

Standard Method of Test  
for

Resilient Modulus of Unbound Granular Base/Subbase Materials  
and Subgrade Soils—SHRP Protocol P46

AASHTO DESIGNATION: T 294-94

1. SCOPE

1.1 This method covers procedures for preparing and testing unbound granular base/subbase materials and subgrade soils for determination of resilient modulus under specified conditions representing stress state beneath flexible and rigid pavements subjected to moving wheel loads.

1.2 The methods described are applicable to: undisturbed samples of natural and compacted subgrade soils, and to disturbed samples of unbound base and subbase and subgrade soils prepared for testing by compaction in the laboratory.

1.3 The value of resilient modulus ( $M_r$ ) determined from this procedure is a measure of the elastic modulus of unbound base and subbase materials and subgrade soils recognizing certain non-linear characteristics.

1.4 Resilient modulus ( $M_r$ ) values can be used with structural response analysis models to calculate pavement structural response to wheel loads, and with pavement design procedures to design pavement structures.

1.5 The values stated in SI units are to be regarded as the standard.

1.6 This standard may involve hazardous materials, operations, and equipment. This standard does not purport to address all of the safety problems associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

2. REFERENCED DOCUMENTS

- 2.1 *AASHTO Standards:*  
M 145 The Classification of Soils and Soil-Aggregate Mixtures for Highway Construction Purposes

- T 11 Amount of Material Finer than 0.075-mm (No. 200 sieve) in Aggregate  
T 27 Sieve Analysis of Coarse and Fine Aggregates  
T 88 Particle Size Analysis of Soils  
T 89 Determining the Liquid Limit of Soils  
T 90 Determining the Plastic Limit and Plasticity Index of Soils  
T 99 The Moisture-Density Relations of Soils Using a 2.5-kg (5.5-lb) Rammer and 305-mm (12-in.) Drop  
T 100 Specific Gravity of Soils  
T 233 Density of Soil-in-Place by Block, Chunk or Core Sampling  
T 265 Laboratory Determination of Moisture Content of Soils

3. SUMMARY OF TEST METHOD

3.1 A repeated axial deviator stress of fixed magnitude, load duration (0.1 second), and cycle duration (1 second) is applied to a cylindrical test specimen. During testing, the specimen is subjected to a dynamic deviator stress and a static confining stress provided by means of a triaxial pressure chamber. The total resilient (recoverable) axial deformation response of the specimen is measured and used to calculate the resilient modulus.

4. SIGNIFICANCE AND USE

4.1 The resilient modulus test provides a basic constitutive relationship between stress and deformation of pavement construction materials for use in structural analysis of layered pavement systems.

4.2 The resilient modulus test provides a means of characterizing pavement construction materials, including subgrade soils under a variety of conditions (i.e. moisture, density, etc.) and stress states that simulate the conditions in pavements subjected to moving wheel loads.

5. BASIC DEFINITIONS

5.1 *Description of Symbols:*

5.1.1  $S_1$  is the total axial stress (major principal stress).

5.1.2  $S_3$  is the total radial stress; that is, the applied confining pressure in the triaxial chamber (minor principal stress).

5.1.3  $S_d = S_1 - S_3$  is the repeated axial deviator stress for this procedure, and is the difference between the major and minor principal stresses in a triaxial test.

5.1.4  $e_1$  is the total axial deformation due to  $S_d$ .

5.1.5  $e_r$  is the resilient (recovered) axial deformation due to  $S_d$ .

5.1.6  $M_r = S_d/e_r$  is defined as the resilient modulus.

5.1.7 Load duration is the time interval the specimen is subjected to a deviator stress.

5.1.8 Cycle duration is the time interval between successive applications of a deviator stress.

5.1.9  $Y_4 = GY_u / 1 + (wG/S)$

where:

- $Y_s$  = unit mass of dry soil, kilograms per cubic meter (pounds per cubic foot)  
 $G$  = specific gravity of soil solids, dimensionless,  
 $w$  = moisture content of soil, (percent),  
 $S$  = degree of saturation (percent), and  
 $Y_w$  = unit mass of water, kilograms per cubic meter (pounds per cubic foot) and may be assumed to be 1000 kilograms per cubic meter (62.4 pounds per cubic foot).

NOTE 1—Both  $w$  and  $S$  must be expressed as numbers (e.g., 20 percent is 20), and shall be reported as numbers.

## 5.2 Terminology:

5.2.1 *Layer*—That part of the pavement produced with similar material and placed with similar equipment and techniques. The material within a particular layer is assumed to be homogeneous.

5.2.2 *Sample*—A representative portion of material from one or more pavement layers.

5.2.3 *Bulk Sample*—That part of the pavement material that is removed from an unbound base or subbase layer or from the subgrade. The material from one layer should *never* be mixed with the material from another layer—even if there is less than the desired amount to perform the specified tests.

5.2.4 *Test Sample*—That part of the unbound base or subbase layer or subgrade which is prepared and used for the specified test. The quantity of the test sample may be the same but will usually be less than the bulk sample.

5.2.5 *Test Specimen*—For the purpose of this procedure, a test specimen is defined as (i) that part of the thin-walled tube sample of the subgrade which is used for the specified tests and (ii) that part of the test sample of unbound granular base or subbase materials or untreated subgrade soils which is remolded to the specified moisture and density condition by recompaction in the laboratory.

5.2.6 *Unbound Granular Base and Subbase Materials*—These include soil-aggregate mixtures and naturally occurring materials used in each layer of base or subbase. No binding or stabilizing

agent is used to prepare unbound granular base or subbase layers.

5.2.7 *Subgrade*—These include natural foundation or embankment soils which are prepared and compacted before the placement of subbase and/or base layers.

5.2.8 *Material Type 1*—For the purposes of this procedure (resilient modulus tests), *Material Type 1* includes: (i) all unbound granular base and subbase material, and (ii) all untreated subgrade soils which meet the criteria of less than 70 percent passing the 2.00-mm (No. 10) sieve and 20 percent maximum passing the 0.075-mm (No. 200) sieve. Testing parameters used for Type 1 unbound materials are different from those specified for Material Type 2. Type 1 will always include AASHTO classification A-1-a soils and may include A-1-b, A-2, or A-3 soils.

5.2.9 *Material Type 2*—For the purpose of this procedure (resilient modulus tests), *Material Type 2* includes all untreated subgrade soils not meeting the criteria given above in Section 5.2.8 (ii). Generally, thin-walled tube samples of untreated subgrade soils fall in this Type 2 category. Type 2 will always include AASHTO classification A-4, A-5, A-6, and A-7 soils and may include A-1-b, A-2, and A-3 soils.

5.2.10 *Resilient Modulus of Unbound Materials*—The modulus of an unbound material is determined by repeated load triaxial compression tests on test specimens of the unbound material samples. Resilient modulus ( $M_r$ ) is the ratio of the amplitude of the repeated axial stress to the amplitude of the resultant recoverable axial strain.

## 6. APPARATUS

6.1 *Triaxial Pressure Chamber*—The pressure chamber is used to contain the test specimen and the confining fluid during the test. A triaxial chamber suitable for use in resilient testing of soils is shown in Figure 1. The chamber is similar to most standard triaxial cells, but is somewhat larger to accommodate the internally mounted load measuring device, and includes additional outlets for the electrical leads from the load measuring device. The deformation is

measured externally with two spring loaded LVDT's as shown in Figure 1. Air shall be used in the triaxial chamber as the confining fluid.

### 6.2 Loading Device:

6.2.1 The external loading device must be capable of providing variable magnitudes of repeated loads for fixed cycles of load and rest period. A closed-loop electro-hydraulic system is required for this procedure.

6.2.2 A load duration of 0.1 seconds and cycle duration of 1 second is required. A haversine shaped stress pulse form shall be used.

### 6.3 Load and Specimen Response Measuring Equipment:

6.3.1 The axial load measuring device should be an electronic load cell and will be located between the specimen cap and the loading piston as shown in Figure 1. The following load cell capacities are recommended:

| Sample Diameter<br>in mm (in.) | Maximum Load<br>Capacity |
|--------------------------------|--------------------------|
| 71 (2.8)                       | 445 N (100 lb)           |
| 102 (4.0)                      | 2570 N (600 lb)          |
| 152 (6.0)                      | 6230 N (1400 lb)         |

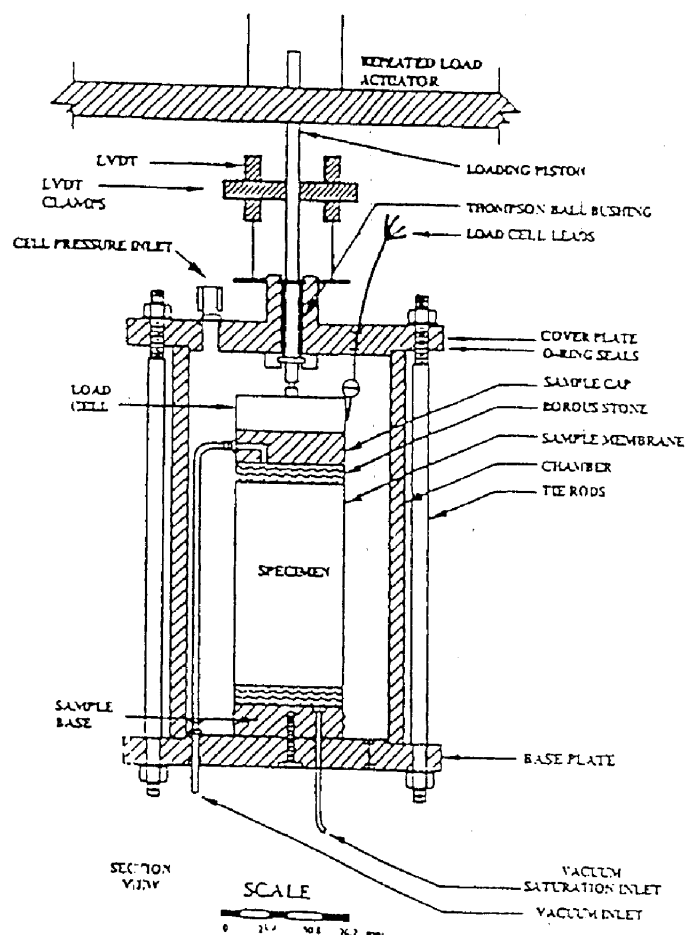
6.3.2 Test chamber pressures shall be monitored with conventional pressure gages, manometers or pressure transducers accurate to 1 kPa (0.1 psi).

6.3.3 *Axial Deformation*—Measuring equipment for all materials shall consist of two Linear Variable Differential Transducers (LVDT's) clamped to the piston rod outside the test chamber as shown in Figure 1. Spring-loaded LVDT's are required. The following LVDT ranges are recommended:

| Sample Diameter<br>in mm (in.) | Range               |
|--------------------------------|---------------------|
| 71 (2.8)                       | ± 1.3 mm (0.05 in.) |
| 102 (4.0)                      | ± 2.5 mm (0.1 in.)  |
| 152 (6.0)                      | ± 6.4 mm (0.25 in.) |

All the LVDT's shall meet the following specifications:

|                     |                            |
|---------------------|----------------------------|
| Linearity           | ±25 percent of full scale  |
| Repeatability       | ±1 percent of full scale   |
| Minimum sensitivity | 2 m V/V(AC) or 5 m V/V(DC) |



NOTE—25.4 mm = 1 in.

FIGURE 1 Triaxial Chamber With External LVDT's and Internal Load Cell

6.3.4 Suitable signal excitation, conditioning, and recording equipment are required for simultaneous recording of axial load and deformations. The signal shall be clean and free of noise (use shielded cables for connections). If a filter is used, it should have a frequency which cannot attenuate the signal. The LVDT's should be wired separately so each LVDT signal can be monitored independently.

NOTE 2—In order to minimize errors in testing specimens, LVDT's should be calibrated daily and load cells should be calibrated once a week using a suitable proving ring. The load cell should be calibrated semi-annually by an external agency. The entire system (transducer, conditioning, and recording devices) should be calibrated using synthetic samples of known modulus. Peri-

odic checks of the system should be performed using reference samples.

6.4 *Specimen Preparation Equipment*—A variety of equipment is required to prepare undisturbed samples for testing and to obtain compacted specimens that are representative of field conditions. Use of different materials and different methods of compaction in the field requires the use of varying compaction techniques in the laboratory. See Annex A and Annex B of this procedure for specimen compaction equipment.

6.5 Equipment for trimming test specimens from undisturbed thin-walled tube samples of subgrade soils shall be as described in T 296.

6.6 *Miscellaneous Apparatus*—This includes calipers, micrometer gauge,

steel rule (calibrated to 0.05 mm (0.02 in.)), rubber membranes from 0.2 to 0.8 mm (0.01 to 0.031 in.) thickness, rubber O-rings, vacuum source with bubble chamber and regulator, membrane expander, porous stones, scales, moisture content cans and data sheets, as required.

## 7. PREPARATION OF TEST SPECIMENS

7.1 *Specimen Size*—Specimen length should not be less than two times the diameter. Minimum specimen diameter is 71-mm (2.8 in.) or five times the nominal particle size. (Nominal particle size is the sieve opening for which 95 percent of the material passes during the sieve analysis.) The following guidelines, based on sieve analysis test results shall be used to determine the test specimen size:

7.1.1 Use the 71-mm (2.8-in.) diameter undisturbed specimen from the thin-walled tube samples for cohesive subgrade soils (Material Type 2). The specimen length shall be at least two times the diameter [142 mm (5.6 in.)] and the specimen shall be prepared as described in Section 7.2. If undisturbed subgrade samples are unavailable or unsuitable for testing, then 71-mm (2.8-in.) diameter molds shall be used to reconstitute Type 2 test specimens.

7.1.2 Use 102-mm (4.0-in.) diameter split molds to reconstitute 203 mm (8-in.) high test specimens for all Type 1 soils when the nominal particle size does not exceed 19.0 mm ( $3/4$  in.).

7.1.3 Use 152-mm (6.0 in.) diameter split molds to prepare 305-mm (12 in.) high test specimens for all Type 1 materials with nominal particle sizes between 19.0 and 31.5 mm ( $3/4$  and  $1\frac{1}{4}$  in.), without removing any coarse aggregate.

7.1.4 If more than 5 percent of a sample is retained on the 31.5-mm ( $1\frac{1}{4}$ -in.) sieve, remove the particles retained on the 31.5-mm sieve prior to specimen preparation. If more than 10 percent of the sample is plus 31.5-mm material, the specimen shall not be tested.

7.2 *Undisturbed Specimens*—Undisturbed subgrade soil specimens are trimmed and prepared as described in T 296, using the thin-walled tube samples of the subgrade soil. Determine the natural moisture content ( $w$ ) of the tube sample following the procedure outlined in

T 265 and record in the test report. Determine the in situ density of the subgrade soil as specified in T 233.

The following procedure shall be followed for the thin-walled tube samples:

7.2.1 To be suitable for testing, a specimen of sufficient length (generally twice the diameter of the specimen after preparation) must be cut from the tube sample, and must be free from defects that would result in unacceptable or biased test results. Such defects include cracks in the specimen, edges sheared off that cannot be repaired during preparation, presence of particles much larger than that typical for the material (example, 25.0-mm (1-in.) gravel in a fine-grained soil), presence of "foreign objects" such as large roots, wood particles, organic material and gouges due to gravel hanging on the edge of the tube.

7.2.2 If a good undisturbed subgrade sample is unavailable from a particular location, a reconstituted specimen shall be prepared as described in Sections 7.3, 7.4, and 7.5. Select a sample for reconstitution. Determine the in situ moisture content ( $w$ ) of material that is representative of the sample to be reconstituted (about 200 grams of the sample for moisture content determination) following the procedure outlined in T 265, and record on the test report. Assume the in-place density measured in the field as the basis for reconstitution. In the absence of the in situ moisture content and if in-place densities are not known, select the optimum moisture content and 95 percent of the maximum dry density (determined for the same layer using T 99 for reconstitution of the test specimen).

7.2.2.1 The moisture content of the laboratory compacted specimen should not vary more than  $\pm 0.5$  percentage point from the in situ moisture content obtained for that layer. The dry density of the laboratory compacted specimens should not vary by more than  $\pm 5$  percent of the in-place dry density for that layer.

7.2.2.2 Where thin-walled tube samples were not retrieved or are unsuitable for testing, then a representative test sample from the bulk samples of subgrade shall be used to prepare reconstituted specimens according to Sections 7.3, 7.4, and 7.5.

7.3 *Laboratory Compacted Specimens*—Reconstituted test specimens shall be prepared to approximate the in

situ dry density ( $Y_d$ ) and moisture content ( $w$ ). These laboratory compacted specimens shall be prepared for all unbound granular base and subbase material and for all subgrade soils for which undisturbed tube specimens could not be obtained.

7.3.1 If the sample is damp, dry it until it becomes friable. Drying may be in air or by use of a drying apparatus such that the temperature does not exceed 60°C (140°F). Then thoroughly break up the aggregations in such a manner as to avoid reducing the natural size of individual particles.

7.3.2 Determine the moisture content ( $w_1$ ) of the air-dried sample. The sample for moisture content shall have a mass of not less than 200 g for samples with a maximum particle size smaller than the 4.75-mm (No. 4) sieve and not less than 500 g for samples with a maximum particle size greater than the 4.75-mm (No. 4) sieve.

7.3.3 Determine the total volume ( $V$ ) of the compacted specimen to be prepared. The height of the compacted specimen must be slightly greater than that required for resilient testing to allow for trimming of the specimen ends. An excess of 13 mm (0.5-in.) is generally adequate for this purpose.

7.3.4 Determine the mass of oven-dry soil solids ( $W_s$ ) and water ( $W_w$ ) required to obtain the desired dry density ( $Y_d$ ) and moisture content ( $w$ ) as follows:

$$W_s \text{ (kilograms)} = Y_d \text{ (kilograms per cubic meter)} \times V \text{ (cubic meters)}$$

$$W_w \text{ (kilograms)} = W_s \text{ (kilograms)} \times w \text{ (percent/100)} \text{ OR}$$

$$W_s \text{ (pounds)} = Y_d \text{ (pounds per cubic foot)} \times V \text{ (cubic feet)}$$

$$W_w \text{ (pounds)} = W_s \text{ (pounds)} \times w \text{ (percent/100)}$$

7.3.5 Determine the total mass of the prepared material sample ( $W_t$ ) required to obtain  $W_s$  to produce the desired specimen of volume  $V$  at dry density  $Y_d$  and moisture content  $w$ .

$$W_t \text{ (grams)} = W_s \times (1 + w/100)$$

7.3.6 Determine the mass of the dried sample ( $W_d$ ), with the moisture content ( $w_1$ ), required to obtain  $W_s$ , including an

additional amount  $W_{da}$  of at least 200 grams to provide material for the determination of moisture content at the time of compaction.

$$W_{da} \text{ (grams)} = (W_s + W_w) \times (1 + w_1/100)$$

7.3.7 Determine the mass of water ( $W_{wa}$ ) required to increase the mass from the existing dried mass of water ( $W_d$ ) to the mass of water ( $W_w$ ) corresponding to the desired compaction moisture content ( $w$ ).

$$W_1 \text{ (grams)} = (W_s + W_w) \times (w_1/100)$$

$$W_2 \text{ (grams)} = (W_s + W_w) \times (w/100)$$

$$W_{wa} \text{ (grams)} = W_2 - W_1$$

7.3.8 Place the mass of the sample ( $W_{da}$ ) determined in Section 7.3.7 into a mixing pan.

7.3.9 Add the water ( $W_{wa}$ ) to the sample in small amounts and mix thoroughly after each addition.

7.3.10 Place the mixture in a plastic bag. Seal the bag and place it in a second bag and seal it.

7.3.11 After mixing and storage, determine the mass of the wet soil and container to the nearest gram and record this value on the appropriate data sheet.

7.4 *Compaction Methods and Equipment for Reconstituting Specimens:*

7.4.1 *Compacting Specimens for Type 1 Materials*—The general method of compaction for these soils will be those of Annex A of this procedure.

7.4.2 *Compacting Specimens for Type 2 Materials*—The general method of compaction for Type 2 materials will be that of Annex B of this procedure.

7.4.3 *Moisture and Density for Compaction*—When the in situ density and moisture content are known from the field data (see Section 7.2.2) the sample should be compacted to this in situ dry density and moisture content.

7.4.4 *Moisture and Density for Compaction when Field Data is not Available*—In the absence of the field data and the in situ density and moisture contents are not known, one of the following procedures is used.

7.4.4.1 *Unbound Granular Base and Subbase Materials (Type 1)*—Use the results of T 180 to establish the maximum dry density and the optimum moisture

content. Select the optimum moisture content and 95 percent of the maximum dry density for sample compaction.

**7.4.4.2 Subgrade Soils (Type 1)**—Subgrade soils may be categorized as Type 1 or as Type 2 according to the criteria of Section 5. In the case of Type 1 subgrade soils, use the results of T 99 to establish the maximum dry density and the optimum moisture content. Select the optimum moisture content and 95 percent of the maximum dry density for sample compaction.

**7.4.4.3 Unbound Material Type 2**—Generally subgrade soils (fine-grained) are included in the unbound material Type 2 category. Select the optimum moisture content and 95-percent maximum dry density for sample compaction as described in Section 7.4.4.2.

**7.4.4.4** The sample dry density and moisture content should not differ by more than 3 percent of the in situ dry density and 1 percentage point of the in situ moisture content respectively for Type 1 materials, and 2 percent of the in situ dry density and 0.5 percent of the in situ moisture content for Type 2 materials, respectively (See Note 3). If the remolded sample does not meet this criteria, it should be discarded.

**NOTE 3**—Example: if the desired dry density is 1922 kg/m<sup>3</sup> (120 lbs/ft<sup>3</sup>) and desired moisture content is 8.0 percent for a Type-1 soil, a dry density between 1864 and 1980 kg/m<sup>3</sup> (116.4 and 123.6 lbs/ft<sup>3</sup>) and a moisture content between 7.0 and 9.0 percent would be acceptable.

**7.4.5** The specimen should be protected from moisture change and tested the same day it is compacted.

**7.5 Specific Gravity**—Determine the specific gravity of solids following T 100.

## 8. TEST PROCEDURE

**8.1 Resilient Modulus Test for Type 2 Soils**—The procedure described in this section is used for undisturbed or laboratory compacted specimens of Type 2 soils as defined in Section 5. Compacted specimens should be tested on the same day after preparation.

**8.1.1 Assembly of Triaxial Chamber**—Specimens trimmed from undisturbed samples and laboratory com-

pacted specimens are placed in the triaxial chamber and loading apparatus in the following steps.

**8.1.1.1** Place the triaxial chamber base assembly on a table close to the loading frame. If the chamber has a removable bottom platen (sample base) tighten it firmly to obtain an air tight seal.

**8.1.1.2** Place a porous stone on the top of the pedestal or bottom end plate of the triaxial chamber.

**8.1.1.3** Carefully place the specimen on the porous stone. Place the membrane on a membrane expander, apply vacuum to the membrane expander, then carefully place the membrane on the sample and remove the vacuum and the membrane expander. Seal the membrane to the pedestal (or bottom plate) with an O-ring or other pressure seals.

**8.1.1.4** Place the top platen (with load cell included) on the specimen, fold up the membrane, and seal it to the top platen with an O-ring or some other pressure seal.

**8.1.1.5** If the specimen has been compacted inside a rubber membrane and the porous stones and sample are already attached to the rubber membrane in place, steps in Sections 8.1.1.2, 8.1.1.3, and 8.1.1.4 are omitted. Instead, the "specimen assembly" is placed on the top of the pedestal or bottom end plate of the triaxial chamber.

**8.1.1.6** Connect the specimen's bottom drainage line to the vacuum source through the medium of a bubble chamber. Apply a vacuum of 7 kPa (1 psi). 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. Leakage through holes in the membrane can frequently be eliminated by coating the surface of the membrane with liquid rubber latex or by using a second membrane.

**8.1.1.7** When leakage has been eliminated, disconnect the vacuum supply and place the chamber on the base plate, the load cell on the porous stone, and the cover plate on the chamber. Insert the loading piston and obtain a firm connection with the load cell. Tighten the chamber tie rods firmly.

**8.1.1.8** Slide the assembly apparatus into position under the axial loading de-

vice. Bring the loading device down and couple it to the triaxial chamber piston and apply a seating pressure to the sample of 14 kPa (2 psi) in order to obtain full contact of the piston with the top platen.

**8.1.2 Conduct the Resilient Modulus Test**—The following steps are required to conduct the resilient modulus test on a specimen of Type 2 soil which has been installed in the triaxial chamber and placed under the loading frame.

**8.1.2.1** Open all drainage valves leading into the specimen.

**8.1.2.2** If it is not already connected, connect the air pressure supply line to the triaxial chamber and apply a confining pressure of 41 kPa (6 psi) to the test specimen. A minimum contact load of 10 percent (1S<sub>d</sub>) of the maximum applied load shall be maintained during all repeated load applications.

**8.1.2.3 Conditioning**—Begin the test by applying 1000 repetitions of a deviator stress of 28 kPa (4 psi) using a haversine shaped load pulse consisting of a 0.1-second load followed by a 0.9-second rest period. 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 initial loading versus reloading. This conditioning also aids in minimizing the effects of initially imperfect contact between the end platens and the test specimen.

**8.1.2.4 Testing Specimen**—The testing is performed following the loading sequence shown in Table 1. Begin by decreasing the deviator stress to 14 kPa (2 psi) (Sequence No. 1, Table 1). Apply 100 repetitions of deviator stress using a haversine shaped load pulse consisting of a 0.1 second load followed by a 0.9-second rest period and record the average of the recovered deformations of the last five cycles on an appropriate data sheet.

**8.1.2.5** Increase the deviator stress to 28 kPa (4 psi) (Sequence No. 2) and repeat step 8.1.2.4 at this new stress level.

**8.1.2.6** Increase the deviator stress to 41 kPa (6 psi) (Sequence No. 3) and repeat step 8.1.2.4 at this new stress level.

**8.1.2.7** Continue the test for the remaining load sequences in Table 1 (4 to 15) recording the vertical recovered deformation. If at any time the permanent