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Evaluation of Bender Elements for Use with Coarse-Grained Soils

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SYNOPSIS The feasibility of using piezo-ceramic bender elements for measuring shear modulus of coarse materials has been reported. If was found that moduli obtained from bender element are repeatable. The results in most cases compare favorably with those obtained by resonant column.

INTRODUCTION

The piezo-ceramic bender elements (B.E.) are becoming quite popular in testing fine-grained sands and clays. Little effort has been focussed on evaluating its limitations with respect to the size and shape of the aggregates, the ranges of density, and the state of stress under which the technique can be used.

A series of tests was performed on different types of sands to investigate the limitations of the bender element technique. Three sands — medium coarse angular, medium coarse round, and coarse angular — were utilized. In addition, perfectly round coarse glass beads were tested. The relative density was typically varied from zero to 100 percent.

The repeatability of results were studied by repeating each experiment several times. The accuracy was evaluated by comparing the moduli obtained by the bender elements with those measured with the resonant column (R.C.) device.

The third aspect considered was the relationships between the moduli measured with the bender elements and empirical relationships previously established in the literature.

BACKGROUND

The bender elements have been mounted and used in various laboratory apparatus to measure shear wave velocities of different soils (Shirley and Hampton, 1978; Dyvik and Madshus, 1985; and Thomann and Hryciw, 1990). However, the feasibility of using bender elements in coarse sands has not been reported in the literature.

Most empirical relationships relate the modulus with the state of stress, void ratio, and strain amplitude. Hardin and Drnevich (1972), amongst other investigators, indicated that a linear-logarithmic relationship (with a slope of approximately 1/2) exists between shear modulus and effective isotropic stress.

Several researchers have proposed empirical relationships for determining shear modulus of sands. Hardin (1978) recommended

$$G_{max}=\frac{A(OCR)}{F(e)}\sigma_o^n P_a^{1-n} \qquad (1)$$

where $F(e) = 0.3+0.7e^2$ (e is void ratio), A = 625, n = 0.5, and P_a = atmospheric pressure (in same units as G_{max} and σ_o').

Richart (1977) based upon tests on round sands and angular crushed quartz suggested

$$G_{max}=A\frac{(B-e)^2}{(1+e)}(\sigma_o')^{0.5} \qquad (2)$$

where A and B are material-related parameters.

Iwasaki and Tatsuoka (1977) recommended

$$G_{max}=A(\gamma)BF(e)(\sigma_o')^{m(\gamma)} \qquad (3)$$

$A(\gamma)$ and $m(\gamma)$ are a function of shear strain, γ, and B is about 1 for uniform clean sands for a wide range of grain sizes. F(e) equals $(2.17-e)^2/(1+e)$. G_{max} and σ_o' are in kg/cm^2.

TESTING PROGRAM

A triaxial device retrofitted with bender elements was used in this study. The receiver and transmitter bender elements were placed in the bottom and top caps of a triaxial device. The elements were fixed in the caps such that at least half 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 small seating loads to maintain contact between the specimen and the end caps. For details regarding testing setup refer to Baig (1991).

Three individual tests were performed on each type of sand having the same soil properties. All tests were conducted by first increasing the confining pressure, "loading", and then decreasing it, "unloading". Specimens were typically prepared at 0%, 10%, 30%, 50% and 100% relative densities.

PROPERTIES OF SANDS TESTED

The three sands tested were named M_A (medium angular), C_A (coarse angular) and M_R (medium round). The index properties for all sands are presented in Table 1. For the medium sands, the fraction that passed Sieve Number 20 (0.85 mm) and retained on Sieve Number 40 (0.425 mm) was used. Sand C_A was from the same stock as sand M_A, but the fraction passing sieve number 4 (4.75 mm) and retained on sieve number 10 (2.00 mm) was selected.

Square wave pulses were used to transmit body waves within the specimen between the transmitter and receiver bender elements. A digital recorder was used to record the signals. 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 1.95 μsec. If the modulus of the material is less than 50 MPa, the modulus is known with an accuracy of better than 2.5 percent.

The under-compaction method (Ladd, 1978) was used in preparing reconstituted specimens. The specimens were reconstituted directly on the bottom pedestal of the triaxial cell where the receiving bender element was installed.

Table 1 - Index Properties of Materials Tested

Material	Shape	Specific Gravity	Extreme Densities		Void Ratios	
			Min	Max	e_{min}	e_{max}
M_A	Angular	2.62	1473	1661	.56	.76
C_A	Angular	2.57	1418	1590	.60	.80
M_R	Round	2.57	1462	1684	.51	.74
Glass Beads	Round					

Glass beads were tested because a round coarse sand could not be found. All particles were reasonably round with a diameter of 4 mm. The maximum and minimum densities were reported as 1575 Kg/m^3 and 1416 Kg/m^3, respectively, which corresponds to minimum and maximum void ratios of 0.59 and 0.75 respectively.

DISCUSSION OF RESULTS

REPEATABILITY TESTS

As indicated before, three different specimens were tested at each relative density. For each series of tests, statistical analyses were conducted to determine the 95 percent confidence interval for the modulus. The repeatability in specimen preparation, testing, and data reduction can be assessed by inspecting the broadness of the confidence interval.

A typical graph, demonstrating the 95 percent confidence interval lines for a specimen of Sand M_A prepared at minimum density (zero percent) is shown in Fig. 1. Based upon the confidence intervals, small scatter in modulus values is observed in the loading sequence (see Fig. 1a). Similar trends were observed for specimens tested at other relative densities.

The amount of scatter in data was larger during the unloading sequence. The reason may be that the contact between the top cap and the specimen might have not been intimate during unloading. The load cell reading was closely monitored during the test. The axial load became less than the constant seating load for confining pressures below 350 KPa.

The variability in the results for various relative densities, as judged by the deviation between the average and the upper and lower bounds of 95 percent confidence intervals, were typically less than 2 and 5 percent for loading and unloading stages, respectively. As such, tests with bender elements on this material exhibit good repeatability.

Repeatability tests were also performed for sands C_A, M_R. The repeatability in the results obtained for these sands were similar to those for sand M_A reported above.

COMPARISON WITH RESONANT COLUMN (RC) TESTS

The results of this study were compared with those obtained from resonant column tests. The RC tests were repeated five times, and BE tests three times. Tests were only conducted at a relative density of 100 percent. The confining pressure was varied from 105 KPa to 350 KPa. Above a confining pressure of 350 KPa the specimen might deform to some extent which could affect the results from the resonant column device. Below a confining pressure of 105 KPa, the quality of data from resonant column tests was poor (see Almadhoun, 1991).

A typical comparison of the results from the two techniques for Sand M_A is presented in Fig. 2. The differences in shear moduli for sand M_A (medium angular) from the two techniques at various confining pressures were never greater than 6 percent (see Fig. 3). As such, the results are generally in good agreement. In addition, both devices yield quite repeatable results. The maximum coefficient of variation was about 5 percent for both test methods.

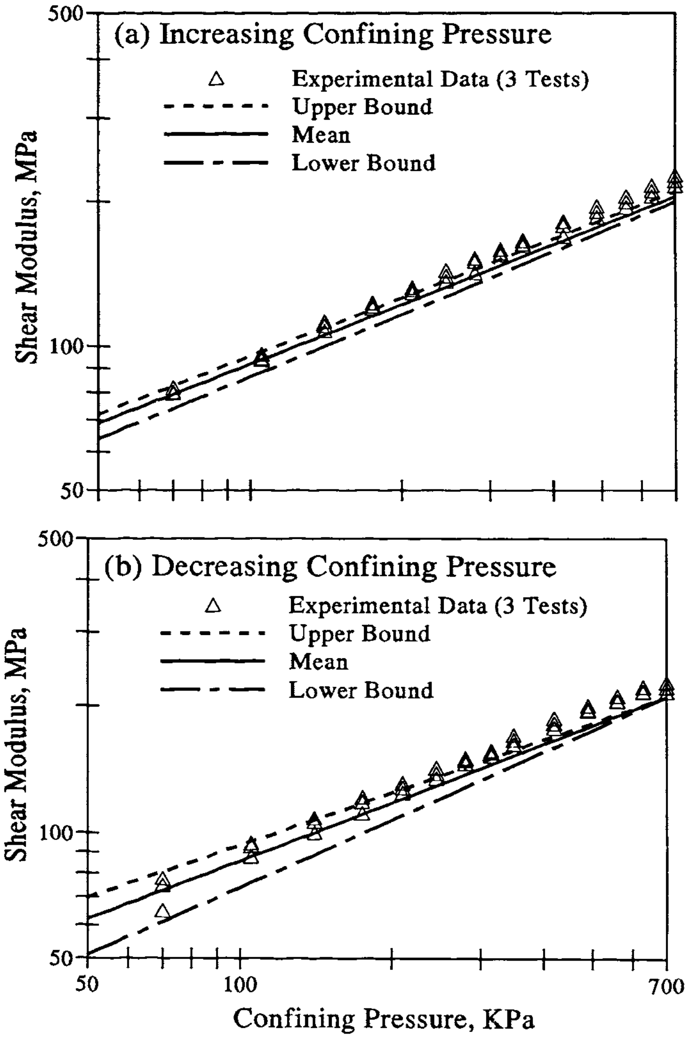


Fig l. **Typical Repeatability in Tests with Bender Elements.**

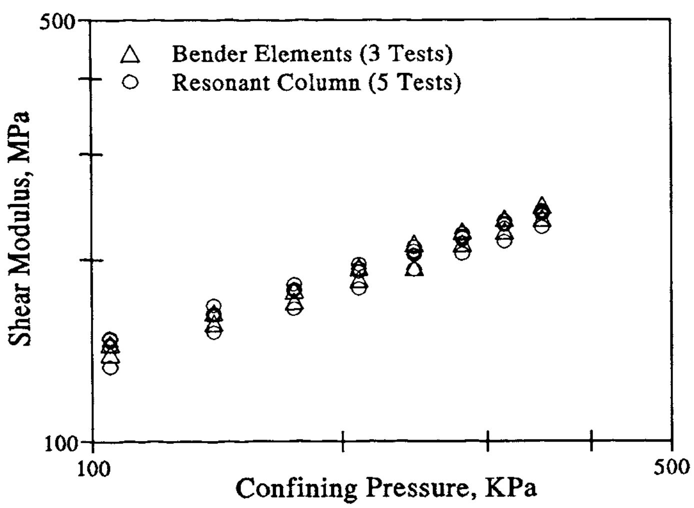


Fig 2. **Comparison of Results from Tests with Bender Elements and Resonant Column.**

The percent differences in shear moduli for sand C_A (coarse angular) at various confining pressures are also presented in Fig. 3. The differences in shear moduli are within 9 percent. Overall, the results are in reasonable agreement. For the BE tests, the coefficient of variation was about 6 percent, except for confining pressures of 245 KPa and 280 KPa, where the variation was about 10 percent. As compared to bender elements, the resonant column data exhibit less variation. Therefore, the resonant column device may produce more repeatable results.

Typically for sand M_R (medium round) at a given confining pressure, shear moduli from the bender elements are higher than those from resonant column tests (see Fig. 3). The differences in shear moduli are about 15 percent for moderate to high confining pressure and about 20 percent for low confining pressures. This can at least partially be due to the fact that for round aggregates rigid contact between the bottom platen of the resonant column and the specimen may not be possible. The effects of coupling on shear modulus have been studied by Almadhoun (1991) for same sand. He indicated that up to 8 percent difference in shear modulus is obtained using various types of coupling. Moduli from the bender elements exhibit coefficients of variation which are less than 2 percent for all confining pressures. The resonant column device also yields similar variation in modulus.

A series of tests was also carried out with both techniques on specimens of glass beads. Moduli from the resonant column tests are typically higher (see Figure 3). The coefficients of variation from resonant column tests and the bender element tests were 3.5 percent and 7 percent, respectively. Therefore, the bender elements yield less repeatable results. Practically speaking, this level of variation may not be unreasonable.

COMPARISON WITH EMPIRICAL RELATIONSHIP

Sand M_A: Moduli obtained from bender elements are compared with those obtained from the three empirical relationships for a relative density of zero in Fig. 4a. The relationships proposed by Richart and Hardin compare quite well and are virtually the same. The third curve, proposed by Iwasaki and Tatsuoka (1977), slightly varies from the other two relationships. The slope of the curve presented by Iwasaki and Tatsuoka compares better with the experimental results.

The absolute average difference in shear modulus for various relative densities are presented in Fig. 4b. The percent differences in shear moduli obtained from each empirical relationship and from the bender elements over the entire range of confining pressures as a function of relative density were averaged. The differences in shear moduli are about $\pm 10\%$ for relative densities less than 50 percent. For a relative density of 100 percent, the difference is about 25 percent. This suggests that empirical relationships may overestimate the shear modulus at maximum relative density.

The maximum differences in shear modulus are less than ± 18 percent for relative densities less than 50 percent. The maximum difference is at a 100 percent relative density for the relationship proposed by Iwasaki and Tatsuoka which is about 35 percent.

Sand C_A: A typical variation in shear modulus with confining pressure, at a zero percent relative density is shown in Fig. 5a. All three empirical curves significantly vary from the experimental data. At high confining pressures, the relationships proposed by Hardin and Richart compare favorably with the experimental data. The absolute average differences in shear modulus for various relative densities, as shown in Fig. 5b, are about 15 percent at all relative densities.

The maximum differences in shear moduli are about 25 percent for 0 and 10 percent relative densities. The difference is about 35%, for relative densities of 30 percent and 50 percent. As the results from the bender elements compare favorably with those of resonant column tests, it may be reasonable to conclude that the empirical relationships are not as good predictors of the properties of this soil.

Sand M_R: Typical variations in shear moduli with confining pressure for experimental data and the three relationships are presented in Fig. 6a. This graph corresponds to a specimens prepared at minimum density. The relationship proposed by Richart (1977) compares quite well with the experimental results. The other two relationships do not compare as closely. The relationship proposed by Iwasaki and Tatsuoka yields values close to the experimental moduli for confining pressures above 350 KPa.

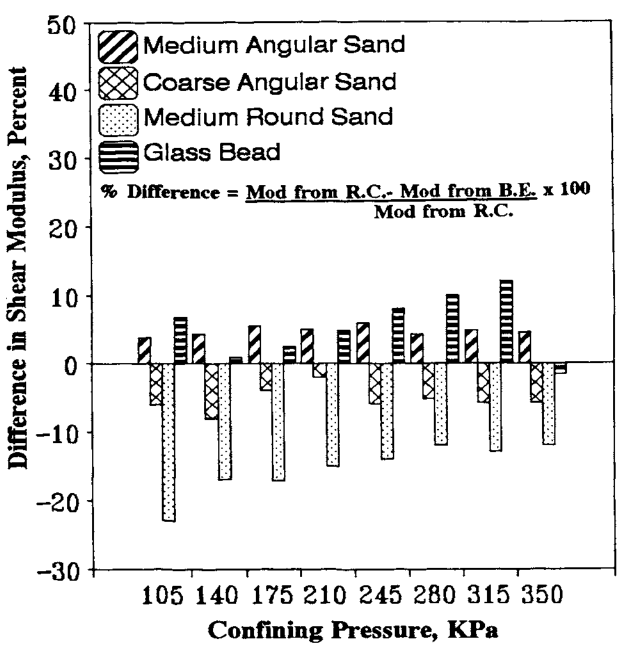
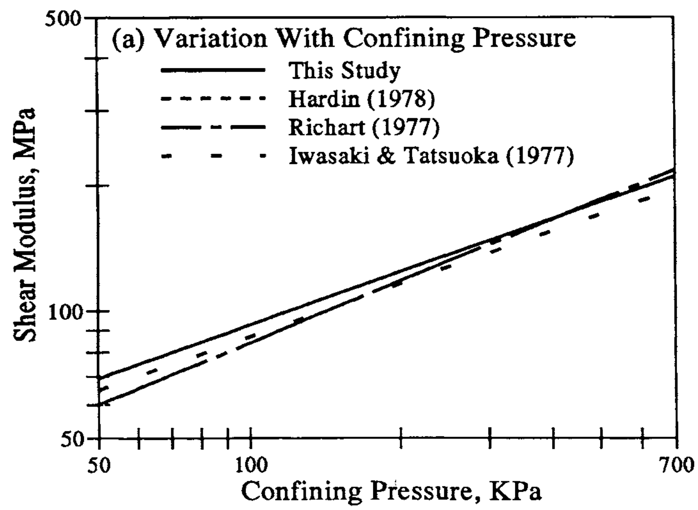


Fig 3. **Differences in Shear Moduli Measured with Bender Elements and Resonant Column.**

The average differences in shear modulus are within ±25 percent (see Fig. 6b). The most representative model is probably the model proposed by Richart. At 10 and 100 percent relative densities, the maximum differences in the shear moduli are about 40 percent and 30 percent from all relationships. For other relative densities, the maximum difference is less than 20 percent.

Glass Beads: Typical variations in shear modulus with confining pressure for relative density of 90 percent from experimental and the three empirical relationships are shown in Fig. 7. All three relationships yield smaller moduli than the moduli obtained by the bender elements irrespective of confining pressure.



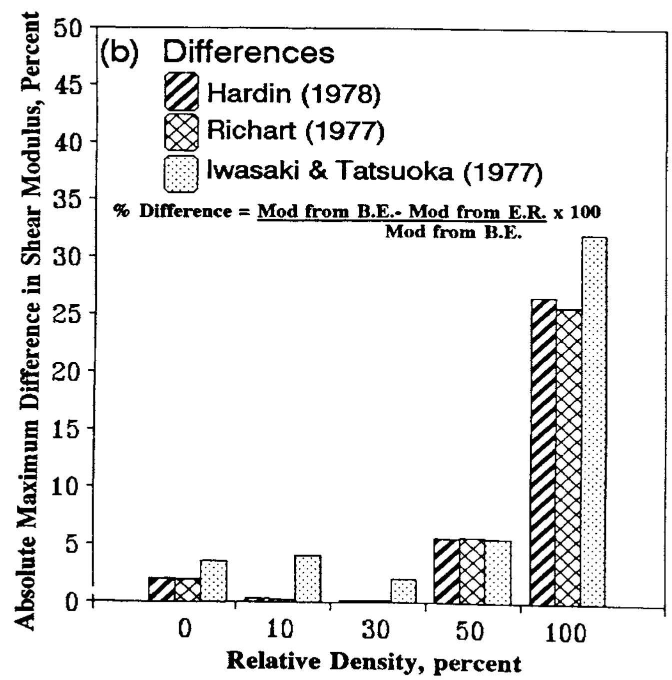


Fig 4. **Comparison of Results from This Study and Empirical Relationships for Sand M_A.**

The average difference in modulus between bender elements and relationships proposed by Hardin, Richart and Iwasaki and Tatsuoka are 24, 29, and 23 percent, respectively. Also, the maximum difference in modulus between bender elements and empirical relationships are about 50 percent. In general, moduli of the glass beads are not accurately predicted with the three relationships.

CONCLUSIONS

Based upon this study, the following conclusions are drawn:

1. The moduli obtained from bender element are repeatable from each series of tests.
2. Shear moduli obtained from the bender elements for M_A (medium angular) and C_A (coarse angular) sands compare well with those obtained from resonant column tests. Moduli of M_R (medium rounded) sands and glass beads obtained by the two methods do not compare as closely.
3. For M_A (medium angular) sands, shear moduli obtained from the bender elements and empirical relationships compare closely for specimens prepared at low to moderate relative densities.
4. In general, the bender elements work well with a large variety of specimens covering all ranges of particle size and shape.

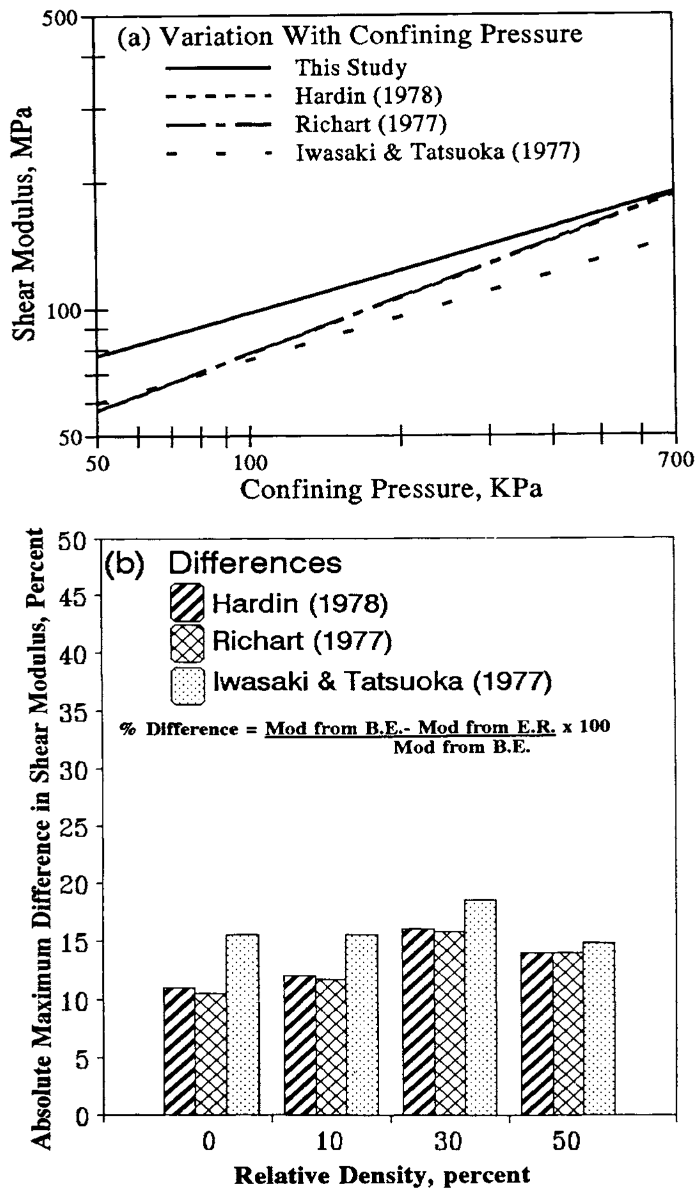


Fig 5. **Comparison of Results from This Study and Empirical Relationships for Sand C_A.**

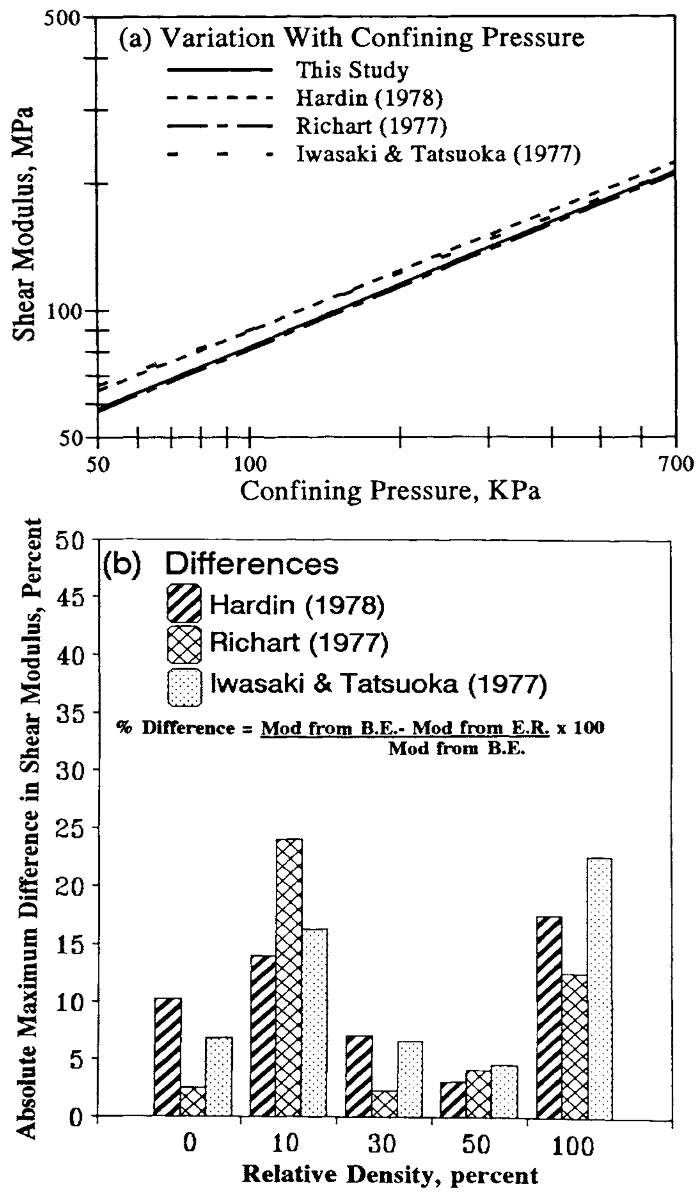


Fig 6. **Comparison of Results from This Study and Empirical Relationships for Sand M_R.**

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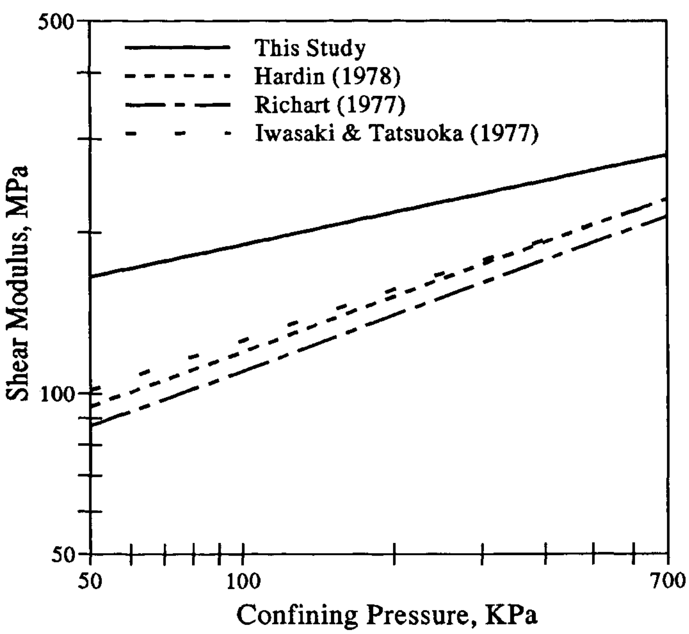

Fig 7. Comparison of Results from This Study and Empirical Relationships for Glass Bead