A PRACTICAL METHOD FOR MEASURING THE RESILIENT MODULUS OF ASPHALT-TREATED MIXES

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• ONE of the most needed highway engineering developments is a method of designing asphalt pavements, which is theoretically sound and, at the same time, practical. Attainment of this objective now seems feasible with the availability of improved procedures (both 5- and 15-layer programs are available from Chevron Asphalt Company in FORTRAN IV/OS) for the analysis of stresses and deformations in pavement structures using either multilayer elastic (1-5) or finite element design methods (6).

Essential to both the multilayer elastic and the finite element design methods are the various values of the resilient modulus, M_R, and Poisson's ratio, ν, of the materials used in the pavement structure. Test methods currently available to measure the M_R of mixes are practical enough to be used for important projects. However, the methods appear to be too complicated or expensive for routine control or mix design purposes. For these reasons, a need still exists for a method that can give a sufficiently accurate M_R with no more effort or expense than is required by the current Hveem or Marshall methods. This paper describes a method that is rapid and economical and appears adequate for use in pavement structural design calculations. Also, the same specimen can first be used to determine the M_R and subsequently be used to determine other properties such as the Hveem or Marshall stabilities.

THEORETICAL BASIS OF THE TEST

An indirect test for measuring the tensile strength of portland cement concrete (PCC) was described in 1953 by Carniero and Barcellus in Brazil (7) and independently by Akazawa (8) in Japan. In this test, cylinders of PCC were crushed by applying uniformly distributed loads along two opposite generatrices. It was shown by mathematical analyses (9, 10) (assuming plane stress) that a uniform compressive load applied perpendicularly to the horizontal diametral plane of a thin disk gives rise to a uniform tensile stress over the vertical diametral plane containing the applied load. A simplified mathematical treatment was given by Frocht (9) who supported his mathematics by photoelastic analyses of plastic disks.

When this approach is applied to dynamically loaded disks or cylinders, it is possible to determine the elastic modulus of the material. This is accomplished by measuring the elastic deformation across the horizontal diameter resulting from the application of a load along the vertical diameter. An expression (11) for the elastic modulus, E, can be developed as follows.

Frocht (9) gives expressions for the stresses, σ_x and σ_y, across the diameter, d, perpendicular to the applied load, P.

$$\sigma_x = \left[2P/\pi td\ (d^2 - 4x^2)/(d^2 + 4x^2)\right]^2$$

$$\sigma_y = -2P/\pi td\ \left[4d^4/(d^2 + 4x^2)^2 - 1\right]$$

where t is the thickness of the disks, and x is the distance from the origin along the abscissa. A typical distribution of these stresses is shown in Figure 1 (taken from

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Frocht, 9). If we assume plane stress and elastic behavior, the expression for the strain, ϵ_x, across the diameter is

$$\epsilon_x = 1/E\ [\sigma_x - \nu(\sigma_y + \sigma_z^{\circ})]$$

where ν is the Poisson's ratio.

By substituting in the preceding expression for σ_x and σ_y, we derive

$$\epsilon_x = 2P/E\pi td\ [(4d^4\nu - 16d^2x^2)/(d^2 + 4x^2)^2 + (1 - \nu)]$$

The total deformation is given by integrating the strain between ±d/2:

$$\Delta = \int_{-d/2}^{d/2} \epsilon_x d_x$$

where Δ = total deformation across the specimen.

By substituting for ϵ_x and integrating between the limits ±d/2, we derive

$$\Delta = P/tE\ [(4/\pi) + \nu - 1]$$

By simplifying and solving for E, we get

$$E = P(\nu + 0.2732)/t\Delta \tag{1}$$

Thus, if the horizontal deformation across a cylinder resulting from an applied vertical load is known, the modulus of elasticity can be calculated.

For purely elastic materials, Eq. 1 should apply for either static or dynamic loadings. For viscoelastic materials, such as asphalt concrete, Eq. 1 should apply reasonably well if the loading time is short enough so that viscous effects are small. Under short-duration dynamic loads on a viscoelastic material, the apparent Young's modulus, E, is frequently defined as the M_R, the material property useful to multilayer elastic or finite element structural design calculations.

EXPERIMENTAL PROCEDURE

In our procedure, a light pulsating load was applied through a load cell across the vertical diameter of a specimen, which caused a corresponding elastic deformation across its horizontal diameter. This dynamic deformation was measured with sensitive transducers requiring only a few grams of activating force. No appreciable restraining force was applied by the transducers. Air pulses were supplied to the pneumatic cylinder from an electrically activated solenoid or a fluidally operated valve.

The assembly is shown in Figure 2, and details of the equipment and procedures are given in the Appendix. The transducers are mounted directly on the specimen so that they ride with any vertical movement. Also, the twin transducers are additive in effect; consequently, horizontal movements or vibrations are automatically canceled. Output from the transducers and load cell are amplified and recorded on a strip chart recorder. An appropriate oscilloscope can also be used. Figure 3 shows a typical trace obtained on an asphalt concrete specimen loaded at 75-lb peak pulse load.

A load duration of 0.1 sec repeated 20 times a minute was chosen because this loading corresponded to the duration used by a number of investigators (12-21). Their various studies included relating laboratory-measured M_R to field behavior within the framework of multilayer elastic design theory. A load duration of 0.1 sec is about the same duration as is obtained with the Benkleman beam method of measuring pavement deflections. Also, nearly 3-sec pauses between load applications permit substantially complete viscoelastic recovery of the specimen.

Figure 1. Stress distribution.

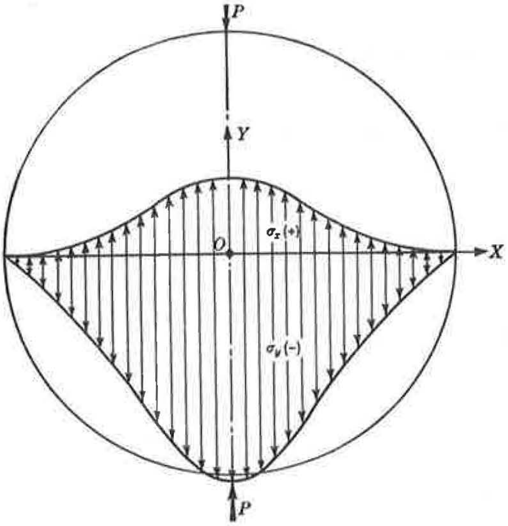


Figure 2. Diametral resilient modulus device.

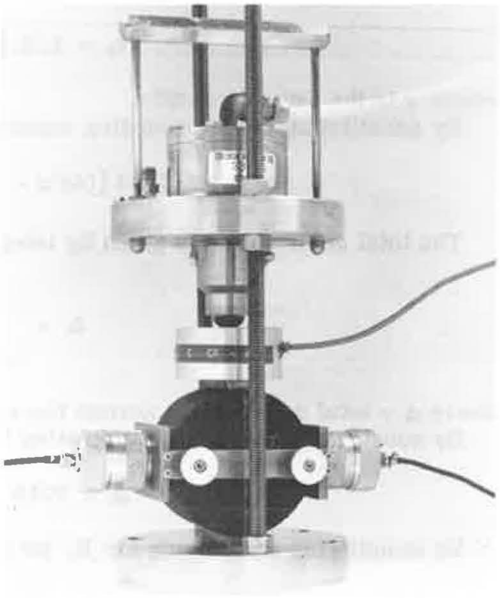
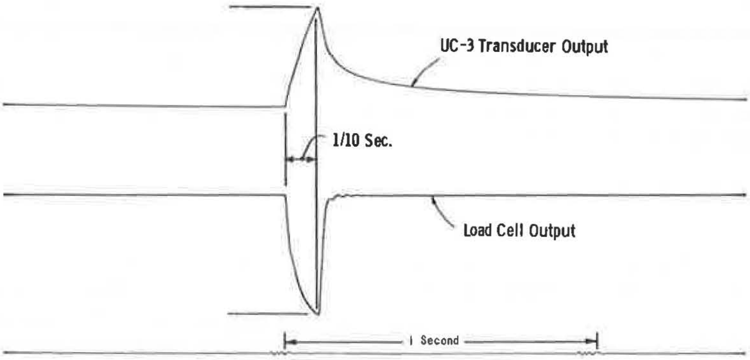


Figure 3. Typical trace of resilient modulus from diametral measurement.



CALCULATION OF M_R FROM DYNAMIC DIAMETRAL MEASUREMENTS

Both the dynamic load, P, and the total deformation, Δ, are taken from recorded traces shown in Figure 3. These values are entered in Eq. 1, where M_R is assumed equal to E.

$$M_R = P(\nu + 0.2732)/t\Delta \quad (2)$$

A range of values for Poisson's ratio can be assumed without excessive error in the calculated M_R. Sayegh (22), using sonic experiments, showed that the ν of asphalt concrete ranges from 0.2 at a strain of 10 µin./in. to 0.5 at strain levels of 300 µin./in. Dehlen (20) demonstrated that the ν for asphalt concrete could vary from 0.35 to 0.5 depending on temperature and deformation. Cragg and Pell (23) found that at room temperature a ν of 0.35 is a reasonable value to assume. As will be shown later, 0.35 for an asphalt concrete gives a reasonable agreement among M_R values as determined by the diametral method when compared with direct tension or compression methods or with flexural methods, which use a temperature of 73 F.

COMPARISON OF M_R VALUES OF POLYMER SPECIMENS USING DIRECT TENSION AND DIAMETRAL METHODS

Both the ν and M_R of three different polymers [Lucite, high molecular weight polyethylene (HMW-PE), and Teflon] were determined by subjecting suitable specimens to 0.1-sec duration repeated direct tensile loads at several levels. The stress on the cross section was monitored by a load cell, while the axial and normal strains were sensed by two pairs of ½-in. strain gauges cemented to opposite sides of the tensile specimens. The M_R values obtained at various stress levels are shown in Figure 4. Poisson's ratios, calculated from the output ratio of strain gauges mounted at right angles to one another, are noted on the figure next to each data point.

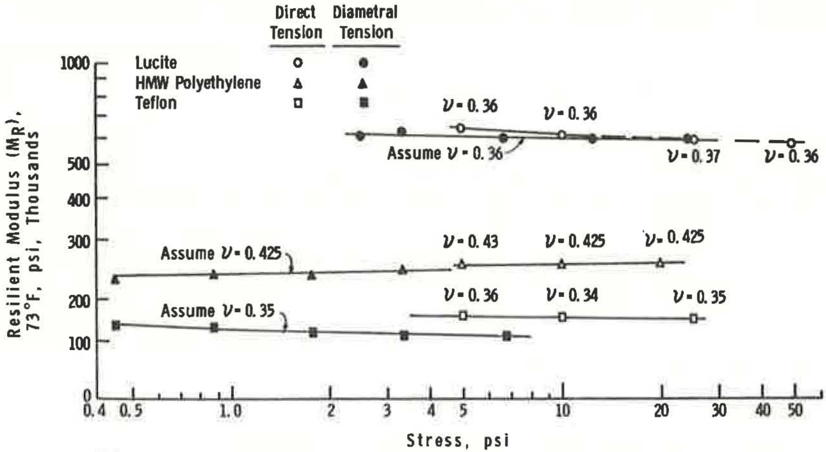
Four-in. diameter cylindrical specimens were made from the same block of polymer as were the respective tensile specimens. The M_R of the cylindrical specimens was determined over a range of loadings by using the diametral method previously described. M_R values were calculated from their diametral deformation together with the ν determined on the tensile specimens. M_R values determined by both methods over a range of stress levels are shown in Figure 4. Both the Lucite and the HMW-PE are shown to give nearly identical values by the two methods at the same stress levels. The values for the Teflon agree within about 12 percent.

COMPARISON OF M_R VALUES OF AC SPECIMENS USING DIRECT TENSION, COMPRESSION, AND DIAMETRAL METHODS

Four-in. diameter by 8-in. tall asphalt concrete (AC) specimens were made from Cache Creek gravel and also from crushed Watsonville granite. Both mixes had the gradation shown in Figure 5, curve I. These mixes contained 5 percent by weight of 85- to 100-penetration asphalt and were compacted by the Hveem kneading compactor. After fabrication, two ½-in. wide slices were removed by a diamond saw from the opposite sides of the cylinder. Two-in. long strain gauges were cemented to these freshly sawed surfaces. Also, about ¼ in. of each end of these cylinders was removed; ½-in. thick brass disks were adhered with epoxy cement to the exposed ends of the specimen. The specimens were then subjected to 0.1-sec tensile or compressive pulsating loads having the same characteristics as those shown in Figure 3. The loads were applied through a load cell fastened to the brass disk that had been cemented to the top of the specimen. The brass disk on the bottom of the specimen was bolted to the bottom plate of the loading device. The M_R at various stress levels was calculated directly from the strains shown by the strain gauges cemented to the sides of the specimens and from the loads shown by the load cell.

After testing by this direct method, a 2½-in. thick section was sliced from the center of each specimen. This section included the same area that had been spanned by the strain gauges in the previous tests. The M_R values of the 2½-in. thick, 4-in. diameter slices were then measured by the diametral method previously described.

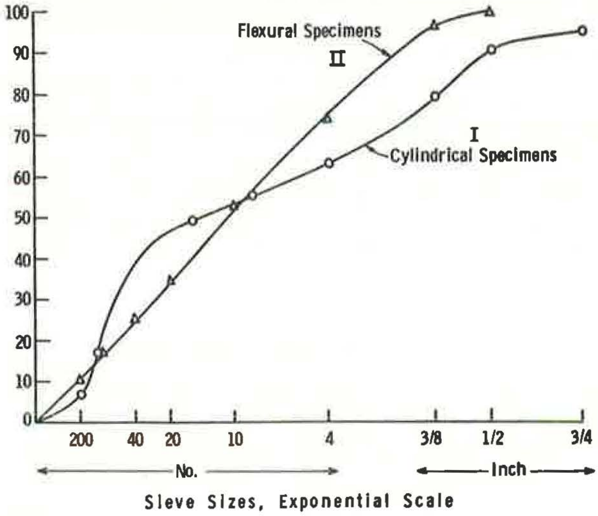
Figure 4. Comparison of resilient modulus of polymers using direct tension and diametral methods.



Notes:

1. Diametral tensile stress is average from center to edge, 42.9% of $\sigma_x = 2P/\pi tD$.
2. Poissons ratio, ν, shown on direct tension data points are measured values.

Figure 5. Gradations of aggregates used.



A typical comparison is shown in Figure 6. Both the direct tensile M_R and direct compressive M_R agree quite well over the range of stresses shown. M_R diametrally measured over a similar range of loading is also shown in Figure 6. These latter values were calculated by assuming three different values for ν: 0.2, 0.35, and 0.5. Good agreement is shown in M_R when a value of 0.35 is assumed for ν. Even when the extreme values of 0.2 and 0.5 are assumed, the calculated value varies only about ±25 percent from the value calculated by using a value of 0.35. Similar agreement was found for other asphalt concrete specimens prepared and tested in the same way.

COMPARISON OF M_R VALUES USING DIAMETRAL AND FLEXURAL METHODS

Bar-shaped asphalt concrete specimens, $1\frac{1}{2}$ by $1\frac{1}{2}$ by 15 in. long, were made from Watsonville crushed granite. These mixes were graded according to curve II shown in Figure 5. They contained 6 percent by weight (dry aggregate basis) of 85- to 100-penetration asphalt. The procedure used for preparing these specimens was described by Deacon (17), and the flexural M_R of these specimens was determined over a range of loadings by four-point loading by the method described also by Deacon (16).

At the same time that the flexural specimens were made, 4-in. diameter by $2\frac{1}{2}$-in. thick cylindrical specimens were also made from this same mix. A comparison of the M_R values determined flexurally with those determined diametrally is shown in Figure 7. The stress levels plotted for the diametral samples are the maximum tensile stress existing in the specimen during the test. The stress values plotted on the flexural specimens are the maximum outer fiber stress. Equipment limitations prevented overlapping of the two stress levels obtained in the two methods. The data suggest that, in the case of the flexurally determined values, the outer fiber stress levels are so high that the response is nonlinear. The M_R values indicated by projection of these flexural values to the lower stress levels used in the diametral tests suggest that the agreement between flexurally determined M_R and diametrally determined M_R values is quite good at similar stress levels.

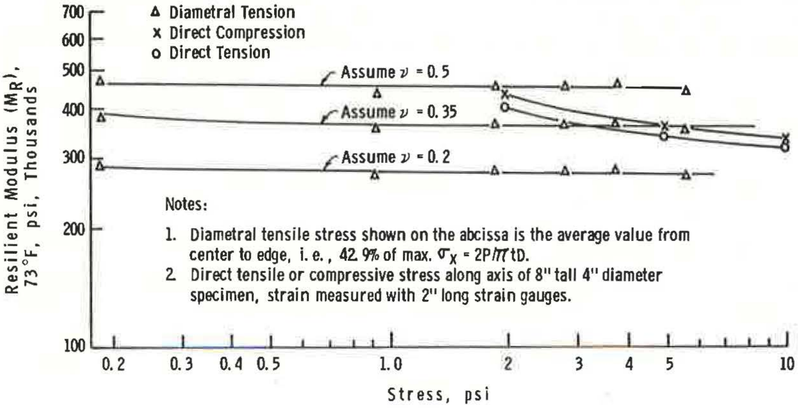
USE OF THE DIAMETRAL RESILIENT MODULUS DEVICE IN MIX DESIGN

Tests, such as the Marshall stability and Hveem stability, are widely used to design asphalt concrete mixes such that the mixes have stabilities adequate to prevent shear failures. These tests are augmented by the Marshall flow and Hveem cohesion tests. These latter tests attempt to prevent design of mixes that have high stabilities at the expense of adequate cohesion. The results of these tests are not necessarily related to the structural value of the mix, although Shook and Kallas (24) found a relation between the Marshall flow-stability ratio and M_R for some mixes. The diametral M_R of an asphalt concrete mix is a value that is directly related to the structural contribution of that layer of mix. The relation is shown by means of the multilayer elastic design or by finite element analysis. To this end, a mix should be designed and optimized for both shear strength and resilient modulus. Ideally, the mix design will also be optimized for fatigue resistance as well. An example of a mix design study on M_R (Fig. 8) shows the effect of the asphalt content on the M_R of the mix. This is the same mix as is shown in Figure 5, curve I. In this particular mix, the optimum plateau for the mix is shown to extend above 7 percent asphalt before it decreases. This test was also demonstrated by Schmidt (25) to be useful in investigating the influence of water on the the M_R.

CONCLUSIONS

A new method is presented for determining the resilient modulus of asphalt-treated mixes. It is low in cost and is more rapid than the currently used routine stability tests. Validity of the method is supported by its reasonable agreement with the M_R values determined by direct M_R tensile measurements on a variety of polymeric samples. Even when a relatively wide range of values is assumed for Poisson's ratio, the diametral method gives M_R values within 25 percent of the values found by direct measure-

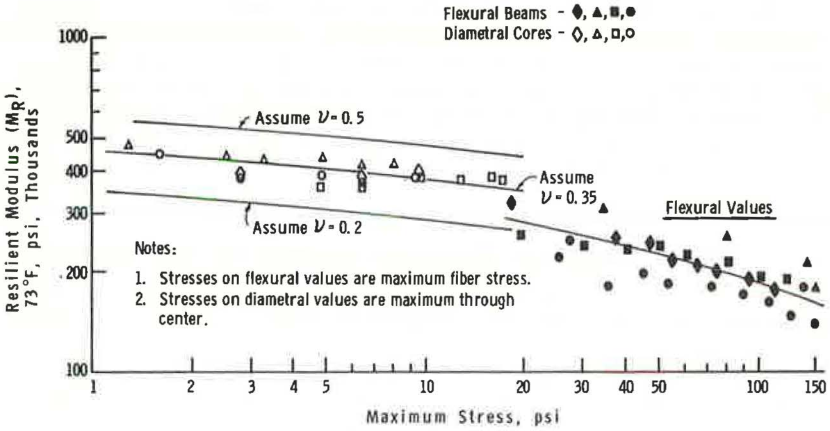
Figure 6. Comparison of resilient modulus of AC specimens using direct tension, compression, and diametral methods.



Notes:

1. Diametral tensile stress shown on the abcissa is the average value from center to edge, i.e., 42.9% of max. $\sigma_x = 2P/\pi tD$.
2. Direct tensile or compressive stress along axis of 8" tall 4" diameter specimen, strain measured with 2" long strain gauges.

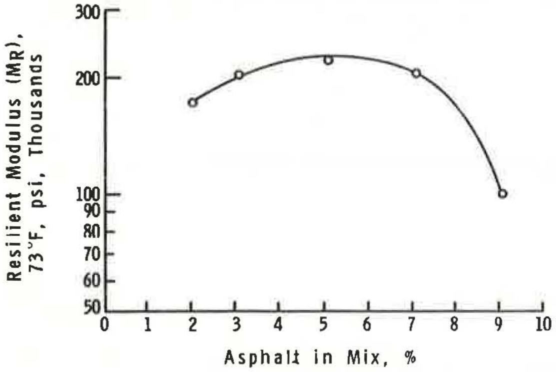
Figure 7. Comparison of resilient modulus using flexural and diametral methods.



Notes:

1. Stresses on flexural values are maximum fiber stress.
2. Stresses on diametral values are maximum through center.

Figure 8. Influence of AC on resilient modulus.



ment of the tensile or compressive M_R on asphalt concrete mixes. M_R values determined flexurally agree almost as well.

The usefulness of the method in designing asphalt-treated mixes for optimum M_R is shown by an example of a mix design relating asphalt content to the M_R.

ACKNOWLEDGMENT

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APPENDIX

TEST APPARATUS AND PROCEDURE

General Description

Equipment used for determining the M_R on asphalt-treated mixes consists first of a repetitive loading device that applies pulsating loads of 0.1-sec duration every 3 sec. Other pulse durations and frequencies may be preferred. This loading device has a pneumatic piston that operates when a pulse of air is supplied from an electrically timed solenoid valve. Alternatively, a fluidal valve can control the air pulses. Mechanical or electrical magnetic loading can also be used.

The pulsating load is sensed as it is transmitted to the specimen by a 150-lb capacity load cell. The cell is placed between the ram from the pneumatic piston and the loading strip on top of the specimen. Output from the load cell is recorded on a strip recorder. A typical recorder is a Hewlett-Packard Model 7702B coupled to a Hewlett-Packard Preamplifier Model 8805A.

The pulsating load, applied across the vertical diameter, results in a corresponding pulsating deformation across the horizontal diameter of the specimen. This horizontal deformation is sensed by a pair of Statham (UC-3) transducers. The two transducers are mounted in a yoke that is clamped to the specimen. (Fabrication details of the yoke and transducer housing assembly are available from Chevron Research Company as Drawing No. B-12828.) The tips of the transducers barely touch the specimen when operating. A horizontal displacement unbalances the bridges in the transducer strain gauges. A corresponding output voltage is pre-preamplified and fed to the input of a Hewlett-Packard Preamplifier Model 8802A. The circuit for the pre-preamplifier is shown in Figure 9. After amplification, the final output is sent to the second channel of the strip recorder. An appropriate oscilloscope can be used instead of the strip recorder. It is not, however, as convenient to use.

Calibration of the Transducers

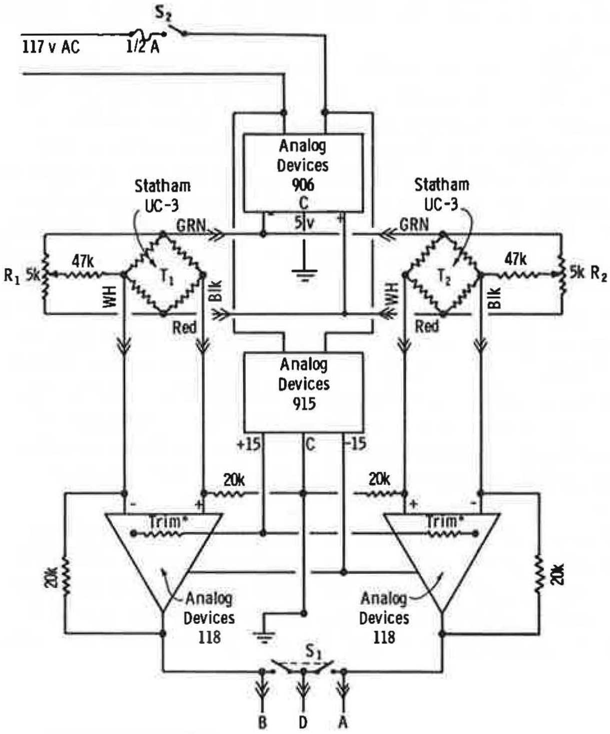
Refer to Figure 9. With power switch S_2 on, no load on the transducers, and switch S_1 switched to ground the output of transducer, T_2, adjust R_1 to obtain an approximate zero output across the black and white leads of the ungrounded UC-3 transducer, T_1. Reverse switch S_1, and repeat adjustment with R_2 to obtain zero output from the other transducer, T_2. This adjustment is not critical and usually needs to be done only when new transducers are installed. Connect leads A, B, and D to appropriate Hewlett-Packard Model 8802A Preamplifier input terminals. Adjust and balance the Hewlett-Packard Preamplifier and recorder according to the manufacturer's instructions.

Mount one of the transducers in the calibrating jig shown in Figure 10. Turn the micrometer adjustment until the recorder just barely responds. Then, tighten the micrometer barrel to obtain 0.003-in. movement. (The total range of the transducer is only about 0.0045 in., so make certain that the calibrating movement is within the range of the transducer.) Note change in output of recorder. Repeat this on the second transducer, average the two outputs, and calculate the microinches for each millivolt reading on the Hewlett-Packard Recorder. This is the calibration factor to be used in subsequent calculations. A convenient way to quickly check the stability and proper operation of the transducer-amplifier-recorder combination is to test a 2-in. thick by 4-in. diameter Lucite disk. The M_R of this material is quite stable and, once determined, can be used as a reference.

Sample Insertion and Preliminary Adjustment

Refer to Figure 11. Place the yoke containing both transducers onto holder E; release locknuts A and A′; and retract both transducer housings, B and B′, by sliding them until the tips, C and C′, of the transducers are protected by being withdrawn inside the faces of the yoke. Loosen all four clamping screws, D, and gently insert the 4-in. diameter sample into the center of the yoke. Put sample onto the bottom centering strip, F. Gently tighten all four rubber-faced clamping screws so that the specimen is

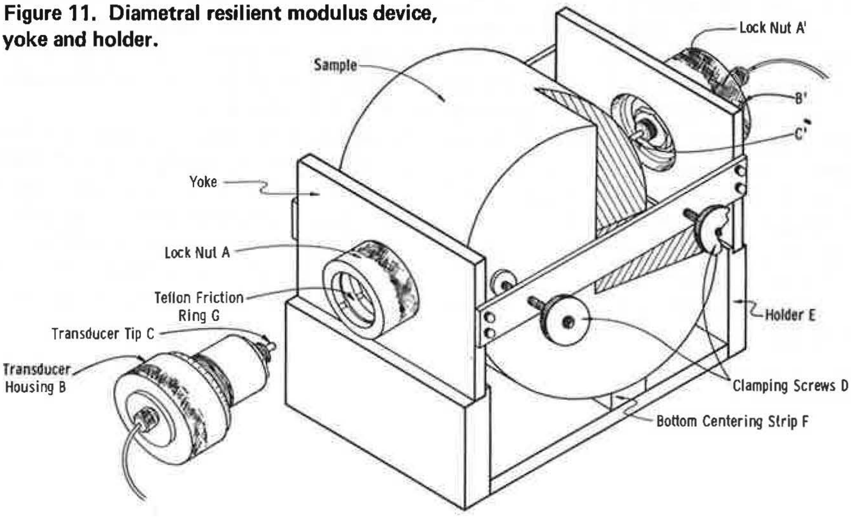
Figure 9. Pre-preamplifier circuit for UC-3 transducer.



*Selected to balance the offset voltage to zero.

Figure 10. Micrometer and jig for calibrating UC-3 transducers.

Figure 11. Diametral resilient modulus device, yoke and holder.



centered and square with respect to the yoke. Remove the specimen and yoke from the holder by lifting the specimen. Do not lift by the yoke. Place into the loading device as shown in Figure 11.

Place the top loading strip on top of the specimen, 180 deg from the bottom loading strip. Place the load cell on top of this top strip, and push shaft from pneumatic piston down until it firmly contacts with load cell.

With locknuts A and A′ loosened, slide transducer housings toward the specimen until the tips are within about 0.005 in. of the specimen. Tighten the locknuts to contract the Teflon friction ring, G, around the micrometer threads on the transducer housing. Set the attenuator on the preamplifier at 50, and advance one of the transducers toward the specimen by rotating the housing. Rotate until the pen on the recorder advances 50 mV (about 200 μin.). Rezero the recorder pen and repeat micrometer adjustment on the second transducer. Both transducers should now be in firm contact with the specimen without having been run in far enough to take up an appreciable part of their range.

In the case of very open mixes or irregular specimens, it may be necessary to form small seating pads on the specimen with plaster of paris. These seating pads may be needed under the clamps, transducer tips, and loading strips. Small ¼-in. diameter seat pads can also be fastened to the tips of the transducers to bridge the opening in specimens made from open mixes. Cores cut from pavements with 4-in. diameter diamond drills usually are only about 3½ in. in diameter, in which case it is necessary to shim up the centering strip in the holder until the transducers are aligned across the diameter of the specimen.

It is most convenient to conduct the testing procedure in a constant-temperature room or chamber. However, the transducers can be waterproofed; and the assembly, including the bottom of the repetitive loading device, can be immersed in a constant-temperature water bath. Mixes frequently react with water and rapidly change their M_R. When held in a water bath to obtain temperature equilibrium, they should be placed in sealed plastic bags.

Operation

Turn on the electric timer and the air to the solenoid valve. Adjust air pressure until desired peak loads are indicated by the load cell on the recorder. Adjust preamplifier attenuation switch until the output from the transducers is within range. Operate the system for 100 cycles at low chart speed, at which time switch the chart speed to 100 mm/sec, and record one or more pulses of the load and deformation. Check the load pulse duration for the desired shape and duration. Adjust timer if necessary. Calculate the deformation from the peak pulse output recorded at the fast chart speed. Use the calibrating factor previously established to calculate the M_R.

Remove the specimen and yoke from the repetitive loading device, replace in holder, retract transducers, and rotate the specimen 90 deg. Reset the transducers and repeat the test with the specimen in this position. The two results obtained on the same specimen rotated 90 deg should be within 10 percent. Mixes made from certain aggregates may vary 20 percent. If the differences are greater than these values, rotate the sample to the original position and repeat. If exceptionally large differences are confirmed, then the particular sample is nonisotropic. Report the average M_R value obtained from the two readings.