Dynamic Response of Paving Materials

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Equipment developed to determine the dynamic properties of paving materials in axial and torsional loading is described. Dynamic properties were determined by the excitation of hollow cylindrical specimens using two independent sinusoidal loads with frequencies up to 30 Hz. An IBM PC/AT equipped with a Metrabyte DASH16 data acquisition board was used to directly control two MTS hydraulic servorams. Menu-driven software was developed, taking advantage of direct memory access channels, so that data acquisition, wave form generation, and closed-loop control could take place simultaneously at rates above 5,000 samples/sec/channel. To convert raw data into graphs and parameters representative of dynamic material properties, a postprocessing menu-driven program was also developed. Dynamic properties of an asphalt concrete, a uniform sand, and a silty clay are presented. For the asphalt concrete, dynamic moduli in axial loading, dynamic shear moduli, internal damping determined in both axial and shear loading, and dynamic Poisson's ratios are presented for tests conducted at temperatures ranging from 11° C to 40° C. For the uniform sand and silty clay, dynamic shear moduli and internal damping as a function of stress state, magnitude of shear strain, and frequency of loading are presented.

Assessing the response of pavement systems to dynamic loads requires knowledge of the applied load spectrum, solutions for representations of pavement systems that permit inclusion of dynamic effects, and measures of the dynamic response of materials that make up pavement systems (*1*).

Recent developments in microcomputers, such as increased speed and memory capabilities, have opened new avenues for data acquisition, process and equipment control, automation, and data analysis for the definition of requisite dynamic properties of pavement materials. A new testing system that uses the capabilities of microcomputers to define these properties is described.

With the system, specimens can be tested as hollow or solid cylinders subjected to axial, torsional, or combined axial and torsional loads at frequencies up to 30 Hz.

Although the primary purpose of this paper is to describe the computer-controlled dynamic testing equipment, results are presented for the elastic and damping characteristics of an asphalt concrete tested over a range of temperatures and for a sand tested over a range of stress conditions. Both materials were tested as hollow cylinders 9 in. (22.8 cm) outside diameter and 18 in. (45.7 cm) high with a wall thickness of 1 in. (2.54 cm). These materials were subjected to axial and torsional stresses permitting the dynamic response of both materials to be defined in compression and shear.

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DYNAMIC LOADING SYSTEM

The test apparatus, termed herein the Dynamic Loading System (DLS), was designed to test hollow cylinders in both torsional and axial loading to attempt to simulate the three-dimensional stress states that occur in pavement materials in situ when subjected to moving dynamic loads. The torsional and axial loads can be applied either independently or simultaneously, which makes possible the rotation of the principal stress axes to follow predefined stress paths. Loads can be applied at frequencies up to 30 Hz, which appear to cover the range of frequencies that might result from loads of trucks operating on rough pavements (*2*).

Advances in microcomputer technology provided a relatively inexpensive way to develop an apparatus in which the accuracy and power of feedback closed-loop control hydraulic systems are combined with the flexibility, automation, and speed capabilities of digital equipment (*3*).

Description of Apparatus

Specimen Dimensions and Pressure Chamber

An axonometric view of the hollow cylindrical specimen and the adjacent apparatus is shown in Figure 1. The hollow cylindrical specimen is 18 in. (45.7 cm) high with a 9-in. (22.8-cm) external diameter and a wall 1 in. (2.54 cm) thick. The specimen is contained between a membrane and cap and base rings made of hard anodized aluminum. A top plate can be placed between the load cell and the cap ring when different interior and exterior confining pressures are required. The apparatus can also be used with solid cylindrical specimens 9 in. in diameter and 18 in. high.

Temperature Control

Temperature control is achieved by circulating the pressurized air contained within the cell through a copper serpentine located in the interior of an insulated box. Heat is transferred to and from the serpentine by heating and cooling systems controlled and monitored by a temperature-sensitive sensor. The feedback sensor is placed inside the return pressure line near the top chamber plate.

Slippage-Free Surfaces

To ensure adequate load transfer between the specimen and the cap and base rings, eight 0.5-in. (1.27-cm) lugs are

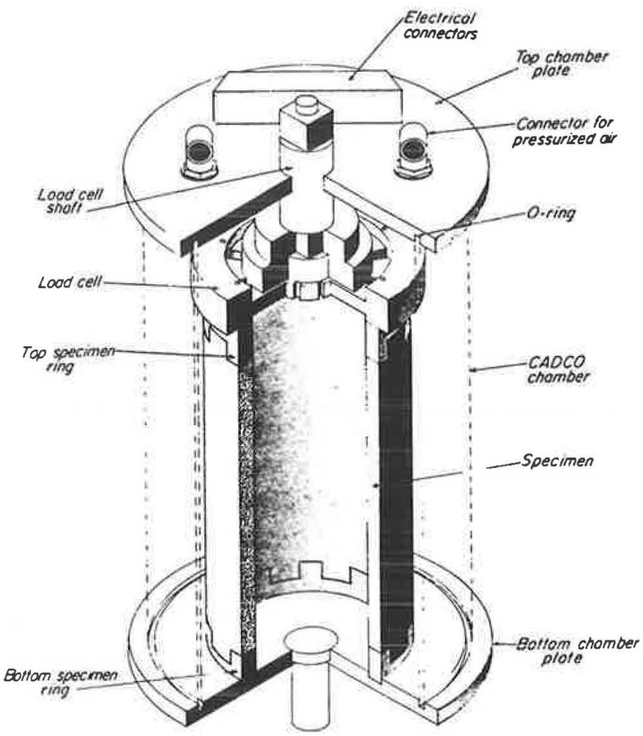

FIGURE 1 Axonometric view of pressure chamber, specimen, and load cell.

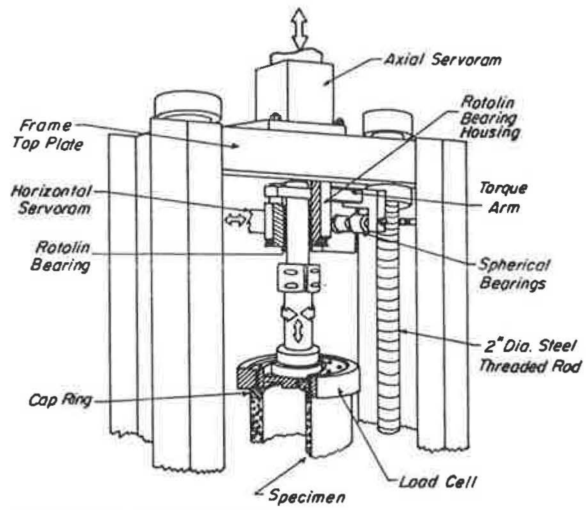

FIGURE 2 Loading system.

mounted on the rings. Under certain loading conditions, other additional means of load transfer to the specimen are not required. However, if complete reversal of torsional stress or axial traction, or both, is required, epoxy adhesive or hydrastone must be used.

Deformation Measurements

Measurements of specimen deformation are made using linear variable differential transformers (LVDTs). The LVDTs used are in constant contact, due to spring-loaded gauging heads, with a target mounted on the specimen. The target can be positioned anywhere on the specimen by using either fastening screws or clamping rings surrounding the specimen, which eliminates possible errors due to end effects.

Loading System

The DLS was designed so that the loaders could be mounted on a heavily reinforced frame beneath which the specimen is placed. Vertical loads are applied by a vertically mounted 10-kip MTS servoram with a 6-in. stroke. Torsional loads are applied by a horizontally mounted 6-in. stroke, 2-kip MTS servoram. The latter, when connected to a torque arm 7 in. (17.78 cm) in length, provides up to a 14-kip/in. torsional moment to the center shaft (Figure 2).

A Rotolin linear and rotary ball bearing with a total linear travel of 1 in. allows the coupling of both loads through the same shaft. Decoupling of the vertical movement of the torque arm from the horizontal movement of the horizontal servoram is made possible by two spherical bearings that limit the angle of the torque to ± 15 degrees.

A wheel-shaped load cell was constructed with eight spokes, each in the form of a rectangular prism. Each of the spokes is assumed to behave as a beam. Vertical and torsional loads can be measured independently because strain gauges are mounted on the centerlines of alternate faces of the beams.

Data Acquisition and Equipment Control

The development of the DLS required that tasks like wave form generation, data acquisition, equipment control, and data processing be accomplished almost simultaneously. To successfully perform them, a microcomputer (IBM PC/AT) was used with a data acquisition board from Metrabyte and a signal-conditioning interface. Figure 3 shows schematically how the elements of the apparatus are interconnected.

Hardware

Digital to analog and analog to digital conversions are performed by Metrabyte's DASH16 expansion board. To interface servovalves, strain gauges, and LVDTs to the Metrabyte board, two electronic devices were built. One, a board (Data Acquisition Interface Card) occupying one of the slots of the IBM PC/AT, provides software-selectable amplification gains for eight channels and software-selectable analog hardware offsets for four of the eight channels; the other, an A/C Signal-Conditioning Unit, provides the excitation for the load cells or the LVDTs, or both, in eight channels and transforms the voltage output of the two D/A channels into current, varying between ± 15 mA, that drives the servovalves.

Software

The software is written in compiled BASIC version 3.0 with

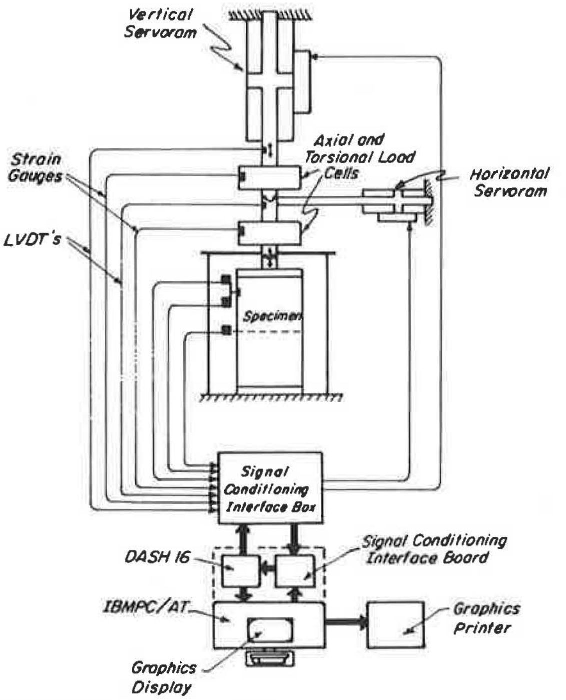

FIGURE 3 Data acquisition and control scheme.

ASSEMBLER subroutine calls addressing specific components or requesting specific tasks, or both. While data are being collected, two servorams must apply independent and synchronized sinusoidal forces, with frequencies of up to 30 Hz, to the specimen. For higher accuracy in test results, feedback closed control loops and high signal resolution are required. Because several types of tests can be performed sequentially on a single specimen, rapid adjustment of signal ranges and rapid change of feedback channels are necessary, forcing the adoption of software-programmable gains and software-programmable analog voltage offsets.

Furthermore, feedback closed-loop control is accurate because the desired signal (COMMAND) is compared with the signal obtained at the probe (FEEDBACK), and an error signal is sent to the servovalves to make any necessary adjustments. When analog equipment is used in feedback closed-loop controls, the time needed to read the feedback signal, compare it with a command value, send out the error value, and reread the feedback value is almost zero [i.e., the rate (number of closed loops/time) is almost infinite]. However, when using digital equipment, time is involved in

1. Converting the feedback signal from analog to digital,
2. Computing the command value,
3. Determining the error signal, and
4. Converting the error signal from digital to analog.

The rate is, therefore, a finite number that must be kept sufficiently high in order to provide complete control of the servorams. To accomplish this, command waves may be generated before testing, provided they are either periodic or of short duration. This frees the computer's central processing unit (CPU) from performing wave generation during testing. If the data acquisition components responsible for feedback data input are CPU independent, taking advantage of direct memory access (DMA) channels, error signal evaluation and output are the only tasks that must be executed during testing.

The menu-driven programs (SETUP, WAVGEN, and DACTEST) were developed so that these requirements could be fulfilled. These programs are described in the following subsections.

SETUP This program prompts the user to input the proper conversion factors, amplification gains, and analog hardware offsets for each of the eight input channels in order to convert input voltage from the probes into engineering units. The set of all of these values constitutes a configuration file. When a specific configuration is required, the program retrieves the file from the hard disk, addresses the data acquisition interface card, and sets the required amplification gain and analog offset for each channel.

WAVGEN This program creates and saves an array containing the values of command waves to be used by DACTEST. To define the waves, the following information is requested:

1. Configuration file name.
2. Feedback channel number of each of the servorams. Both of the servorams can be controlled with the feedback from any of the eight available channels. Stress or strain closed-loop control is initiated simply by selecting the correct feedback channel.
3. Frequency, amplitude, phase angle, wave form, and gain for each of the command waves. The software can perform feedback closed-loop control at a rate of 5,000 points/sec/servoram. Therefore, a 1-Hz sine wave would be defined by 5,000 points, but a 50-Hz wave would be defined by 100 points.
4. Definition of data acquisition schedules. To accurately perform closed-loop control, very high rates of data acquisition are necessary. However, for data analysis a smaller number of conversions is needed. Saving all of the data points would not only be next to impossible but inefficient. The data acquisition schedule tells the computer which periods to save for later analysis.

This information is saved in a test-type file. Several types of tests can be created and saved by several runs of WAVGEN.

DACTEST A testing sequence can consist of a series of different or identical tests, or even a single test, defined by the name of the file created by WAVGEN. For each test within the sequence, the program requests a name for the file in which the resultant data are to be stored.

Every 1/5000 sec DASH16, from its DMA controllers, updates 16 computer memory bytes (two for each input channel) with a digital value corresponding to the voltage present in each of the eight channels. This allows values present in the probes to be placed directly in memory (with only a 1/5000-sec delay) without spending CPU time. Control of the servorams is maintained by sending the difference between the feedback values and the command values, multiplied by a constant (GAIN), to the D/A channels of the DASH16 board. GAIN depends on the stiffness of the specimen, the oil pressure, the stiffness of the frame, and the frequency and amplitude of the loads. This constant is automatically adjusted by the software for each situation.

After completion of each individual test, data are retrieved from random access memory and stored on the hard disk (for each test 64 Kb of data can be collected). This is accomplished while simultaneously maintaining control of the servorams.

Data Analysis

Data analysis for this type of testing is lengthy. Accordingly, two postprocessor programs (OPTMZER and ANALYSR) were developed to convert data obtained during a testing sequence into material properties.

OPTMZER

Data produced by DACTEST during a testing sequence are stored in a macrofile. OPTMZER reads the macrofile and creates a number of files equivalent to the number of tests in the testing sequence. For each of the tests, it also creates a file containing the values of the amplitude, mean, and phase angle of the individual sinusoidal waves from each channel and in each period. These values are statistically obtained by the method of least squares. The information is converted and stored in engineering units, taking into consideration the amplification factor and the analog offset used during testing.

ANALYSR

Programs for data analysis derive their productiveness from the specificity of their function. ANALYSR is specifically designed to interpret data from dynamic tests retrieved with DACTEST. The program's menu-driven construction makes it user friendly.

Most pavement materials at low strain levels exhibit response characteristics that can be approximately described by linear viscoelastic models. To determine the dynamic properties of a material (complex modulus and internal damping), a testing sequence based on stress- or strain-controlled sinusoidal excitation was used.

If a sinusoidal force [$P = P_o \sin(\omega t)$] is applied to a specimen composed of an ideal massless linear viscoelastic material, the deformation response will be sinusoidal and at the same frequency, but it will lag by a phase angle (δ) as given by the following expression:

$$X = X_o \sin(\omega t - \delta) \tag{1}$$

At each instant the relationship between P and X of the specimen is therefore a function of P_o/X_o and δ. It can be shown that if

$$P = P_o \exp(i\omega t)$$

then

$$X = X_o \exp[i(\omega t - \delta)]$$

$$P/X = P_o/X_o \exp(i\delta) = k_s' + ik_s'' = k_s^*$$

$$P_o/X_o = | k_s'^2 + k_s''^2 |^{1/2} = | k_s^* |$$

$$\tan \delta = k_s''/k_s'$$

where k represents a modulus determined in axial or shear loading.

For engineering applications, it is convenient to express the axial dynamic modulus as

$$E^* = E(1 + 2\beta_a i) \tag{2}$$

and the dynamic shear modulus as

$$G^* = G(1 + 2\beta_s i) \tag{3}$$

where β_a and β_s are measures of internal damping under axial and shear loadings, respectively. It should also be noted that

$$\beta = \tan \delta / 2 \tag{4}$$

Thus the internal damping of an ideal massless viscoelastic material can be directly derived from the phase angle (δ) (between the sinusoidal forces and the sinusoidal displacements at the top of the specimen) and the stiffness modulus (from the ratio of the amplitudes).

However, materials are not massless and some exhibit damping behavior with nonelliptical stress-strain loops dependent on the strain level. The program makes the necessary adjustments incorporating corrections for the mass of the specimen and load cell and corrections for nonlinear viscous materials.

SPECIMEN PREPARATION

Specimen Mold

To prepare hollow cylindrical specimens, a typical unit consisting of inner and outer molds is required (Figure 4). The outer mold is a hard anodized aluminum cylinder that has been divided in half. After the two half cylinders have been secured, the tube can be fastened to the bottom plate. The inner mold, designed to be inwardly collapsible, can be removed without imposing stress on the specimens. When asphalt specimens are compacted, stainless steel sleeves are used to protect the mold from abrasive action by the aggregate. Vacuum grooves are provided on the inside wall of the outer mold and on the outside wall of the inner mold to keep in position a 0.020-in.-thick latex membrane that is used when fabricating fine-grained soil and sand specimens.

Compacting Equipment and Procedure

For the fabrication of hollow cylindrical specimens with materials requiring kneading compaction, special compaction

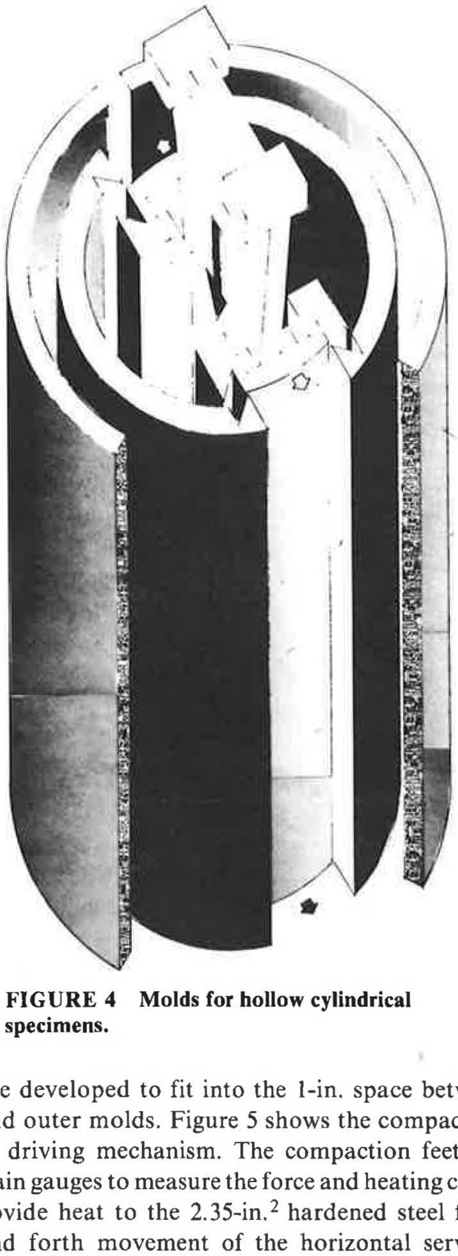

FIGURE 4 Molds for hollow cylindrical specimens.

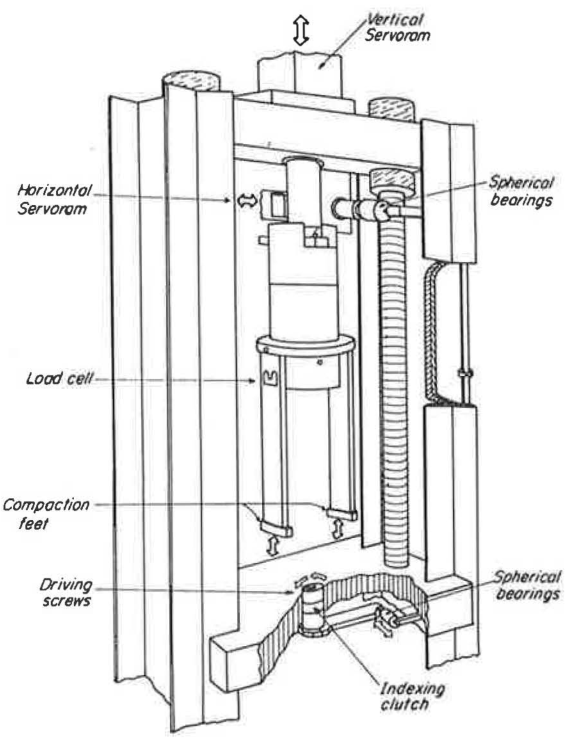

FIGURE 5 Compaction equipment.

feet were developed to fit into the 1-in. space between the inner and outer molds. Figure 5 shows the compaction feet and the driving mechanism. The compaction feet contain both strain gauges to measure the force and heating cartridges that provide heat to the 2.35-in.^{2} hardened steel feet. The back and forth movement of the horizontal servoram is converted into intermittent rotation of a driving screw by means of an indexing clutch. The mold is fastened to the driving screw and thus rotates intermittently, sliding over a Teflon sheet. Both servorams are controlled by a computer program called COMPACT. Unlike those of other kneading compactors, the inputs for this program are (*a*) specimen density, (*b*) mass of an individual batch of material, and (*c*) compaction pressure. The number of tamps of the compaction feet is dependent on the required density for each batch.

DYNAMIC PROPERTIES OF AN ASPHALT CONCRETE PAVING MIXTURE

Material and Specimen Preparation

A dense-graded asphalt concrete with granite aggregate (from Watsonville, California) was used in this study. The gradation of the aggregate conforms to the state of California specifications for Type B mixtures (Figure 6). The asphalt cement used was an AR-4000 produced by Chevron. An asphalt content of 5.5 percent by weight of aggregate was selected. Specimens were prepared using the DLS in its compaction mode with a required specific gravity of 2.49, compaction measure of 350 psi, and compaction time (duration of each tamp) of 4 sec.

The specimen, weighing 40 lb, was compacted using 17 batches. The first batch weighed 6 lb, the last 4 lb, and the others 2 lb each. The final layer was compacted with a static load of 40,000 lb, which was applied for 20 min; this permitted placement and leveling of the top ring (with lugs). For the specimens tested thus far, the specific gravity actually obtained was 2.44. Although visual inspection showed that the procedure produced specimens of uniform density, the

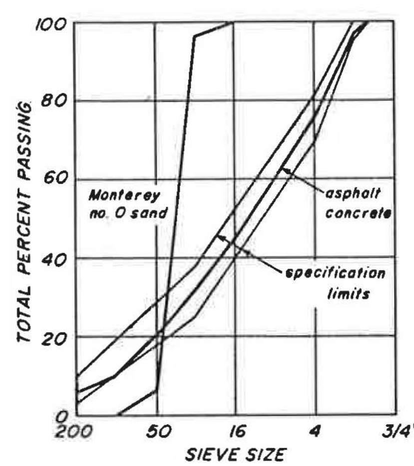

FIGURE 6 Gradations for asphalt concrete aggregate and sand.

desired density of 2.49 was not achieved because of deformation of the frame, the compaction feet, the mold, and the specimen while the compaction load was applied. This caused errors in the readings of the heights of the batches. This disparity can be corrected, however, by requesting a proportionally higher density.

Test Procedures and Results

Several vertical and torsional sinusoidal loads were applied to the specimen at three different temperatures (11°C, 25°C, and 40°C). At 11°C the vertical sinusoidal compression stress had a mean value of 40 psi and amplitude of 70 psi; the torsional sinusoidal loads produced shear stresses with a mean value of 12 psi and an amplitude of 20 psi. At 25°C and 40°C the axial values were 25 and 40 psi and shear stresses were 4 and 6 psi, respectively. At each temperature level the frequency of the sinusoidal loads was varied between 0.5 and 20 Hz (i.e., 0.5, 1.0, 5.0, 10, 15, and 20 Hz). A total of 200 loading cycles were applied at each frequency. (At 0.5 Hz, 60 cycles were applied, and, at 1.0 Hz, 100 cycles were applied.) All tests were performed under stress control (feedback from the load cells) with LVDTs placed 2.5 in. from the ends of the specimens. Each specimen was initially tested at 11°C, then at 25°C and at 40°C. This sequence was repeated three times. A specimen was maintained at each temperature level for at least 3 hr before testing. Vertical vibratory loads (20 to 0.5 Hz) were applied first, then torsional vibrations (20 to 0.5 Hz). This sequence was repeated twice at each temperature.

The effect of temperature and frequency on the variation of the dynamic modulus (E^*) and the dynamic shear modulus of G^* is shown in Figure 7. Repeatability of the results after various tests have been performed indicates that the dynamic properties of the specimen are not influenced by previous testing frequencies and temperatures. Thus several different tests can be performed on the same specimen using various frequencies, temperatures, load applications, and levels of stress without changing the data significantly. The stiffness moduli exhibit, however, strong dependence on frequency and temperature.

From stress-strain hysteresis loops the internal damping can be determined. Figure 8 shows a typical loop obtained at 1 Hz and 40°C. The effect of temperature and frequency on the values of internal damping, measured under vertical loading, and those measured under torsional loading is plotted in Figure 9. It is interesting to note that the difference increases with temperature. Temperature and frequency effects are particularly noticeable in the values of the dynamic Poisson's ratio [$\nu^* = E^*/(2.G^*) - 1$] shown in Figure 10. Similar results are reported elsewhere (*4*).

DYNAMIC PROPERTIES OF A SAND

Material and Specimen Preparation

The sand used for this study was a dry, cohesionless, uniformly graded Monterey sand No. 0 with a D_{50} of 0.5 mm (Figure 6), a minimum dry density of 88 lb/ft^3, and a

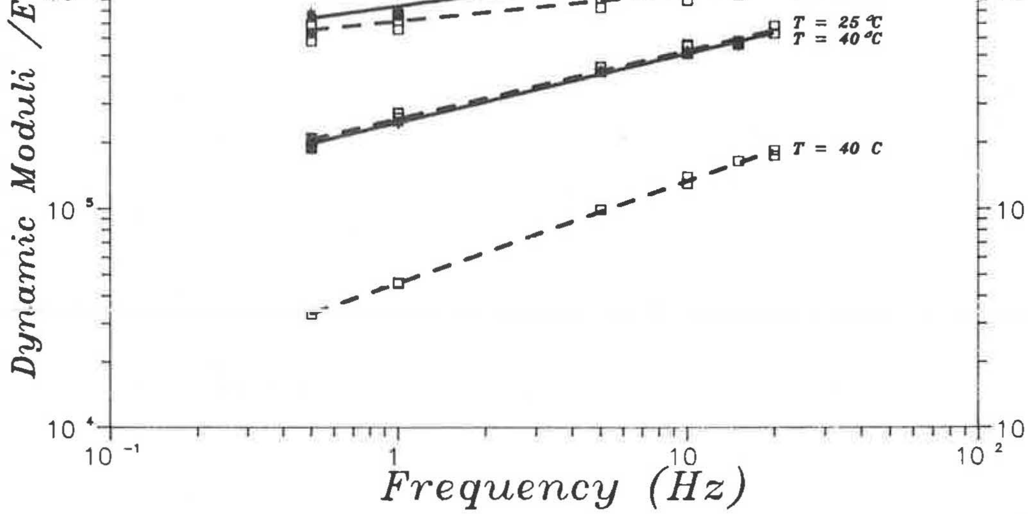

FIGURE 7 Influence of frequency and temperature on the dynamic moduli of an asphalt concrete in compression and shear.

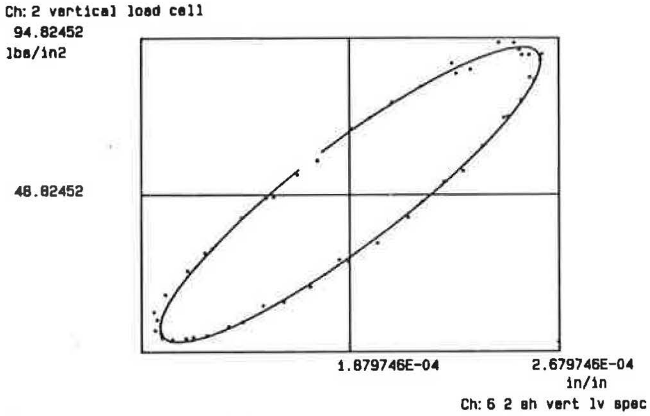

FIGURE 8 Hysteresis loop for an asphalt concrete mixture.

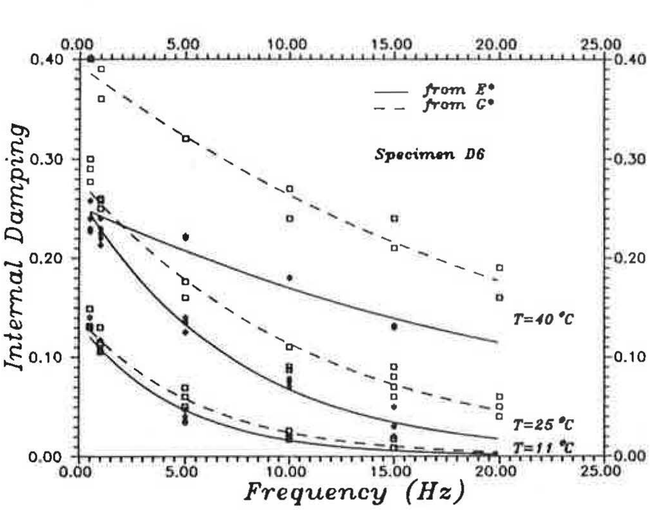

FIGURE 9 Influence of temperature and frequency on the damping characteristics of an asphalt concrete.

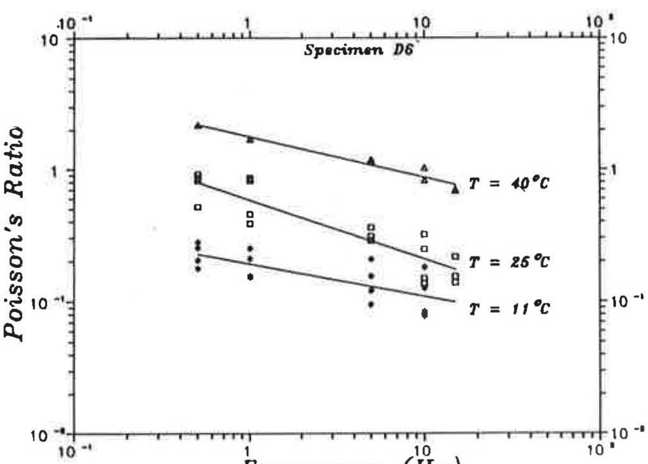

FIGURE 10 Influence of temperature and frequency on Poisson's ratio, asphalt concrete.

maximum dry density of 105 lb/ft^3. For this specimen a relative density of 90 percent was obtained using a vibrating table.

To fabricate the specimen, the sand was confined by a latex rubber membrane 0.020 in. thick and U-shaped in cross section. Holes in the bottom of the membrane allow the bottom ring to be securely attached to the bottom plate and also permit vacuum to be applied through porous stones placed in the ring. When the sample was nearly completed, the top ring was set in place. While the mold continued to vibrate, additional sand was poured through holes in the top ring to achieve the desired density even between the lugs. On completion, the membrane was rolled over the top ring and sealed with O-rings. A vacuum was then applied to the specimen and the mold was removed. Visual inspection indicated that this method produced a sample of uniform shape and density.

Testing Procedures and Results

In a series of tests, the influence of the mean effective stress frequency and strain level on the dynamic shear was investigated. At each strain level (0.01, 0.1, and 1 percent) tests were conducted at three different levels of effective mean stress (26, 20, and 16 in. Hg). The tests were performed under torsional strain control and vertical stress control.

Figure 11 shows a comparison of dynamic shear modulus (G^*) with the shear strain (percentage) for three different mean confining stresses. The mean stress was measured in inches of mercury and corresponds to the level of vacuum applied to the specimen. All tests were performed under no axial load. It was further determined that no relationship exists (for the sand tested) between dynamic shear modulus and frequency over the range of 0.5 to 10 Hz. This is shown in Figure 12 for the range of frequencies and at different stress and strain levels.

Internal damping was computed from stress-strain hysteresis loops (Figure 13). The resulting values were plotted against the shear strain in Figure 14. From the data it can be inferred that an increase in the magnitude of the shear strain results in an increase in the internal damping. However, the scattering of the data implies some frequency effects.

Figure 15 shows the effect of frequency at different stress and strain levels on the internal damping. The results suggest that the effect of frequency on internal damping varies differently with different levels of stress and that damping is not affected by the mean stress level.

All of the data reported were obtained from tests on a single specimen. The final test on the same specimen was conducted at a very high level of strain, 7.5 percent, and resulted in the destruction of the specimen. Figure 16 shows the deformation that occurred during testing. Channel 0 shows axial displacements and Channel 1 torsional displacement. The path of Channel 1 shows that the software automatically adjusted the gain until the desired amplitude was reached. It is significant that initially the specimen contracted and then the specimen dilated until testing was stopped. Because there was no pore fluid, dilation of the sample resulted in plastic strain softening of the specimen in distinct banded areas. Visual inspection showed the formation of helical deformation lines on the sample. Formation of these bands indicates that the material was failing in these regions according to the Mohr-Coulomb hypothesis.

The findings in this series of tests are consistent with the results reported by Seed and Idriss (*5*).

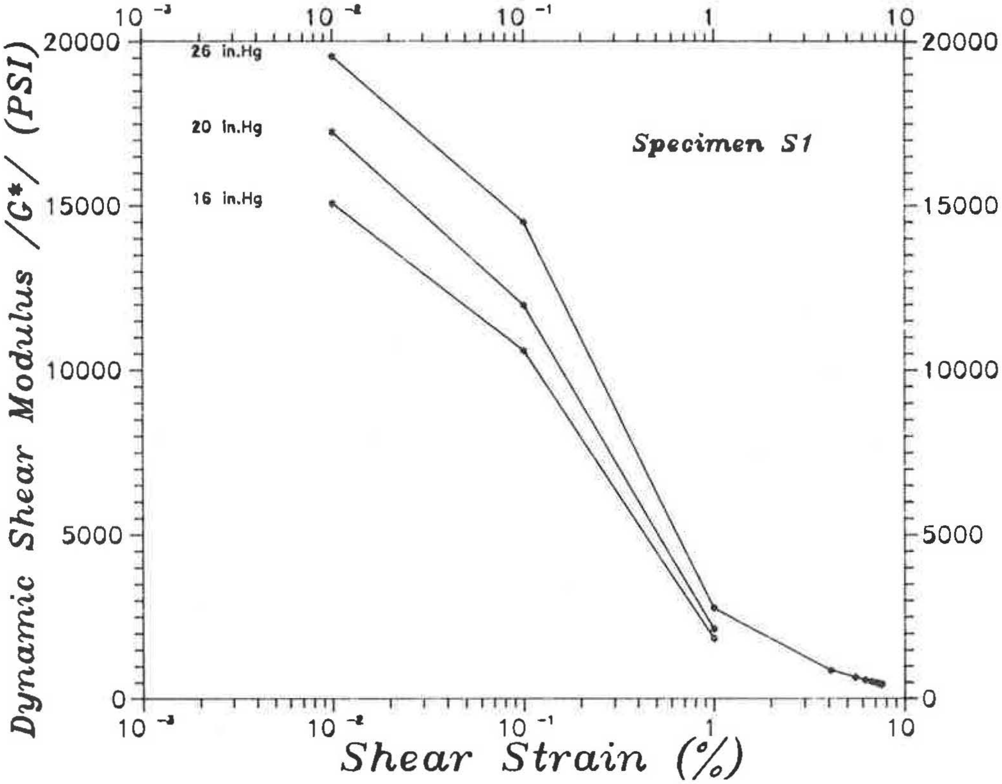

FIGURE 11 Relationship between dynamic shear modulus and shear strain for a range of confining pressures: Monterey sand, 90 percent relative density.

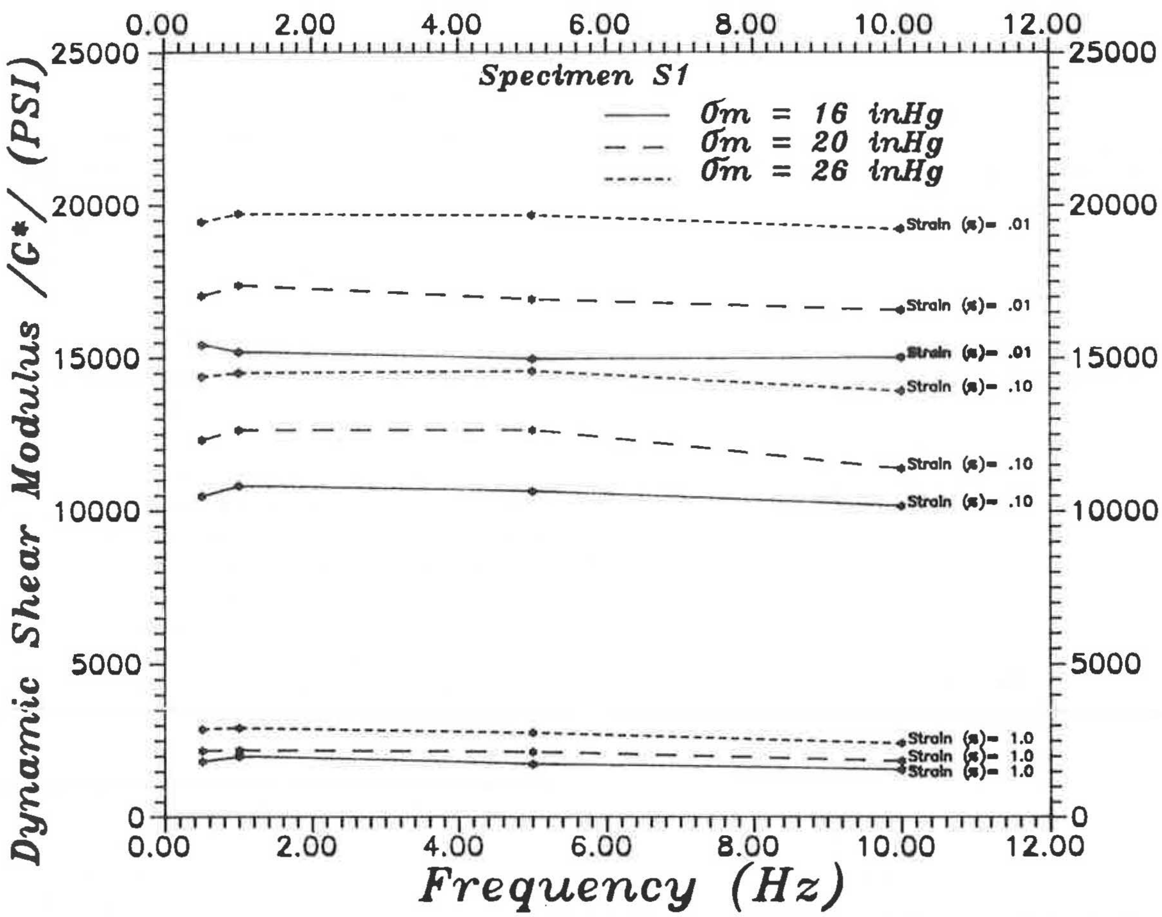

FIGURE 12 Relationship between dynamic shear modulus and frequency: Monterey sand, 90 percent relative density.

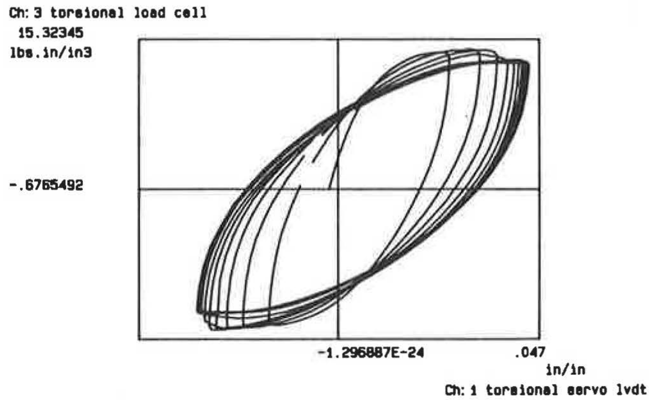

FIGURE 13 Hysteresis loops: Monterey sand, 90 percent relative density, frequency of loading 0.5 Hz.

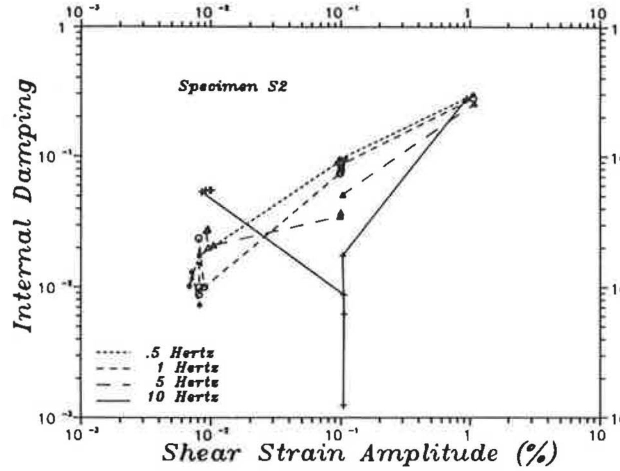

FIGURE 14 Internal damping versus shear strain: Monterey sand, 90 percent relative compaction.

DYNAMIC PROPERTIES OF A SILTY CLAY

Material and Specimen Preparation

A silty clay from Vicksburg, Mississippi (material supplied by the Geotechnical Laboratory of the U.S. Army Corps of Engineers Waterways Experiment Station), was used for this portion of the investigation (liquid limit = 35, plasticity index = 13). A compaction procedure similar to that for the asphalt concrete was used. The compactive effort selected was approximately equivalent to that used in the modified AASHTO (T 180) compaction test. For the specimen the data of which are reported herein, the resulting dry density was 116 lb/ft^3 (1858 kg/m^3) and the molding water content was 14 percent.

The specimen, weighing 35 lb (15.9 kg), was compacted using 17 batches; the initial batch weighed 5.5 lb (2.5 kg), the final 3.25 lb (1.48 kg), and the intermediate ones 1.75 lb (0.80 kg) each. After kneading compaction, the specimen was subjected to a static leveling load of 25,000 lb (111.2 kN). To ensure a smooth-surfaced specimen, the compaction mold was lined with a Teflon sleeve.

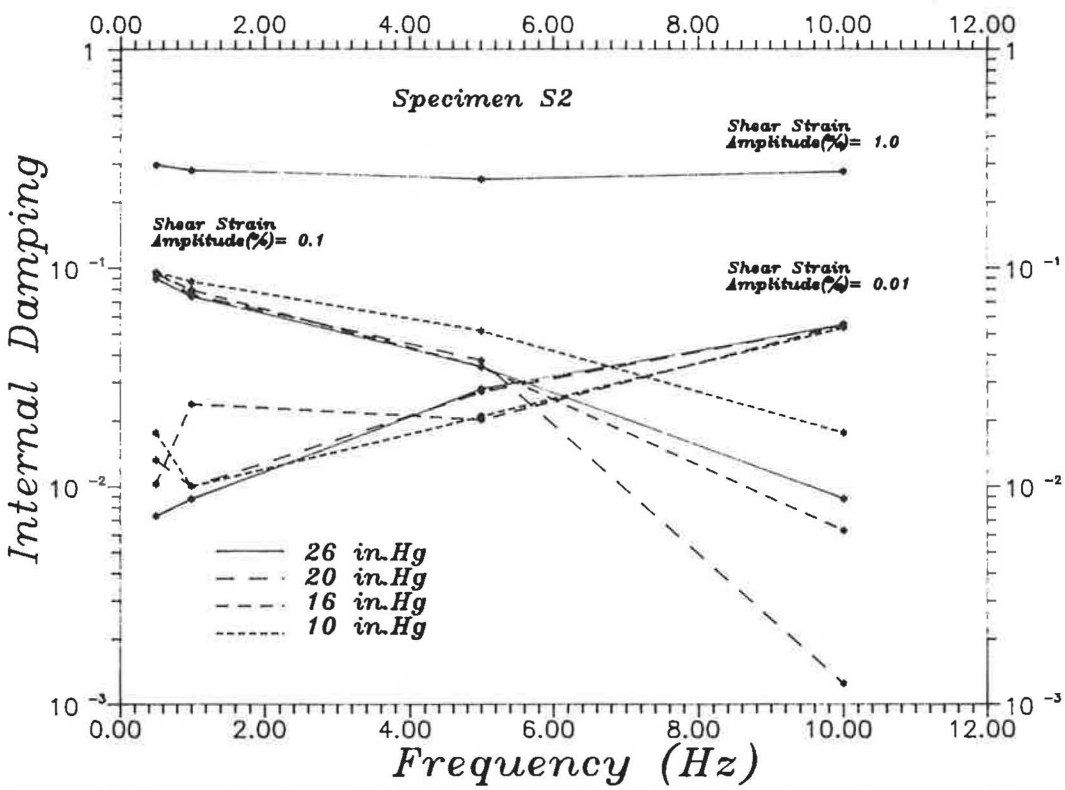

FIGURE 15 Internal damping versus frequency over a range of values of mean stress and for a range of shear strains: Monterey sand, 90 percent relative density.

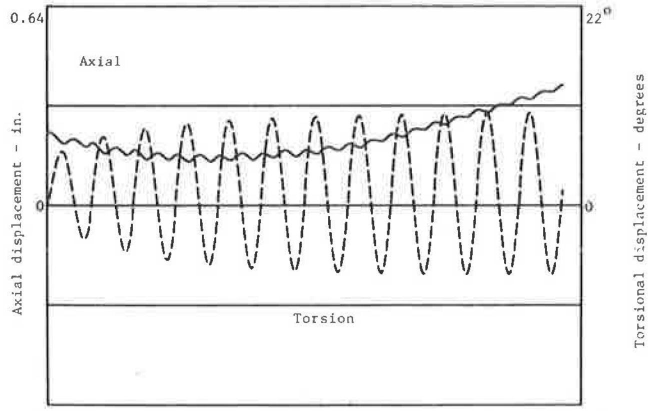

FIGURE 16 Displacement occurring during testing of Monterey sand at 7.5 shear strain.

Testing Procedures and Results

The specimen was tested at three strain levels (0.01, 0.1, and 1.0 percent), four frequency levels (0.5, 1.0, 5.0, and 10 Hz), and four levels of confining pressure (29, 20, 11, and again 29 in. Hg). Confining pressure was applied through vacuum for at least 10 hr before testing. During testing, approximately 30 sinusoidal load cycles were applied at each level.

Figure 17 shows the effect of shear strain amplitude and confining stress on dynamic shear modulus. To obtain these results, the confining pressure was changed at each strain level; this was done to mitigate the effects on the results of damage that might occur at higher strain levels. Repeatability of results at 29 in. Hg after several cycles were applied at 20 and 11 in. Hg indicates that the number of load applications (though applied at lower confining pressures and over a range of frequencies) does not significantly alter the dynamic shear modulus values.

Frequency effects on shear modulus are negligible for this particular specimen, as seen in Figure 18.

When the specimen was tested at a strain level of 1.0 percent, the lugs induced cracking. Although this phenomenon was not observed in tests on the asphalt concrete or sand, it does suggest that the lugs should not be used for relatively brittle materials (this clay compacted to a relatively high density and at a water content slightly to the left of the line of optimums). Instead, the rings should be bonded to the specimen with an adhesive.

The effect of confining stress, frequency, and strain amplitude on damping was also evaluated. A typical hysteresis loop is shown in Figure 19. The data shown in Figure 20 suggest that internal damping increases with increase in shear strain amplitude but is little affected by confining pressure. The scattering of data is thought to be due to the frequency effects. Figure 21 shows the variation of internal damping with frequency at each strain level. From these data, it can be inferred that the frequency effect is similar at each strain level because the slopes of the lines are similar.

SUMMARY AND CONCLUSIONS

The DLS described herein and used to determine the dynamic properties for three pavement materials illustrates microcomputer capabilities in a research environment. Beyond the economic advantage of replacing expensive equipment (i.e., strip chart recorders, function generators, and closed-loop controllers) microcomputers present (*a*) the added advantage of eliminating the need for time-consuming data reduction and (*b*) the ability to control several processes involving different pieces of equipment simultaneously. The ability to control the values of three principal axes of stress or strain over a representative range of frequencies and temperatures provides a valuable tool for determining material properties.

Results of the test program for the asphalt concrete illustrate the dependence of the stiffness and damping characteristics of the mixture on frequency, temperature, and mode of loading.

Some nonlinearities are apparent in the response characteristics of this asphalt concrete. This is evidenced, for

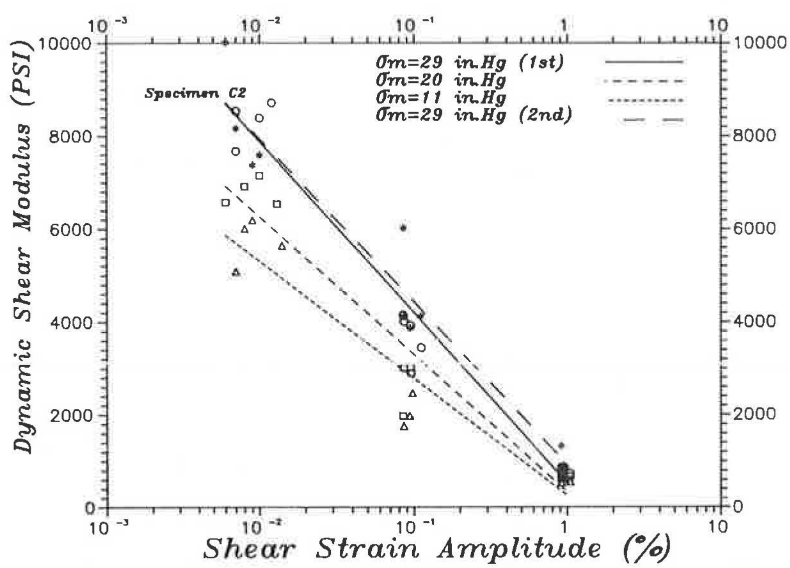

FIGURE 17 Influence of shear strain amplitude on the dynamic shear modulus of a silty clay specimen at three different confining pressures.

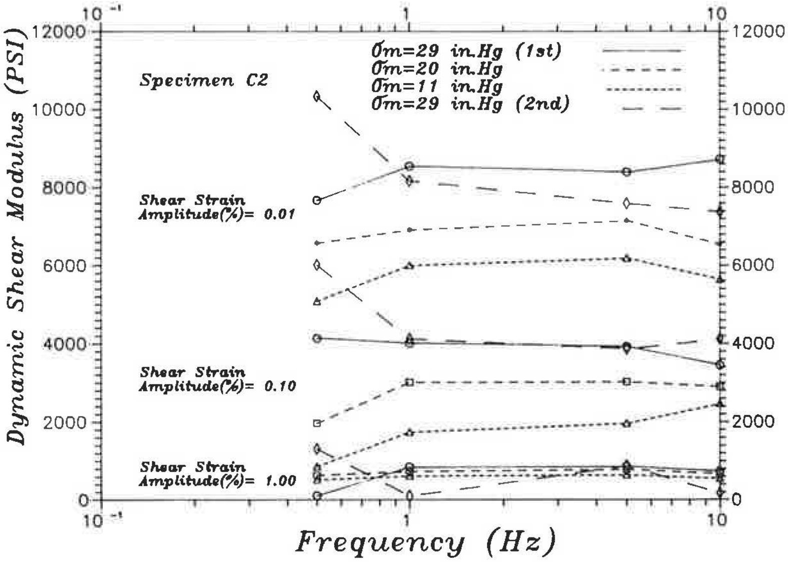

FIGURE 18 Influence of frequency loading on dynamic shear modulus.

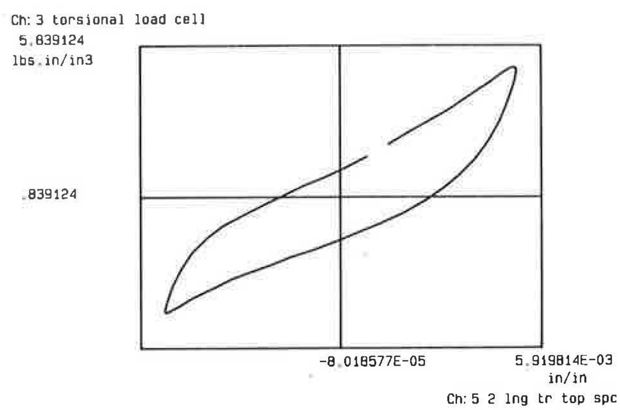

FIGURE 19 Typical hysteresis loop for Vicksburg silty clay at 1 Hz and a strain amplitude of 1 percent.

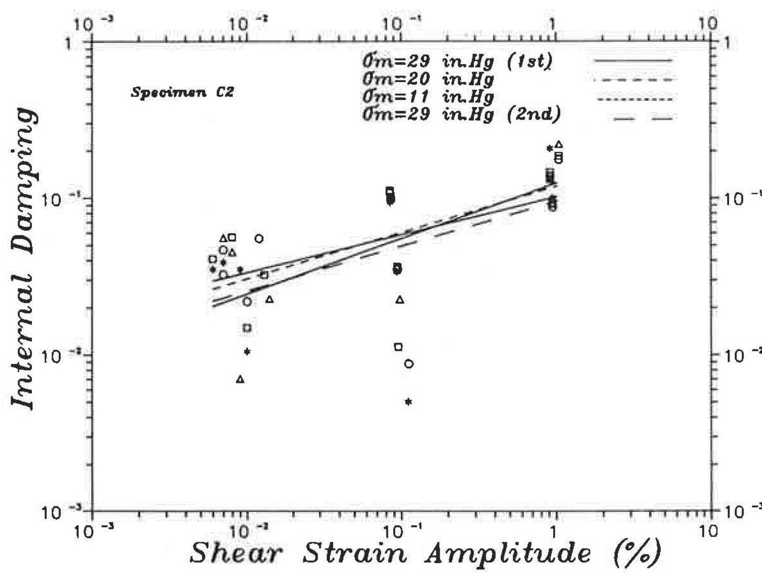

FIGURE 20 Variation of internal damping as a function of strain level for a silty clay.

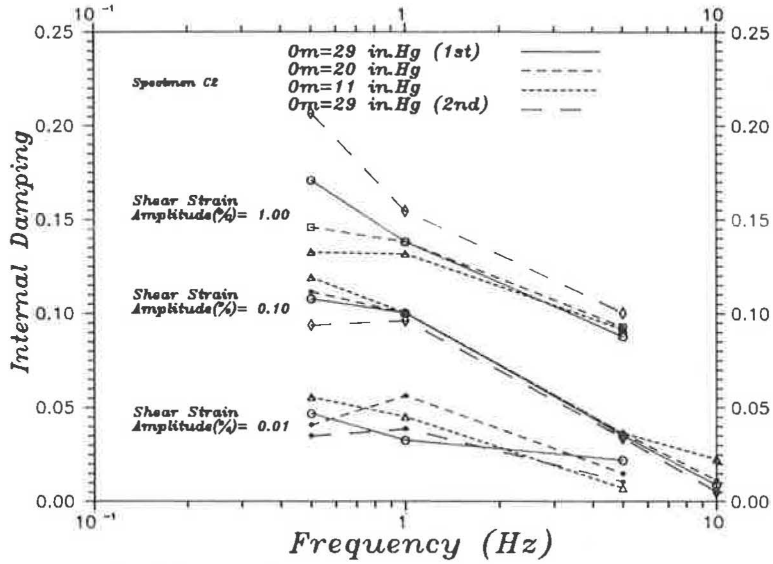

FIGURE 21 Influence of load frequency on internal damping at different strain levels for Vicksburg silty clay.

example, by changes in values for internal damping computed from the stiffness moduli (E^* and G^*). As the differences in damping determined in the axial and shear modes of loading increase, computed Poisson's ratios exceed 0.5 indicating some volume increase—most likely in the shear mode of loading.

This investigation also considered the effect of frequency, confining pressure, and strain level on the dynamic shear modulus and the internal damping characteristics of sand and silty clay. The data clearly indicate that frequency has no influence on the dynamic shear modulus of either clay or sand specimens (within the ranges tested). Frequency does, however, have a marked effect on the internal damping of both materials. For the sand studied, it was observed that frequency effects vary with strain level whereas, for silty clay, the effects were identical at all strain levels.

Dynamic moduli so obtained can be used to determine the stresses, strains, and deflections in pavement systems for moving vehicles, provided the time histories of the loads are available. This is possible, using a computer code, SAPSI, recently developed by S. S. Chen and J. Lysmer. Work by Sousa (*6*) contains an illustration of such an approach.

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REFERENCES

1. J. L. Lysmer, C. L. Monismith, J. B. Sousa, and S. S. Chen. *Pavement Response to Dynamic Loads.* Transportation Laboratory, State of California Department of Transportation, University of California, Berkeley, Oct. 1985.
2. T. D. Gillespie et al. *Influence of Size and Weight Variables on the Stability and Control Properties of Heavy Trucks.* Report UMTRI-83-10/2. University of Michigan, Ann Arbor, April 1983.
3. N. Sitar and Y. D. Wang. Cyclic Test Control and Data Acquisition Using a Microcomputer. *Proc., Second National Conference on Microcomputers in Civil Engineering*, Orlando, Fla., 1984, pp. 6-8.
4. J. F. Hills and W. Heukelom. The Modulus and Poisson's Ratio of Asphalt Mixes. *Journal of the Institute of Petroleum*, Vol. 55, No. 541, Jan. 1969.
5. H. B. Seed and I. M. Idriss. *Soil Moduli and Damping Factors for Dynamic Response Analysis.* Report EERC 70-10. University of California, Berkeley, Dec. 1970.
6. J. Sousa. *Dynamic Properties of Pavement Materials.* Ph.D. dissertation. University of California, Berkeley, Nov. 1986.

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