wide range of soil stiffnesses.

Thomann and Hryciw (*6*) installed the bender elements in a new device called the Bender Element-Oedometer (BEO) device. They tested fine sands (Ottawa 100–200) and Glacierway silt. The purpose of these tests was to determine the shear moduli measured by the bender element technique and compare them with those obtained from a resonant column device at at-rest condition. In addition, bender elements were incorporated in a BEO device to study the effects of soil anisotropy on the small strain shear modulus.

A triaxial device incorporating bender elements was used in this research. A schematic of the device is shown in Figure 1. The

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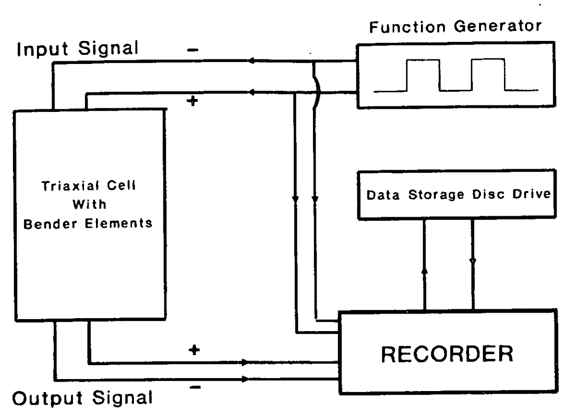
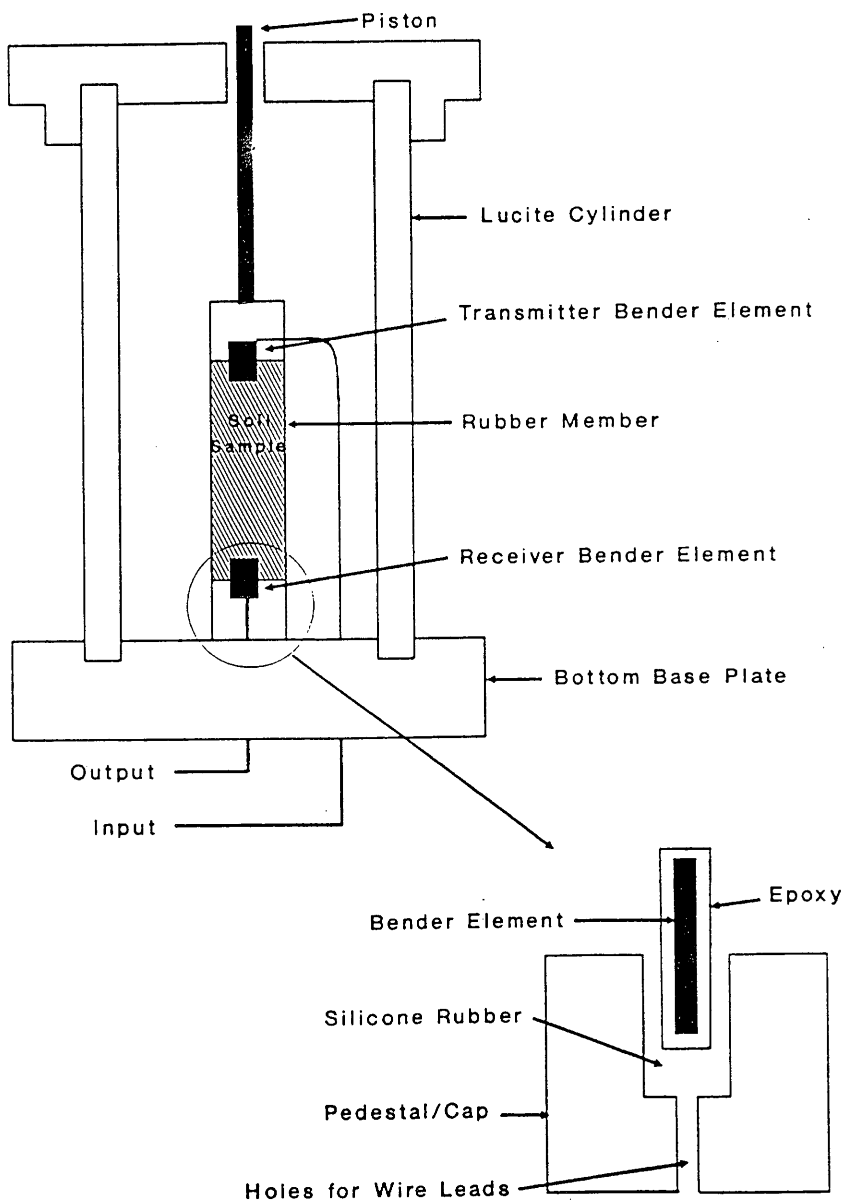


(*a*)



(*b*)

FIGURE 1(*a*) Schematic diagram shows assembled testing devices. (*b*). Schematic of bender elements installed in triaxial device.

receiver and transmitter bender elements were placed in the bottom and top caps of a triaxial device. The two end caps were specially designed and machined to accommodate the elements. The slots were then filled with silicone rubber and wire leads were run through the drainage holes in the bottom base plate of the triaxial cell. The elements were fixed in the caps such that at least two-thirds of their lengths were cantilevered. The cantilevered portion was inserted in the soil specimen to be tested. The triaxial load frame was used to apply very small seating loads to keep the specimens and the end caps in contact.

The major parameter measured with the bender elements is the travel time of seismic waves (especially shear waves) through the specimen along its longitudinal axis. Square wave pulses are applied to the transmitting element to couple body wave energy to one end of the specimen. The energy propagates within the specimen and is sensed by the receiving bender elements. A digital recorder was used to record the signals sensed by the receiving element. To enhance the quality of data recorded, tests were repeated 25 times, and their resulting signals were averaged. The signals were recorded at a sampling rate of 256 kHz which corresponds to an accuracy in travel time of approximately 2 μsec. As indicated by Baig (*7*), if the modulus of the material is less than 350 MPa, the modulus is known with an accuracy of better than 1.5 percent for a 150-mm long specimen. This level of accuracy is only due to travel time, and other factors such as mismeasurement of the length of the specimen may contribute to less accurate results.

Typical input and output traces are shown in Figure 2. One input and two output signals are shown. The two output signals correspond to two separate tests and are obtained by changing the polarity of the input voltage. When the polarity of the input is changed, the polarity of the propagated wave changes as well. The two outputs can be combined to minimize the ambiguity in the identification of the arrival time. The input record simply corresponds to the rise of the signal from zero to a maximum of about 10 volts. Some

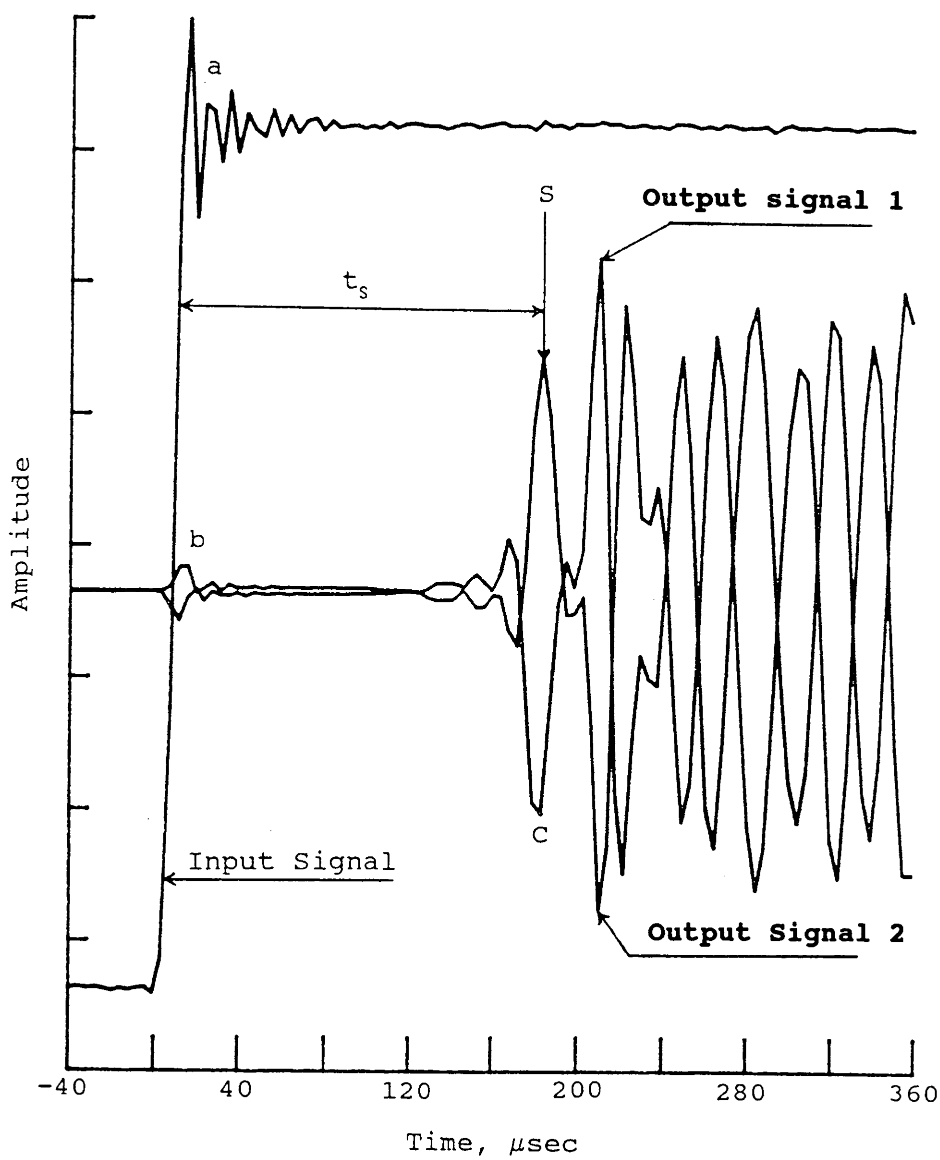


FIGURE 2 Typical input and output signals.

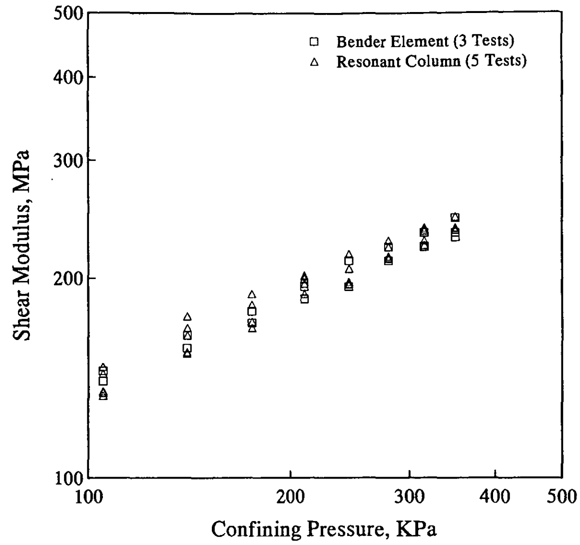


FIGURE 3 Comparison of shear modulus results from bender elements and resonant column device.

reverberation, marked *a* in the input signal is due to the nature of the wave generator.

The two output signals, aside from change in polarity, are similar. Before point *b*, the output is quiet and close to zero. This corresponds to pre-triggering events. At point *b*, some leakage of the input signal, probably through the recorder, occurs. This point coincides with the rise in the input. Point *S*, corresponds to the arrival of the shear wave. Therefore, the travel time, *t*[itinf]s[r], is the time interval between the rise of input record and Point *S*.

The shear modulus, *G*, can be calculated as follows.

$$G = (L/t_s)^2 \times \rho \quad (2)$$

where ρ is mass density, and *L* is the tip-to-tip spacing between the transmitting and receiving bender elements.

Young's modulus, *E*, can be easily calculated by assuming a Poisson's ratio, ν, for the specimen using:

$$E = 2G(1 + \nu) \quad (3)$$

In the present study, a Poisson's ratio of 1/3 was assumed for calculation of Young's modulus.

ACCURACY AND PRECISION

To determine the accuracy and precision of the bender elements setup used in this study, a series of test were carried out (*8*). A summary of the results are presented here.

Variations between moduli obtained with the resonant column and bender elements with confining pressure are compared in Figure 3. Resonant column tests are well established in the geotechnical-earthquake engineering area and are considered one of the most reliable and accurate methods for determining moduli of soils specimens (*9,10*).

The variation in modulus with confining pressure from three entirely different tests with the bender elements and five resonant column tests are shown in Figure 3. The results from the three bender element tests are quite similar. Based on more than 50 tests on sands and clays, Nazarian and Baig (*8*) reported that the precision (repeatability) of the bender element tests is better than 5 percent.

The moduli obtained with the resonant column device and the bender elements are typically within ±6 percent for most soils. Therefore, one can confidently utilize the bender elements to obtain accurate moduli.

PRESENTATION OF RESULTS

Test Program

To evaluate the feasibility of utilizing bender elements in determining the resilient modulus of subgrades, a test program was developed. A sand and a clay resident to El Paso, Tex., were selected. The index properties of these two materials are reported in the next section. Four different proportions of sands and clays were mixed to obtain a wide variety of compositions. The different proportions tested are presented in Table 1. The percentage of clay in different specimens varied from 30 to 90 percent. For each mixture, tests were carried out at three nominal water contents—optimum, 2 percent wet of optimum, and 2 percent dry of optimum. Tests were repeated two or three times for each mixture and at each water content to evaluate the repeatability.

A given specimen was first tested using the conventional resilient modulus tests following a modified version of the AASHTO T-274 protocol (*11*). The same specimen was then carefully transferred to the triaxial cell that contained the bender elements and tested at confining pressures of 14, 28, and 42 kPa, respectively. The results were then directly compared as discussed later in this report.

TABLE 1 Total Quantity of Specimens Tested

Specimen Composition (percent)		Number of Specimens		
Clay	Sand	2% Dry of Optimum	Optimum	2% Wet of Optimum
90	10	3	3	3
70	30	3	3	3
50	50	2	3	3
30	70	2	2	2

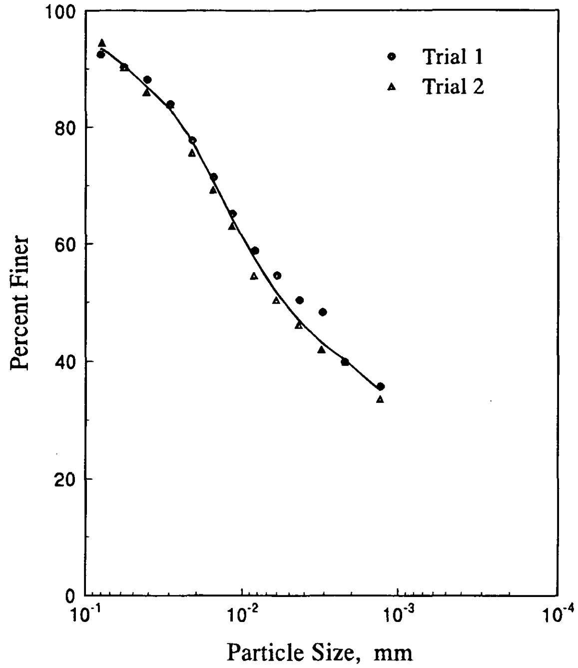


FIGURE 4 Grain size distribution for clay.

The main two modifications made to AASHTO T-274 are (*11*) fewer number of load repetition at each sequence (i.e., 25 cycles as opposed to 100 cycles for AASHTO), and less destructive loading sequence (i.e., smaller ratios of the deviatoric stress to confining pressure). Nazarian and Feliberti (*11*) indicated that the modified test program minimizes the degradation of the specimen due to the previous loading history.

Index Properties of Materials

The grain size distribution of the clay is shown in Figure 4. The Atterberg limits were also obtained. The liquid limit and plasticity limit were 44.1 and 20.5 percent, respectively. The plasticity index is therefore 23.6 percent. Based on the Atterberg limits and gradation, the clay was classified as "CL" in the Unified Soil Classification System (USCS) and A-7-6 according to the AASHTO Classification System. The maximum dry density of the clay using the standard Proctor method was 11699 kg/m^3 and the optimum water content was 16.0 percent.

The sand was first sieved. Only the fraction passing no. 40 sieve and retained on no. 60 sieve was utilized to minimize segregation. The maximum and minimum densities of the sand were 11713 and 11494 kg/m^3, respectively. The sand was classified as SP in the USCS and A-3 in the AASHTO Classification System.

As indicated before, the specimens tested were composed of a mixture of the sand and clay above. The Atterberg limits and Proctor moisture-density tests were performed on each mixture. The liquid limit, plastic limit, and plasticity index for each mixture are reported in Table 2. As expected, as the clay content increases the

TABLE 2 Index Properties of Sand-Clay Mixtures

Mixtures Clay(percent)/ Sand (percent)	Liquid Limit (percent)	Plastic Limit (percent)	Plasticity Index (percent)	Classification (AASHTO/USCS)	Maximum Density (Kg/m^3)	Optimum Moisture Content (percent)
100/0	44.7	20.5	24.2	A-6/CL	1699	16.0
90/10	37.5	18.6	18.9	A-6/CL	1953	18.4
70/30	30.5	16.3	14.2	A-6/CL	1696	16.9
50/50	23.2	15.7	7.5	A-6/ML-CL	1791	15.2
30/70	17.3	13.8	3.5	A-2-4/SC	1837	10.3
0/100	--	--	Non Plastic	A-3/SP	1697	--

-- not applicable

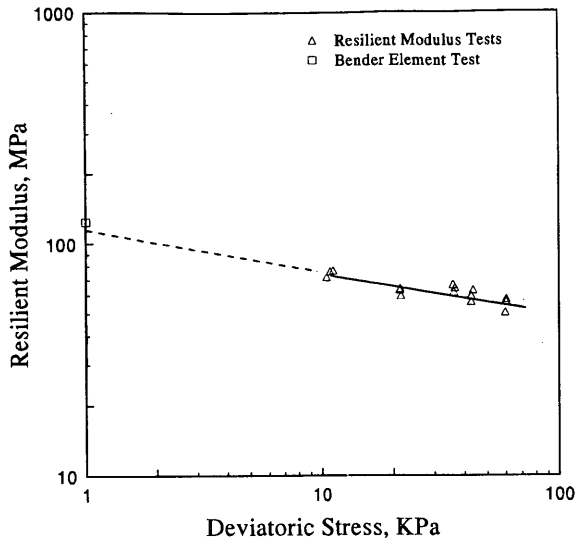


FIGURE 5 Variation in resilient modulus with deviatoric stress for a 90 percent clay-10 percent sand specimen.

liquid limit significantly increases, whereas the plastic limit only slightly increases.

The optimum moisture content and maximum dry density for each mixture are also shown in Table 2. As the clay content increases (up to a clay content of 70 percent) the maximum dry density decreases and the optimum water content increases. However, for a clay content of 90 percent, the maximum dry density sharply increases.

Resilient Modulus

A typical variation in modulus with deviatoric stress from resilient modulus tests for a mixture of 90 percent clay and 10 percent sand at optimum moisture content is shown in Figure 5. There is not much scatter in the data. At each deviatoric stress, the variation in modulus is due to the variation in confining pressure. This trend more or less held true for the remaining mixtures (*12*).

Data obtained from bender element tests on identical specimen are also incorporated in Figure 5. These data were arbitrarily plotted at a deviatoric stress of 1 kPa, given the low deviatoric stresses exerted to the specimen. The results from the two techniques are in relatively good agreement.

A typical graph of variation in resilient modulus with clay contents for various sand-clay mix specimens are presented in Figure 6.

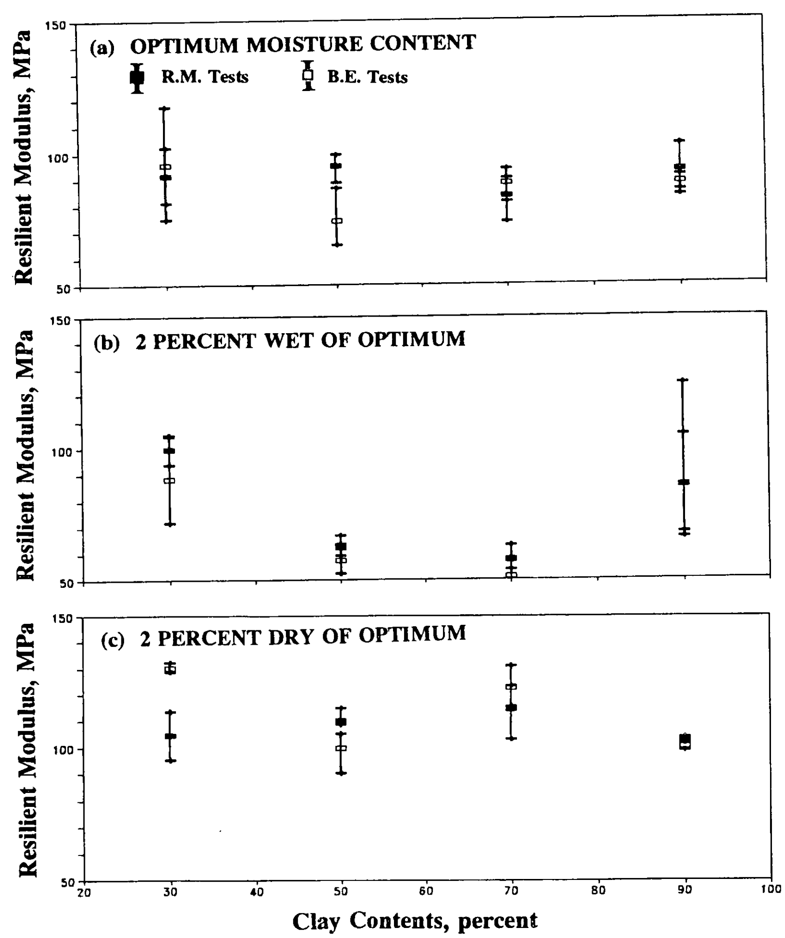


FIGURE 6 Variations in resilient modulus with clay content from resilient modulus and bender element tests.

Figures 6a, 6b, and 6c illustrate results for specimens prepared at optimum moisture content, 2 percent wet of optimum moisture content and 2 percent dry of optimum moisture content, respectively. The extreme values as well as the average resilient moduli are plotted for the three specimens tested at three confining pressures and different deviatoric stresses. The abbreviation R.M. is for resilient modulus, whereas B.E. is for bender elements in Figure 6.

Some scatter in the data is evident. The reasons for the scatter are several, and typically deal with the inherent problems with both testing techniques. With the bender elements, the major problems during these tests were: 1) the difficulty with inserting the bender elements into the specimen (especially for the specimens prepared at the dry of optimum, 2) inability to control the dynamic deviatoric stresses, and 3) the possibility of misestimating Poison's ratio.

The major problem with the resilient modulus tests is the typical levels of repeatability associated with the testing protocol. A repeatability of better than 10 percent is difficult when the specimen is not grouted (*12*). The major reason for the variability is the differences in the uniformity between the specimens tested for each mix due to difficulties in maintaining the uniformity in compaction.

One other factor ignored during this study is that the specimens were tested with the bender elements after they had already subjected to a stress history during the resilient modulus tests. As indicated above, studies performed by Nazarian and Feliberti (*11*) indicated that this parameter should not be of great significance if their proposed loading sequence is followed. However, it would have been desirable to verify this.

Comparison of Results

The results from all tests are compared in Figure 7. Moduli obtained from resilient modulus tests at a given confining pressure are plotted on the x-axis and the moduli obtained from the bender elements at the same confining pressure are plotted on the y-axis. The line-of-equality and the best-fit line are also plotted on the same graph. In addition, the 95 percent confidence interval lines are also

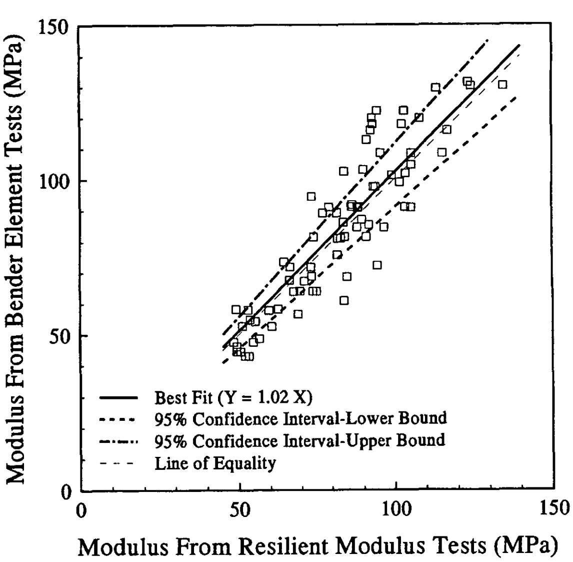


FIGURE 7 Comparison of resilient moduli obtained from resilient modulus and bender element techniques.

included. Moduli obtained from the two techniques are comparable. The best-fit line follows the line of equality fairly well. As indicated in the figure, the slope of the best fit line is about 1.02. This can be interpreted that in general the results are in reasonable agreement.

The 95 percent confidence interval lines bound the best-fit line with a relatively narrow band. The slope of the lines for lower and upper bounds are 0.91 and 1.11, respectively. This may be an indication that in most cases the bender elements can predict the resilient modulus of a specimen with sufficient and reasonable accuracy.

SUMMARY AND CONCLUSIONS

This report contains a technique for rapidly determining the resilient modulus of subgrades. The resilient modulus determined with bender elements is only a function of travel time of body waves within the specimen and does not depend on several parameters as in other conventional methods. More tests are necessary to draw any definite conclusions.

Based on this study, the following conclusions can be drawn:

1) With the bender elements, the resilient modulus of subgrades can be predicted with a reasonable accuracy.

2) The method is cost-effective when resilient modulus values are needed for a large number of specimens in a short turn-around time.

3) The results obtained from both methods were in reasonably good agreement. Some variation in moduli are found due to various limitations related to both methods.

ACKNOWLEDGMENT

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REFERENCES

1. Shirley, D. J., and L. D. Hampton. Shear Wave Measurement in Laboratory Sediments. *Journal of the Acoustical Society of America*, Vol. 63, No. 2, 1978, pp. 607–613.
2. Schultheiss, P. J. Simultaneous Measurements of P & S Wave Velocities During Conventional Laboratory Soil Testing Procedures. *Marine Geotechnology*, Vol. 4, No. 4, 1981, pp. 343–367.
3. Hamdi, F., and D. T. Smith. The Influence of Permeability on Compressional Wave Velocity in Marine Sediments. *Geophysical Prospecting*, No. 30, 1982, pp. 622–640.
4. Dyvik, R., and R. Madshus. Lab Measurement of G_{max} Using Bender Elements. In *Advances in the Art of Testing Soils under Cyclic Conditions* (V. K. Khosla, ed.), American Society of Civil Engineering, New York, NY, 1985.
5. Academy of Sciences. *Liquefaction of Soils during Earthquakes.* National Academy Press, Washington, D.C., 1985.
6. Thomann, T. G., and R. D. Hryciw. Laboratory Measurement of Small Strain Modulus under K_0 Conditions. *Geotechnical Testing Journal*, Vol. 13, No. 2, 1990, pp. 97–105.
7. Baig, S. *Evaluation of Piezo-Ceramic Bender Elements for Measuring Low-Amplitude Shear Modulus of Various Soils.* Master's thesis. The University of Texas at El Paso, Tex.
8. Nazarian, S., and S. Baig. Evaluation of Bender Elements for Use with Coarse-Grained Soils. In *Third International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics*, St. Louis, Mo., Vol. 1, 1995, pp. 89–94.

9. Drnevich, V. P. Recent Developments in Resonant Column Testing. Presented at Annual Meeting of the American Society of Civil Engineering, Detroit, Mich., October 1985, 29 pp.
10. Isenhower, W. M., K. H. Stokoe, and J. C. Allen. Instrumentation for Torsional Shear/Resonant Column Measurement Under Anisotropic Stresses. *Geotechnical Testing Journal*, Vol. 10, No. 4, 1987, pp. 183–191.
11. Nazarian, S., and M. Feliberti. Methodology for Resilient Modulus Testing of Cohesionless Subgrades. *Transportation Research Record 1406*, TRB, National Research Council, Washington, D.C., 1994, pp. 108–115.
12. Feliberti, M., S. Nazarian, and T. Srinivasan. *Critical Evaluation of Parameters Affecting Resilient Modulus Tests of Subgrades*. Research Report 1177-2, Center for Geotechnical and Highway Materials Research, The University of Texas at El Paso, Texas.

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