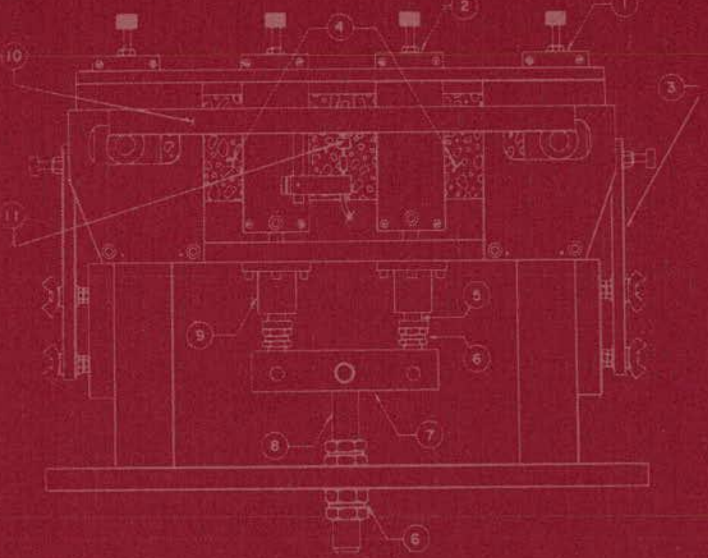

Test Procedures for Characterizing Dynamic Stress-Strain Properties of Pavement Materials

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Transportation Research Board
National Research Council
National Academy of Sciences

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The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competence and with regard for appropriate balance.

This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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CONTENTS

FOREWORD

The purpose of this document is to compile for the highway engineer and researcher the dynamic testing procedures for evaluating the resilient moduli of highway materials that have been found to give reasonable results. It is hoped that such a document will encourage the eventual establishment of standard test procedures for use by researchers and practicing engineers. The use of standardized test procedures would permit the direct comparison of experimental test results obtained by various research organizations.

Some of the various test methods described in this report may give considerably different results. No attempt is made to recommend the most appropriate test method for specific conditions. Caution therefore should be exercised in selecting appropriate test methods for characterizing in the laboratory the material properties representative of field conditions.

This report was written as a part of the activities of the Transportation Research Board's Committee on Strength and Deformation Characteristics of Pavement Sections. John A. Deacon, who was at the time committee chairman, appointed a subcommittee cochaired by Eugene L. Skok, Jr., and Bernard F. Kallas to prepare this report. The report was completed under the committee chairmanship of Richard D. Barksdale. The report was written by Bernard F. Kallas, Carl L. Monismith, Eugene L. Skok, Jr., Q. L. Robnett, Richard D. Barksdale, Thomas W. Kennedy, and Kamran Majidzadeh and was edited by Richard D. Barksdale. Other committee members helped review this document and assisted in its development. Appreciation is extended also to W. M. Sangster, Director of the School of Civil Engineering, Georgia Institute of Technology, for the financial support necessary for the preparation of most of the figures.

INTRODUCTION

During the past 10 to 15 years, people have shown considerable interest in the use of various elastic and viscoelastic layered system theories to predict the physical response of structural pavement sections. Use of such models has become more common because, by using modern high-speed digital computers, one can rapidly solve more complicated layered pavement system models than one could in the past. When an elastic layered theory is used to predict pavement response, one must either evaluate experimentally or estimate the modulus of elasticity and Poisson's ratio of each layer in the system. Therefore, the problem of determining the critical conditions for design and the pertinent material properties for each layer still remains.

The stress-strain properties of materials used in highway construction can vary greatly because of a number of factors including stress state, pulse rate and duration, temperature, degree of saturation, density, age, and method of testing. A variety of different methods for evaluating the dynamic material properties of pavement materials have been developed in recent years by a number of researchers. A review of many of the testing procedures for evaluating the modulus of elasticity and Poisson's ratio of highway materials and an extensive list of references have been presented elsewhere (1).

Because of the wide variation in measured material properties that can occur with variations in test conditions and procedures, procedures should be specified and described carefully when one presents and uses the test results. Standardized test procedures are especially desirable if the test results are to be used by several different agencies. The purpose of this document is to present several acceptable methods currently being used for determining the stress-strain properties of pavement materials for use in elastic layered theories.

The laboratory testing techniques given in this Special Report include both the test procedure and a description of sample preparation and the type of equipment that is necessary to perform the tests. Testing procedures are given for determining the dynamic modulus of elasticity by using the following tests: (a) repeated load triaxial test, (b) complex modulus test, (c) flexural bending test, (d) indirect tensile test, and (e) resonant column method. In addition, a simplified, approximate test procedure is given for determining the dynamic modulus for cohesive soils. The procedures presented should be considered as somewhat standardized; eventually, after some modifications, it is hoped that these procedures can be developed into standard test methods for determining the elastic modulus and Poisson's ratio for use with layered theories. This Special Report also defines some of the problems involved in the dynamic testing of highway materials and suggests methods of sample preparation and test procedures that tend to minimize these problems.

FUNDAMENTAL CONSIDERATIONS

Proper evaluation of pavement material properties requires careful consideration of many factors including (a) magnitude, speed, and nature of traffic loading; (b) short- and long-term environmental conditions; (c) construction variables; and (d) nature of materials being tested (stabilized, cohesive, granular). That the test should simulate as closely as practical in situ environmental conditions and the stress state occurring under the action of the moving (or static) wheel loads is the basic philosophy that should be used in evaluating material properties. Considerable judgment must be used in estimating the overall long-term environmental effects such as degree of saturation and density of pavement materials. Work should be done according to degree of saturation rather than moisture content because the former appears to be a more basic variable.

Under field service conditions, variation in the dynamic modulus and, to a lesser extent, Poisson's ratio that is due to changes in environmental factors such as degree of saturation and temperature can have significant effects on the overall performance of the pavement. Even though reasonably accurate values of the dynamic modulus of pavement materials may be obtained in the laboratory under carefully controlled conditions, extreme care must be exercised in incorporating these data into mechanistic design procedures.

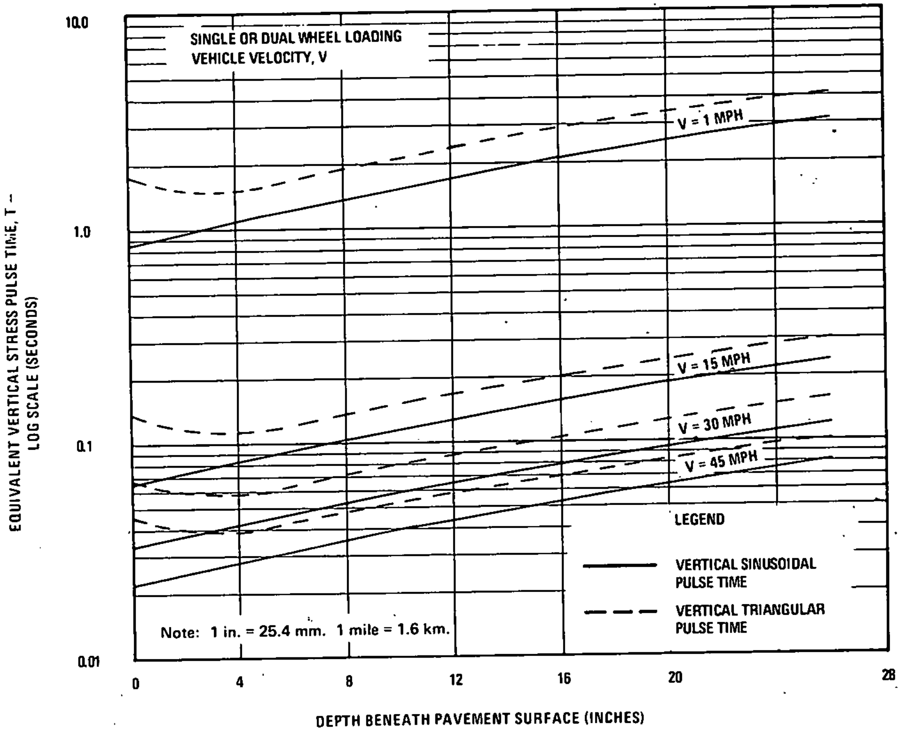
SELECTION OF STRESS PULSE

When a wheel load moves past an element of material located within the pavement system, the element is subjected to a simultaneous buildup in both the major and minor principal stresses. Currently, for routine laboratory testing, only the major principal stress (axial stress in a triaxial test) needs to be varied if care is taken in selecting the confining pressure. The actual stress pulse applied by a moving wheel load is close to half sine in shape. Preliminary results, however, indicate that triangular, sinusoidal, and half sine pulses all can be used to simulate actual in situ stress provided care is taken in selecting the magnitude and duration of the pulse. For conventional flexible pavement structures and spring and summer temperatures, the duration of the stress pulse varies primarily with element location on point of loading and with vehicle speed. The data shown in Figure 1 are suggested as a practical guide for use in selecting the duration of the stress pulse that should be used in performing a dynamic laboratory test.

DYNAMIC MODULI

For moderate stress levels, the elastic response of most subgrade soils, unstabilized granular materials, and stabilized materials becomes relatively constant after

Figure 1. Variation of equivalent vertical stress pulse time with vehicle velocity and depth (3).



approximately 100 to 200 load repetitions. Studies also indicate that a single test specimen usually can be used to characterize the nonlinear elastic response of most paving materials. This can be accomplished with 1 specimen by determining the elastic bounce at several different confining pressures and deviator stresses, or temperature in the case of asphalt concrete, provided care is exercised to increase gradually the severity of the stress level.

For triaxial testing, results indicate that, when the dynamic modulus is greater than about 15,000 lbf/in.^{2} (103 500 kPa), special measuring clamps or special optical tracking equipment should be attached to the specimen to eliminate end effects and slop in the system. Clamps suitable for use on cylindrical specimens will be described in another section of this Special Report.

A specimen tested in a triaxial cell probably should be tested with the drainage valves leading to the inside of the specimen open because of the conditions of a material sample beneath pavement subjected to many load repetitions. In determining dynamic modulus when only 100 to 200 load applications are to be applied, the method of drainage probably will not have a significant effect on the resultant dynamic modulus in most instances. If the test is performed over a period of days and drainage is permitted, then the specimen may dry out and become hard because of the development of significant amounts of capillary tension.

POISSON'S RATIO

Because of problems associated with reliable measurements of Poisson's ratio and because the response of pavement is relatively insensitive to reasonable variations in this parameter, estimated values of Poisson's ratio can be used at this time as an engineering approximation for the mechanistic design procedure. Typical ranges in the variation of Poisson's ratio have been found to be as follows:

Material	Poisson's Ratio
Asphalt concrete	0.25 to 0.35
Unstabilized granular subgrades, subbases, and bases	0.30 to 0.40
Silty subgrades	0.35 to 0.45
Clay subgrades	0.40 to 0.50
Soil cement	0.10 to 0.25

If Poisson's ratio is to be measured, measuring clamps that fit around the cylindrical triaxial specimen can be used.

INFLUENCE OF TYPE OF MATERIAL

One should carefully consider the type of material when selecting both the test method and test conditions such as stress level. For unbound cohesive and granular materials, either the repeated load triaxial test or the complex modulus test is well suited for evaluating elastic properties.

In general, the dynamic modulus of cohesive soils decreases rapidly with increasing magnitude of repeated axial stress up to a point; then it increases at a greatly reduced rate. For some types of soils, dynamic modulus is relatively unaffected by small changes in confining pressure. The effect of confining pressure on the dynamic modulus appears to become greater as clay content decreases or the material becomes stiffer. Numerous studies of the dynamic modulus of sands, gravels, and crushed stones have shown that the dynamic modulus significantly increases with increases in confining pressure and is only slightly affected by reasonable variations in the magnitude of the repeated axial stress.

Results of dynamic triaxial tests have indicated that temperature and rate or frequency of loading have a significant effect on the stiffness of asphalt-bound materials. Asphalt content, type of asphalt, air voids, aggregate grading, and type of aggregate have a considerably smaller effect on stiffness. The dynamic modulus determined from flexural and indirect tensile tests has been found to be as small as half the value determined from triaxial tests. Probably the actual in situ modulus for asphalt concrete is somewhere between the values determined from flexural and triaxial tests.

Repeated load tests performed on cylindrical specimens of cement-bound materials have shown that the dynamic modulus of soil cement decreases with increases in confining pressure. Furthermore, laboratory results indicate that the dynamic modulus measured by using the triaxial test may be as much as 10 times greater than that obtained in repeated flexural tests. Results of the flexural tests probably should be used for stabilized materials in layered theories because this test more closely simulates conditions of bending, which occurs in very stiff base layers. Also, because of cracking with time in cement-treated and asphalt concrete bases, the effective modulus will tend to decrease significantly over time.

SPECIMEN PREPARATION AND COMPACTION PROCESSES

To obtain specimens that are representative of field conditions, one must use great care in preparing, handling, and storing the test specimens. Furthermore, use of different materials and different methods of compaction in the field will require the use of varying compaction techniques in the laboratory. This section will describe methods that can be used to prepare cohesive soils, granular soils, and asphalt concrete for laboratory use. Typical equipment required is as follows:

1. Compaction apparatus;
2. Loading equipment [static machine with a 10- to 30-ton (9- to 27-Mg) capacity, kneading compactor for cohesive soils and stabilized materials, and vibratory compactor for granular soils];
3. Calipers, micrometer gauge, and steel rule [calibrated to 0.01 in. (0.254 mm)];
4. Rubber membranes from 0.01 to 0.025 in. (0.254 to 0.635 mm) in thickness;
5. Rubber O-rings;
6. Vacuum source with bubble chamber and regulator;
7. Membrane stretcher;
8. Scales;
9. Weighing pans; and
10. Porous stones.

COMPACTED COHESIVE SPECIMENS

The resilient character of compacted clays is dependent on the structure imparted to the soil particles by the compaction process. (The unified soil classification system is used to define a clay soil.) Laboratory compaction processes must be selected in accordance with the expected field compaction conditions. Any compaction process that causes shearing deformation in a clay soil having a degree of saturation greater than 80 percent results in a dispersed (or parallel) clay structure. Clays with a dispersed structure exhibit greater deformation than would the same soil with a flocculated (random) structure tested under identical conditions. Some general criteria can be used to guide selection of the appropriate compaction conditions for clay soils.

1. If the field compaction conditions will be at a water content corresponding to less than 80 percent of the saturation water content and the in-service water content is expected to remain less than the 80 percent saturation value, then any of the standard impact, gyratory, kneading, or static procedures may be used to simulate the in-service condition.
2. If the field compaction will be at a water content corresponding to greater than 80 percent of the saturation water content and the in-service water content is expected

to remain greater than the 80 percent saturation value, then the compaction process must be of the shearing type. That is, an impact, gyratory, or kneading process must be used to simulate the dispersed structure in service.

3. If the field compaction conditions will be at a water content corresponding to less than 80 percent of the saturation water content and the in-service conditions are expected to result in a degree of saturation greater than 80 percent, then static compaction must be used to simulate the flocculated structure in service.

In Figure 2, resilient modulus is shown as isograms on a chart of dry density versus water content. The form shown in Figure 2 has general application to compacted clay soils and may be used to guide the selection of a test program.

1. If the range of compaction conditions and the range of in-service conditions are known, select an appropriate laboratory compaction method. Prepare and test samples at dry densities and water contents within the in-service range such as that shown in Figure 2.
2. If the service conditions are not well defined, then prepare and test specimen over a substantial range of dry densities and water contents. Display the results as shown in Figure 2 and use the resilient modulus in conjunction with other properties such as rutting and swelling to select the range of field placement conditions.

Specimen Size

The diameter of the specimen to be tested is determined by a lower bound of approximately 2.5 in. (63.5 mm) or by 4 to 5 times the maximum size of particle in the material. This lower bound represents a minimum size that can be expected to provide a reasonable representation of the larger mass of material in a pavement. Specimen length should not be less than 2 times the diameter.

Moisture-Density Relationship

Four steps should be followed to determine moisture-density relationship.

1. Establish the moisture-density relationship for the soil according to 1 of the following procedures: (a) ASTM D 1557-AASHO T-180, (b) ASTM D 698-AASHO T-99, (c) California 216F, or (d) some other standard method. Prepare a graph showing dry density and water content as described in the standard procedure chosen.
2. Determine the specific gravity of the soil according to the appropriate procedure (ASTM D 854 or California 209A).
3. Use the data obtained in steps 1 and 2 to determine 100 percent and 80 percent of saturation at various densities. Place this information on the graph drawn in step 1; that is, draw a 100 percent and an 80 percent saturation line.
4. Select the densities, water contents, and compaction method to be used to prepare specimen.

Preparation of Soil for Compaction

Ten steps should be followed to prepare soil for compaction.

1. Determine the water content W_1 percent of the soil (if other than oven-dried material is to be used).
2. Determine the volume V_s of the compacted specimen to be prepared. For other than static compaction methods, the height of the compacted specimen must be greater than that required for resilience testing to allow for trimming of the specimen ends. An excess of 0.5 in. (13 mm) generally will be adequate.

3. Determine the sample weight of the oven-dried soil W_s and water W_w required to obtain the desired dry density γ_d and water content W percent as follows:

$$W_s \text{ in pounds} = \gamma_d \text{ in pounds per cubic foot} \times V_s \text{ in cubic feet}$$

$$W_s \text{ in grams} = W_s \text{ in pounds} \times 453$$

$$W_w \text{ in pounds} = \gamma_d \text{ in pounds per cubic foot} \times \frac{W \text{ percent}}{100}$$

$$W_w \text{ in grams} = W_w \text{ in pounds} \times 453$$

4. Determine the sample weight of other than oven-dried soil (W_{ss}) required to obtain W_s. An additional amount of approximately 500 g should be allowed, and the excess should be used to determine the water content at the time of compaction.

$$W_{ss} \text{ in grams} = (W_s \text{ in grams} + 500)\left(1 + \frac{W_1}{100}\right)$$

5. Determine the weight of water (W_{aw}) required to increase the weight from the existing (W_{1w}) to the desired (W_w).

$$W_{1w} \text{ in grams} = (W_s + 500)\left(\frac{W_1}{100}\right)$$

$$W_{aw} \text{ in grams} = W_w - W_{1w}$$

6. Determine the wet weight of soil (W_{wet}) to be compacted.

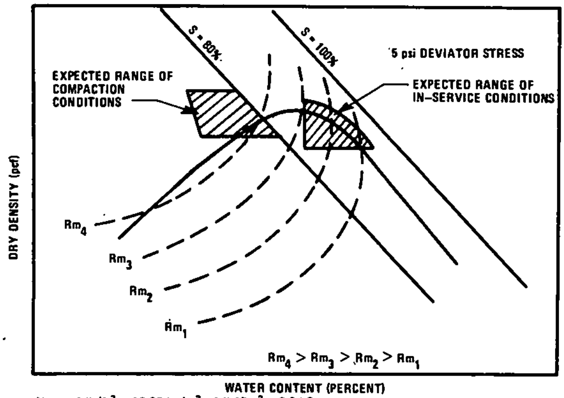
$$W_{wet} \text{ in grams} = W_s \times \left(1 + \frac{W \text{ percent}}{100}\right)$$

7. Place the mass of soil determined in step 3 into a mixing pan.
8. Add the water to the soil in small amounts and mix thoroughly after each addition.
9. Place the mixture in a plastic bag. Seal the bag and knead the soil with the fingers to obtain uniform dispersion of water throughout the soil. The mixture should be stored in the plastic bag in an atmosphere of 75 percent relative humidity for 12 to 24 h. Ensure a complete seal by using 2 or more bags.
10. After mixing and storage, weigh the wet soil and bag to the nearest gram and record this value on a form for compacted clays as shown in Figure 3.

<u>Compaction by Impact or Kneading Methods</u>

Specimens prepared in standard molds associated with impact or kneading methods

Figure 2. Result of resilence tests on compacted clays, variation of dry density with water content.



Note: 1 lb/ft³ = 16.02 kg/m³. 1 lbf/in.² = 6.9 kPa.

Figure 3. Sample data recording form for compacted clays.

Soil sample__________

Location__________
Sample no.__________
Specific gravity__________

Soil Specimen Measurements
Diameter
Top__________
Middle__________
Bottom__________
Average__________
Membrane thickness__________
Net diameter__________
Height of specimen plus cap and base__________
Height of cap and base__________
Initial length__________

Soil Specimen Weight
Initial weight of container plus wet soil, g__________
Final weight of container plus wet soil, g__________
Weight of wet soil used__________

Soil Specimen Volume
Initial area, in.^{2}__________
Volume,[a] in.^{3}__________
Wet density, lb/ft^3__________
Water content, percent__________
Percent saturation__________
Dry density, lb/ft^3__________

Date__________
Compaction method__________

Vertical spacing between LVDT clamps, in.__________

Chamber pressure, lbf/in.^{2}__________

Constants
Vertical LVDT__________
Horizontal LVDT__________
Load cell__________
Comments__________

			Vertical Values				Horizontal Values			
Load Cell Chart Reading	Deviator Load (lb)	σ_d (lbf/in.^{2})	LVDT Chart Reading	Deformation (in.)	ϵ_{R1} (in./in.)	$M_R = \sigma_d/\epsilon_{R1}$ (lbf/in.^{2})	LVDT Chart Reading	Deformation (in.)	ϵ_{R3} (in./in.)	$\nu_R = \epsilon_{R3}/\epsilon_{R1}$

[a]Initial area times initial length.

(ASTM D1557, ASTM D698, California 216F, Harvard miniature compaction, or California or Triaxial Institute kneading compaction) may not be of the correct dimensions for direct use in resilience testing. However, molds of the correct dimensions can be obtained, and the methods can be adapted to the new mold sizes. This generally will require adjustments in the number of compacted layers or the number of tamps per layer or both. Large compacted specimens can be prepared and the correct size trimmed from these.

1. Establish the number of layers N to be used to compact the soil. Determine the weight of wet soil required per layer W_L.

$$W_L \text{ in grams} = \frac{W_{wet}}{N}$$

2. Place the mass of soil determined in step 1 in the mold. Compact according to the standard procedure. Scarify the surface of the layer.
3. Repeat step 2.
4. After compaction, use approximately 200 g of the remaining wet soil to determine water content.
5. Carefully remove the specimen from the mold. Trim the ends to provide plane surfaces.
6. Weigh the specimen to the nearest gram. Determine the average height and diameter to the nearest 0.01 in. (0.254 mm). Record these values on a form for compacted clays as shown in Figure 3.

The specimen is now ready for resilience testing. If there will be a delay of more than a few minutes before beginning the resilience testing, the specimen should be carefully wrapped in plastic to prevent evaporation. Note that fine-grained cohesive soils compacted wet of optimum (especially when a dispersed structure is developed) exhibit thixotropic strength gains with time. The limited data reported in the literature (2) indicate that a curing period of 1 to 7 days (depending on the soil) is usually sufficient to minimize the thixotropic strength gain effects on the resilient modulus. Limited results also indicate that a few hundred "conditioning" stress applications may be sufficient to eliminate or minimize this effect when the specimens are immediately tested after preparation.

Compaction by Static Loading

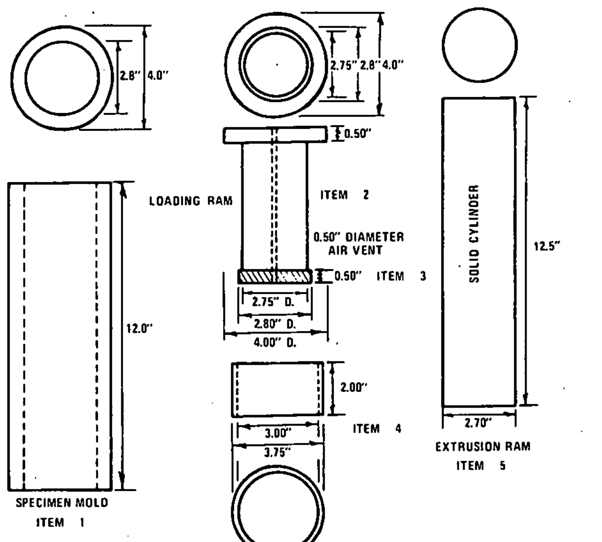
In the absence of standard methods for static compaction, the following procedure may be used. The process is one of compacting a known weight of wet soil to a volume that is fixed by the configuration of the mold assembly. A typical mold assembly for the preparation of a specimen with a 2.8-in. (71.12-mm) diameter and 6-in. (152.4-mm) height by using 3 layers is shown in Figure 4. To meet specific needs, equipment of differing size and number of layers can be developed.

1. Establish the number of layers N to be used to compact the soil. Determine the weight of wet soil per layer.

$$W_L \text{ in grams} = \frac{W_{wet}}{N}$$

2. Place 1 of the loading rams into the sample mold.
3. Place the mass of soil determined in step 1 in the sample mold. Use a spatula

Figure 4. Apparatus for compaction by static loading.



MATERIALS LIST
STATIC COMPACTION APPARATUS

ITEM	NO. REQUIRED	MATERIAL
1	1	NICKEL STEEL
2	2	ALUMINUM
3	2	TEFLON
4	2	LUCITE
5	1	ALUMINUM
6	1	LUCITE

Note: 1 in. 25.4 mm.

to draw the soil away from the edge of the mold and form a slight mound in the center.

4. Insert the second loading ram and place the assembly in the loading machine. Apply a small load. Adjust the mold so that it rests equidistant between the CLAMPS of the loading rams. Soil pressures developed by the initial loading will serve to hold the mold in place. By having both loading rams reach the 0-volume change positions simultaneously, one can obtain more uniform layer densities.

5. Slowly increase the load until the loading ram caps rest firmly against the mold. Hold the load at or near the maximum load for a period of time. The rate of loading and load duration depend on the amount of soil rebound. The slower the rate of loading is and the longer the load is held, the less the rebound is.

6. Decrease the load to 0 and remove the assembly from the loading machine.

7. Remove a loading ram. Scarify the surface of the compacted layer, put the correct weight of soil for a second layer in place, and adjust the soil as in step 3. Add a spacer ring and insert the loading ram.

8. Invert the assembly and repeat step 7.

9. Place the assembly in the loading machine. Load slowly while holding the load at or near maximum when the spacer disk firmly contacts the mold.

10. Repeat steps 6, 7, 8, and 9 as required.

11. Use approximately 200 g of the remaining soil for a measurement of water content.

12. Place the extruder ram into the sample mold and force the specimen out of the sample mold into the extruder mold.

13. Use the extruder mold to carefully slide the compacted specimen onto a glass plate.

14. Determine the weight of the compacted specimen to the nearest gram. Measure the height and diameter to the nearest 0.1 in. (2.54 mm). Record these values on a form for compacted clays as shown in Figure 3.

The specimen is now ready for resilience testing. If there will be a delay of more than a few minutes before beginning the resilience testing, the specimen should be carefully wrapped in plastic to prevent evaporation. (Refer to the note on thixotropic effects given after step 7 under compaction by impact or kneading methods.)

COMPACTED GRANULAR SPECIMENS

Of particular concern in the preparation of granular soil specimens is the extent to which these materials can be handled (in removing them from a mold and transporting and placing them in the triaxial cell). Granular soils that exhibit sufficient cohesion to permit handling can be prepared by the methods described for compacted clay soils; however, it is generally not necessary to consider soil structure effects. The exception is some silts that also may exhibit strength properties that are dependent on compaction conditions.

This section contains some items that can be applied generally to compacted granular soils, but this section mainly is directed to compaction of materials that cannot be handled between compaction and testing.

Specimen Size

The diameter of the specimen to be tested is determined by a lower bound of approximately 2.5 in. (63.5 mm) or by 4 to 5 times the maximum size of particle in the material. This lower bound represents a minimum size that can be expected to provide a reasonable representation of the larger mass of material in a pavement.

Specimen length should not be less than 2 times the diameter.

Moisture-Density Relationship

Four steps should be followed to determine moisture-density relationship.

1. Establish the moisture-density relationship for the soil according to 1 of the following procedures: (a) ASTM D 1557-AASHO T-180, (b) ASTM D 698-AASHO T-99, (c) California 216F, or (d) some other standard method. Prepare a graph of dry density and water content.
2. Determine the specific gravity of the soil by using 1 of the following procedures: (a) ASTM D 854, (b) ASTM C 127, (c) California 206D, (d) California 207D, or (e) some other standard.
3. Use the data from steps 1 and 2 to determine 100 percent of saturation at various densities. Draw the curve for 100 percent saturation on the graph drawn in step 1.
4. Select the densities and water contents at which specimens are to be prepared. These usually will consist of several values covering the expected in-service range. Note that material that has a moderately high permeability and is to be tested at 100 percent saturation generally is prepared in an oven-dried or air-dried state and saturated by back-pressure techniques or capillary saturation.

Preparation of Soil for Compaction

Cohesionless granular materials are compacted most readily by use of a split mold mounted on the base of the triaxial cell as shown in Figure 5. Compaction forces are generated by a vibrator, such as a small, hand-operated air hammer. Nineteen steps should be followed to prepare soil for compaction.

1. Determine the water content (W_1 percent) of the soil (if other than oven-dried material is to be used).
2. Tighten the sample base into place on the triaxial cell base. It is essential that an airtight seal be developed.
3. Place the porous stone plus the sample cap on the sample base. (Two stones are required for saturated specimens, but generally only the lower stone would be used for tests at lower water contents unless drainage from both ends is desired.) Determine the height of base, cap, and stone to the nearest 0.01 in. (0.254 mm), and record

this value on a form for granular soils as shown in Figure 6.

4. Remove the sample cap and upper porous stone. Measure the thickness of the rubber membrane with a micrometer gauge. Record this value on a form for granular soils as shown in Figure 6.

5. Place the rubber membrane over the sample base and lower porous stone. Fix the membrane in place with an O-ring seal.

6. Place the split-mold sample former around the sample base and draw the rubber membrane up through the mold. Tighten the split mold firmly into place. Exercise care to avoid pinching the membrane.

7. Stretch the membrane tightly over the rim of the mold. Apply a vacuum to the mold to remove all membrane wrinkles. The membrane now should fit smoothly around the inside perimeter of the mold. The vacuum is maintained throughout the compaction procedure.

8. Use calipers to determine to the nearest 0.01 in. (0.254 mm) the inside diameter of the membrane-lined mold. Determine to the nearest 0.01 in. (0.254 mm) the distance from the top of the porous stone to the rim of the mold.

9. Determine the volume of specimen to be prepared. The diameter of the specimen is the diameter determined in step 8, and the height is a value less than that determined in step 8 but at least 2 times the diameter.

10. Determine the weight of material that must be compacted into the volume determined in step 9 to obtain the desired density and water content. (The section on preparing clay soils for compaction contains further information on this.)

11. Determine the number of layers to be used for compaction. Normally, layer depths will be 1 to 1.5 in. (25.4 to 38.1 mm). Determine the weight of soil required for each layer and the thickness of each layer.

12. Place the required mass of soil into a mixing pan. (Allow approximately 300 g more than required for compaction; the excess is to be used for determining the water content.) Add the required amount of water and mix thoroughly.

13. Determine the weight of wet soil plus water and record on a form for granular soils as shown in Figure 6.

14. Place the amount of wet soil required for 1 layer into the mold. Exercise care to avoid spillage. Use a spatula to draw the material away from the edge of the mold and form a small mound at the center of the mold.

15. Insert the vibrator head and vibrate the soil until the distance from the surface of the compacted layer to the rim of the mold is equal to the distance measured in step 8 minus the thickness of the lift determined in step 11. This may require removal and reinsertion of the vibrator head several times until experience is obtained in gauging the required vibration time.

16. Repeat steps 14 and 15 for each new lift. The measured distance from the surface of the compacted layer to the rim of the mold is successively reduced by the thickness of each new lift from step 11. The final surface should be a smooth, horizontal plane.

17. When compaction is completed, observe the weight of the mixing pan plus excess soil and record it on a form for granular soils as shown in Figure 6. The weight determined in step 13 less the weight observed now is the weight of wet soil incorporated in the specimens. Use approximately 200 g of the excess material to determine water content.

18. Place the porous stone and sample cap on the surface of the specimen. Roll the rubber membrane off the rim of the mold and over the sample cap. If the sample cap projects above the rim of the mold, the membrane should be sealed tightly against the cap with an O-ring seal. If it does not, the seal can be applied later.

19. Disconnect the vacuum supply from the mold. Place the entire assembly on the loading machine in preparation for resilience testing.

COMPACTED CYLINDRICAL ASPHALT CONCRETE SPECIMENS

This method, which is similar to that which is to be published as an ASTM test method,

Figure 5. Apparatus for vibratory compaction of granular materials.

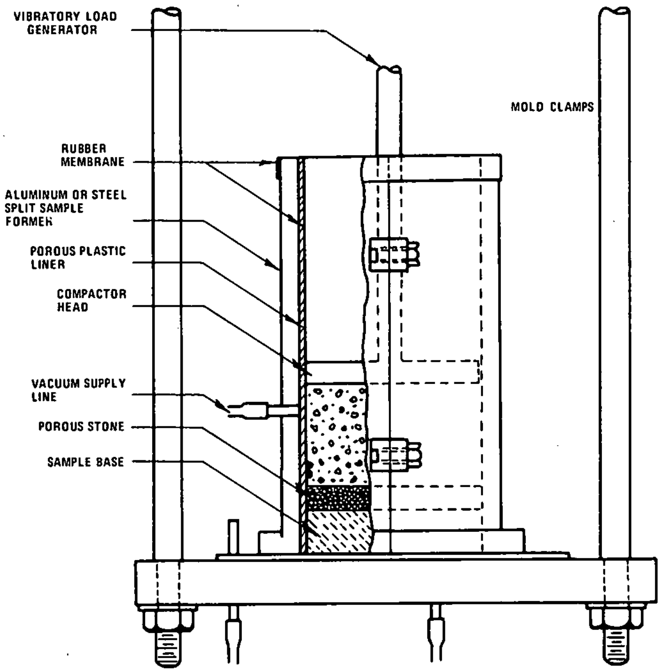


Figure 6. Sample data recording form for granular soils.

Soil sample________
Location________
Sample no.________
Specific gravity________

Soil Specimen Measurements
Diameter
Top________
Middle________
Bottom________
Average________
Membrane thickness________
Net diameter________
Height of specimen plus cap and base________
Height of cap and base________
Initial length________

Soil Specimen Weight
Initial weight of container plus wet soil, g________
Final weight of container plus wet soil, g________
Weight of wet soil used________

Soil Specimen Volume
Initial area, in.^{2}________
Volume,[a] in.^{3}________
Wet density, lb/ft^3________
Water content, percent________
Percent saturation________
Dry density, lb/ft^3________
Void ratio________

Date________
Compaction method________
Vertical spacing between LVDT clamps, in.________

Constants
Vertical LVDT________
Horizontal LVDT________
Load cell________
Comments________

						Vertical Values				Horizontal Values			
σ_3 (lbf/in.^{2})	Load Cell Chart Reading	Deviator Load (lb)	$\sigma_d = \sigma_1 - \sigma_3$ (lbf/in.^{2})	$\frac{\sigma_1}{\sigma_3}$	θ (lbf/in.^{2})	LVDT Chart Reading	Deformation (in.)	ϵ_{R1} (in./in.)	$M_R = \sigma_d/\epsilon_{R1}$ (lbf/in.^{2})	LVDT Chart Reading	Deformation (in.)	ϵ_{R3} (in./in.)	$\nu_R = \epsilon_{R3}/\epsilon_{R1}$

[a]Initial area times initial length.

covers the preparation of cylindrical specimens 4 in. (101.6 mm) in diameter and approximately 8 in. (203.2 mm) high of bituminous paving mixture suitable for complex and resilient modulus tests. The method is intended for dense-graded bituminous concrete mixtures containing aggregate up to 1 in. (25.4 mm) maximum size.

Test Specimens

Prepare 3900 g of the bituminous mixture as specified by ASTM D1560.

Apparatus

An apparatus should be used that meets the specifications given by ASTM D1561 except that steel molding cylinders with 0.25-in. (6.35-mm) wall thickness, 4-in. (101.6-mm) inside diameter, and 10-in. (254-mm) height should be used.

Procedure

Three steps should be followed for determining compaction temperature, molding specimens, and applying static load.

1. Use the compaction temperature for bituminous mixtures as specified by ASTM D1561.
2. Heat the compaction mold to the temperature specified in step 1. Place the compaction mold in position in the mold holder and insert a paper disk 4 in. (101.6 mm) in diameter to cover the baseplate of the mold holder. Weigh out half the required amount of bituminous mixture for 1 specimen at the specified temperature and place uniformly in the insulated feeder trough, which has been preheated to the compaction temperature for the mixture. By means of the variable transformer that controls the heater, maintain a sufficiently hot compactor foot to prevent the mixture from adhering to it. By means of a paddle of suitable dimensions to fit the cross section of the trough, push 30 approximately equal portions of the mixture continuously and uniformly into the mold while applying 30 tamping blows at a pressure of 250 lbf/in.^{2} (1725 kPa). Immediately place the remaining half of the mixture uniformly in the feeder trough. Push 30 approximately equal portions of the mixture continuously and uniformly into the mold while applying 30 tamping blows at pressure of 250 lbf/in.^{2} (1725 kPa). If sandy or unstable material is involved and there is undue movement of the mixture under the compactor foot, reduce the compaction temperature and compactor foot pressure until kneading compaction can be accomplished.
3. Immediately after compaction with the California kneading compactor, apply a static load to the specimen by using a compression testing machine. Apply the load by the double plunger method in which metal followers are employed as free-fitting plungers on the top and bottom of the specimen. Apply the load on the specimen at a rate of 0.05 in./min (0.021 mm/s) until an applied pressure of 1,000 lbf/in.^{2} (6900 kPa) is reached. Release the load immediately. After the compacted specimen has cooled to the point at which it will not deform on handling, remove it from the mold. Place the specimen on a smooth flat surface and allow it to cool to room temperature. The cylindrical sample will have approximately the same bulk specific gravity as specimens prepared according to ASTM D1559 and ASTM D1561.

COMPACTED ASPHALT CONCRETE BEAM SPECIMENS

This method, which is similar to that which is to be published as an ASTM test method, covers the preparation of beam specimens of bituminous paving mixture suitable for flexural modulus and flexural fatigue tests. The method is intended for dense-graded bituminous concrete mixtures containing aggregate up to 1.5 in. (38.1 mm) maximum size.

Test Specimens

The beam test specimens should have a rectangular cross section of 3.25 in. (82.5 mm) by approximately 3.5 in. (88.9 mm) and a length of 15 in. (381 mm). Prepare approximately 7000 g of the bituminous mixture as specified by ASTM D 1560.

Apparatus

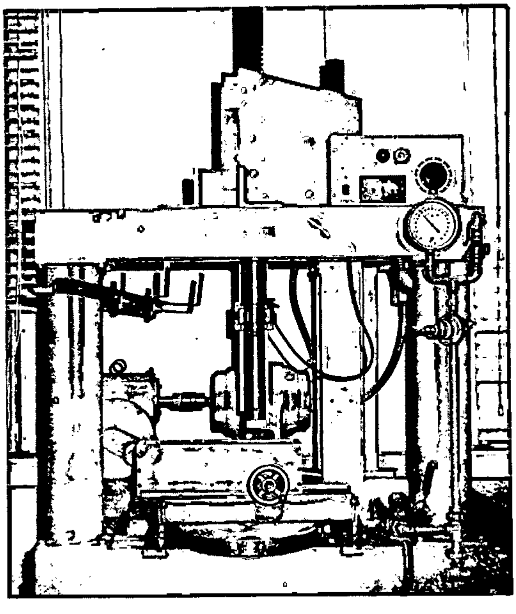
The apparatus shall be as specified by ASTM D 1561 except that the compactor shall be equipped with a specially modified compaction mold assembly and tamping foot as shown in Figure 7.

Procedure

Three steps should be followed for determining compaction temperature, molding specimens, and applying static load.

1. Use the compaction temperature for bituminous mixtures as specified by ASTM D 1561.
2. Heat the compaction mold to the compaction temperature specified in step 1. Place the mold on the sliding base assembly of the California kneading compactor and place a paper that is 3.25 in. (82.5 mm) wide and 15 in. (381 mm) long on the mold baseplate. Weigh out half of the required amount of bituminous mixture for 1 specimen and place it in the compaction mold in a layer of uniform thickness. By means of the variable transformer that controls the heater, maintain a sufficiently hot compactor foot to prevent the mixture from adhering to it. When applying tamping blows to the mixture, turn the base assembly table hand wheel ⅛ revolution to move the mold laterally 0.75 in. (19 mm) after each tamping blow. Apply 20 tamping blows at a foot pressure of 200 lbf/in.^{2} (1380 kPa). Place the remaining half of the bituminous mixture in the compaction mold in a layer of uniform thickness. Apply 45 tamping blows at a foot pressure of 200 lbf/in.^{2} (1380 kPa). Apply the final 45 tamping blows at a foot pressure of 300 lbf/in.^{2} (2070 kPa). If sand or unstable material is involved and there is undue movement of the mixture under the compactor foot, reduce the compaction temperature and compactor foot pressure until kneading compaction can be accomplished.
3. Immediately after compaction in the California kneading compactor, place the leveling bar on top of the specimen. By means of a compression testing machine, apply a static load on the specimen

Figure 7. California kneading compactor equipped with modified tamping foot and compaction mold assembly.



at the rate of 0.05 in./min (0.021 mm/s) until an applied pressure of 1,000 $lbf/in.^2$ (6900 kPa) is reached. Release the load immediately. After the compacted specimen has cooled sufficiently so that it will not deform on handling, remove it from the mold. Place the specimen on a smooth flat surface and allow it to cool to room temperature. The beam specimens have approximately the same bulk specific gravity as specimens prepared according to ASTM D 1559 and ASTM D 1561.

RESILIENCE TESTING OF UNSTABILIZED SOILS

The objective of this method is to define the resilient characteristics of untreated granular and cohesive soils for conditions that represent a reasonable simulation of the in situ state of stress in pavements subjected to moving wheel loads. Procedures described define resilient character in a triaxial state of stress when pressure in the triaxial chamber acts as a static all-around stress and when a repeated axial deviator stress of fixed magnitude, frequency, and load duration is applied to the soil from a force generator located outside the triaxial chamber. A simplified approximate procedure for testing unstabilized cohesive soils will be presented in another section of this Special Report. The notations used in this section are as follows:

σ_1 = total axial stress applied to the cylindrical specimen,
σ_2 = total radial stress applied to the cylindrical specimen,
σ_3 = confining pressure for the triaxial test,
$\sigma_d = \sigma_1 - \sigma_3$ = deviator stress (repeated axial stress for the procedure),
ϵ_1 = total axial strain due to σ_d,
ϵ_3 = total radial strain due to σ_d,
ϵ_{R1} = recovered axial strain,
ϵ_{R3} = recovered radial strain,
$M_R = \dfrac{\sigma_d}{\epsilon_{R1}}$ = resilient modulus,
$\nu_R = \dfrac{\epsilon_{R3}}{\epsilon_{R1}}$ = resilient Poisson's ratio,
$\theta = \sigma_1 + 2\sigma_3 = \sigma_d + 3\sigma_3$ = sum of the principal stresses in the triaxial state of stress,
σ_1/σ_3 = principal stress ratio,
$\gamma_d = \dfrac{G \cdot \gamma_w}{1 + (wG/S)}$ = unit weight of dry soil,
γ_w = unit weight of water,
G = specific gravity of soil,
W = water content of soil,
S = degree of saturation, and
$e = \dfrac{G}{\gamma_d}\gamma_w - 1$ = void ratio.

Load duration is the time interval the sample is subjected to a stress deviator. Cycle duration is the time interval between successive applications of a stress deviator.

TEST EQUIPMENT

Triaxial Test Cell

A triaxial cell suitable for use in resilience testing of soils is shown in Figure 8. This equipment is similar to most standard cells except that it is somewhat larger to facilitate the internally mounted load and deformation measuring equipment and has additional outlets for the electrical leads from the measuring devices. For the type of equipment shown in Figure 8, air would be used as the cell fluid.

The external loading source may be any device capable of providing a variable load of fixed cycle and load duration. The device can range from simple cam and switch control of static weights or air pistons to closed loop electrohydraulic systems. A load duration of 0.1 s and a cycle duration of 3 s have been found to be satisfactory for many applications.

Deformation Measurement

Deformation-measuring equipment consists of linear variable differential transformers (LVDTs) attached to the soil specimen by a pair of clamps. Four LVDTs are used; 2 are for the measurement of axial deformation, and 2 are for the measurement of horizontal or radial deformation. The clamps and LVDTs are shown in position on a soil specimen in Figure 8. Details of the clamps are shown in Figure 9. Load is measured by placing a load cell between the sample cap and the loading piston as shown in Figure 8.

Use of the type of measuring equipment that has just been described offers several advantages.

1. It is not necessary to reference deformations to the equipment that deforms during loading.
2. The effect of end-cap restraint on soil response is virtually eliminated.
3. The horizontally mounted LVDTs permit the measurement of the resilient Poisson effect.
4. Any effect of piston friction is eliminated by measuring loads at the caps of the sample.

It is necessary to maintain suitable recording equipment in addition to the measuring devices. It is desirable to have simultaneous recording of load and deformations. The number of recording channels can be reduced by wiring the leads from the LVDTs so that only the average signal from each pair is recorded. By introducing switching and balancing units, one can use a single-channel recorder. Use of a single-channel recorder, however, will not permit the making of simultaneous recordings.

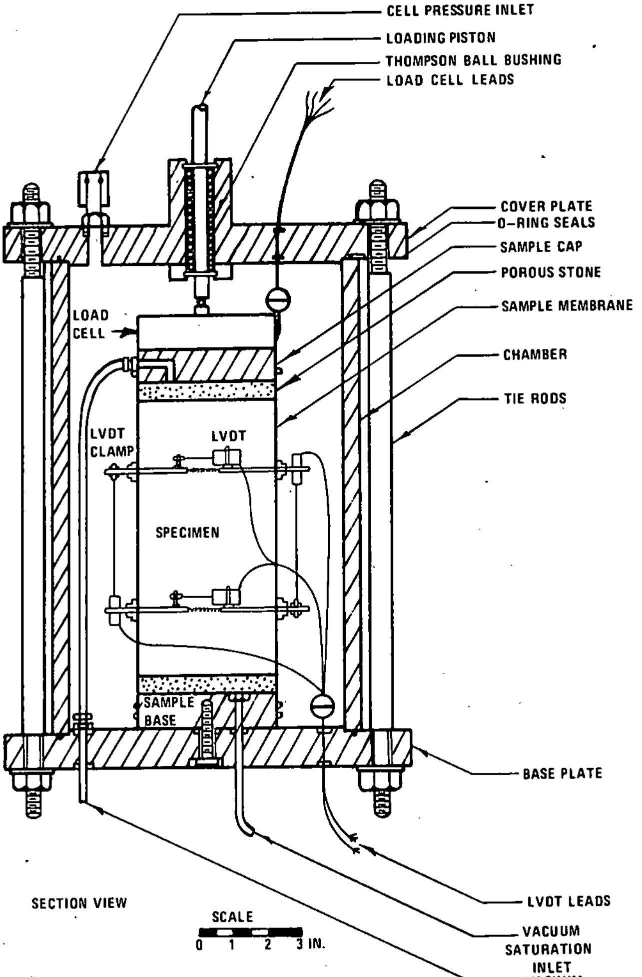
RESILIENCE TESTING OF COHESIVE SOILS

Test Method

Twenty steps make up the test method for resilience testing of cohesive soils.

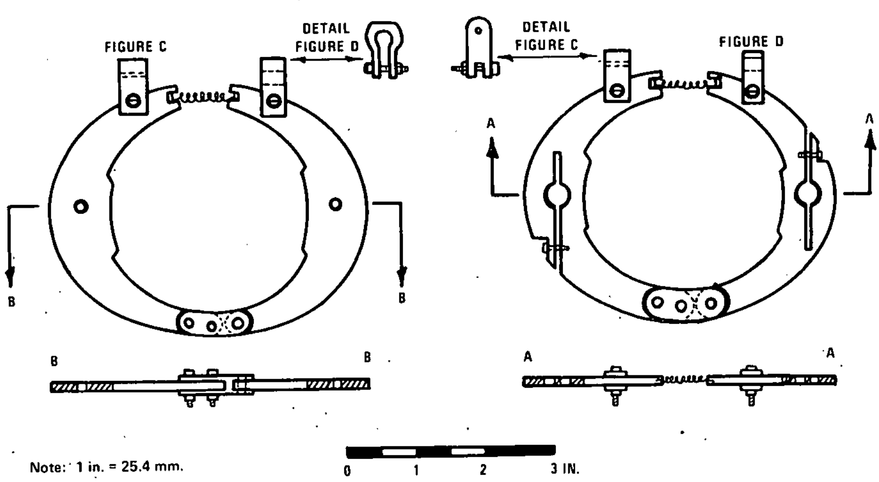
1. Place the triaxial cell base assembly on the platform of the loading machine. Tighten the sample base firmly to obtain an airtight seal.
2. Close the valve on the vacuum lead to the sample cap. (This line is not required for testing clays; closing the valve will prevent loss of air from the chamber during testing.)
3. Carefully place the specimen on the sample base. (Porous stones are not

Figure 8. Apparatus for resilience testing of soils.



Note: 1 in. = 25.4 mm.

Figure 9. Clamps for holding linear variable differential transformers in measuring axial deformation and diameter change.



Note: 1 in. = 25.4 mm.

necessary for testing clay soils unless a drained condition is desired.)

4. Place the sample cap on the specimen.

5. Stretch a membrane tightly over the interior surface of the membrane stretcher. Slip the stretched membrane carefully over the specimen. Roll the membrane off the stretcher onto the sample base and cap. Remove the stretcher. Place O-ring seals around the base and cap.

6. Connect the vacuum-saturation line to the vacuum source through the medium of a bubble chamber [a vacuum of 5 to 10 $lbf/in.^2$ (34.5 to 69 kPa) generally is adequate]. If bubbles are absent, an airtight seal has been obtained. If bubbles are present, check for leakage caused by poor connections, holes in the membrane, or imperfect seals at the cap and base. The existence of an airtight seal ensures that the membrane will remain firmly in contact with the specimen. This is essential for use of the clamp-mounted LVDTs. Leakage through holes in the membrane can frequently be eliminated by coating the surface of the membrane with a rubber latex or by using a second membrane.

7. When leakage has been eliminated, disconnect the vacuum supply.

8. Extend the lower LVDT clamp and slide it carefully down over the specimen to approximately the lower quarter point of the specimen.

9. Repeat step 8 for the upper clamp and place it at the upper quarter point. Ensure that both clamps lie in horizontal planes.

10. Connect the LVDTs to the recording unit and balance the recording bridges. This will require recorder adjustments and adjustment of the LVDT stems. When a recording bridge balance has been obtained, determine to the nearest 0.01 in. (0.254 mm) the vertical spacing between the LVDT clamps and record this value on a form for compacted clays as shown in Figure 3.

11. Place the triaxial chamber into position. Set the load cell in place on the sample cap.

12. Place the cover plate on the chamber. Insert the loading piston and obtain a firm connection with the load cell.

13. Tighten the tie rods firmly.

14. Slide the assembled apparatus into position under the axial loading device. Bring the loading device to a position where it nearly contacts the loading position.

The resilient properties of compacted clays are affected only slightly by the magnitude of the confining pressure. For most applications, the effect of confining pressure can be disregarded. For silty soils, however, the effect of confining pressure is much greater. The confining pressure used should approximate the expected in situ horizontal stresses. These generally will be on the order of 1 to 5 $lbf/in.^2$ (6.9 to 34.5 kPa). A chamber pressure of 3 $lbf/in.^2$ (20.7 kPa) would be a reasonable value for most testing. Resilient properties of cohesive soils are greatly dependent on the magnitude of the deviator stress (repeated axial stress). It is, therefore, necessary to conduct the test for a range in deviator stress values. For example, test at 0.5, 1.0, 2.0, 3.0, 4.0, 5.0, 7.5, 10, and 15 $lbf/in.^2$ (3.45, 6.9, 13.8, 20.7, 27.6, 34.5, 51.75, 69, and 103.5 kPa).

15. Connect the chamber pressure supply line and apply confining pressure (equal to chamber pressure).

16. Rebalance the recording bridges for the LVDTs and balance the load-cell recording bridge.

17. Begin the test by applying 200 repetitions of a deviator stress of approximately 1 $lbf/in.^2$ (6.9 kPa) and then 200 repetitions each at 3, 5, 7.5, and 10 $lbf/in.^2$ (20.7, 34.5, 51.75, and 69 kPa). The foregoing stress sequence constitutes sample conditioning, that is, the elimination of the effects of the interval between compaction and loading and the elimination of the effects of initial loading versus reloading.

18. Decrease the deviator load to the lowest value to be used. Apply 200 repetitions of load and record both the horizontal and vertical recovered deformations at or near the 200th repetition. [The deformation measured by the horizontal LVDTs is approximately twice the actual deformation on the diameter because of the locations

of the hinge and the LVDT (Figure 9).]

19. Increase the deviator load and record deformations as in step 18. Repeat over the range of deviator stresses to be used.

20. At the completion of the loading, reduce the chamber pressure to 0. Remove the chamber LVDTs and load cell. Use the entire specimen for determining water content.

Calculations and Presentation of Results

The results of resilience tests can be presented in a summary table such as that given in a form for compacted clays as shown in Figure 3. The results also can be presented graphically as shown in Figure 10. A form similar to that of Figure 10 may be used to display the resilient Poisson's ratio.

RESILIENCE TESTING OF GRANULAR SOILS

Test Method

A number of steps make up the test method for resilience testing of granular soils.

1. Connect the vacuum-saturation inlet to a vacuum source and apply 5 to 10 $lbf/in.^2$ (34.5 to 69 kPa) of vacuum through the medium of a bubble chamber. The vacuum serves a dual purpose in testing granular material. It serves to detect leakage and to impart a stress-induced rigidity to the material to prevent collapse when the sample mold is removed. This vacuum supply is maintained until step 9.
2. Carefully remove the sample mold. Seal the membrane to the sample cap if this has not been done. Determine to the nearest 0.1 in. (2.54 mm) the height of specimen plus cap and base and the diameter of the specimen plus membrane. Record these values on a form for granular soils as shown in Figure 6.
3. Observe the presence or absence of air bubbles in the bubble chamber. Eliminate system leakage by using methods previously described for compacted clays.
4. When leakage has been eliminated, place the LVDT clamps on the specimen and balance the recorder bridges as described previously for clay soils.
5. Connect the vacuum inlet line to the sample cap if the specimen is to be tested in a saturated state. If the specimen is not to be tested in a saturated state, this line is not connected and is sealed to prevent loss of air from the chamber.
6. Determine to the nearest 0.01 in. (0.254 mm) the spacing between the LVDT clamps and record this value.
7. Place the load cell on the sample cap, assemble the remainder of the cell, and tighten the tie rods firmly. Slide the assembly under the axial loading assembly.
8. Connect the chamber pressure supply line and apply a pressure of 5 $lbf/in.^2$ (34.5 kPa).
9. Remove the vacuum supply from the vacuum-saturation inlet and open this line to the atmosphere.

If the specimen is to be saturated before testing, steps 10 through 13 are required. If the specimen is not to be saturated before testing, the test continues with step 14.

10. Connect the vacuum supply to the vacuum inlet (at top of specimen) and connect the vacuum-saturation inlet to a source of deaired, distilled water.
11. Apply a vacuum of 2 to 3 $lbf/in.^2$ (13.8 to 20.7 kPa), open the water supply valve, and allow water to be drawn slowly upward through the sample.
12. Continue to flush water through the system to remove all entrapped air. To evaluate the presence or absence of air from the sample requires that one observe pore pressures. When all air has been eliminated, an increase in chamber pressure

Figure 10. Result of resilience tests on compacted clays, typical variation in resilient modulus with deviator stress.

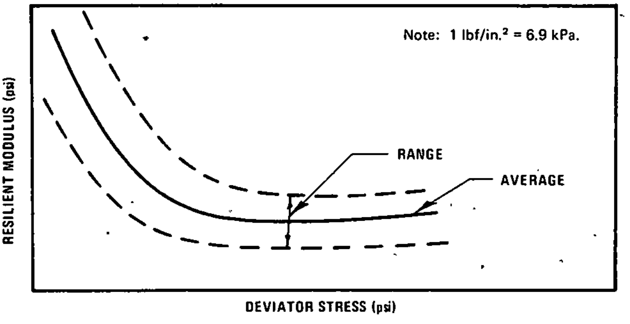
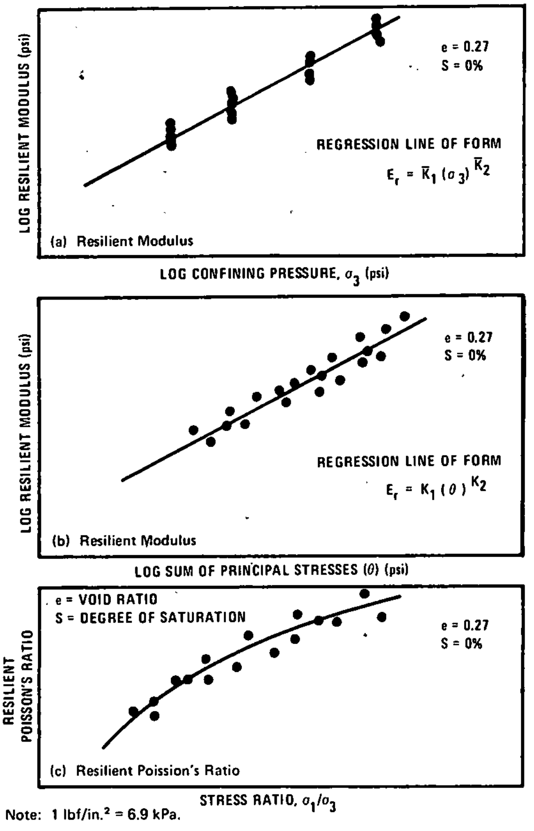


Figure 11. Results of resilience tests on granular soils, regression constants.



Note: 1 lbf/in.² = 6.9 kPa.

Figure 12. Results of resilience tests on granular soils, void ratio.

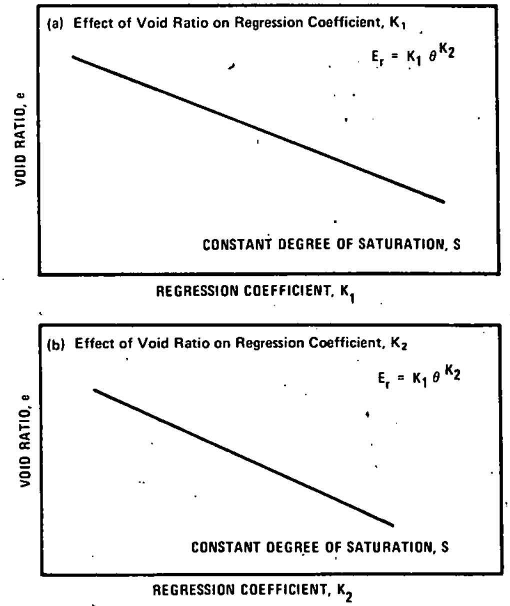
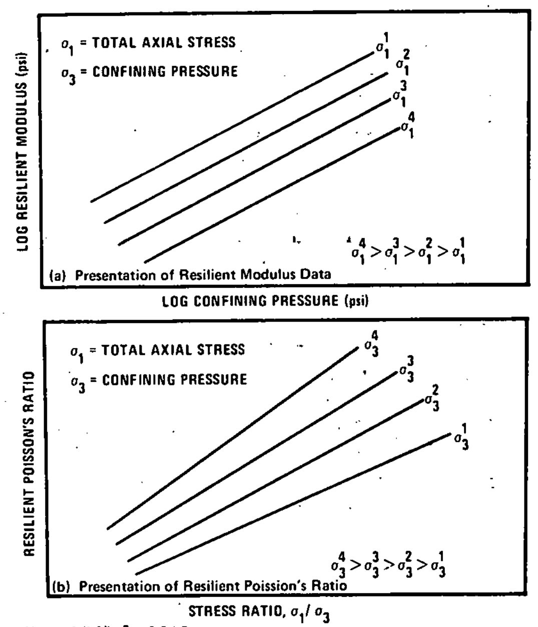


Figure 13. Results of resilience tests on granular soils, axial stress and confining pressure.



Note: 1 lbf/in.^{2} = 6.9 kPa.

(with valves to the water supply and vacuum supply closed) will result in an equal increase in pore pressure. (In view of the wide variety of pore-pressure measuring devices, no attempt will be made in this report to describe a procedure.)

13. Increase the chamber pressure to 10 lbf/in.^{2} (69 kPa); apply a 5-lbf/in.^{2} (34.5-kPa) back pressure to the water supply while closing the vacuum inlet valve. The effective confining pressure [5 lbf/in.^{2} (34.5 kPa)] on the specimen is now equal to the chamber pressure [10 lbf/in.^{2} (69 kPa)] minus the back pressure [5 lbf/in.^{2} (34.5 kPa)].

14. Rebalance the recorder bridges to the load cell and LVDTs.

15. Select the range of stresses at which the test is to be performed.

The resilient modulus of granular soils is dependent on the magnitude of the confining pressure and nearly independent of the magnitude of the repeated axial stress. The resilient Poisson's ratio is largely dependent on the principal stress ratio. Therefore, it is necessary to test granular materials over a range of confining and axial stresses. (The confining pressure is equal to the chamber pressure for dry and wet specimens and is equal to the chamber pressure less the back pressure for saturated specimens.) A suggested stress range for confining pressures is 1, 3, 5, 7.5, 10, 15, and 20 lbf/in.^{2} (6.9, 20.7, 34.5, 51.7, 69, 103.5, and 138 kPa). At each confining pressure, test at 5 values of deviator stress corresponding to multiples (1, 2, 3, 4, 5) of the cell pressure.

16. Before beginning to record deformations, apply a series of conditioning stresses to the material to eliminate initial loading effects. The greatest amount of volume change occurs during the application of the conditioning stresses. Simulation of field conditions suggests that drainage of saturated samples be permitted during the application of these loads but that the test loading (beginning with step 20) be conducted in an undrained state.

17. Set the axial load generator to apply a deviator stress of 10 lbf/in.^{2} (69 kPa) (that is, a stress ratio equal to 3). Activate the load generator and apply 200 repetitions of this load. Stop the loading.

18. Set the axial load generator to apply a deviator stress of 25 lbf/in.^{2} (172.5 kPa) (that is, a stress ratio equal to 6). Activate the load generator and apply 200 repetitions of this load. Stop the loading.

19. Repeat step 18 while maintaining a stress ratio equal to 6 by using the following order and magnitude of confining pressures: 10, 20, 10, 5, 3, and 1 lbf/in.^{2} (69, 138, 69, 34.5, 20.7, and 6.9 kPa).

20. Begin the recorded test by using a confining pressure of 1 lbf/in.^{2} (69 kPa) and an equal value of deviator stress. Record the resilient deformations after 200 repetitions. Increase the deviator stress to twice the confining pressure and record the resilient deformations after 200 repetitions. Repeat until a deviator stress of 5 times the confining pressure is reached (stress ratio of 6).

21. Repeat step 20 for each value of confining pressure.

22. When the test is completed, decrease the back pressure to 0, reduce the chamber pressure to 0, and dismantle the cell. Remove the LVDT clamps and so forth. Remove the soil specimen and use the entire amount of soil to determine the water content.

Calculations and Presentations of Results

Calculations can be performed by using the tabular arrangement from a form for granular soils as shown in Figure 6.

Individual test results and series are most readily presented in graphical form, such as that shown in Figure 11. Plotting the regression constants of Figure 11 versus void ratio as shown in Figure 12 provides a convenient means of interpolating for particular field conditions.

Materials such as fine sands, silts, and those with only small amounts of clay may display properties somewhat different than those shown in Figure 11, which demonstrates their dependence on both cell pressure and deviator stress. Graphical displays such as those shown in Figure 13 would then be more appropriate.

COMPLEX MODULUS TESTING OF PAVEMENT MATERIALS

Laboratory procedures are discussed below for determining the complex modulus of paving materials for conditions that represent a reasonable simulation of the in situ state of stress in pavements subjected to moving wheel loads. This test can be performed inside a triaxial cell at appropriate continuing pressures.

TEST EQUIPMENT

Loading and Load Measurement Equipment

An electrohydraulic testing system with a proper function generator capable of generating a sine or half sine function at frequencies between 1 to 20 cycles/s is suitable for complex modulus testing. However, a much less expensive eccentric-cam mechanical testing system also can be used to apply a sinusoidal loading to the specimen. Any recording device that can follow the output from the testing system can be used for recording the load and deformation to which the specimen is subjected.

A sample cap as shown in Figure 14 is required to transfer the load to the sample as well as to help in the measurement of axial deformation. Clamps such as those shown in Figures 8 and 9 also can be used to eliminate end effects in stiff materials.

Deformation Measurement Equipment

An LVDT attached to a suitable support (Figure 15) can be used for measurement of sample deformations. Leg A or leg B or both leg A and leg B of this support can be used for clamping with the testing machine platform (Figure 16). Figure 17 shows a complex modulus test apparatus.

A fast-responding 2-channel recorder capable of recording load on one channel and deformations on another channel is preferable so that load and deformation may be recorded simultaneously.

Additional Equipment

Additional equipment necessary for complex modulus testing includes the following:

1. Scales;
2. Weighing pans;
3. Mixer;

Figure 14. Sample cap for complex modulus test..

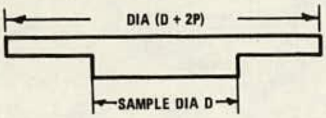


Figure 15. Linear variable differential transformer support for complex modulus test.

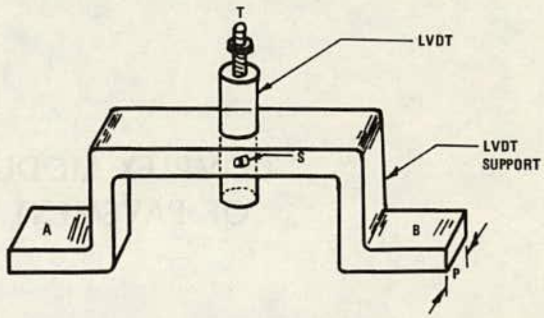


Figure 16. Experimental setup for complex modulus testing.

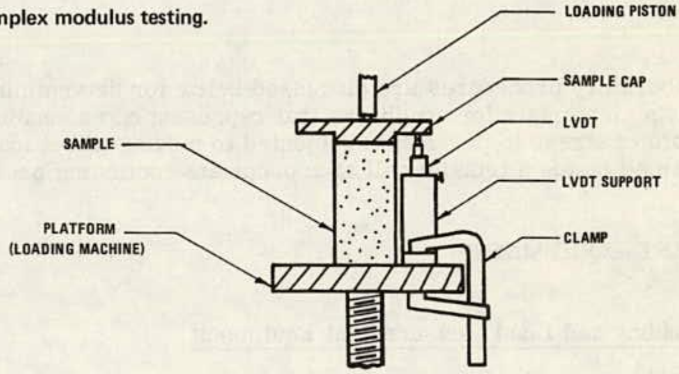


Figure 17. Complex modulus test apparatus.

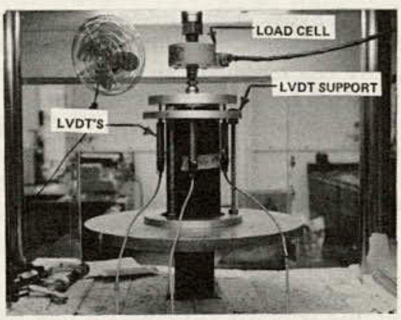


Figure 18. Sample data recording form for complex modulus testing.

Sample no.__________ Date__________

Load

Static, lb__________ Temperature, deg F__________

Dynamic, lb__________ σ^*, lbf/in.^{2}__________

Sample height, in.__________

Frequency of Loading (cycles/s)	Deformations of Sample (in.)								Avg Defor-mation (in.)	E*
	Position 1	Position 2	Position 3	Position 4	Position 5	Position 6	Position 7	Position 8		
1										
5										
8										
10										
12										
15										
20										

4. Compaction apparatus;
5. Calipers, micrometer gauge, and steel rule calibrated to 0.01 in. (0.254 mm); and
6. Thermometer.

COMPACTION

The laboratory compaction process for specimens should be selected in accordance with the expected field compaction conditions as discussed in the section on specimen preparation and compaction processes.

SPECIMEN SIZE

Specimen length should not be less than 2 times the diameter. Minimum diameter of the specimen should not be less than 4 times the maximum size of aggregate used in the mix as recommended in ASTM standards. Specimens 2.75 in. (69.8 mm) in diameter and 5.5 in. (139.7 mm) high are recommended for all mixes having maximum size aggregates less than 0.5 in. (12.7 mm). For methods of preparing the specimens, refer to the section on specimen preparation and compaction processes.

COMPLEX MODULUS TESTING

Fifteen steps make up the test method for complex modulus testing.

1. Mark the center of the load axis on the loading machine platform. Mark 8 radial lines passing through this center so that they are equally spaced at 45-deg intervals. Number these radial lines from 1 to 8.
2. Carefully place the specimen on the platform of the loading machine and center it.
3. Place the sample cap on the specimen and center it. Place a ball bearing between the loading piston and this cap.
4. Place the LVDT with its support over position number 1 as marked on the platform so that the tip T (Figure 15) of LVDT touches the cap on the specimen but so that the LVDT support does not touch any part of the specimen (Figure 16).
5. Adjust the height of the LVDT with the help of screw S (Figure 15) so that it is close to null position. Balance the recording pen according to the procedure specified for the recorder operation.
6. Apply a small load [say, 1 lb (0.45 kg)] on the sample to take care of any machine instability during testing.
7. Select an appropriate frequency of loading as discussed under fundamental considerations.
8. Increase the cyclic load on the sample to the desired level and apply 100 cycles. (A separate experiment should be performed to establish the linearity range for the specimen. The load level is to be selected so that it is always below the limit for the upper point in linear range.)
9. Record the load and deformation on the sample and record the frequency of loading on the form.
10. Increase the frequency of loading to the next desired value and record the response. Repeat this procedure by increasing the frequency each time until all the frequencies have been tested.
11. Move the LVDT to the next position and repeat steps 4 through 10, but there is no need to apply the load for 100 cycles as specified in step 8.
12. Make readings for all 8 positions marked on the platform. The observations and results may be recorded conveniently in a table such as that shown in Figure 18.
13. Calculate the complex modulus E* shown in the last column of the sample form

shown in Figure 18 as follows:

$$\epsilon^* = \frac{\text{average axial dynamic deformation of the sample in 8 positions}}{\text{height of the sample}}$$

$$\sigma^* = \frac{\text{maximum axial dynamic load on the sample}}{\text{area of sample top}}$$

$$E^* = \frac{\sigma^*}{\epsilon^*}$$

14. Use special care for field samples to get the top and bottom on a plane at a right angle to the loading axis. Cap with a suitable material if the surfaces are not parallel.

15. Plot the results on an E* versus frequency graph.

FLEXURAL MODULUS TESTING OF STABILIZED MATERIALS

Laboratory procedures for the determination of flexural modulus of bituminous paving layers containing aggregate with maximum sizes up to 1.5 in. (38.1 mm) are described in this section. The flexural modulus of a simply supported beam specimen subjected to 2 symmetrical concentrated loads applied near the center is determined during the controlled-stress mode of flexural fatigue testing. The flexural modulus is determined immediately after 200 load applications and is a measure of the initial stiffness of the bituminous paving.

The extreme-fiber stress σ, extreme-fiber strain ϵ, and flexural stiffness modulus E_s of simply supported beam specimens subjected to the 2-point loading that produces uniaxial bending stresses are calculated by the following formulas:

$$\sigma = \frac{3aP}{bt^2}$$

$$\epsilon = \frac{12td}{(3\ell^2 - 4a^2)}$$

$$E_s = \frac{Pa(3\ell^2 - 4a^2)}{48Id}$$

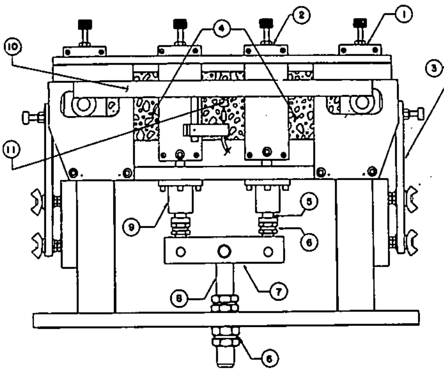
where

a = 0.5 (reaction span length - 4) in inches (millimeters),
P = dynamic load applied to deflect beam upward in pounds (kilograms),
b = specimen width in inches (millimeters),
t = specimen depth in inches (millimeters),
d = dynamic deflection of beam center in inches (millimeters),
ℓ = reaction span length in inches (millimeters), and
I = specimen moment of inertia in inches^4 (m^4).

TEST EQUIPMENT

The repeated flexure apparatus is shown in Figure 19. It accommodates beam specimens 15 in. (381 mm) long with widths and depths that do not exceed 3 in. (76.2 mm). A 3,000-lb-capacity (1350-kg-capacity) dynamic testing system capable of applying

Figure 19. Repeated flexure apparatus for testing stabilized materials.



repeated tension-compression loads in the form of sine or half sine waves of 0.1-s duration and rest periods of about 4 to 9 times the load duration provides suitable loading for flexural modulus determinations during flexural fatigue tests. Both pneumatic and electrohydraulic testing systems have been found to be suitable for this type of testing. The 2-point loading produces an approximately constant bending moment over the center 4 in. (101.6 mm) of a 15-in.-long (381-mm-long) beam specimen with widths and depths not exceeding 3 in. (76.2 mm). A sufficient load, approximately 10 percent of which will deflect the beam upward, is applied in the opposite direction, which forces the beam to return to its original horizontal position and holds it at the position during the rest period. Adjustable stop nuts installed on the flexure apparatus loading rod prevent the beam from bending below the initial horizontal position during the rest period.

The dynamic deflection of beam center is measured with an LVDT. A Shaevitz 100 MHR is an LVDT that has been found suitable. The LVDT core is attached to a nut bonded with epoxy cement to the center of the specimen. Outputs of the LVDT and the load cell of the electrohydraulic testing machine through which loads are applied and controlled are fed to any suitable recorder. The repeated flexure apparatus is enclosed in a controlled-temperature cabinet capable of controlling temperatures within 0.5 F (0.28 C). A Missimer Model-100 x 500-CO_2 plug-in temperature conditioner has been found to provide suitable temperature control.

SPECIMEN PREPARATION

Beam specimens 15 in. (381 mm) long, 3.5 in. (88.9 mm) deep, and 3.25 in. (82.5 mm) wide are prepared according to ASTM D 3202 or the asphalt concrete beam preparation method described under the specimen preparation and compaction processes section of this Special Report. If there is undue movement of the mixture under the compactor foot during beam compaction, then temperature, foot pressure, and number of tamping blows should be reduced. Similar modifications to compaction procedures should be made if specimens with less density are desired. A diamond blade masonry saw is used to cut test specimens 3 in. (76.2 mm) or slightly less deep and 3 in. (76.2 mm) or slightly less wide from the 15-in.-long (381-mm-long) beams. Specimens with suitable dimensions also may be cut from pavement samples. The widths and depths of the specimens are measured to the nearest 0.01 in. (0.254 mm) at the center and at 2 in. (50.8 mm) on both sides from the center. Mean values are determined and used for subsequent calculations.

TEST PROCEDURES

The repeated flexure apparatus loading clamps are adjusted to the same level as the reaction clamps. The specimen is clamped in the fixture by using a jig to position the centers of the 2 loading clamps 2 in. (50.8 mm) from the center of the beam and to position centers of the 2 reaction clamps 6.5 in. (165.1 mm) from beam center. Double layers of Teflon sheets are placed between the specimen and the loading clamps to reduce friction and longitudinal restraint caused by the clamps.

After the beam has reached the desired test temperature, repeated loads are applied. The duration of a load application is 0.1 s; the rest period between loads is 0.4 s. The applied load should be that which produces an extreme-fiber stress level suitable for flexural-fatigue tests. For fatigue tests on typical bituminous concrete paving, the following ranges of extreme-fiber stress levels are suggested:

1. 55 F (12.78 C) and 150 to 400 lbf/in.^{2} (1035 to 2760 kPa),
2. 70 F (21.11 C) and 75 to 300 lbf/in.^{2} (517.5 to 2070 kPa), and
3. 85 F (29.44 C) and 35 to 200 lbf/in.^{2} (241.5 to 1380 kPa).

The beam center-point deflection and applied dynamic load are measured immediately after 200 load applications for calculation of ϵ, σ, and E_s.

The flexural modulus may be determined for other extreme-fiber stress levels and for other temperatures. The described apparatus and procedures have been found suitable for flexural modulus tests at temperatures ranging from 40 to 100 F (4.44 to 37.78 C) and for extreme fiber levels up to 400 lbf/in.^{2} (2760 kPa). The extreme-fiber stress level for flexural modulus tests at any temperature should not exceed that which causes specimen fracture before at least 1,000 loads are applied.

PRESENTATION OF RESULTS

The report of flexural stiffness modulus test results should include the following:

1. Density of test specimens;
2. Length, width, and depth of specimens;
3. Number of load applications if other than 200;
4. Specimen temperature;
5. σ;
6. ϵ; and
7. E_s.

E_s is strongly dependent on temperature and also quite dependent on stress. This behavior may be shown graphically by plotting E_s versus σ for each test temperature.

INDIRECT TENSILE TEST

Procedures for the determination of Poisson's ratio ν, modulus of elasticity E, and tensile strength S_T of pavement materials by using the indirect tensile test are described in this section. The indirect tensile test involves loading a cylindrical specimen with compressive loads that act parallel to and along the vertical diametrical plane as shown in Figure 20. To distribute the load and maintain a constant loading area, the compressive load is applied through a 0.5-in.-wide (12.7-mm-wide) steel loading strip that is curved at the interface with the specimen and has a radius equal to that of the specimen.

This loading configuration develops a relatively uniform tensile stress perpendicular to the direction of the applied load and along the vertical diametrical plane that ultimately causes the specimen to fail by splitting or rupturing along the vertical diameter (Figure 21). By measuring the applied load at failure and by continuously monitoring the loads and the horizontal and vertical deformations of the specimen, one can estimate S_T, ν, and E.

TEST EQUIPMENT

The basic testing apparatus includes a loading system and a means of measuring the applied loads, horizontal deformations of the specimens, and vertical deformations of the specimens.

The loading system consists of loading equipment, a loading device, and loading strips. The external load can be supplied by any loading system that can apply compressive loads preferably at a prescribed loading rate. Ideally, a closed loop electrohydraulic system should be used to accurately control the loading rate. A relatively high deformation rate should be used to simulate rapidly applied pavement loadings. A deformation rate of 2 in./min (0.84 mm/s) has been used although difficulties with measuring and recording loads and deformations have been experienced.

Some type of loading device should be used to ensure that the loading platens and strips remain parallel during the test. A loading device that has proved to be satisfactory is a modified, commercially available die set with upper and lower platens constrained to remain parallel during the test. Mounted on the upper and lower platens are 0.5-in.-wide (12.7-mm-wide) steel loading strips with a curved loading surface whose radius of curvature is equal to the radius of the specimen.

DEFORMATION- AND LOAD-MEASURING EQUIPMENT

Preferably, the load should be measured by a load cell to obtain electrical readouts that can be recorded continuously. Horizontal deformations of the specimens are

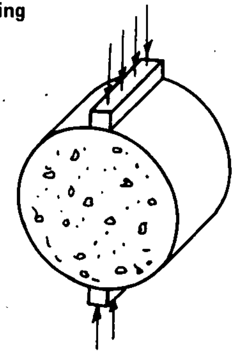


Figure 20. Cylindrical splitting test specimen with compressive load being applied.

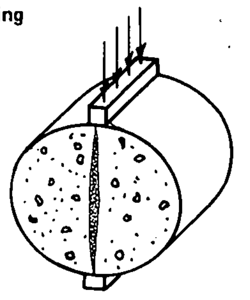


Figure 21. Cylindrical splitting test specimen failing under compressive load.

measured by using a device basically consisting of 2 cantilevered arms with attached strain gauges. Deformation of the specimen or deflection of the arms at points of contact with the specimen has been calibrated with the output from the strain gauges mounted on the arms.

Vertical deformations are measured by a direct-current LVDT. The LVDT also can be used to control the vertical deformation rate during the test by providing an electrical signal related to the relative movements of the upper and lower platens if a closed-loop electrohydraulic load system is used.

SPECIMEN PREPARATION

Cylindrical laboratory specimens or field cores can be tested. However, care should be exercised to ensure that the specimen does not have significant surface irregularities that will interfere with the proper seating contact between the specimen and the loading strips. The maximum size of the specimen is limited by the clearance in the loading device. The largest diameter specimen that can be tested in the device is approximately 6 in. (152.4 mm).

TEST PROCEDURE

Six steps make up the indirect tensile test procedure.

1. Determine the height and diameter of the specimen.
2. Carefully center the specimen on the lower loading strip.
3. Slowly lower the upper platen until light contact is made between the specimen and the upper loading strip.
4. Place the horizontal deformation measuring device with light contact between the arms and the specimen.
5. Load the specimen at a constant deformation rate.
6. Record the load versus horizontal deformation and load versus vertical deformation.

CALCULATION OF TENSILE PROPERTIES

The theoretical relationships used in calculating E, ν, and S_T are complex and require integration of various mathematical functions. However, by assuming a specimen diameter, one can make the required integrations and simplify the relationships. These simplified relationships for calculating E, ν, S_T, and total tensile strain at failure ϵ_T for

4-in.-diameter (101.6-mm-diameter) and 6-in.-diameter (152.4-mm-diameter) specimens with a 0.5-in.-wide (12.7-mm-wide) curved loading strip are as follows (1 in. = 25.4 mm; 1 lbf/in.^{2} = 6.9 kPa):

Tensile Property	4-In.-Diameter Specimen	6-In.-Diameter Specimen
S_T, lbf/in.^{2}	$0.156 \frac{P_{fail}}{h}$	$0.105 \frac{P_{fail}}{h}$
ν	$\frac{0.0673DR - 0.8954}{-0.2494DR - 0.0156}$	$\frac{0.04524DR - 0.6804}{-0.16648DR - 0.00694}$
E, lbf/in.^{2}	$\frac{S_H}{h}[0.9976\nu + 0.2692]$	$\frac{S_H}{h}[0.9990\nu + 0.2712]$
ϵ_T	$X_{TF}\left[\frac{0.1185\nu + 0.03896}{0.2494\nu + 0.0673}\right]$	$X_{TF}\left[\frac{0.0793\nu + 0.0263}{0.1665\nu + 0.0452}\right]$

where

P_{fail} = total load at failure in pounds (kilograms),
h = height of specimen in inches (millimeters),
DR = deformation ratio $\frac{Y_T}{X_T}$ = the slope of line of best fit between vertical deformation Y_T and the corresponding horizontal deformation X_T up to P_{fail},
S_H = horizontal tangent modulus $\frac{P}{X_T}$ = the slope of the line of best fit between load P and X_T for loads up to P_{fail}.

It is recommended that the line of best fit be determined by the least squares method.

TESTING FOR SHEAR MODULUS AND DAMPING OF SOILS BY THE RESONANT COLUMN METHOD

The resonant column method of testing has been described in detail elsewhere (3). This method covers the determination of the shear modulus and damping capacity of cylindrical specimens of soils either in undisturbed or remolded conditions by vibration by means of the resonant column technique. The vibration apparatus and specimen may be enclosed in a triaxial chamber and subjected to an all-around pressure and axial load. The test is considered nondestructive when the strain amplitude caused by vibration is less than about 10^{-4} in./in. (mm/mm). Thus many measurements may be made on the same specimen for various states of confining pressure. Because the modulus of pavement materials is strain (and stress) dependent, the materials should be tested at strain levels similar to those existing in the pavement.

A resonant column is defined as a cylindrical specimen or column of soil attached to a rigid pedestal of sufficient inertia to make the motion of the attached end of the specimen essentially 0 during vibration of the specimen. An apparatus is attached to produce sinusoidal excitation and measure the vibration amplitude of the end of the specimen. The frequency of excitation is adjusted to produce resonance of the system (column), which is composed of the specimen and the attached excitation apparatus. The system resonant frequency in this test is the frequency at which the sinusoidal excitation force is in phase with the velocity of the vibration end of the specimen. For low damping, it is permissible to assume that this frequency will correspond to a value that produces maximum amplitude of displacement. The dynamic shear modulus and damping capacity can be calculated from the results of the resonant column test. The shear modulus is assumed to be the elastic shear modulus of a uniform, linearly elastic specimen of the same mass, density, and dimensions as the soil specimen used in the resonant column test. The modulus of elasticity E is determined

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

where

G = dynamic shear modulus, and
ν = dynamic Poisson's ratio.

When using this method, one should remember that the E of paving materials is significantly influenced by the strain amplitude at which the test is performed. Therefore, a strain amplitude should be used that is representative of what the specimen will be subjected to in the field.

SIMPLIFIED TEST METHOD FOR DETERMINING THE RESILIENT MODULUS OF COHESIVE SOILS

The simplified test method described in this chapter is similar to the method for cohesive soils described in the section on resilience testing of unstabilized soils. This simplified method is part of a production-type resilience testing procedure that has been developed for and used extensively with fine-grained cohesive soils. A more complete description of the simplified testing procedure is given elsewhere (4).

In general, the procedure consists of preparing sets of at least three 2-in.-diameter (50.8-mm-diameter) by 4-in.-high (101.6-mm-high) cylindrical specimens by using a miniature kneading compactor. The specimen sets are prepared at moisture and density conditions representative of expected field conditions and then are tested by using the simplified method.

The method takes advantage of the simplicity, ease of testing, and minimal equipment requirements normally associated with an unconfined compression-type repeated load test (i.e., $\sigma_3 = 0$). Because no confining pressure is required, a triaxial cell is not needed.

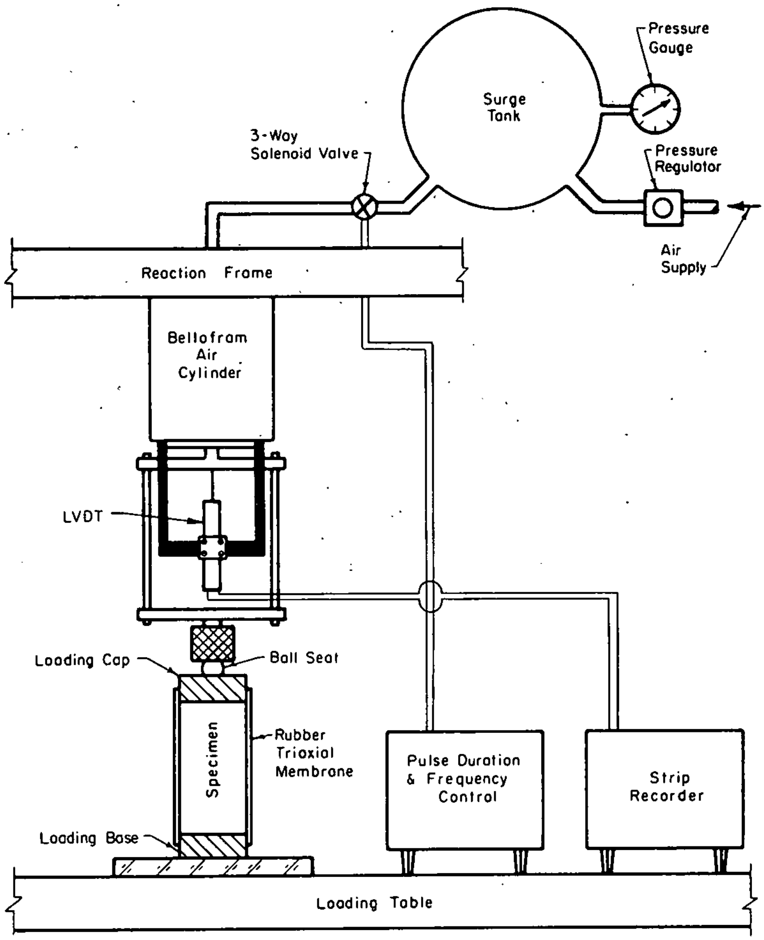
Justification for not using a confining pressure during the testing of cohesive soils lies in the fact that (a) the magnitude of confining pressure normally encountered in a subgrade is typically in the range of 1 to 5 lbf/in.^{2} (6.9 to 34.5 kPa) and (b) the effect of small magnitudes of confining pressure on the resilient response of fine-grained cohesive soils is very slight and typically is less than "between specimen" testing variability.

An additional advantage inherent in the simplified method is the use of an LVDT mounted in line with the longitudinal axis of the test specimen, which eliminates the need for mounting deformation measuring equipment on the specimen. It is important that the LVDT be mounted in this position because of the effect that eccentricity has if the LVDT is mounted to the side. A schematic diagram of the mounting position of the LVDT and the resilience testing equipment is shown in Figure 22.

As indicated in the section on fundamental considerations, something such as LVDT clamps or optical tracking equipment should be used for deformation measurement if the resilient modulus is greater than about 15,000 lbf/in.^{2} (103 500 kPa). However, for fine-grained cohesive soils, the axially mounted LVDT is satisfactory provided a sufficiently rigid machine is used.

It is suggested that at least 3 specimens be tested for a given set of variables and that the results be averaged. The reason for this is that "between specimen" variability for typical laboratory resilient testing is substantial (typical coefficients of variation of 10 to 15 percent or higher are not uncommon for cohesive soils and this type of test); thus the results from 1 specimen may be substantially different from the average of the results from a number of specimens.

Figure 22. Repeated load testing apparatus for simplified resilient modulus test.



SIMPLIFIED TEST METHOD

Ten steps make up the simplified test method.

1. Carefully place the specimen on the loading base.
2. Carefully place the loading cap on top of the specimen.
3. Stretch a rubber membrane tightly over the interior surface of a membrane stretcher. Carefully slip the stretched membrane over the specimen. Roll the membrane off the stretcher onto the base and cap. Remove the stretcher. Place O-ring seals or rubber bands around the base and cap. (The purpose of the membrane is to prevent loss of moisture during the test.)
4. Place the membrane-encapsulated specimen into position in the loading machine as shown in Figure 22. A steel ball bearing is placed between the top loading cap and the axial loading device. It is important to obtain proper alignment of the specimen and axial loading device to minimize eccentricities.

Resilient properties of cohesive soils are greatly dependent on the magnitude of the deviator stress (total repeated axial stress in this case). It is therefore necessary to conduct the test over a range of deviator stress values, for example: 3, 5, 7.5, 10, 15 lbf/in.^{2} (20.7, 34.5, 51.75, 69, 103.5 kPa) and possibly higher values.

A conditioning phase is used to properly seat the loading cap and base and eliminate or minimize initial loading effects.

5. Condition the specimen with 1,000 applications (load duration of 0.060 s and cycle duration of 3 s) of an axial stress equal to about 7 lbf/in.^{2} (48.3 kPa) followed by 20 applications each of an axial stress of 3, 5, 7.5, 10, and 15 lbf/in.^{2} (20.7, 34.5, 51.75, 69, and 103.5 kPa). (Observe permanent axial deformation during the latter stages of the conditioning phase. If appreciable permanent deformation starts to accumulate, then eliminate the higher values of axial conditioning stress from the conditioning phase.)
6. Decrease the deviator stress to about 3 lbf/in.^{2} (20.7 kPa).
7. Apply approximately 10 to 20 deviator stress applications and record the resilient axial deformation.
8. Increase the axial stress level incrementally about 3 lbf/in.^{2} (20.7 kPa).
9. Repeat step 7.
10. Repeat step 8 and step 7 until the desired upper value of axial stress is reached. An upper value of at least 20 to 25 lbf/in.^{2} (138 to 172.5 kPa) is recommended.

CALCULATIONS AND PRESENTATION OF RESULTS

The results of the resilience test can be presented in the form of a summary table or graphically as in Figures 2 and 10.

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