



# HMEC

Highway Materials Engineering Course

PARTICIPANT WORKBOOK

LABORATORY MANUAL



## Soil Tests



U.S. Department of Transportation  
Federal Highway Administration

MODULE

# B



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## **Introduction**

The scope of soil tests covers everything from classification to compaction, density to drainage, consolidation to expansion, and liquid limit to plastic limit. Measurement of these factors plays a key role in determining how soil will behave when placed as the base foundations for roadways. The testing related to these properties shows expected performance of a soil over varying conditions.

## **Laboratory Safety**

### **Personal Protective Equipment**

All participants in the laboratory experience must wear the following safety equipment at all times:

- Safety glasses
- Safety shoes or shoe covers
- Other safety equipment may be necessary for certain tests

### **Heat**

Ovens will be heated to temperatures of approximately 110 °C. Heat-resistant gloves must be worn when working with hot asphalt samples and putting materials in or retrieving them from the ovens.

### **Ensuring Your Safety**

For your safety, please follow all instructions provided by the laboratory experience instructors. Do not touch or handle equipment unless you have been given permission to do so.

### **Guidance on Precision Estimates**

Each of the test methods described herein provide single-operator (repeatability) and multilaboratory (reproducibility) precision estimates. The single-operator precision provides an estimate of the expected variation of tests performed on the same material, by the same operator, using the same equipment in the same laboratory. The multilaboratory precision provides an estimate of the expected variation of two tests performed on the same material, by different operators, using different equipment in different laboratories. If the differences between properly performed tests exceeds these values, the testing practices and equipment should be investigated to determine the cause of the variation.

**Laboratory Procedures and Time Needed to Complete**

<b>Standard Designation</b>	<b>Test Name</b>	<b>Total Time</b>	<b>Active Time</b>
AASHTO R 58	Standard Practice for Dry Preparation of Disturbed Soil and Soil-Aggregate Samples for Test	12.5 hours	30 minutes
AASHTO T 27	Standard Method of Test for Sieve Analysis of Fine and Coarse Aggregates	13 hours	1 hour
AASHTO T 88	Standard Method of Test for Particle Size Analysis of Soils	38 hours	25 hours
AASHTO T 89	Standard Method of Test for Determining the Liquid Limit of Soils	Up to 15 hours	2 hours
AASHTO T 90	Standard Method of Test for Determining the Plastic Limit and Plasticity Index of Soils	Up to 14 hours	2 hours
AASHTO T 99	Standard Method of Test for Moisture-Density Relations of Soils Using a 2.5-kg (5.5-lb.) Rammer and a 305-mm (12-in.) Drop	30.5 hours	14.5 hours
AASHTO T 180	Standard Method of Test for Moisture-Density Relation of Soils Using a 4.45-kg (10-lb.) Rammer and a 457-mm (18-in.) Drop	30.5 hours	14.5 hours
AASHTO T 100	Standard Method of Test for Specific Gravity of Soils	14–32 hours	2 hours
AASHTO T 208	Standard Method of Test for Unconfined Compressive Strength of Cohesive Soil	1 hour	30 minutes
AASHTO T 216	Standard Method of Test for One-Dimensional Consolidation Properties of Soils	1–14 days	24 hours
AASHTO T 296	Standard Method of Test for Unconsolidated, Undrained Compressive Strength of Cohesive Soils in Triaxial Compression	1.5 hours	1 hours
AASHTO T 297	Standard Method of Test for Consolidated, Undrained Triaxial Compression Test on Cohesive Soils	2–5 days	48 hours
AASHTO T 307	Standard Method of Test for Determining the Resilient Modulus of Soils and Aggregate Materials	2 hours	1 hour

## **AASHTO R 58, Standard Practice for Dry Preparation of Disturbed Soil and Soil-Aggregate Samples for Test**

### **Background Information**

The dry preparation test method describes preparation methods of soil and soil-aggregate samples as they are received from the field, prior to performing other testing on the samples, such as mechanical analysis (T 88) and physical tests (T 89, T 90, T 100).

### **Significance and Use**

The purpose of the test is to prepare samples as received from the field for mechanical analysis and physical tests by reducing the sample to the appropriate test size. This method describes how to prepare samples, regardless of moisture content and composition. It is critical that the sample be prepared properly to ensure that the applicable test results will accurately reflect the true characteristics of the material.

### **Related Tests and Specifications**

- AASHTO T 88, Standard Method of Test for Particle Size Analysis of Soils
- AASHTO T 89, Standard Method of Test for Determining the Liquid Limit of Soils
- AASHTO T 90, Standard Method of Test for Determining the Plastic Limit and Plasticity Index of Soils
- AASHTO T 100, Standard Method of Test for Specific Gravity of Soils
- AASHTO T 248, Reducing Samples of Aggregate to Testing Size

### **Timeline for Completion**

Preparation time: 12 hours.

Samples must be air-dried before the preparation phase. This is typically done overnight so that preparation can begin the following day.

Sieving time: 30 minutes.

Samples are separated over sieves and portions are selected for use in further testing.

Total preparation time: 12.5 hours.

## Apparatus

- Drying Apparatus (optional) – Capable of drying samples at a temperature not exceeding 60 °C (140 °F). Alternatively, samples may be air-dried.
- Sample Splitter or Riffle Sampler (optional) – Alternatively, splitting or quartering methods as described in AASHTO T 248 may be used to obtain a representative sample.
- Balance
- Sieves – The following sieves may be needed, depending on the specific tests for which the sample is being prepared: 4.75 mm (#4), 2.00 mm (#10), 0.425 mm (#40), and others.
- Pulverizing Apparatus – Either a mortar and rubber-covered pestle (Figure 1) or a mechanical device with a power-driven, rubber-covered muller. Other types of apparatus are satisfactory, provided the aggregations of soil particles are broken up without reducing the natural size of the individual grains.



*Figure 1: Mortar and rubber covered pestle*



## Sample Preparation

The amounts of material required to perform the individual tests are as follows.

*Table 1: Minimum Sample Size for Various Tests*

Test Method	Minimum Amount of Prepared Material Required
T 88	Sandy soils: 110 g passing 2.00 mm (#10) Silty or clayey soils: 60 g passing mm (#10) Material for coarse sieve analysis: Refer to Table 2
T 89	100 g passing 0.425 mm (#40)
T 90	20 g passing 0.425 mm (#40)
T 100	Volumetric flask method: 25 g passing 2.00 mm (#10); Stoppered bottle method: 10 g passing 2.00 mm (#10)
Shrinkage factors	30 g passing 0.425 mm (#40)
Field Moisture	50 g passing 0.425 mm (#40)
Check and Referee Tests	100 g passing 0.425 mm (#40)

*Table 2: Minimum Sample Size for AASHTO T 88 Coarse Sieve Analysis*

Diameter of Largest Particle, mm (in.)	Minimum Sample Mass, kg
9.5 (3/8)	0.5
25 (1)	2.0
50 (2)	4.0
75 (3)	5.0

## Procedure

### Step 1

Dry the sample as received from the field thoroughly at a temperature not exceeding 60 °C (140 °F).

### Step 2

Obtain a representative test sample of the amount require for the specific tests (refer to the requirements in the Sample Preparation section) using the sample splitter (Figure 2), or by splitting or quartering.



Figure 2: Riffle sample splitter

### Step 3

Break up the aggregations of soil particles with the pulverizing apparatus.

### Step 4

Determine the portion of the dried sample selected for T 88 and the physical tests. This is the mass of the total sample uncorrected for hygroscopic moisture.

### Step 5

Separate this portion into fractions by one of the following methods.

#### *Method 1*

Using 2.00 mm (#10) sieve – Separate the dried sample into two fractions using a 2.00-mm sieve. Grind the fraction retained on the sieve with the pulverizing apparatus, and separate the material again on the 2.00-mm sieve.

**Note: If the sample contain brittle particles, such as flakes of mica, fragments of sea shells, etc., pulverize the material carefully and with just enough pressure to free the finer material that clings to the coarser particles.**

#### *Method 2*

Using 4.75-mm and 2.00-mm (#4 and #10) sieves – Separate the dried sample into two fractions using the 4.75-mm sieve. Grind the fraction retained on the sieve with the pulverizing apparatus, and separate the material again on the 4.75-mm sieve. Thoroughly mix the fractions passing the 4.75-mm sieve and obtain a representative portion adequate for the desired tests using the sample splitter, or by splitting or quartering. Separate this portion on the 2.00-mm sieve and process it as described in step 5 a. Record the mass of the material retained on the 2.00-mm sieve for later use in the T 88 coarse sieve analysis calculations.

### Step 6

Test Sample for T 88 and T 100:

1. Save the material retained on the 2.00-mm sieve from step 5 a, or the material retained on the 4.75-mm sieve after the second sieving from step 5 b, for use in the coarse sieve analysis.
2. Thoroughly mix the fractions passing the 2.00-mm sieve in both sieving operations and obtain representative portions adequate for the tests (see Sample Preparation) using the sample splitter, or by splitting and quartering.

### Step 7

Test Sample for Physical Tests (T 89, T 90, Shrinkage Factors, Field Moisture Equivalent, Check and Referee tests).

Separate the remaining portion of the material passing the 2.00-mm sieve into two parts using a 0.425-mm sieve. Grind the fraction retained on the sieve with the pulverizing apparatus, and separate the material again on the 0.425-mm sieve. Regrind and re-sieve the material until only a small portion of material passes the 0.425-mm sieve. Thoroughly mix all the fractions passing the 0.425-mm sieve and set aside for use in performing the physical tests.

### Common Errors

- The pestle is not rubber-covered.
- The sample is dried at 110 °C instead of 60 °C.
- The wrong sieve sizes are used.
- The individual sample masses are incorrect.

## **AASHTO T 27, Standard Method of Test for Sieve Analysis of Fine and Coarse Aggregate**

### **Background Information**

The sieve analysis, commonly known as the gradation test, is an essential test for all soils and aggregates. The sieve analysis determines the gradation, or distribution of aggregate particles, by size, within a given sample. These results are used to determine compliance with design, production control requirements, and verification specifications. The gradation data can be used to calculate relationships between various aggregates, or aggregate and soil blends, to check compliance with such blends, and to predict trends during production by plotting gradation curves graphically. When this test is used in conjunction with other tests, the sieve analysis is a powerful quality control and quality acceptance tool.

### **Significance and Use**

This test method is often used in conjunction with AASHTO T 11 for determination of the material passing the 75- $\mu\text{m}$  (#200) sieve. Accurate determination of the material passing the 75- $\mu\text{m}$  (#200) sieve cannot be made with this test alone.

The results of AASHTO T 27 are used in conjunction with AASHTO M 145 for classification of soils and soil-aggregate mixtures for highway construction purposes.

### **Related Tests and Specifications**

- AASHTO T 2, Sampling of Aggregates
- AASHTO T 11, Standard Method of Test for Materials Finer Than 75- $\mu\text{m}$  (#200) Sieve in Mineral Aggregates by Washing
- AASHTO T 248, Reducing Samples of Aggregate to Testing Size

### **Timeline for Completion**

Preparation Time: 12 hours

Samples must be dried to constant mass before completion. This is typically done overnight so that testing can begin the following day.

Active Testing Time: 30 minutes

Sample is cooled to room temperature and then weighed, sieved, and then individual sieved fractions are weighed.

Calculations: 30 minutes

The percent of material passing each sieve is calculated and the results are graphed.

Total test time: 13 hours

### **Apparatus**

- Sieves – Nest of sieves meeting the requirements of AASHTO M 92. Sieves come in many different shapes and sizes. Typically, sieves that are round with a diameter of 8 or 12 in., or larger square or rectangular sieves are used for this test.
- Balance – Capable of weighing the sample mass to 0.1%.
- Oven – Capable of drying  $110 \pm 5$  °C ( $230 \pm 9$  °F).
- Mechanical Shaker (Optional) – Must provide a vertical or lateral and vertical motion to the sieve and provide sieving thoroughness within a reasonable time. Although the mechanical shaker is not necessary to complete this test, it is normally used for most sieving operations. There are three types of mechanical sieve shakers that are typically used for this test: Mary-Ann, Ro-Tap, and Screen Shaker. Other types of mechanical sieve shakers may be used, as long as they create motion of the sieves to cause the particles to bounce, tumble, or otherwise turn so as to present different orientations to the sieving surface. The requirement for sieving sufficiency must be met regardless of the type of mechanical shaker used.

### **Mechanical Shaker Sieving Sufficiency**

If a mechanical sieve shaker is used, the sufficiency of the sieving action of the device must be verified. Sieving must be continued for a sufficient period so that, after completion of the sieving operation, not more than 0.5% by mass of the total sample passes any sieve during 1 minute of continuous hand sieving.

Sieving sufficiency of mechanical shakers should be verified regularly for the types of materials that are typically tested in the laboratory, and for each sieve size used. AASHTO R 18 requires that sieving sufficiency be verified at a minimum interval of 12 months. The sieving time used during routine testing should be adjusted to the minimum amount of time required to meet the 0.5% requirement.

**Note: Sieving times over 10 minutes can degrade the material under test.**

Example: A  $\frac{3}{4}$ -in. sieve is checked for sieving sufficiency. The total weight of the sample is 2074.2 grams.

$$\frac{\text{Mass of Material that Passed the Sieve During Hand Sieving}}{\text{Total Mass of Sample}} \times 100 =$$

$$\frac{2.5 \text{ g}}{2074.2 \text{ g}} \times 100 = \mathbf{0.12\%}$$

The results indicate that 0.12% of the material passed the ¾-in. sieve during hand sieving. The percentage is less than 0.5%, so the check for sieving sufficiency indicates that the thoroughness of sieving is adequate.

### Sample Preparation

The samples should be obtained from the field in accordance with AASHTO T 2 and reduced to the test size in accordance with AASHTO T 248. Samples should be dried to a constant mass in an oven maintained at  $110 \pm 5 \text{ }^{\circ}\text{C}$  ( $230 \pm 9 \text{ }^{\circ}\text{F}$ ). The test size is determined by the nominal maximum particle size of the aggregate. For fine aggregate, use a minimum of 300 g, and for coarse aggregate, or a mixture of coarse and fine aggregate, use the information in Table 3.

*Table 3: Minimum Sample Mass for Coarse Aggregate Samples for T 27*

Nominal Maximum Size Aggregate, mm (in.)	Minimum Mass of Test Sample, kg (lb.)
9.5 (3/8)	1 (2)
12.5 (1/2)	2 (4)
19.0 (3/4)	5 (11)
25.0 (1)	10 (22)
37.5 (1½)	15 (33)
50.0 (2)	20 (44)
63.0 (2½)	35 (77)
75.0 (3)	60 (130)
90.0 (3½)	100 (220)

### Procedure

#### Step 1

Assemble the proper sieves for the sieve nest from largest sieve on top to the smallest mesh size on the bottom. A pan should be placed underneath and a lid should be placed on top of the sieve stack. If the sample was washed in accordance with AASHTO T 11 prior to running this test, a 75-µm (#200) sieve must be used.

**Step 2**

Weigh the sample to the nearest 0.1% as W1. This weight is used to check for any loss or gain of material during sieving.

**Step 3**

Place the oven-dried sample in the set of sieves. Be cautious to not overload any of the sieves. If it looks as though a particular sieve or several sieves may become overloaded, review the possible solutions discussed in Step 7.

**Step 4**

Place the sample and sieves in a mechanical shaker or hand sieve the set. If hand sieving, do not force particles to pass through the openings.

**Step 5**

If using a mechanical shaker, continue sieving for the amount of time determined to be adequate during the check for sieving sufficiency. If hand sieving, continue the sieving process until no more than 0.5% by mass of the total sample passes any sieve during 1 minute of continuous hand sieving.

**Step 6**

Weigh the amount of material retained on each sieve and in the sieve pan by placing each fraction, starting with the largest mesh size, in a tared pan placed on the balance. Record the mass indicated on the balance for each size fraction. The balance can be tared before each consecutive size fraction is added to the pan, or the balance can remain untared and the weight of each size fraction recorded cumulatively (additional guidance is provided in the calculation section).

**Step 7**

Review the data collected to ensure that the sieves were not overloaded during the sieving process. The mass retained in a particular sieve with openings smaller than the #4 sieve should be less than 200 grams for an 8-in. diameter sieve, and 469 grams for a 12-in. diameter sieve. Sieves with openings that are larger than the #4 sieve should retain a maximum amount of material in accordance with guidance on sieve overloading for other sizes of sieves, including square or rectangular sieves, which can be found in Section 8.3 of AASHTO T 27.

Table 4: Guidance on Sieve Overloading

Sieve	Opening (mm)	Mass (g) – 8 in. dia.	Mass (g) – 12 in. dia.
#4	4.75	338	469
¼ in.	6.3	449	796
⅜ in.	9.5	677	1,055
½ in.	12.5	891	1,592
¾ in.	19	1,354	3,183

**Note: Why avoid overloading sieves?** If there is too much material on a given sieve, then each individual particle will not have proper access to the sieve screen, which affects the efficiency of the sieving process. In addition, an excess of material on the sieve may cause undue damage to the sieve mesh, especially on small-sized sieve openings.

If any of the sieves are found to be overloaded, the results of the sieve analysis are invalid and the sample should be retested. Overloading of the sieves can be prevented in a number of ways, including the following:

- Insert an additional sieve with opening sizes that are between the sieve that may be overloaded and the sieve immediately below it.
- Split the sample into two or more portions, sieving each portion individually and combining the results obtained before completing the calculations.
- Utilize sieves with a larger frame size.
- If the material is a mixture of fine and coarse material, the portion of the sample finer than the 4.75-mm (#4) sieve may be distributed among two or more sets of sieves to prevent overloading of individual sieves.
- If the material is a mixture of fine and coarse material, the portion of the sample finer than the 4.75-mm (#4) sieve can be reduced in size in accordance with Section 8.31.5 of AASHTO T 27.

## Calculations

The results of the analysis can be calculated as cumulative percent passing, cumulative percent retained, or as a percentage passing based on individual size fractions. Results should be calculated to the nearest 0.1% based on the original dry mass of the sample. If the material was first washed in accordance with AASHTO T 11, include the mass of material finer than the 75- $\mu\text{m}$  (#200) sieve by T 11 as the basis for calculating all percentages.



**Step 1**

Determine the total mass of the sample ( $W_1$ ). If AASHTO T 11 was performed on the material prior to performing the sieve analysis,  $W_1$  will be the initial mass recorded before running AASHTO T 11. If AASHTO T 11 was not performed in conjunction with the sieve analysis, then  $W_1$  will be the initial mass of the sample prior to sieving.

**Step 2**

The method used to calculate the percent of material retained on each sieve will depend upon whether or not the balance is tared between the addition of each size fraction or if the size fractions were weighed cumulatively.

*If the balance was tared between the addition of each size fraction*

Determine the percentages as follows:

$$\text{Percent Retained} = \frac{\text{Mass Retained on Sieve}}{W_1} \times 100$$

Determine the cumulative percent of material retained on each by adding the mass of material of all the larger sieve mesh sizes to the mass of material on sieve  $x$ ,  $S_x$ . Determine the cumulative percent retained as a percentage of the original sample mass,  $W_1$ :

$$\text{Cumulative Mass Retained } (\Sigma_x) = S_1 + S_2 \dots S_x$$

$$\text{Cumulative \% Retained } (W_2) = \frac{\Sigma_x}{W_1} \times 100$$

$$\% \text{ Passing} = 100 - W_2$$

If AASHTO T 11 was performed on the material prior to sieving, add the percent passing the 75- $\mu\text{m}$  (#200) sieve from T 11 to the percent passing the 75- $\mu\text{m}$  (#200) sieve from the sieve analysis for the total number reported.

*If masses were determined cumulatively*

Determine the percent passing each sieve from the cumulative mass recorded for each sieve size,  $(\Sigma_x)$

$$\% \text{ Passing} = 100 - \frac{\Sigma_x}{W_1} \times 100$$

## Step 3

Determine if the total mass of material after sieving is within 0.3% of the original sample mass:

$$\% \text{ Difference} = \frac{\text{Total Sample Mass Before Sieving}}{\text{Total Sample Mass After Sieving}} \times 100$$

If the mass of material lost during the sieving operation exceeds 0.3%, the test results should not be used for acceptance purposes and the test should be performed with a new sample.

Sample Loss: If sample loss during the sieving operation exceeds 0.3%, it is recommended that an investigation take place to determine where the sample loss occurred. The most common cause of sample loss is inadequate cleaning of the test sieves after the sieving operation.

## Example Calculations

Information from AASHTO T 11:

- Original dry mass of sample before washing (W1) = **2086.8 g**
- Dry mass of sample after washing (B) = **2041.5 g**
- Mass of minus 200 from wash (C) = **45.3 g**

Testing completed using 8-in. diameter sieves has the following results.

Sieve Opening Size	Individual Mass Retained on Each Sieve ( $S_x$ )	Mass of Material Retained, Cumulative ( $\Sigma_x$ )	Total Percent Passing $100 - \frac{\Sigma_x}{W_1} \times 100$
25.0 mm (1 in.)	0.0	0.0	100
19.0 mm (¾ in.)	148.5	148.5	92.9
12.5 mm (½ in.)	227.6	376.1	82.0
9.5 mm (⅜ in.)	290.3	666.4	68.1
4.75 mm (#4)	302.8	969.2	53.6
2.36 mm (#8)	378.0	1,347.2	35.4
1.18 mm (#16)	20.9	1,368.1	34.4
600 µm (#30)	81.4	1,449.5	30.5
300 µm (#50)	275.7	1,725.2	17.3
150 µm (#100)	238.1	1,963.3	5.9
75 µm (#200)	65.6	2,028.9	2.8
Pan + C			

Total Mass after Sieving (D): **2041.1g**

Calculations:

Total Minus #200 Material (Pan + C): **57.5 g**

Mass Lost During Sieving ( $G = B - D$ ): **0.4 g**

Percent Lost During Sieving ( $(G/B) \times 100$ ): **0.02% (must be < 0.3%)**

**Note: Notice that in this example, 8-in. diameter sieves were used for testing, and the #8, 50, and 100 sieves were overloaded (i.e., more than 200 g was retained on each sieve). Therefore, these test results are invalid. In this case, the sample should be retested.**

### Reporting the Test Results

For each sieve, report one of the following, in accordance with the specification being followed: (1) the total percentage of material passing each sieve, (2) the total percentage of material retained on each sieve, or (3) the total percentage of material retained between consecutive sieves.

Percentages should be reported to the nearest whole number. If the percentage of material passing the 75- $\mu\text{m}$  (#200) sieve is less than 10%, report this value to the nearest 0.1%.

The results of AASHTO T 27 are often plotted on a semi-logarithmic graph with the percent passing on the y-axis, and the sieve size plotted on the x-axis (log scale). For the example described previously, the plot would look as shown in Figure 3.

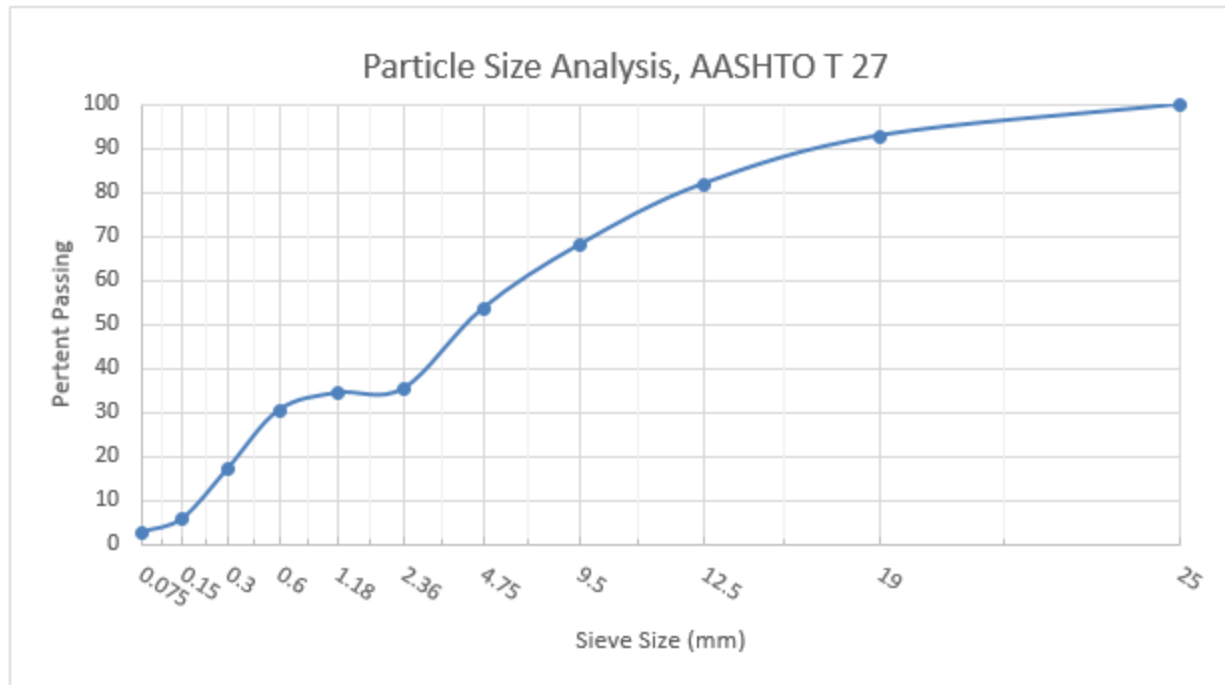


Figure 3: Graphical Plot of AASHTO T 27 Sieve Analysis

### Interpreting and Utilizing the Test Results

The results of AASHTO T 27 are used in conjunction with AASHTO M 145 to classify soil and soil-aggregate mixtures. For more information on utilizing sieve analysis results of soil samples, please review the section of the manual on AASHTO M 145.

### Common Errors

- The most commonly-observed errors made by technicians performing AASHTO T 27 are as follows:
- The time of sieving is longer than 10 minutes, which may lead to aggregate degradation.
- The sample mass used does not meet the minimum required mass according to the nominal maximum size of the aggregate used.
- More than 0.3% of the original sample mass is lost during the sieving operation.
- The balance is not capable of weighing the sample to 0.1% of the sample mass.
- Sieves are overloaded during the test procedure.

## Data Sheets

Information from AASHTO T 11:

Original dry mass of sample before washing ( $W_1$ ) =

Dry mass of sample after washing (B) =

Mass of minus 200 from wash (C) =

Testing completed using 8-in. diameter sieves:

Sieve Opening Size	Individual Mass Retained on Each Sieve ( $S_x$ )	Mass of Material Retained, Cumulative ( $\Sigma_x$ )	Total Percent Passing $100 - \frac{\Sigma_x}{W_1} \times 100$
25.0 mm (1 in.)			
19.0 mm (¾ in.)			
12.5 mm (½ in.)			
9.5 mm (⅜ in.)			
4.75 mm (#4)			
2.36 mm (#8)			
1.18 mm (#16)			
600 um (#30)			
300 um (#50)			
150 um (#100)			
75 um (#200)			
Pan + C			

Total Mass after Sieving (D):

Calculations:

Total Minus 200 Materials (Pan + C) =

Mass Lost During Sieving ( $G = B - D$ ) =

Percent Lost During Sieving ( $(G/B) \times 100$ ) (must be  $< 0.3\%$ ) =

## **AASHTO T 88, Standard Method of Test for Particle Size Analysis of Soils**

### **Background Information**

The particle size analysis of soils, commonly known as the hydrometer test, is a very common and important test for all soils. The hydrometer test, based on Stokes' Law, makes it possible to determine the particle size distribution within a sample when the particles are too small to analyze using sieves. This law states that larger particles will settle out of the solution more rapidly than the smaller ones. When using a sieve to determine particle size (AASHTO T 27), particle size can typically be determined down to 75  $\mu\text{m}$ . However, with the help of a hydrometer, it is possible to establish particle sizes down to 1  $\mu\text{m}$ . As particles settle, a density gradient is created. This can be used to identify the properties of the particles within a suspension.

### **Significance and Use**

This test method is often used in conjunction with AASHTO T 27 for determining a combined sieve analysis for both coarse and fine-grained materials.

### **Related Tests and Specifications**

- AASHTO M 145, Classification of Soils and Soil-Aggregate Mixtures for Highway Construction Purposes
- AASHTO R 58, Standard Practice for Dry Preparation of Disturbed Soil and Soil-Aggregate Samples for Test
- AASHTO T 27, Sieve Analysis of Fine and Coarse Aggregate
- AASHTO T 265, Laboratory Determination of Moisture Content of Soils

### **Timeline for Completion**

Preparation Time: 12 hours

Sample is prepared in accordance with AASHTO R 58.

Test Time: 25 hours

Agitating the sample, transferring it into the cylinder, taking 24 hours' worth of readings, washing the sample over the #200 (75  $\mu\text{m}$ ) sieve.

Calculations: 1 hour

Calculations are typically determined by appropriate software.

Total Test Time: 38 hours

### Apparatus

- Oven – Maintains  $110 \pm 5$  °C ( $230 \pm 9$  °F).
- Balance
- Stirring Apparatus – A mechanically-operated stirring apparatus consisting of an electric motor mounted to turn a replaceable stirring paddle at not less than 10,000 rpm (Figure 4).



*Figure 4: Stirring apparatus and dispersion cup*

- Dispersion cup
- Hydrometer – Meeting the requirements of either an ASTM 151 H or an ASTM 152 H (Figure 5).





Figure 5: 152 H hydrometer

- Sedimentation Cylinders – A glass cylinder marked for a volume of 1,000 mL.
- Thermometer – Calibrated and readable to 0.5 °C (1 °F).
- Sieves – Standard sieve set consists of 75 mm (3 in.), 50 mm (2 in.), 25 mm (1 in.), 9.25 mm ( $\frac{3}{8}$  in.), 4.75 mm (#4), 2.00 mm (#10), 0.425 mm (#40), and 0.075 mm (#200). Additional sieves may also be used.
- Constant Temperature Room or Water Bath
- Beaker – Capacity of at least 250 mL but not greater than 500 mL.
- Timing Device – Readable to the nearest second.
- Moisture Content Containers – With close-fitting lids.
- Stirring Device – Any nonporous device suitable for stirring the mixture without losing material.
- Dispersing Agent – A solution of sodium hexametaphosphate used in distilled or demineralized water at a rate of 40 g/L.

### Sample Preparation

The minimum amount of required material depends on the maximum particle size, but shall not be less than the amount shown in Table 5.

Table 5: Minimum Amount of Required Material

Normal Size of Largest Particles Standard (Alternate)	Approximate Minimum Weight of Portion
9.5 ( $\frac{3}{8}$ in.)	0.5 kg
25 (1 in.)	2 kg
50 (2 in.)	4 kg
75 (3 in.)	5 kg

The test sample for particle size analysis shall be prepared in accordance with AASHTO R 58. The sample size of material passing the 2.00 mm (#10) sieve shall be either approximately 100 g for sandy soil or 50 g for silty or clayey soils, with an additional 10 g taken for a hygroscopic

moisture determination. The coarser portion of the test sample retained on the 2.00 mm (#10) sieve is sieved over the appropriate nest of sieves.

#### Determination of the Composite Correction

A composite correction must be determined in order to calculate the test results. The procedure for determining the composite correction is described in detail in AASHTO T 88. The composite correction is used to correct for the following when performing the final calculations:

- The specific gravity of the sodium hexametaphosphate solution.
- Reading the hydrometer at the top of the meniscus instead of the bottom.
- Temperature of the solution.

**Reading the hydrometer: Although hydrometers are manufactured to be read at the bottom of the meniscus formed by the liquid on the stem, the soil slurry formed during the test makes this impossible. In this case, the readings must be taken at the top of the meniscus and a correction applied.**

#### Determination of Hygroscopic Moisture

Determine the mass of the sample for the hygroscopic moisture sample, dry the sample, and determine the moisture content in accordance with AASHTO T 265.

### Procedure

#### Step 1

Take the appropriate sized sample and place it in a 250 mL beaker, cover with 125 mL of dispersing agent solution, stir and allow to soak for a minimum of 12 hours.

#### Step 2

Wash the contents of the beaker into the dispersion cup, fill the cup with water until it is more than half full, and disperse the contents for 60 seconds with the mechanical stirring apparatus.

#### Step 3

After dispersion, transfer the mixture to a glass cylinder and add distilled or demineralized water until it reaches the 1,000 mL mark.

#### Step 4

Using a rubber stopper or the palm of the hand to cover the opening of the cylinder, turn the cylinder upside down (1st turn) and back (2nd turn) 60 times in a period of 60 seconds.

Turning the cylinder: When preparing the cylinder for turning, the use of a rubber stopper is the best practice. This keeps the possibility of losing material from the cylinder at a minimum. Keep in mind that inverting the cylinder down and back counts as two turns.

#### Step 5

After shaking, record the time immediately. Take hydrometer readings at 2, 5, 15, 30, 60, 250, and 1,440 minutes (24 hours) after the time is recorded. Insert the hydrometer approximately 25 to 30 seconds prior to taking a reading in order to allow the hydrometer to stabilize.

#### Step 6

Record the temperature of the soil suspension immediately following each hydrometer reading.

#### Step 7

After each reading, place the hydrometer in a graduate of clean water using a spinning motion.

#### Step 8

Following the final hydrometer reading, wash the contents of the cylinder over a 0.075 mm (#200) sieve. Dry the retained fraction in an oven at  $110 \pm 5$  °C ( $230 \pm 9$  °F) and perform a sieve analysis on the material.

### Calculations

Determine the Percentage of Hygroscopic Moisture

$$\text{Percentage of Hygroscopic Moisture} = \frac{W - W_1}{W_1} \times 100$$

Where:

- $W$  = mass of air-dried soil
- $W_1$  = mass of oven-dried soil

Determine the Percentage of Soil in Suspension

The percentage of dispersed soil in suspension represented by different corrected hydrometer readings depends upon both the amount and the specific gravity of the soil dispersed.

For hydrometer 152H:

$$P = \frac{Ra}{w} \times 100$$

For hydrometer 151 H:

$$P = \frac{1606 (R - 1) a}{w} \times 100$$

Where:

- $P$  = percentage of originally dispersed soil remaining in suspension
- $R$  = corrected hydrometer reading
- $w$  = mass in grams of soil originally dispersed minus the hygroscopic moisture
- $a$  = constant depending on the density of the suspension as shown in Table 6

Table 6: Values of “a,” for Different Specific Gravities

Specific Gravity, $G$	Constant, $a$
2.95	0.94
2.85	0.96
2.75	0.98
2.65	1.00
2.55	1.02
2.45	1.05
2.35	1.08

### Determining the Diameter of Soil Particles in Suspension

According to Stokes’ Law:

$$d = \sqrt{\frac{30 n L}{980 (G - G_1) T}}$$

Where:

- $d$  = maximum grain diameter in millimeters
- $n$  = coefficient of viscosity of the suspending medium (in this case water) in Pa·s
- $L$  = distance from the surface of the suspension to the level at which the density of the suspension is being measured, mm. This distance is known as effective depth.  
**Effective Depth: The effective depth varies for each type of hydrometer and can be determined from Table 2 in the standard.**
- $T$  = interval of time from beginning of sedimentation to the taking of the reading (minutes)

- $G$  = specific gravity of soil particles
- $G_1$  = specific gravity of the suspending medium (approximately 1.0 for water)

## Reporting the Test Results

The accumulated percentages of grains of different diameters shall be plotted on semi logarithmic paper to obtain a grain size accumulation curve, such as that shown in Figure 6. The results of the sieve analysis portion of the test and the hydrometer portion of the test are combined to create the cumulative grain size accumulation curve.

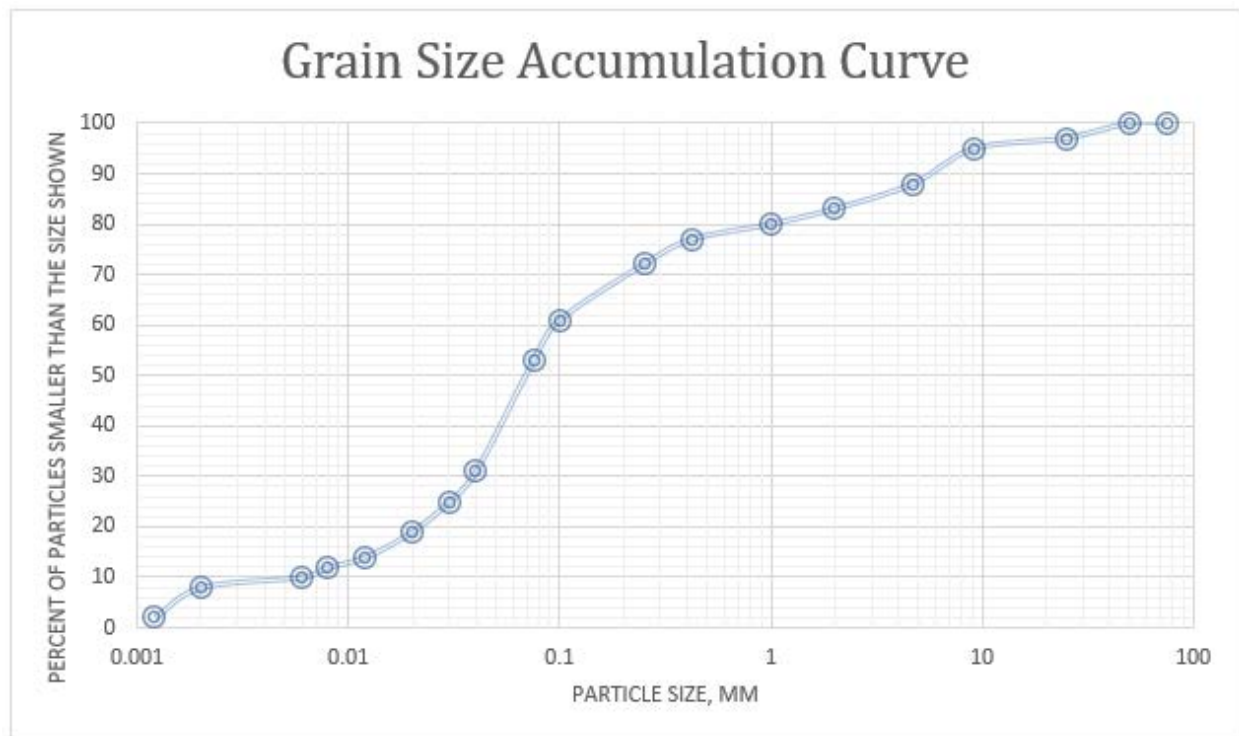


Figure 6: Grain Diameter Accumulation Curve

## Common Errors

- Hydrometer readings were not recorded at the correct time(s), typically due to a lag in the starting time.
- The hydrometer was not cleaned properly between readings.
- Temperature readings were not taken after each hydrometer reading.
- The composite correction was not calculated or reported correctly.
- The cylinder was turned at an improper rate or an improper amount of times.

## Data Sheets

Name: \_\_\_\_\_

Date: \_\_\_\_\_

Hydrometer: \_\_\_\_\_

Mass Coarse Material: \_\_\_\_\_

Hygroscopic Moisture Determination	
Mass of Dish (g)	
Mass of Dish and Air Dry Soil (g)	
Mass of Air Dry Soil (g)	
Mass of Dish and Oven Dry Soil (g)	
Mass of Oven Dry Soil (g)	
Mass of Moisture Lost (g)	
Hygroscopic Moisture (%)	

Sample Mass Determination	
Specific Gravity [T100], G	
Constant, A	
Air-Dry Mass Without Hygroscopic Moisture, W (g)	
Correction Mass, W (g)	

Hydrometer Test									
Time (min.)	Hydrometer Reading	Temp (°C)	Composite Correction Reading	Temp (°C)	Corrected Reading (R)	Effective Depth (L)	K	D	P
2									
5									
15									
30									
60									
250									
1440									

Sieve Analysis		
Mass Retained After Drying (g)		Percent Passing
Mass Retained on #40 (g)		
Mass Retained on #200 (g)		
Mass in Pan (g)		

## **AASHTO T 89, Standard Method of Test for Determining the Liquid Limit of Soils**

### **Background Information**

The liquid limit of a soil is the water content, in percent, at which a soil changes from a plastic to a liquid state. The liquid limit and plastic limit tests (AASHTO T 90) are used to determine the plasticity index of soils, which is used for soil classification purposes. The liquid limit, along with plastic limit and shrinkage limit, are known as Atterberg limits. The liquid limit test can be performed using Method A (multipoint method) or Method B (one point method).

### **Significance and Use**

The Atterberg limits can be used to distinguish between silt and clay soils. These distinctions are used in assessing soils on which structures are to be built. Soils retain water when wet, and some soils expand in volume. The amount of expansion is dependent on the ability of the soil to absorb water as well as the structural composition of the material itself. Atterberg limit tests are mainly used on clayey or silty soils since these soils react with water by expanding and shrinking. These types of soils also have varying shear strengths, depending on water content. The swelling and shrinking process is directly related to shear failure, and the soil is therefore subject to fail in construction processes.

### **History**

Atterberg limits were created by Albert Atterberg (1846–1916), a Swedish chemist and agricultural scientist. In 1932, the Atterberg limits were standardized by Arthur Casagrande (1902–1981), an Austrian-born American civil engineer. The flat Casagrande grooving tool used for the liquid limit test is named after Mr. Casagrande.

### **Related Tests and Specifications**

- AASHTO R 58, Standard Practice for Dry Preparation of Disturbed Soil and Soil-Aggregate Samples for Test
- AASHTO T 90, Standard Method of Test for Determining the Plastic Limit and Plasticity Index of Soils
- AASHTO T 146, Wet Preparation of Disturbed Soil Samples for Test
- AASHTO T 265, Laboratory Determination of Moisture Content of Soils

### **Timeline for Completion**

Preparation Time: Up to 12 hours

Sample is prepared in accordance with AASHTO R 58, which requires the sample to be air-dried. Sample is mixed with water and can be tested immediately.

Test Time: 2 hours

The liquid limit device is inspected prior to each use. The prepared sample is placed in the cup of the device. The sample in the cup is divided with the grooving tool. The cup is repeatedly dropped until the groove in the soil closes. A water content sample is taken. The water content sample is dried to constant mass.

Calculations: 5 minutes

The percent moisture in each water content sample is calculated. A flow curve is prepared if the multipoint method is used, and the liquid limit is determined.

Total Test Time: Up to 15 hours

### **Apparatus**

- Liquid Limit Device – Manually or mechanically operated, consisting of a brass cup and carriage.
- Gauge Block – About 10 mm in thickness and 50 mm in length; may be attached to the end of the grooving tool.
- Grooving Tool – Curved or flat (Casagrande tool).
- Spatula - Or pill knife having a blade about 75-100 mm in length and 20 mm in width.
- Mixing Dish – Made of unglazed porcelain or similar, about 115 mm in diameter.
- Distilled or Demineralized Water
- Moisture Content Containers – Made of corrosion-resistant material with close-fitting lids.
- Balance – Readable to 0.01 g.
- Oven – Maintains  $110 \pm 5$  °C.



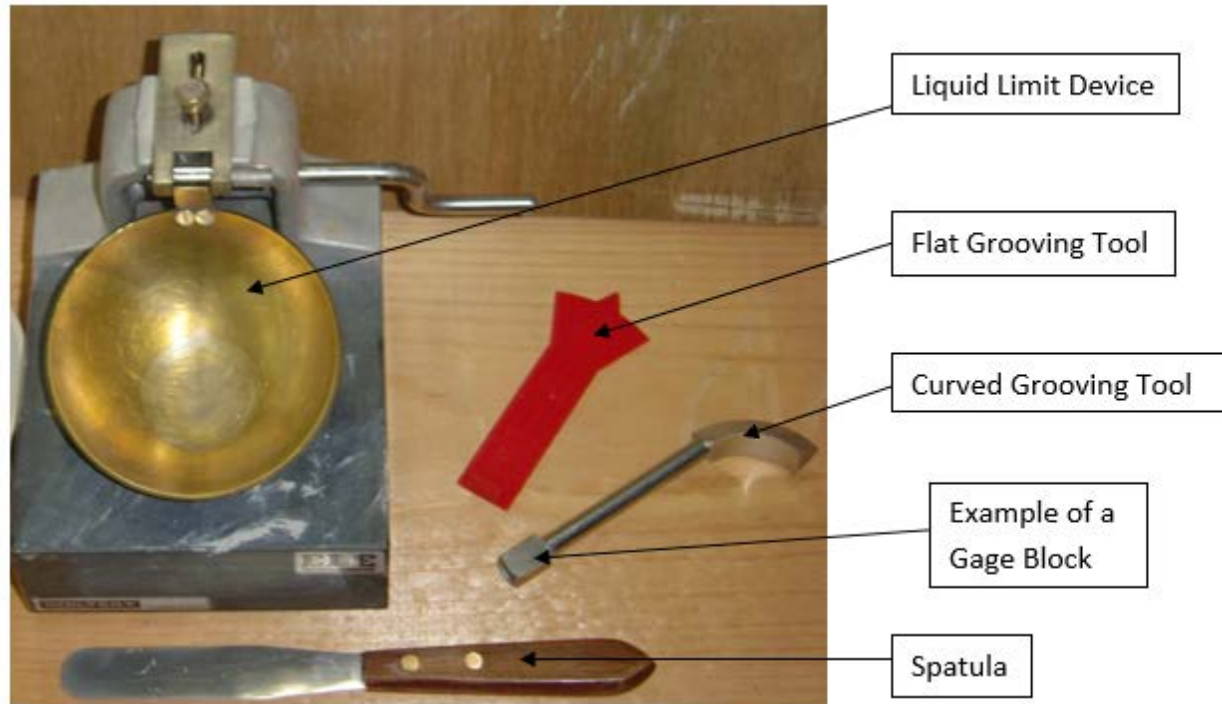


Figure 7: Liquid Limit Test Apparatus

### Sample Preparation

A sample having a mass of about 100 g (Method A) or 50 g (Method B) is taken from material passing the 425- $\mu\text{m}$  (#40) sieve obtained in accordance with AASHTO R 58. For structural analysis, Method B of AASHTO T 146 is used.

### Procedure – Method A

#### Step 1

Inspect the liquid limit device to ensure it is in good working order.

#### Step 2

Using the gauge block, adjust the height of drop of the liquid limit cup in accordance with the test method. This shall be done prior to each day's testing.

#### Step 3

Place the dry sample in the mixing dish and mix with distilled or demineralized water in the amount of 15–20 mL (Method A) or 8–10 mL (Method B), using the spatula.

#### Step 4

Add water in increments of 1–3 mL, thoroughly mixing the water and sample before adding more water. Continue to add more water until the sample is of a stiff consistency.

**Step 5**

Place a sufficient amount of the moistened soil in the lower part of the brass cup of the liquid limit device. Level and spread the soil with the spatula to a depth of 10 mm at maximum thickness.

**Step 6**

Divide the soil in the cup in half vertically (see Figure 8) with the grooving tool.



*Figure 8: Groove in Soil Made by Grooving Tool*

**Step 7**

Lift and drop brass cup of the liquid limit device approximately two revolutions per second until the two sides of the divided sample come in contact at the bottom of the groove along a distance of about 13 mm.

**Step 8**

Record the number of shocks required to close the groove if in the range of 25–35 shocks. If the number of shocks is not in that range, repeat steps 4 through 14 until the groove closes in that range.

**Step 9**

Remove a slice of soil approximately the width of the spatula, extending from edge to edge of the soil cake at right angles to the groove and including the portion of the groove where the soil flowed together.

**Step 10**

Place the soil slice in a container and dry in accordance with AASHTO T 265 to determine the moisture content.

**Step 11**

Return the soil remaining in the brass cup to the mixing dish.

**Step 12**

Repeat steps 5 through 11, adding enough water to bring the soil to a more fluid condition.

**Step 13**

Remove the second and third moisture content samples when the groove closes in the range of 20–30 and 15–25 shocks, respectively.

**Step 14**

The range of the three determinations shall be at least 10 shocks.

**Procedure – Method B****Step 1**

Follow steps 1 through 7 of Method A.

**Step 2**

Obtain a preliminary groove closure in the range of 22–28 shocks. Do not remove a moisture content sample.

**Step 3**

Immediately return the soil remaining in the cup to the mixing dish and, without adding any water, repeat steps 1 through 7 of Method A.

**Step 4**

If the second closure occurs in the range of 22–28 shocks and is within two shocks of the first closure, obtain a moisture content sample in accordance with steps 9 and 10 of Method A.

**Note: Groove closures between 15 and 40 blows are acceptable for Method B if variations of  $\pm 5\%$  of the true liquid limit value are tolerable.**

**Calculations****Step 1**

The water content of the soil is calculated to the nearest whole percent as follows:

$$\text{Percentage Moisture} = \frac{\text{Mass of Water}}{\text{Mass of Oven - Dried Soil}} \times 100$$

## Step 2

Calculate the liquid limit.

### Method A

A “flow curve” that represents the relation between moisture content and corresponding number of shocks is plotted on semi-logarithmic graph. The flow curve is a straight line drawn through the three plotted points. The moisture content corresponding to the intersection of the flow curve with the 25-shock ordinate is the liquid limit.

### Method B

The liquid limit is determined by one of the following methods: (1) the nomograph, (2) the correction factor method, or (3) by any other method of calculation that produces equally accurate values.

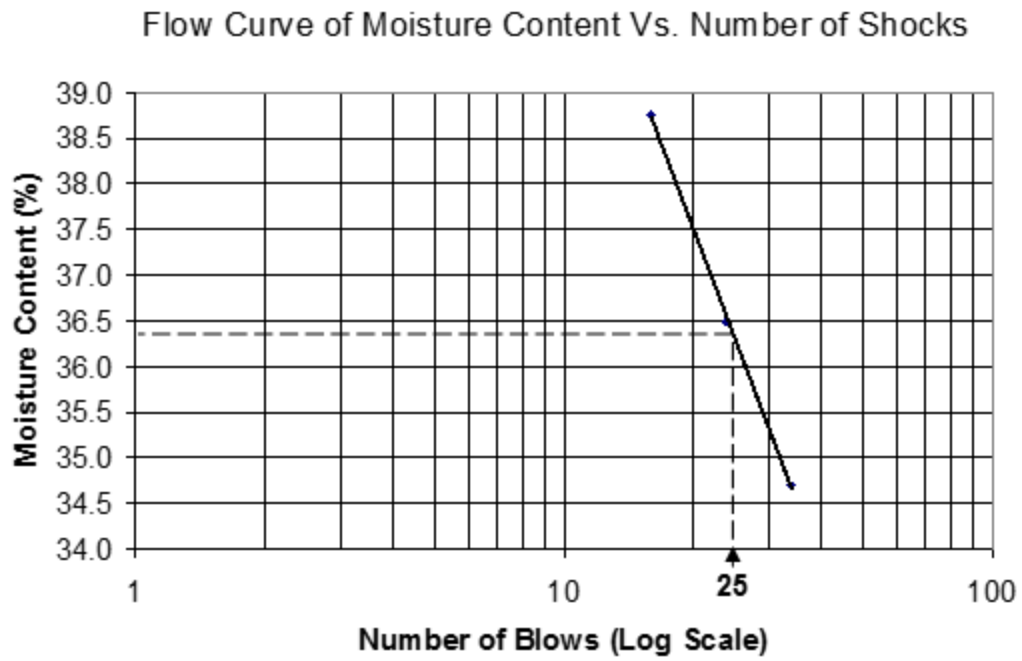
## Example Calculations

Determine the moisture content of each sample.

Container Number	1	2	3
Number of Shocks	27	22	17
Mass of Empty Container (A)	22.59g	23.22g	17.13g
Mass of Container + Wet Soil (B)	29.81g	34.18g	26.26g
Mass of Container + Dry Soil (C)	27.95g	31.25g	23.71g
Mass of Wet Soil (D = B-A)	7.22g	10.96g	9.13g
Mass of Dry Soil (E = C-A)	5.36g	8.03g	6.58g
Moisture Content ([D-E]/E*100)	35%	36%	39%

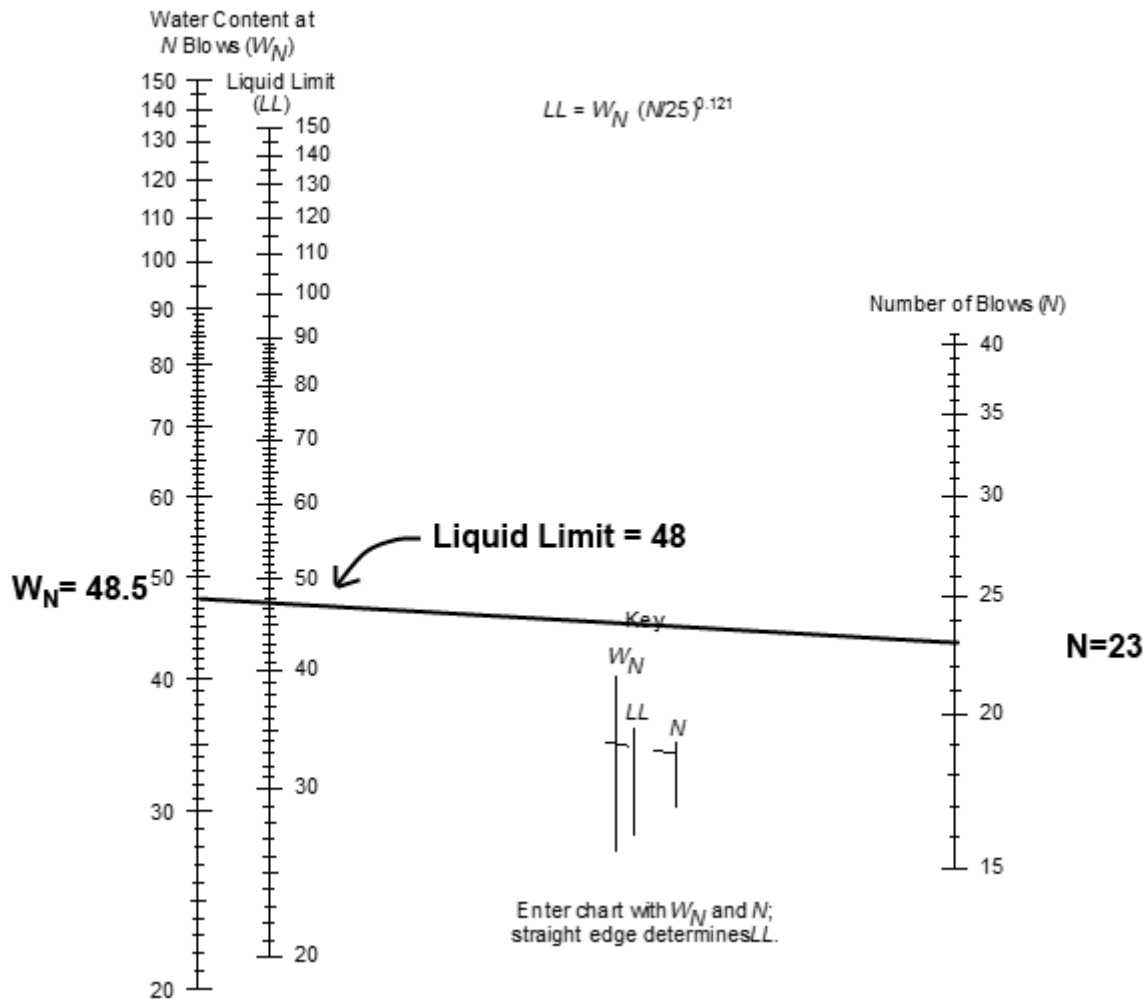
### Method A

Using semi-logarithmic graph paper, plot the moisture contents on the x-axis and the number of shocks on the logarithmic scale. Draw a straight line through the points. The liquid limit is the moisture content corresponding to the intersection of the line at 25 shocks:



## Method B

Refer to AASHTO T 89 for more information. The nomograph method is the easiest way to determine the liquid limit using the one point method. Here is an example of how to use this chart:



## **Reporting the Test Results**

The liquid limit is reported to the nearest whole number.

## **Interpreting and Utilizing the Test Results**

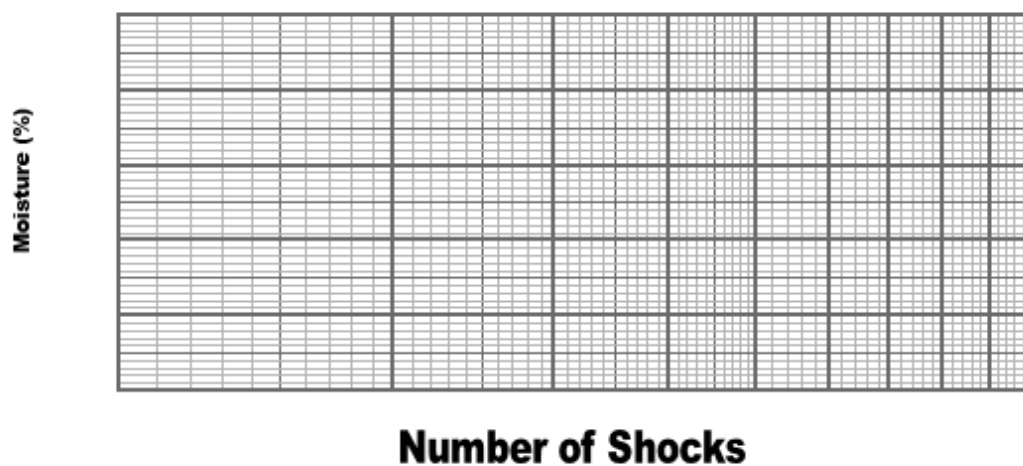
Atterberg limit tests are widely used in the preliminary design stage of structures to ensure that the soil will have an appropriate amount of shear strength and limited change in volume due to expanding and shrinking at different moisture contents.

## **Common Errors**

- Liquid limit device and/or grooving tool is worn.
- Height of liquid limit device not checked before testing.
- Number of shocks does not meet requirements.
- Liquid limit not calculated correctly.

## Data Sheet

	Container Number	1	2	3
	Number of Shocks			
<b>A</b>	Mass of Empty Container (g)			
<b>B</b>	Mass of Container + Wet Soil (g)			
<b>C</b>	Mass of Container + Dry Soil (g)			
<b>D = B - A</b>	Mass of Wet Soil (g)			
<b>E = C - A</b>	Mass of Dry Soil (g)			
<b><math>[(D - E)/E] * 100</math></b>	<b>Moisture Content (%)</b>			





## **AASHTO T 90, Standard Method of Test for Determining the Plastic Limit and Plasticity Index of Soils**

### **Background Information**

The plastic limit of a soil is the lowest water content at which the soil remains plastic. The liquid limit (AASHTO T 89) and plastic limit tests are used to determine the plasticity index of soils, which is used for soil classification purposes. The plasticity index (PI) is a measure of the plasticity of a soil. It is the range in water content within which the material remains in a plastic state. The PI is the difference between the liquid limit and plastic limit.

### **Significance and Use**

The Atterberg limits can be used to distinguish between silt and clay soils. These distinctions are used in assessing soils on which structures are to be built. Soils retain water when wet, and some soils expand in volume. The amount of expansion is dependent on the ability of the soil to absorb water as well as the structural composition of the material itself. Atterberg limit tests are mainly used on clayey or silty soils since these soils react with water by expanding and shrinking. These types of soils also have varying shear strengths depending on water content. The swelling and shrinking process is directly related to shear failure, and the soil is therefore subject to fail in construction processes.

### **History**

Atterberg limits were created by Albert Atterberg (1846–1916), a Swedish chemist and agricultural scientist. In 1932, the Atterberg limits were standardized by Arthur Casagrande (1902–1981), an Austrian-born American civil engineer. The flat Casagrande grooving tool used for the liquid limit test is named after Mr. Casagrande.

### **Related Tests and Specifications**

- AASHTO R 58, Standard Practice for Dry Preparation of Disturbed Soil and Soil-Aggregate Samples for Test
- AASHTO T 89, Standard Method of Test for Determining the Liquid Limit of Soils
- AASHTO T 146, Wet Preparation of Disturbed Soil Samples for Test
- AASHTO T 265, Laboratory Determination of Moisture Content in Soils

### **Timeline for Completion**

Preparation Time: Up to 12 hours

Sample is prepared in accordance with AASHTO R 58 or AASHTO T 146, which requires the sample to be air-dried. Sample is mixed with water and can be tested immediately.

Test Time: 2 hours

The prepared sample is rolled into a thread of uniform diameter in increments until the soil crumbles. The crumbled portions are dried to constant mass.

Calculations: 5 minutes

The percent moisture in the crumbled portions is calculated and reported as the plastic limit. The plasticity index is determined by subtracting the plastic limit from the liquid limit value determined in AASHTO T 89.

Total test time: Up to 14 hours

### **Apparatus**

- Mixing Dish – Made of unglazed porcelain or similar, about 115 mm in diameter.
- Surface for Rolling – Ground glass plate or smooth, unglazed paper.
- Plastic Limit Rolling Device (optional) – As shown in Figure 1 of AASHTO T 90, including unglazed paper that can be attached to the plates of the rolling device.
- Distilled or Demineralized Water
- Moisture Content Containers – Made of corrosion-resistant material with close-fitting lids.
- Balance – Readable to 0.01 g.
- Oven – Maintains  $110 \pm 5$  °C.

### **Sample Preparation**

If only the plastic limit is required, take 20 g of the material passing the 425- $\mu$ m (#40) sieve obtained in accordance with AASHTO R 58 or AASHTO T 146. Place the soil in the mixing dish and mix with enough distilled or demineralized water until the soil can be easily shaped into a ball. Remove an 8-g portion for the test sample.

If both the liquid limit and plastic limit are required, remove an 8-g portion of the wet and mixed soil that was prepared for the liquid limit test in AASHTO T 89. The soil should be easily shaped into a ball without sticking to the fingers. If the soil is too dry, add more water and re-mix.

## Procedure

### Step 1

Select a 1.5 to 2.0 g portion of the 8-g mass of soil obtained above.

### Step 2

Form the small portion of soil into an ellipse.

### Step 3

Roll the soil into a 3-mm diameter thread at a rate of 80–90 strokes per minute by one of the following methods, counting one stroke as a complete forward and back motion:

#### *Hand-Rolling Method*

Roll the soil mass between the palm or fingers and the glass plate or paper until a thread about 3 mm in diameter is formed. This should take no longer than 2 minutes.



*Figure 9: Hand-rolling method*

#### *Rolling Device Method*

Place the soil mass on the bottom plate of the device. Put the top plate in contact with the soil. Roll the top plate back and forth until the plate comes in contact with the side rails. This should take no longer than 2 minutes.

**Note: The pin that holds the cup in place on the liquid limit device is approximately 3 mm in diameter and can be used as a visual guide when rolling the plastic limit specimens to a diameter of 3 mm.**

### Step 4

Break the thread into 6 or 8 pieces.

### Step 5

Squeeze the pieces back into an ellipse and reroll.

**Step 6**

Repeat steps 3 through 5 until the thread crumbles and the soil can no longer be rolled into a thread. Do not attempt to produce failure when the thread is exactly 3 mm in diameter by reducing the rate of rolling and/or hand pressure.

**Step 7**

Place the crumbled portions into a tared container and cover the container.

**Step 8**

Repeat steps 1 through 7 until the entire 8-g mass is tested. Place all crumbled portions in the same container.

**Step 9**

Determine the moisture content of the soil in the container in accordance with AASHTO T 265 and record the results.

**Calculations****Step 1**

The plastic limit (PL) is expressed as the water content of the soil as follows:

$$\text{Plastic Limit} = \frac{\text{Mass of Water}}{\text{Mass of Oven - Dried Soil}} \times 100$$

**Step 2**

Calculate the plasticity index (PI) as follows:

$$\text{Plasticity Index (PI)} = \text{Liquid Limit (LL)} - \text{Plastic Limit (PL)}$$

**Step 3**

If the liquid limit or plastic limit cannot be determined, report the plasticity index as non-plastic (NP).

**Step 4**

When the plastic limit is  $\geq$  the liquid limit, report the plasticity index as NP.

**Example Calculations**

Determine the plastic limit (PL) of the sample:

<b>Container Number</b>	1
<b>Mass of Empty Container (A)</b>	22.59g
<b>Mass of Container + Wet Soil (B)</b>	29.81g
<b>Mass of Container + Dry Soil (C)</b>	27.95g
<b>Mass of Wet Soil (D = B-A)</b>	7.22g
<b>Mass of Dry Soil (E = C-A)</b>	5.36g
<b>Moisture Content <math>([D-E]/E*100)</math></b>	35%

Determine the plasticity index (PI) of the sample. Assume the liquid limit (LL) was determined to be 36 from AASHTO T 89:

$$PI = LL - PL$$

$$PI = 36 - 35$$

$$PI = 1$$

### Reporting the Test Results

The plastic limit and plasticity index are reported to the nearest whole number.

### Interpreting and Utilizing the Test Results

Atterberg limit tests are widely used in the preliminary design stage of structures to ensure that the soil will have an appropriate amount of shear strength and limited change in volume due to expanding and shrinking at different moisture contents.

### Common Errors

- The glass plate does not meet the requirements.
- The sample mass is incorrect.
- The crumbled portions of soil in the container are not covered during testing.
- The entire 8-g sample is not tested.

## Data Sheet

	Container Number	1
<b>A</b>	Mass of Empty Container (g)	
<b>B</b>	Mass of Container + Wet Soil (g)	
<b>C</b>	Mass of Container + Dry Soil (g)	
<b>D = B - A</b>	Mass of Wet Soil (g)	
<b>E = C - A</b>	Mass of Dry Soil (g)	
<b>(D - E)/E*100</b>	<b>Plastic Limit (PL) [%]</b>	

$$PI = LL (\text{ }) - PL (\text{ })$$

$$PI = \text{ }$$

## **AASHTO T 99, Standard Method of Test for Moisture-Density Relations of Soils Using a 2.5-kg (5.5-lb.) Rammer and a 305-mm (12-in.) Drop & AASHTO T 180, Standard Method of Test for Moisture-Density Relation of Soils Using a 4.45-kg (10-lb.) Rammer and a 457-mm (18-in.) Drop**

### **Background Information**

Commonly called the Proctor test, this test procedure is used to determine the relationship between moisture content and the density of compacted soils. From this information, the optimum moisture content, which produces the maximum compacted density is determined. In testing, granular soil is compacted with a standard amount of energy over a range of moisture contents to identify the optimum moisture content for maximum dry density. In other words, the objective of the moisture-density test is to determine the amount of water to add to the soil to ensure that it reaches its maximum strength at a given force of compaction. When the soil in the field is compacted based on the proctor results, it will be able to withstand heavy loads without settling further. Soils are typically at their highest level of stability and strength at their maximum density. AASHTO T 99 and T 180 are essentially the same test procedure. The compactive effort used in AASHTO T 180 is greater than that used in AASHTO T 99. The test procedure was named after Ralph Roscoe Proctor, who discovered the correlation between moisture content and compacted density.

### **Significance and Use**

Field density and moisture values are obtained from the nuclear density gauge (AASHTO T 310) or a sand cone apparatus (AASHTO T 191) and are compared to the results of the Proctor test to determine if an acceptable level of compaction has been achieved.

### **History**

Named after Ralph Roscoe Proctor, who discovered the correlation between moisture content and compacted density.

### **Related Tests and Specifications**

- AASHTO T 191, Density of Soil In-Place by the Sand-Cone Method
- AASHTO T 310, In-Place Density and Moisture Content of Soil and Soil-Aggregate by Nuclear Methods (Shallow Depth)
- AASHTO T 265, Laboratory Determination of Moisture Content of Soils

## Timeline for Completion

Preparation Time: 16 hours

Samples are air-dried, sieved, and a representative portion is obtained based on which method is being performed.

Test Time: 14 hours

Moisture is added to the sample, compacted, trimmed, the mass is determined, and a moisture content is obtained for each of the four points.

Calculations: 30 minutes

The moisture content, wet density, dry density, and a moisture density relationship graph is created. From the graph, the optimum moisture content and maximum density are obtained.

Total Test Time: 30.5 hours

## Apparatus

- Molds – Consisting of a metal cylinder that has solid walls, a detachable collar, and a base plate. Molds can be either 4 or 6 in. in diameter, depending upon the method and material to be utilized in testing.
- Rammer – Either manually or mechanically operated for compacting the soil into the mold. A 5.5-lb. rammer is used for AASHTO T 99, and a 10.5-lb. rammer is used for AASHTO T 180.
- Sample Extruder
- Balances and Scales – One that is readable to 5 g and another that is readable to 0.1 g.
- Drying Oven –  $110 \pm 5$  °C ( $230 \pm 9$  °F).
- Straightedge – Made of hardened steel that is at least 250 mm (10 in.) long, has a beveled edge, and one edge plane to 0.250 m (0.01 in.).
- Sieves – 50 mm (2 in.), 19.0 mm ( $\frac{3}{4}$  in.), and 4.75 mm (#4).
- Mixing Tools
- Containers

## Sample Preparation

Dry the sample, which was obtained from the field, in air or in the oven at a temperature not exceeding 60 °C (140 °F) until it becomes friable. Pulverize the sample without reducing the natural size of the individual particles, and sieve according to Table 7. Discard the coarse



material. Select a representative sample that meets the minimum mass requirements outlined in Table 7. If the oversized particles exceeds 5% by mass, and the specimen is used for field density compaction control, a correction has to be applied in accordance with T224.

*Table 7: Method Determination and Sample Mass Requirements*

Requirements	Method A	Method B	Method C	Method D
<b>Designated Sieve</b>	4.75-mm (#4)		19.0-mm (3/4 inch)	
<b>Max. Allowable % Retained</b>	40	40	30	30
<b>Minimum Sample Mass</b>	3 kg (7 lb.)	7 kg (16 lb.)	5 kg (11 lb.)	11 kg (25 lb.)

## Procedure

### Step 1

Moisten the representative sample with enough water until it is about 4% below optimum moisture content.

### Step 2

Select the appropriate equipment for the testing method:

*T99*

5.5-lb. rammer, 12 in. drop, three layers, mold size and particle size in Table 8: Mold Size, Particle Size, and Number of Blows for Method A, B, C, and D.

*AASHTO T 180*

10.5-lb. rammer, 18 in. drop, five layers, mold size and particle size in Table 8: Mold Size, Particle Size, and Number of Blows for Method A, B, C, and D.

*Table 8: Mold Size, Particle Size, and Number of Blows for Method A, B, C, and D*

Methods	Mold Size	Particle Size	Number of Blows
<b>Method A</b>	4 in.	- #4	25
<b>Method B</b>	6 in.	- #4	56
<b>Method C</b>	4 in.	- ¾ in.	25
<b>Method D</b>	6 in.	- ¾ in.	56

**Step 3**

Obtain the mass of the mold and baseplate (B).

**Step 4**

A layer of soil is placed in mold and the soil is lightly tamped down with a manual rammer or a 2-in. diameter similar device.

**Step 5**

Compact the soil into the mold with appropriate number of blows for the method selected, as described in Table 8: Mold Size, Particle Size, and Number of Blows for Method A, B, C, and D.

**Step 6**

After each of the first two (T 99) or four (T 180) layers, the excess soil is to be trimmed and evenly distributed over the surface of the layer.

**Step 7**

After the final layer is compacted, the collar is to be removed and the soil is to be trimmed to the top of the mold with the straightedge.

**Step 8**

Only for Method C and D, fill in any holes that develop during trimming with unused or trimmed soil.

**Step 9**

Obtain the mass of the mold and contents (A) to the nearest 5 g (0.01 lb.) and calculate the wet-density (W1).

**Step 10**

The soil is removed from the mold using the sample extruder, the sample is sliced vertically through the center, and the moisture sample (100 g for Method A or B and 500 g for Method C and D) is obtained from one of the cut faces (as show is Figure 10: Moisture Content Area Illustration) and weighed immediately.

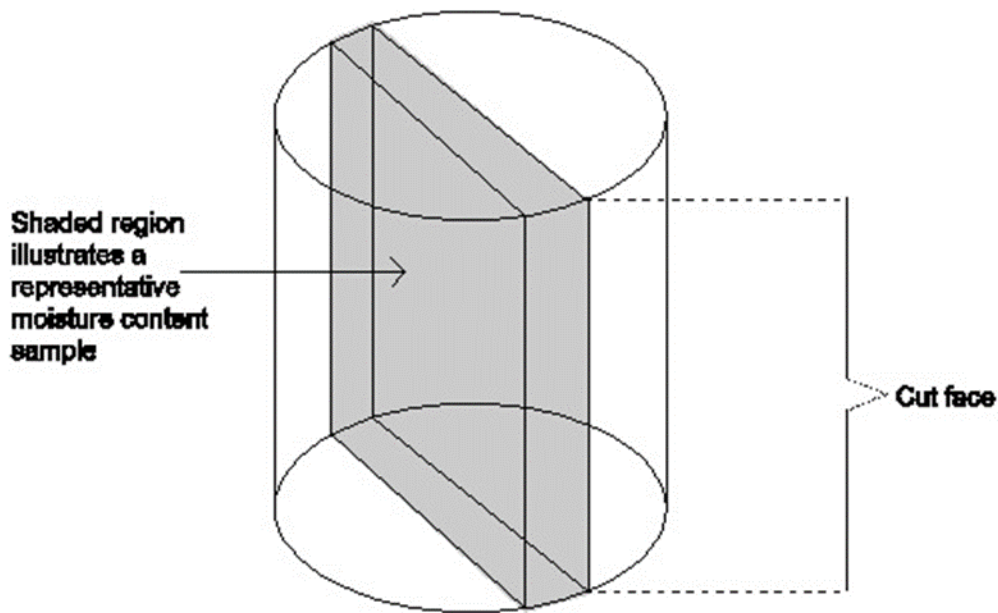


Figure 10: Moisture Content Area Illustration

#### Step 11

The remaining soil is then pulverized so it can pass a 4.75-mm (#4 sieve), recombine the soil, and increase the water content by 1–2%.

**Note: Water content increments should not exceed 2.5% except in the cases where heavy clay or organic soils exhibiting flat, elongated curves are encountered. In these cases, a maximum water content increment shall not exceed 4%.**

#### Step 12

If the soil is fragile or a heavy-textured clayey material, a new sample has to be obtained for each point.

- These samples are mixed with water varying approximately 2% from point to point
- The moisture content of the points will bracket the optimum moisture content such that two of the points are below optimum, two are above optimum, and one sample is near optimum.
- These samples shall be placed in a covered container and allowed to sit for at least 12 hours.

#### Step 13

Steps 3 through 12 are repeated for each increment of water until the wet unit mass either decreases or stabilizes.

## Calculations

### Step 1

The moisture content (w) has to be calculated in accordance of T 265.

$$w = \frac{\text{mass of water}}{\text{mass of oven dried soil}}$$

### Step 2

The mold factor (F) can be related to the volume (V) as follows:

$$F = \frac{1}{V}$$

### Step 3

Determine the wet-density using the mold factor (F) or volume (V); mass of compacted specimen and mold (A); and mass of mold (B).

$$W_1 = (A - B) * F \text{ or } W_1 = \frac{(A - B)}{V}$$

### Step 4

The dry density (W) is then related to the wet density using the moisture content (w, in percent).

$$W = \frac{W_1}{w + 100} * 100$$

## Example Calculations

Method: A

Optimum Moisture Content: 10%

Max. Dry Density: 128 lbf/ft<sup>3</sup>

Point #	1	2	3	4	5
Mold ID	3	3	3	3	3
Volume of Mold (V)	0.0009394m <sup>3</sup>	0.0009394 m <sup>3</sup>	0.0009394 m <sup>3</sup>	0.0009394 m <sup>3</sup>	0.0009394 m <sup>3</sup>
Mass of Mold (B)	2,013.4g	2,013.4g	2,013.4g	2,013.4g	2,013.4g
Mass of Mold & Specimen (A)	3,945.4g	4,036.1g	4,137.8g	4,092.2g	4,038.8g
Mass of Specimen (M <sub>g</sub> )	1,932.0g	2,022.7g	2,124.4g	2,078.8g	2,025.4g
Mass of Specimen (M <sub>lb</sub> ) [M/453.6]	4.2593lb.	4.4592 lb.	4.6834 lb.	4.5829 lb.	4.4652 lb.
Wet Density (W <sub>1</sub> )	128.39 lbf/ft <sup>3</sup>	134.42 lbf/ft <sup>3</sup>	141.17 lbf/ft <sup>3</sup>	138.14 lbf/ft <sup>3</sup>	134.60 lbf/ft <sup>3</sup>
Dry Density (W)	-kg/m <sup>3</sup>	-kg/m <sup>3</sup>	-kg/m <sup>3</sup>	-kg/m <sup>3</sup>	-kg/m <sup>3</sup>
Dry Density (W <sub>lb</sub> )	120.63 lbf/ft <sup>3</sup>	124.19 lbf/ft <sup>3</sup>	128.06 lbf/ft <sup>3</sup>	122.88 lbf/ft <sup>3</sup>	117.57 lbf/ft <sup>3</sup>
Dry Unit Weight (Y) (W*62.43)	-	-	-	-	-

Point #	1	2	3	4	5
Mold ID	3	3	3	3	3
Mass of Container & Lid (C)	34.93g	35.53g	83.45g	83.36g	44.62g
Mass of Container, Lid, & Wet Specimen (D)	135.71g	170.24g	323.71g	261.02g	219.46g
Mass of Container, Lid, & Dry Specimen (E)	129.62g	159.99g	301.39g	241.39g	197.34g
Mass of Water (F) [D-E]	6.09g	10.25g	22.32g	19.63g	22.12g
Mass of Dry Sample (G) [E-C]	94.69g	124.46g	217.94g	158.03g	152.72g
Percent Water Content (w)	6.43%	8.24%	10.24%	12.42%	14.48%

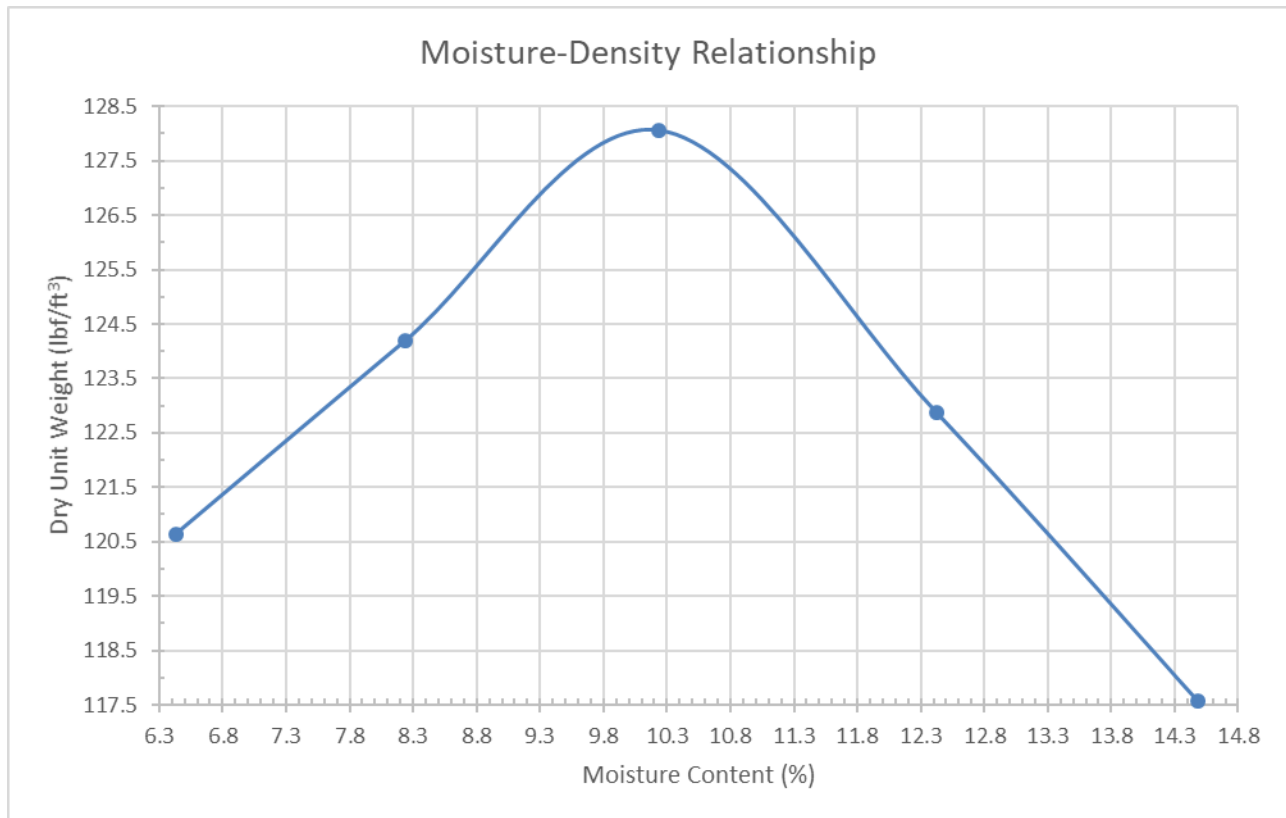


Figure 11: Moisture-Density Relationship (with the black line showing the maximum dry unit weight and optimum moisture content with the black lines)

**Note:** Be sure to carefully watch the units and to make corrections as needed. Most masses are gathered in grams, but kg or lbs. may also be used in the calculations.

### Reporting the Test Results

Report the following:

1. The method used.
2. The optimum moisture content, as a percentage, to the nearest whole number.
3. The maximum dry density in either kg/m<sup>3</sup> to the nearest 10 kg/m<sup>3</sup> or in lb/ft<sup>3</sup> to the nearest whole number.

### Interpreting and Utilizing the Test Results

Figure 11, the line starting at the peak of the curve and intersecting the vertical axis is the point at which the sample is at its maximum dry density. The line starting at the peak of the curve and intersecting the horizontal axis is the point at which the sample is at its optimum moisture

content. This information is used to correlate optimum conditions with actual field conditions. This information is compared by an engineer to figure out the percent compacted that the field is compared to the laboratory data.

**Common Errors**

- Not lightly tamping the soil before compaction.
- Not trimming between layers during compaction.
- Not obtaining the moisture content from the correct area of the sample, which includes all three (Method A/B) or five (Method C/D) layers, edge to edge.
- Mixing up the units during calculation.

## Data Sheets

Name: \_\_\_\_\_

Date: \_\_\_\_\_

Method: \_\_\_\_\_

Optimum Moisture Content: \_\_\_\_\_

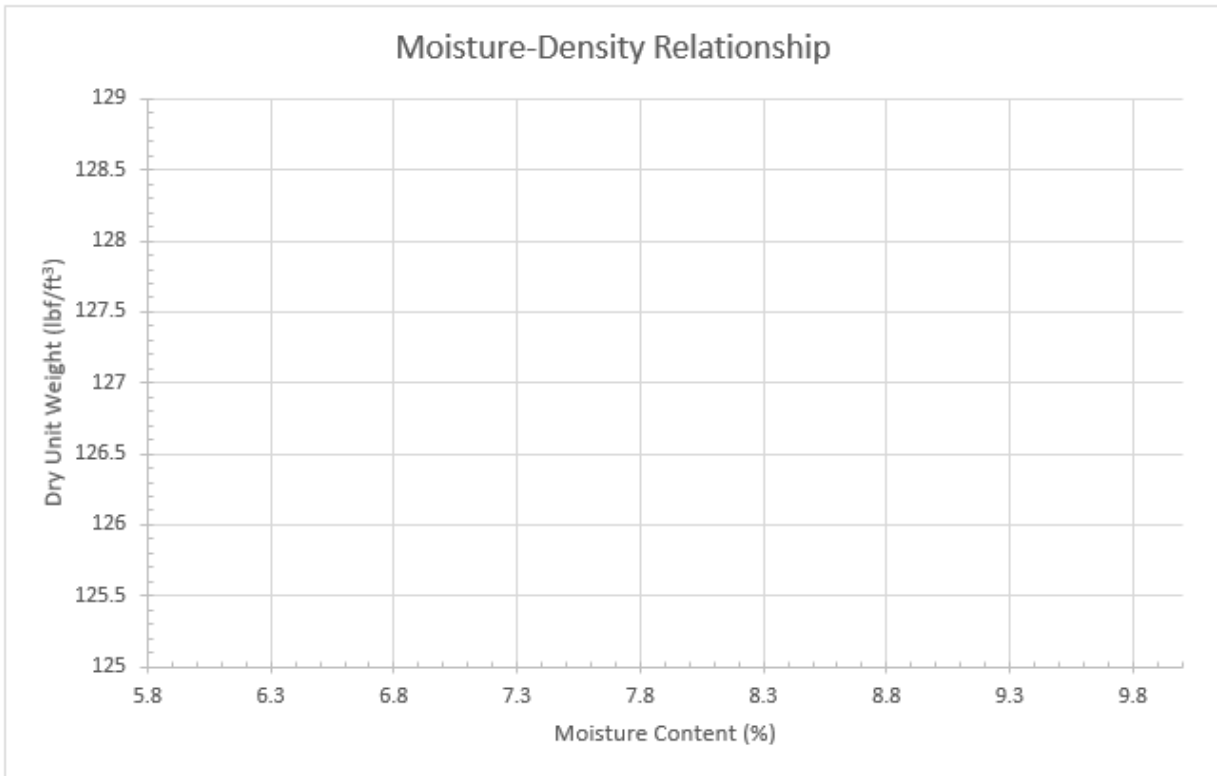
Max. Dry Density: \_\_\_\_\_

Type of Face: \_\_\_\_\_

	Point #	1	2	3	4	5	6
	Mold ID						
V	Volume of Mold (m <sup>3</sup> )						
B	Mass of Mold (g)						
A	Mass of Mold & Specimen (g)						
M <sub>g</sub>	Mass of Specimen (g)						
M <sub>lb</sub>	Mass of Specimen (lb.) [M/453.6]						
W <sub>1</sub>	Wet Density (kg/m <sup>3</sup> )						
W	Dry Density (kg/m <sup>3</sup> )						
W <sub>lb</sub>	Dry Density (lb/ft <sup>3</sup> )						
Y	Dry Unit Weight (W*62.43)						

	Point #	1	2	3	4	5	6
	Container ID						
C	Mass of Container & Lid (g)						
D	Mass of Container, Lid, & Wet Specimen (g)						
E	Mass of Container, Lid, & Dry Specimen (g)						
F	Mass of Water (g) [D-E]						
G	Mass of Dry Sample (g) [E-C]						
w	Percent Water Content (%)						





## **AASHTO T 100, Standard Method of Test for Specific Gravity of Soils**

### **Background Information**

This test method covers the determination of the specific gravity of soils using a volumetric flask for material passing a 4.75-mm (#4) sieve. The specific gravity is the ratio of the mass of a unit of volume of a material with a stated temperature to the mass of the same volume of gas-free distilled water at a stated temperature.

### **Significance and Use**

The specific gravity of soil is used in most equations expressing the phase relationship between air, water, and solids in a known volume of material.

### **Related Tests and Specifications**

- AASHTO M 92, Standard Specification for Wire-Cloth Sieves for Testing Purposes
- AASHTO M 145, Classification of Soils and Soil-Aggregate Mixtures for Highway Construction Purposes
- AASHTO M 146, Standard Specification for Terms Relating to Subgrade, Soil-Aggregate, and Fill Materials
- AASHTO M 231, Weighing Devices Used in the Testing of Materials
- AASHTO T 85, Specific Gravity and Absorption of Coarse Aggregate
- AASHTO T 88, Standard Method of Test for Particle Size Analysis of Soils

### **Timeline for Completion**

Preparation Time: 12 hours

Samples are prepped in accordance with the test method in a natural moisture condition or an oven-dry condition. Sample preparation varies depending on whether it is a fine-grained soil or coarse-grained soil.

Test Time: 2–20 hours

The samples are placed in the volumetric flask or bottle and de-aired by vacuuming or boiling.

The flask or bottle is then filled to calibrated capacity, cleaned, and dried. The mass and temperature of the contents is determined.

Calculations: 5 minutes

The specific gravity is calculated using a software program, spreadsheet, or by hand from the equations in T 100. The value is reported with the temperature corrected to 20 °C.

Total Test Time: 14-32 hours

### Apparatus

- Balance – Readable to 0.01 g for use with the volumetric flask, readable to 0.001 g for use with the stoppered bottle.
- Oven – A thermostatically controlled drying oven capable of maintaining a temperature of  $110 \pm 5$  °C ( $230 \pm 9$  °F).
- Thermometer – Capable of measuring the temperature within the testing range to 0.5 °C (1 °F).
- Volumetric Flask – Either a volumetric flask with at least 100 mL capacity or a stoppered bottle having a capacity of at least 50 mL (Figure 12). The stopper should be of the same material as the bottle and of such a size that it can be easily inserted to a fixed depth in the neck of the bottle. The stopper should be equipped with a small center hole to permit the emission of air and surplus water.



Figure 12: A 100 mL flask and stoppered bottle

### Volumetric Flask and Stoppered Bottle Calibration

Prior to testing, the volumetric flask or bottle must be calibrated. The calibrated weight of the volumetric flask or bottle is determined by filling the container to its calibrated capacity with distilled water and recording the mass. Calibration should be conducted using distilled water at anticipated ranges of temperatures likely to prevail during laboratory testing. For the volumetric flask, the calibration mark is usually a white line mid-way up the neck. The volumetric flask should be filled until the bottom of the meniscus reaches the line. For stoppered bottles, the bottle is filled to capacity and stoppered allowing the excess water to

overflow. Masses are determined to 0.01 g for the volumetric flask and 0.001 g for the stoppered bottle.

### **Sample Preparation**

Samples are obtained from material passing the 4.75-mm (#4) sieve or the 2.36-mm (#10) sieve if the specific gravity is being determined for use with AASHTO T 88, Standard Method of Test for Particle Size Analysis of Soils. The soil samples must be in a natural moisture condition or oven dried prior to the test.

Non-clayey samples containing natural moisture are split or quartered to a size that will yield a minimum of 25 g for a volumetric flask or 10 g for a stoppered bottle of dry material, minus the anticipated moisture weight.

Clayey samples containing natural moisture are selected in the same way and then prepped according to T 88 by soaking the soil in a sodium hexametaphosphate solution for a minimum of 12 hours prior to dispersing them to separate the clays to individual particle size.

Oven-dry samples are selected in the same way and dried at  $110 \pm 5$  °C ( $230 \pm 9$  °F) prior to testing for at least 12 hours, or to constant mass.

### **Procedure**

#### **Step 1**

If using an oven dried sample, record the dry mass of the material. Samples containing natural moisture will be dried to constant mass at the conclusion of the test and weighed.

#### **Step 2**

The prepared samples are placed into the volumetric flask or bottle and covered to a maximum of  $\frac{3}{4}$  full for the volumetric flask or half full for the bottle.

#### **Step 3**

Remove the air from the volumetric flask or bottle. This can be accomplished using the following methods:

- a. Vacuum the volumetric flask or bottle at less than 100 mm Hg absolute pressure while occasionally agitating the sample. High plasticity samples may require 6 to 8 hours to release air, while low plasticity soils may require 4 to 6 hours.
- b. Boil the volumetric flask or bottle for a minimum of 10 minutes while occasionally agitating the sample.

**Note:** If using a stoppered bottle and performing the boiling method, the stopper must be removed prior to applying heat. Also, boil the samples gently. Volumetric flasks can boil over, resulting in a loss of material. Bottles are susceptible to breaking under a heavy boil as they are very thin and the pressure build up can fracture the glass.

**Step 4**

If the samples were boiled, let them cool to room temperature for 1 hour before continuing the test.

**Step 5**

Fill the volumetric flask or stoppered bottle to its calibrated capacity.

**Step 6**

Make sure the outside of the volumetric flask or stoppered bottle is cleaned and dried. If using a volumetric flask, roll up a paper towel and clean the neck (Figure 13).



*Figure 13: Cleaning the neck of the volumetric flask*

**Step 7**

Determine the mass of the volumetric flask or stoppered bottle. Masses are determined to 0.01 g for the volumetric flask and 0.001 g for the stoppered bottle.

**Step 8**

Record the temperature of the contents of the volumetric flask or bottle.

**Step 9**

If the sample contained natural moisture, pour the contents into a pan, making sure to rinse all the particles out of the volumetric flask or bottle and dry them to constant mass in an oven at  $110 \pm 5$  °C ( $230 \pm 9$  °F). At the conclusion, allow the samples to cool to room temperature and determine the dry mass of the material.

**Calculations****Step 1**

Specific gravity values are reported based on water at 20 °C unless otherwise specified. The temperature determined in the laboratory is corrected using a “K” constant given in Table 9. The K value is found by dividing the relative density of water at temperature  $T_x$  by the relative density of water at 20.0 °C.

*Table 9 “K” Constants*

Temperature in °C	Relative Density of Water	Correction Factor <i>K</i>
18	0.9986244	1.0004
19	0.9984347	1.0002
20	0.9982343	1.0000
21	0.9980233	0.9998
22	0.9978019	0.9996
23	0.9975702	0.9993
24	0.9973286	0.9991
25	0.9970770	0.9989
26	0.9968156	0.9986
27	0.9965451	0.9983
28	0.9962652	0.9980
29	0.9959761	0.9977
30	0.9956780	0.9974

**Step 2**

Calculate soil specific gravity, based on water temperature  $T_x$ , as follows:

$$\text{Specific gravity, } T_x/T_x = \frac{W_o}{[W_o + (W_a - W_b)]}$$

Where:

- $T_x$  = temperature of the contents of the pycnometer when mass  $W_b$  was determined, in degrees Celsius
- $W_o$  = mass of sample of oven-dried soil in grams
- $W_a$  = mass of pycnometer filled with water at temperature  $T_x$ , in grams
- $W_b$  = mass of pycnometer filled with water and soil at temperature  $T_x$ , in grams

### Step 3

Calculate soil specific gravity, based on water at 20 °C, as follows:

$$\text{Specific gravity } T_x / 20^\circ\text{C} = K \times \text{Specific gravity, } T_x/T_x$$

### Example Calculations

$$T_x = 26.1^\circ\text{C}$$

$$W_o = 24.89 \text{ g}$$

$$W_a = 351.53 \text{ g}$$

$$W_b = 367.15 \text{ g}$$

$$\text{Specific gravity, } T_x/T_x = 24.89/[24.89 + (351.53 - 367.15)]$$

$$\text{Specific gravity, } T_x/T_x = 2.685$$

$$\text{Specific gravity } T_x/20^\circ\text{C} = 0.9986 \times 2.685$$

$$\text{Specific gravity } T_x/20^\circ\text{C} = 2.681$$

### Reporting the Test Results

Specific gravity is calculated to the nearest 0.01 for volumetric flasks and 0.001 for stoppered bottles.

**Data Sheets**

$T_x$ (temperature of pycnometer contents, °C)	
$W_o$ (mass of sample of oven-dried soil, grams)	
$W_a$ (mass of pycnometer filled with water, grams)	
$W_b$ (mass of pycnometer filled with water and soil, grams)	
K value (taken from Table 9)	



## **AASHTO T 208, Standard Method of Test for Unconfined Compressive Strength of Cohesive Soil**

### **Background Information**

This test method covers the determination of the unconfined compressive strength of cohesive soil in the undisturbed, remolded, or compacted condition, using strain-controlled application of the axial load and provides an approximate value of the strength of cohesive soils in terms of total stresses.

### **Significance and Use**

The primary purpose of the unconfined compression test is to quickly obtain the approximate compressive strength of soils that possess sufficient cohesion to permit testing in the unconfined state.

### **Related Tests and Specifications**

- AASHTO T 89, Standard Method of Test for Determining the Liquid Limit of Soils
- AASHTO T 90, Standard Method of Test for Determining the Plastic Limit and Plasticity Index of Soils
- AASHTO T 100, Standard Method of Test for Specific Gravity of Soils
- AASHTO T 207, Standard Method of Test for Thin-Walled Tube Sampling of Soils
- AASHTO T 265, Laboratory Determination of Moisture Content of Soils
- AASHTO T 296, Standard Method of Test for Unconsolidated, Undrained Compressive Strength of Cohesive Soils in Triaxial Compression

### **Timeline for Completion**

Preparation Time: 30 minutes to 1 hour

The undisturbed, remolded, or compacted specimen must be extruded or compacted, trimmed, and measured in accordance with Section 6 of the standard.

Test Time: 15 minutes

Sample is loaded into the compression device, the deformation indicator is zeroed, and an axial strain of 0.5 to 2% per minute is applied until the specimen fails in axial compression or 15% strain is reached. Then, moisture content is performed and a photo is taken.

Calculations: Commonly, calculations are performed concurrently with testing using computer software.

### Apparatus

- Compression Device
- Deformation Indicator – Such as a dial indicator or linear variable differential transformer (LVDT), graduated to 0.02 mm (0.001 in.) or better.
- Dial Comparator – Or other suitable device for measuring the physical dimensions of the specimen to within 0.1% of the measured dimension.

**Note: Vernier calipers are not recommended for soft specimens, which will deform as the calipers are set on the specimen.**

- Timer – A timing device readable to the nearest second.
- Balance
- Other Equipment – Equipment for determining the moisture content as specified in AASHTO T 265, specimen carving and trimming tools, remolding apparatus, etc.

### Sample Preparation

Undisturbed Specimens – Prepare undisturbed specimens from large undisturbed samples or from samples secured in accordance with T 207.

Remolded Specimens – Specimens may be prepared either from a failed undisturbed specimen or from a disturbed sample, providing it is representative of the failed undisturbed specimen.

Compacted Specimens – Specimens shall be prepared to the predetermined water content and density prescribed by the individual assigning the test.

### Procedure

#### Step 1

Place the specimen in the loading device centered on the bottom platen. Adjust the loading device so that the upper platen just makes contact with the specimen.

#### Step 2

Zero the deformation indicator.

#### Step 3

Apply the load to produce an axial strain at a rate of 0.5 to 2% per minute. The rate should be chosen so that the time to failure does not exceed about 15 minutes.

**Step 4**

Record load, deformation, and time values at sufficient intervals to define the stress-strain curve (usually 10 to 15 points are sufficient when recording the data manually).

**Step 5**

Continue loading until the load values decrease with increasing strain, or until 15% strain is reached.

**Note: Softer materials that will exhibit larger deformation at failure should be tested at a higher rate of strain. Conversely, stiff or brittle materials that will exhibit small deformations at failure should be tested at a lower rate of strain.**

**Step 6**

Make a sketch or take a photo of the specimen showing the slope angle of the failure surface if the angle is measurable.

**Step 7**

Determine the moisture content of the specimen according to AASHTO T 265.

**Calculations****Step 1**

Calculate the axial strain to the nearest 0.1% for a given applied load:

$$\text{axial strain} = \frac{\text{length change of specimen}}{\text{initial length of specimen}}$$

**Step 2**

Calculate the average cross-sectional area for a given applied load:

$$\text{Average cross-sectional area} = \frac{\text{initial average cross-sectional area}}{(1 - \text{axial strain for given load as \%})}$$

**Step 3**

Calculate the compress stress to three significant figures, or nearest 1 kPa (0.01 ton/ft<sup>2</sup>), for a given applied load:

$$\text{Compressive stress (kPa)} = \frac{1000 * \text{given applied load (N)}}{\text{average cross-sectional area (m}^2\text{)}}$$

**Step 4**

Graph the relationship between compressive stress and axial strain. Report the maximum value of compressive stress, or the compressive stress at 15% axial strain, whichever is secured first, and report it as the unconfined compressive strength.

**Reporting the Test Results**

Report the following information:

1. The identification information for the sample including soil classification, symbol, type of specimen (undisturbed, remolded, compacted, etc.), project number, location, boring number, sample number, depth, etc.
2. Initial dry density, water content, and degree of saturation (if computed).
3. Unconfined compressive strength and shear strength.
4. Average height and diameter of specimen, height-to-diameter ratio.
5. Average rate of strain to failure and strain at failure.
6. Failure sketch or photo (Figure 14).
7. Stress-strain graph (Figure 15).
8. If determined, report sensitivity value.
9. Remarks noting any unusual conditions or sample issues, such as shells or pebbles.



Figure 14: Photo of a failed T 208 specimen

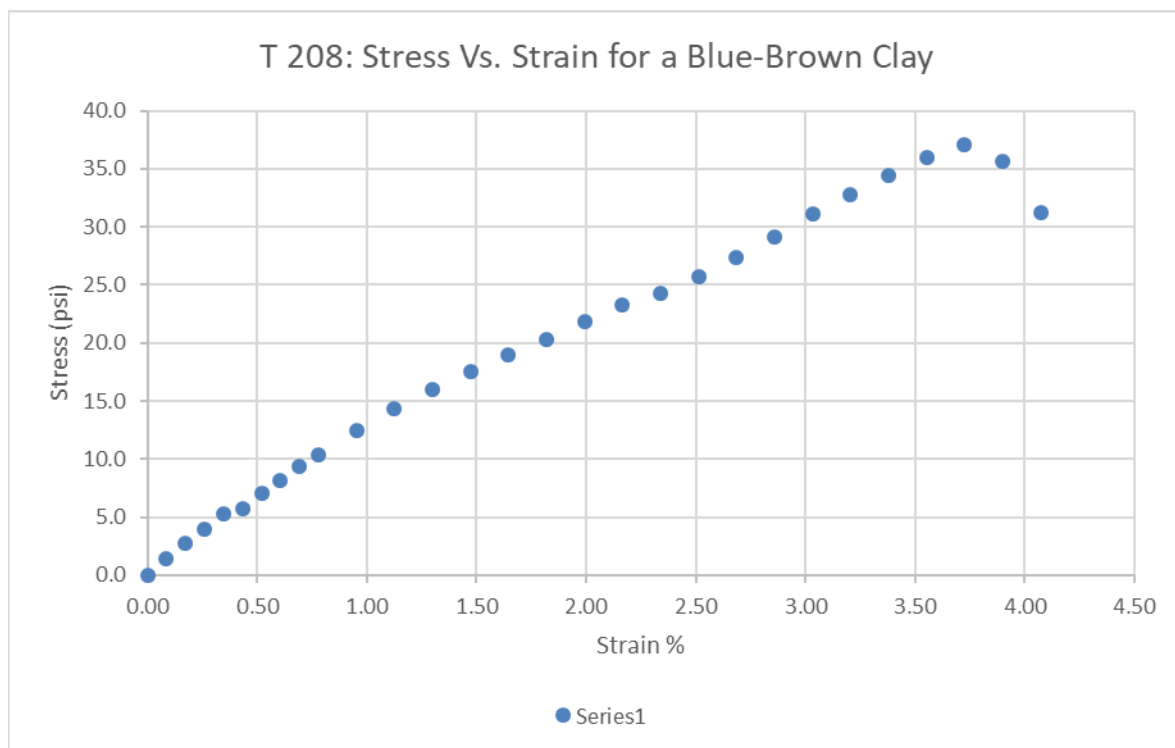


Figure 15: Stress-Strain Diagram for T 208 Compressive Strength of Soil

## **Interpreting and Utilizing the Test Results**

The compressive strength value obtained from this test is typically a low estimate of a material's strength (as seen Figure 15). If this conservative estimate of strength is not sufficient for the proposed project, the results of this test can be used to determine which areas should be subjected to more detailed testing.

## **Common Errors**

- Tube samples must be prepared with care to ensure that they yield data that is representative of the material being tested. The samples should be trimmed carefully to ensure the sample has a uniform cross-sectional area, ends that are flat and perpendicular to the sides, and that the moisture content does not change during trimming.

## Data Sheets

Technician name		Date	
Job number		Location	
Boring number		Sample number	
Description of sample		Optimum Moisture %	

Moisture content	Before testing	After testing	Optional
Tare #			
Wet soil + tare + lid	(g)	(g)	(g)
Dry soil + tare + lid	(g)	(g)	(g)
Tare + lid	(g)	(g)	(g)
Moisture Content	%	%	%

Specimen diameter	At 1/4 height	At 1/2 height	At 3/4 height
Diameter 1	(mm)	(mm)	(mm)
Diameter 2	(mm)	(mm)	(mm)
Diameter 3	(mm)	(mm)	(mm)
Average diameter	(mm)		

Specimen height	At 0° rotation	At 120° rotation	At 240° rotation
Height	(mm)	(mm)	(mm)
Average height	(mm)		
0.5% axial strain / min.	(mm/min.)	2% axial strain / min.	(mm/min.)
Sample mass before testing	(g)		

Strain rate selected for testing:

Reading	Load dial	Strain dial	Reading	Load dial	Strain dial
0			12		
1			13		
2			14		
3			15		
4			16		
5			17		
6			18		
7			19		
8			20		
9			21		
10			22		
11			23		

## **AASHTO T 216, Standard Method of Test for One-Dimensional Consolidation Properties of Soils**

### **Background Information**

When buildings, foundations, or embankments are placed on soil, a degree of settlement will take place. This settlement occurs through a process referred to as consolidation. During consolidation, the water is slowly forced out of the soil by applied external loads, leading to a reduction in the void ratio of the soil. During consolidation, the pore water pressure decreases and the effective stress within the soil increases. The rate the soil consolidates is based on the change on volume, or compressibility, and the ease with which water is able to flow through the soil structure.

### **Significance and Use**

The consolidation test (also known as the oedometer test) is performed by subjecting the soil specimen to a series of constant-stress loads. The deformation of the soil specimen is measured. A soil consolidation test is considered one-dimensional, because the sample is placed in a metal ring that prevents soil movement to the sides. Pressure is applied axially to simulate the load placed on soil from an embankment, foundation, or building. Drainage of the specimen is permitted during the test. In the real world, it is important to know how much a particular soil will settle, either when subjected to a certain load or after a certain period of time.

Another factor evaluated by the consolidation test is the amount of swelling or rebound that can occur if the load is removed. If construction occurs on soils that contain a high level of moisture, the soil can swell if the load has not fully compressed the soil. Swelling of the soil could damage foundations and structures, so it is important to understand the soil behavior if loads are added or removed.

### **Related Tests and Specifications**

- AASHTO T 88, Standard Method of Test for Particle Size Analysis of Soils
- AASHTO T 89, Standard Method of Test for Determining the Liquid Limit of Soils
- AASHTO T 90, Standard Method of Test for Determining the Plastic Limit and Plasticity Index of Soils
- AASHTO T 100, Standard Method of Test for Specific Gravity of Soils
- AASHTO T 207, Standard Method of Test for Thin-Walled Tube Sampling of Soils
- AASHTO T 265, Laboratory Determination of Moisture Content of Soils



## Timeline for Completion

Preparation Time: 30 minutes to 1 hour

Specimens may originate from sampling tubes, undisturbed block samples, or by remolding specimens in the laboratory to specific conditions. Specimens must be trimmed carefully and loaded into the consolidometer.

Test Time: 24 hours to 14 days

Specimens are subjected to an initial seating load and then to increments of total stress. The duration of the test will vary significantly depending on the soil characteristics and desired loading schedule.

Calculations (typically completed using computer software):

Dry mass, water content, dry unit weight, volume of solids, void ratio, degree of saturation, and coefficient of consolidation are determined. In addition, time-deformation curves are generated using either the log of time or the square root of time.

Total Test Time: 1 day to 14 days

## Apparatus

- Loading Device – A suitable device for applying vertical loads or total stresses to the specimen.

**Note: Most loading devices use pneumatic pressure or dead weights to apply the desired load.**

The device should be capable of maintaining specified loads for long periods of time and should permit quick application of a given load increment without significant impact.

Load Application: Quick application of the load is important. For machines that use dead weights, it is sometimes necessary to combine several different weights to achieve the desired test load. Many consolidometers are equipped with a mechanical means to hold the loading arm stationary while weights are added or removed.

- Consolidometer – A device to hold the specimen in a ring that is either fixed to the base or floating with porous disks on each face of the specimen.
- Porous Disks – Made of silicon carbide, aluminum oxide, or similar noncorrosive material. The grade of the disks shall be fine enough to prevent intrusion of soil into the pores. If necessary, a filter paper may be used to prevent intrusion of the soil into the disks.

- Specimen Trimming Device – A trimming turntable or a cylindrical cutting ring for trimming the sample down to the inside diameter of the consolidometer ring with a minimum of disturbance.
- Deformation Indicator – To measure change in specimen height.
- Timing Device – With 1-second readability.
- Miscellaneous Materials and Supplies – Distilled or demineralized water, spatulas, knives, and wire saws, used in preparing the specimen.
- Balance, Drying Oven, and Water Content Containers – As described in AASHTO T 265.

## Sampling

AASHTO T 207 covers procedures and apparatus that may be used to obtain undisturbed samples generally satisfactory for testing. Specimens may also be trimmed from large undisturbed block samples fabricated and sealed in the field. Finally, remolded specimens may be prepared from bulk samples to density and moisture conditions stipulated by the agency requesting the test.

Selecting Test Specimens: The quality of consolidation test results diminishes greatly with sample disturbance. Careful examination of the sample is essential in the selection of specimens for testing.

## Specimen Preparation

1. All possible precautions should be taken to minimize disturbance of the soil or changes in moisture and density during specimen preparation. Avoid vibration, distortion, and compression.
2. Prepare test specimens in an environment where soil moisture change during preparation is minimized.
3. Trim the specimen and insert it into the consolidation ring.
4. Trim the specimen flush with the plane ends of the ring. At no time should the specimen extend beyond the specimen ring or extension collar.
5. Determine the initial wet mass of the specimen,  $M_{To}$ , in the consolidation ring by measuring the mass of the ring with the specimen and subtracting the mass of the ring.
6. Determine the initial height,  $H_o$ , of the specimen to the nearest 0.025 mm (0.001 in.) by taking the average of at least four evenly spaced measurements over the top and bottom surfaces of the specimen.

7. Compute the initial volume,  $V_o$ , of the specimen to the nearest 0.25 cm<sup>3</sup> (0.015 in.<sup>3</sup>) from the diameter of the ring and the initial specimen height.
8. Obtain two or three natural water content determinations of the soil in accordance with T 265 from material trimmed adjacent to the test specimen, if sufficient material is available.
9. When index properties are specified by the requesting agency, store the remaining trimmings taken from the specimen and determined to be similar material in a sealed container.

### Soil Index Property Determinations

The determination of index properties is an important addition to, but not a requirement of, the consolidation test. These determinations should be made on the most representative material possible.

**Note: Changes to the moisture content of the specimen shall be minimized. A high-humidity environment is typically used when trimming samples.**

**Specific Gravity** – The specific gravity shall be determined in accordance with T 100.

**Note: Fibrous soils, such as peat, and those soils that are easily damaged by trimming, may be transferred directly from the sampling tube to the ring, provided the ring has the same diameter as the sample tube.**

Specimens obtained using a ring-lined sampler may be used without prior trimming, provided they comply with the requirements of ASTM D3550 and this test method.

**Atterberg Limits** – The liquid limit shall be determined in accordance with T 89. The plastic limit and plasticity index shall be determined in accordance with T 90.

**Particle-Sized Distribution** – The particle-sized distribution shall be determined in accordance with T 88. A particle-sized analysis may be helpful when visual inspection indicates that the specimen contains a substantial fraction of coarse-grained material.

### Procedure

#### Step 1

Dry, porous disks and filters must be used with dry, highly expansive soils. Damp disks may be used for partially saturated soils. Saturated disks may be used when the specimen is saturated

and known to have a low affinity for water. Assemble the ring with specimen, porous disks, filter disks (when needed), and the consolidometer.

#### Step 2

Place the consolidometer in the loading device and apply a seating pressure of 5 kPa (100 lbf/ft<sup>2</sup>).

#### Step 3

Adjust the deformation indicator and record the initial zero reading, do.

**Note: The specimen must not be allowed to swell in excess of its initial height prior to being loaded beyond its preconsolidation pressure. Detailed procedures for the determination of one-dimensional swell or settlement potential of cohesive soils is covered by ASTM D4546.**

#### Step 4

Subject the specimen to increments of constant total stress. The specific loading schedule will depend on the purpose of the test, but should conform to the following guidelines.

#### Step 5

The standard loading schedule shall consist of a load increment ratio (LIR) of one that is obtained by doubling the pressure on the soil to obtain values of approximately 12, 25, 50, 100, 200, etc. kPa (250, 500, 1,000, 2,000, 4,000, etc. lbf/ft<sup>2</sup>).

#### Step 6

The standard rebound or unloading schedule should be selected by halving the pressure on the soil (that is, use the same increments as above, but in reverse order). However, if desired, each successive load can be only one-fourth as large as the preceding load.

#### Step 7

Before each pressure increment is applied, record the height or change in height,  $df$ , of the specimen. Two alternative procedures are available that specify the time sequence of readings and the required minimum load duration. Longer durations are often required during specific load increments to define the slope of the characteristic straight-line secondary compression portion of the deformation versus log-of-time graph. For such increments, sufficient readings should be taken near the end of the pressure increment to define this straight-line portion. It is not necessary to increase the duration of other pressure increments during the test.

#### *Test Method A*

The standard load increment duration shall be 24 hours for at least two load increments, including at least one load increment after the preconsolidation pressure has been exceeded, record the height or change in height,  $d$ , at time intervals of approximately 0.1, 0.25, 0.5, 1, 2,

4, 8, 15, and 30 minutes, and 1, 2, 4, 8, and 24 hours (or 0.09, 0.25, 0.49, 1, 4, 9 minutes, etc.), measured from the time of each incremental pressure application. Take sufficient readings near the end of the pressure increment period to verify that primary consolidation is completed. For some soils, a period of more than 24 hours may be required to reach the end-of-primary consolidation. In such cases, load increment durations greater than 24 hours are required. The load increment duration for these tests is usually taken at some multiple of 24 hours and should be the standard duration for all load increments of the test. The decision to use a time interval greater than 24 hours is usually based on experience with particular types of soils. If, however, there is a question as to whether a 24-hour period is adequate, a record of height or change in height with time should be made for the initial load increments in order to verify the adequacy of a 24-hour period. Load increment durations other than 24 hours shall be noted in the report. For pressure increments where time versus deformation data are not required, leave the load on the specimen for the same length of time as when time versus deformation readings are taken.

#### *Test Method B*

For each increment, record the height or change in height,  $d$ , at time intervals of approximately 0.1, 0.25, 0.5, 1, 2, 4, 8, 15, 30 minutes, and 1, 2, 4, 8, and 24 hours (or 0.09, 0.25, 0.49, 1, 4, 9 minutes, etc.) The standard load increment duration shall exceed the time required for completion of primary consolidation or by criterion set by the requesting agency. The report shall contain the load increment duration for each increment.

**Note: It is often desirable to change the reading frequency to improve interpretation of the data. More rapid consolidation will require more frequent readings.**

#### **Step 8**

Disassembly – To minimize swell during disassembly, rebound the specimen back to the seating load (5 kPa). Once height changes have ceased (usually overnight), dismantle quickly after releasing the final small load on the specimen. Remove the specimen and the ring from the consolidometer and wipe any free water from the ring and specimen. Determine the mass of the specimen in the ring and subtract the tare mass of the ring to obtain the final wet specimen mass,  $MT_f$ . The most accurate determination of the specimen dry mass and water content is found by drying the entire specimen at the end of the test. If the soil sample is homogeneous and sufficient trimmings are available for the specified index testing then determine the final water content  $w_f$ , in accordance with AASHTO T 265 and dry mass of solids,  $M_d$ , using the entire specimen. If the soil is heterogeneous or more material is required for the specified index testing, then determine the final water content,  $w_{fp}$ , in accordance with T 265 using a small wedge-shaped section of the specimen. The remaining undried material should be used for the specified index testing.

## Calculations

Due to the complexity and duration of the method, calculations and graphs associated with this standard are primarily completed using computer software.

Required calculations include:

- Dry mass, water content, dry density, dry unit weight, void ratio, volume of solids, degree of saturation, and coefficient of consolidation.
- Soil index property determinations (if performed), including soil specific gravity, Atterberg limits, and particle-size distribution.
- Time-Deformation Properties: Two alternative procedures are provided to present the data, determine the end-of-primary consolidation, and compute the rate of consolidation—square root of time and log of time.
- Load-Deformation Properties: Tabulate the deformation or change in deformation,  $df$ , readings corresponding to the end of each increment and, if using Test Method B, corresponding to the end-of-primary consolidation,  $d_{100}$ .
- Calculate the coefficient of consolidation,  $C_v$ , obtained from deformation-time curve data and the equation specified in the method. It indicates the rate of compression under a load increment.

## Interpreting and Utilizing the Test Results

Data from testing can be substantial. The interpretation and utilization of the results are performed by the engineer assigned to the project.

## Common Errors

- Initial measurements of the specimen height and diameter are not determined accurately.
- Seating load used is not appropriate for the specimen being tested, either too light or too heavy.
- Consolidometer is not standardized properly to account for machine deflection.
- Specimens are not handled carefully during preparation, especially when extracted from sampling tubes, altering their moisture content and soil structure.
- Specimens are allowed to swell during the application of the seating load. The specimen extruder did not extrude in a smooth and uniform rate.

## Reporting of Test Results

1. Project name and location, boring number, sample number, and depth.
2. Description and classification of the soil, specific gravity of solids, Atterberg limits, and the grain-sized distribution shall also be reported when available.
3. Preconsolidation pressure.
4. Test Procedure:
  - a. Trimming procedure used.
  - b. Condition of test specimen (natural moisture or inundated, pressure at inundation).
  - c. Method of testing (A or B), and test method used to compute coefficient of consolidation.
  - d. List of loading increments and decrements, void ratios and load increment duration (if differing from 24 hours), end of increment deformation results, and, for Test Method B, end-of-primary deformation results and coefficient of consolidation.
5. Graphical Presentations:
  - a. Graph of deformation versus log time or square root of time for those load increments where time rate readings were taken (Figure 19 and Figure 20).
  - b. Graph of void ratio versus log of pressure curve or percent compression versus log of pressure curve (Figure 18).
  - c. In cases where time rate of deformation readings have been taken for several load increments, prepare a graph of the log of coefficient of consolidation versus average void ratio or average percent compression for the respective load increments (Figure 19). Alternatively, a graph of coefficient of consolidation or log of coefficient of consolidation versus log of average pressure may be used. If time rate readings were obtained for only two-load increments, simply tabulate the values of  $C_v$  versus the average pressure for the increment.

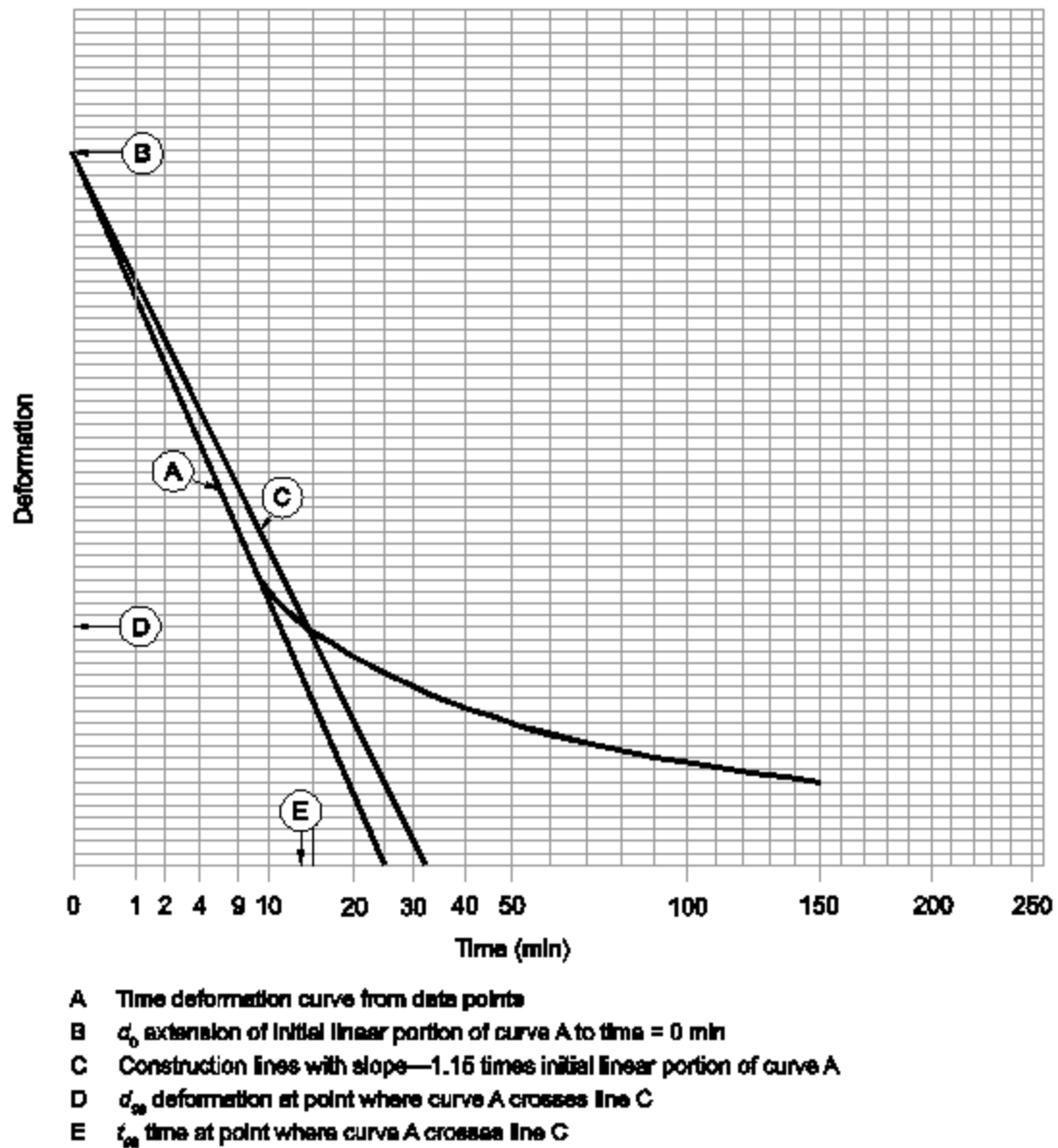
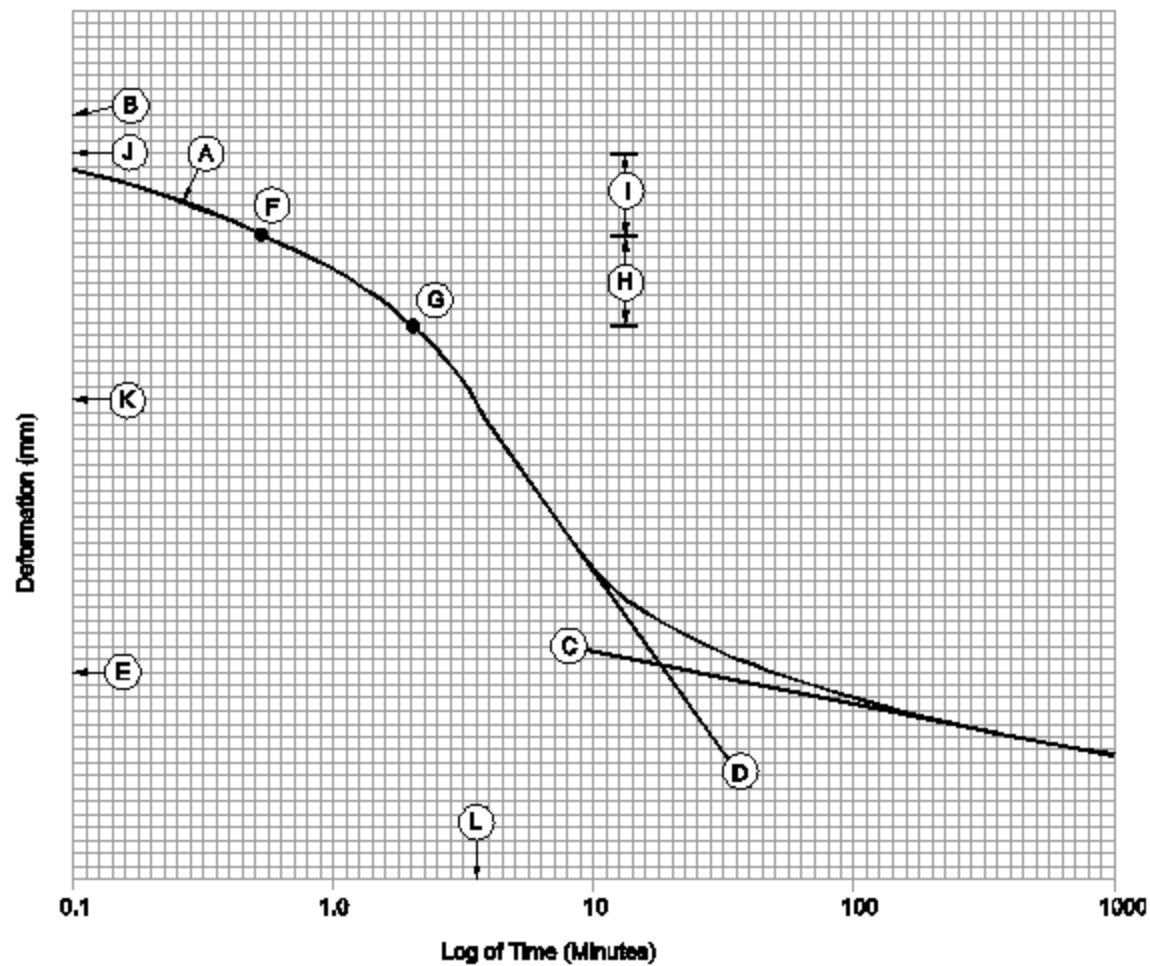


Figure 16: Square Root of Time





- A Time-deformation curve from data points
- B Deformation at time—0 minutes
- C Extension of final linear portion of curve
- D Extension of steepest linear portion of curve
- E  $\sigma_{1,00}$  deformation at intersection of lines C and D
- F  $t_1$  selected point in time
- G  $t_2$  time at four times  $t_1$  (deformation at time  $t_2$  should be less than 50% and larger than 25% of the total deformation for load increment)
- H Increment of deformation between times  $t_1$  and  $t_2$
- I Increment of deformation equal to F
- J  $\sigma_0$  calculated initial deformation
- K  $\sigma_{0,0}$  mean of  $\sigma_0$  and  $\sigma_{1,00}$
- L  $t_{0,0}$  time at  $\sigma_{0,0}$

Figure 17: Log of Time

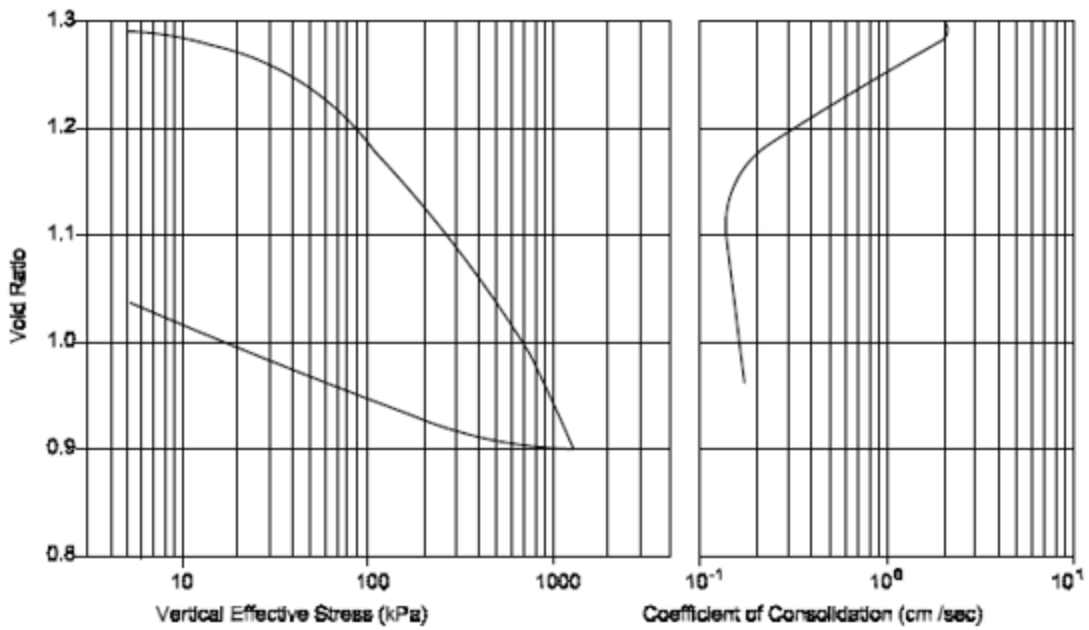


Figure 18: Consolidation Test Summary Plots

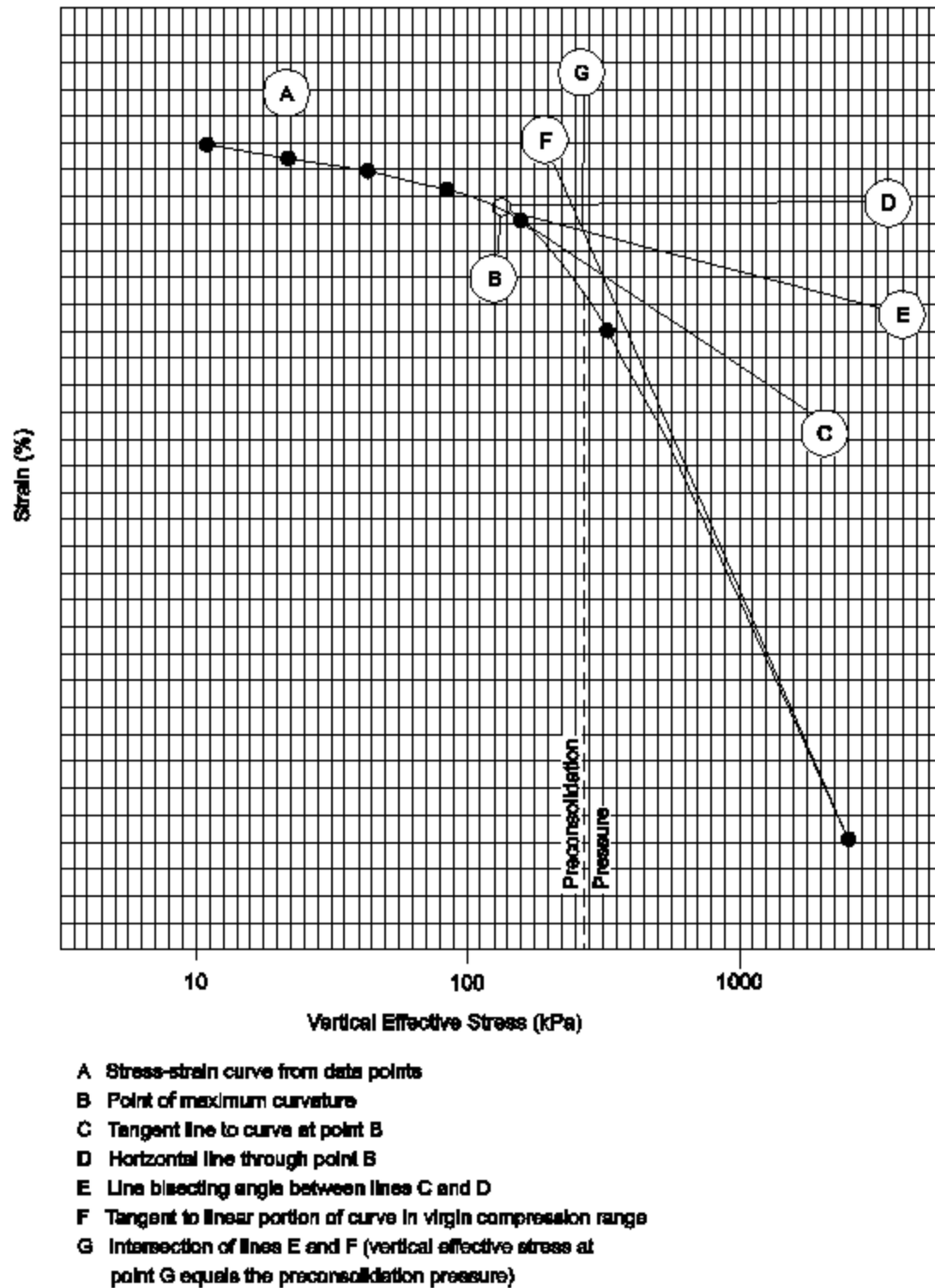


Figure 19: Preconsolidation Stress from Casagrande Method

## Data Sheets

## Consolidation – Time Deformation Readings

Load Increment =

Date	Time	Dial reading (0.0001 in.)	Elapsed time T (min)
			0
			0.25
			0.5
			0.75
			1
			1.5
			2
			4
			6
			8
			10
			15
			20
			25
			30
			45
			60
			120
			240
			480
			960
			1,440

## **AASHTO T 296, Standard Method of Test for Unconsolidated, Undrained Compressive Strength of Cohesive Soils in Triaxial Compression**

### **Background Information**

This test method covers the determination of unconsolidated strength and stress-strain relationships for a cylindrical specimen of either an undisturbed or remolded cohesive soil sheared undrained in compression at a constant rate of axial deformation (strain controlled).

### **Significance and Use**

The strength in this test is measured under undrained conditions and is applicable to field conditions where soils are subjected to a change in stress without time for consolidation to take place (unconsolidated condition), and the field stress conditions are similar to those in the tests.

The shear strength determined from the test expressed in terms of total stresses or effective stresses is commonly used in embankment stability analyses, earth pressure calculations, and foundation design.

### **Related Tests and Specifications**

- AASHTO T 89, Standard Method of Test for Determining the Liquid Limit of Soils
- AASHTO T 90, Standard Method of Test for Determining the Plastic Limit and Plasticity Index of Soils
- AASHTO T 100, Standard Method of Test for Specific Gravity of Soils
- AASHTO T 207, Standard Method of Test for Thin-Walled Tube Sampling of Soils
- ASTM D2216, Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass
- ASTM D2487, Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System)

### **Timeline for Completion**

Preparation Time: 30 minutes to 1 hour

The undisturbed, remolded or compacted specimen must be extruded or compacted, trimmed, and measured.

Test Time: 1 hour

The specimen is mounted in the compression chamber and placed in the axial loading device. After loading, the confining pressure is applied to the specimen.

After approximately 10 minutes, the specimen is then axial loaded to a strain rate of approximately 1% for 15–20 minutes until 15% strain is reached, or when the deviator stress has decreased. Finally, the axial load and chamber pressure are removed from the specimen, the specimen is photographed, and the moisture content is determined.

Calculations: If software is used, the calculations are performed concurrently with testing

The calculations performed in T 296 are commonly performed using computer software.

Total Test Time: 1 to 1.5 hours

### **Apparatus**

- Axial Loading Device – The axial compression device may be a screw jack driven by an electric motor through a geared transmission, a hydraulic or pneumatic loading device.
- Axial Load-Measuring Device – The axial load-measuring device may be a load ring, electronic load cell, or hydraulic load cell.
- Triaxial Compression Chamber – The triaxial chamber must be able to withstand a chamber pressure equal to the sum of the effective confining pressure and back pressure.
- Axial Load Piston – The piston passing through the top of the chamber and its seal must be designed so the variation in axial load due to friction does not exceed 0.1% of the axial load at failure and so there is negligible lateral bending of the piston during loading.
- Chamber Pressure Control Device – The chamber pressure control device shall be capable of applying and controlling pressure to within 2 kPa (0.25 psi) for chamber pressures less than 200 kPa (28 psi) and to within 1% for chamber pressures greater than 200 kPa (28 psi).
- Chamber Pressure Measurement Device – The chamber pressure measuring device shall be capable of measuring pressures to the tolerances listed above. It may be a Bourdon gauge, pressure manometer, electronic pressure transducer, or any other device capable of measuring pressures to the stated tolerances.
- Deformation Indicator – The vertical deformation of the specimen is usually determined from the travel of the piston acting on the top of the specimen. The deformation indicator shall have a travel range of at least 20% of the initial height of the specimen and may be a dial indicator, LVDT, extensometer, or other measuring device meeting the requirements for accuracy and range.

- Specimen Cap and Base – An impermeable rigid cap and base shall be used to prevent drainage of the specimen. The specimen cap and base shall be constructed of a noncorrosive impermeable material and each shall have a circular plane surface of contact with the specimen and a circular cross-section. The diameter of the cap and base shall be equal to the initial diameter of the specimen.

**Note: The stress produced by the specimen cap can exceed 1 kN/m<sup>2</sup> (0.145 psi) provided the test data is corrected for the effects of that stress.**

- Rubber Membrane – The rubber membrane used to encase the specimen shall provide reliable protection against leakage.
- Specimen-Size Measurement Devices – Devices used to determine the height and diameter of the specimen shall measure the respective dimensions to within 0.1% of the total dimension.

**Note: Circumferential measuring tapes are recommended over calipers for measuring the diameter.**

- Recorders – Specimen behavior may be recorded manually or by electronic digital or analog recorders. If electronic recorders are used, it shall be necessary to calibrate the measuring devices through the recorder using known input standards.
- Sample Extruder – Hand-operated, mechanical, and hydraulic extruders are acceptable provided the device (1) is capable of extruding the soil core from the sampling tube in the same direction of travel in which the sample entered the tube, (2) has a length of travel at least equal to the required untrimmed test length of the sample and permits the extrusion to occur in one operation without resetting the piston or extrusion mechanism, (3) can be operated at a relatively uniform rate, and (4) causes negligible disturbance of the sample.
- Weighing Device – The specimen weighing device shall determine the mass of the specimen to an accuracy of within 0.05% of the total mass of the specimen.
- Testing Environment – The shear portion of the test shall be performed in an environment where temperature fluctuations are less than  $\pm 4$  °C ( $\pm 7.2$  °F) and there is no direct contact with sunlight.

## Sample Preparation

### Specimen Size

The specimen shall be cylindrical, with a minimum diameter of 33 mm (1.3 in.). The average height to diameter ratio shall be between 2 and 2.5. The largest particle shall be smaller than 1/6 the specimen diameter.

Undisturbed Specimens – Prepare undisturbed specimens from large undisturbed samples or from samples secured in accordance with T 207 or other acceptable undisturbed tube sampling

procedures. Specimens obtained by tube sampling may be tested without trimming, except for cutting the end surfaces plane and perpendicular to the longitudinal axis of the specimen, provided soil characteristics are such that no significant disturbance results from sampling.

#### Remolded Specimens

Prepare the specimen by first thoroughly working the previously undisturbed specimen, which has been tested and is still encased in the rubber membrane, with the fingers. Then reform the specimen by forming within a mold having dimensions such that the remolded specimen dimensions will be equal to those of the undisturbed specimen.

#### Compacted Specimens

Prepare specimens using the compaction method, predetermined water content, and unit mass prescribed by the individual assigning the test. Compacted specimens may be prepared by compacting material in at least six layers, using a pressing or kneading action, into a split.

**Note: It is common for the unit mass of the specimen after removal from the mold to be less than the value based on the volume of the mold. This occurs as a result of the specimen swelling after removal of the lateral confinement due to the mold.**

**Note: Experience indicates that it is difficult to compact, handle, and obtain valid results with specimens that have a degree of saturation that is greater than about 90%.**

#### Prior to Mounting Specimen

If deemed necessary, check the rubber membrane for leaks. Place the membrane on the membrane expander or, if it is to be rolled onto the specimen, roll the membrane on the cap or base. Attach the pressure-control device to the chamber base. Finally, place the rubber membrane around the specimen and seal it at the cap and base with two rubber O-rings or other positive seal at each end. A thin coating of silicon grease on the vertical surfaces of the cap and base will aid in sealing the membrane.

#### Procedure – Loading

##### Step 1

Assemble the triaxial chamber.

##### Step 2

Bring the axial load piston into contact with specimen cap several times to permit proper seating and alignment without exceeding load of 0.5% of estimated compressive strength.



**Note: If piston weight exceeds 0.5% of estimated compressive strength, the piston shall be locked in place above the specimen cap after seating and alignment are checked, and kept locked until the chamber pressure application.**

**Step 3**

Record the reading on the deformation indicator when the piston is brought into contact the final time.

**Step 4**

Attach the pressure-maintaining and measurement device and fill the chamber with confining fluid.

**Note: Although the confining “fluid” is typically a liquid, compressed air, or other gasses may be used.**

**Step 5**

Wait approximately 10 minutes after applying the chamber pressure before continuing the test.

**Step 6**

Adjust the axial load-measuring device adjusted to compensate for friction and thrust.

**Step 7**

Record the initial reading on deformation indicator when the piston contacts the specimen cap.

**Step 8**

Apply an axial load to produce an axial strain of approximately 1% per minute for plastic soils or 0.3% per minute for brittle soils.

**Step 9**

Continue the loading to 15% axial strain.

**Note: Loading may be stopped when deviator stress has peaked then dropped 20%, or when axial strain has reached 5% beyond strain at peak deviator stress.**

**Step 10**

Record load and deformation values at the following points (minimum):

1. At about 0.1, 0.2, 0.3, 0.4 and 0.5% strain.
2. Then at increments of 0.5% strain until 3% strain is reached.
3. Then at increments of 1% strain until 15% axial strain is achieved.

**Note: Alternate intervals for readings may be used if sufficient points are obtained to define the stress-strain curve.**

### **Procedure – Removing Specimen**

#### **Step 1**

Remove the axial load and reduce the chamber and back pressures to zero.

#### **Step 2**

Quickly remove the specimen with the drainage valves remaining closed.

#### **Step 3**

Remove the rubber membrane.

**Note: If the specimen is to be used for index tests, it should be weighed prior to removing material for index property tests and a representative portion of it should be used to determine final water content.**

#### **Step 4**

Sketch a picture or take a photograph of the specimen showing the mode of failure.

#### **Step 5**

Determine the water content of entire specimen (if possible).

### **Calculations**

Due to the complexity, calculations and graphs associated with this standard are primarily completed using computer software.

### **Interpreting and Utilizing the Test Results**

The interpretation and utilization of the results are performed by the engineer assigned to the project.

### **Common Errors**

- Cap or base are not of the design specified.
- Data collection is not calculated or reported correctly.
- The number of sample dimension measurements taken does not meet specification.
- The testing environment is exposed to direct sunlight.
- The water content procedural step is not performed.

**Reporting the Test Results and Data Sheets**

The reporting and collecting of this data is normally performed by computer software.

## **AASHTO T 297, Standard Method of Test for Consolidated, Undrained Triaxial Compression Test on Cohesive Soils**

### **Background Information**

This test method covers the determination of strength and stress-strain relationships of a cylindrical specimen of either an intact, reconstituted, or remolded saturated cohesive soil. Specimens are consolidated and sheared in compression without drainage at a constant rate of axial deformation (strain controlled).

This test method provides for the calculation of total and effective stresses, and axial compression by measurement of axial load, axial deformation, and pore-water pressure.

This test method provides data useful in determining strength and deformation properties of cohesive soils such as Mohr strength envelopes and Young's modulus. Generally, three specimens are tested at different effective consolidation stresses to define a strength envelope.

### **Significance and Use**

The shear strength of a saturated soil in triaxial compression depends on the stresses applied, time of consolidation, strain rate, and the stress history experienced by the soil.

In this test method, the shear characteristics are measured under undrained conditions and are applicable to field conditions where soils that have been fully consolidated under one set of stresses are subjected to a change in stress without time for further consolidation to take place (undrained condition), and the field stress conditions are similar to those in the test method.

Using the pore-water pressure measured during the test, the shear strength determined from this test method can be expressed in terms of effective stress. This shear strength may be applied to field conditions where full drainage can occur (drained conditions) or where pore pressures induced by loading can be estimated, and the field stress conditions are similar to those in the test method. The shear strength determined from the test expressed in terms of total stresses (undrained conditions) or effective stresses (drained conditions) is commonly used in embankment stability analyses, earth pressure calculations, and foundation design.

### **Related Tests and Specifications**

- ASTM D422, Standard Method of Test for Particle Size Analysis of Soils
- ASTM D4318, Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils

- ASTM D854, Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer
- ASTM D2216, Laboratory Determination of Water Content of Soil and Rock by Mass
- ASTM D2435, Standard Test Methods for One-Dimensional Consolidation Properties of Soil Using Incremental Loading

### **Timeline for Completion**

Preparation Time: 2–3 hours

The intact specimen or reconstituted specimen must be extruded or compacted, trimmed, and measured. The specimen must then be dry or wet mounted.

Test Time: 48–120 hours

The specimen is back-pressure saturated until the value of  $B$  is equal to or greater than 0.95. The specimen is then allowed to consolidate for at least one log cycle of time or one overnight period after 100% primary consolidation has been reached. Finally, the specimen is axial loaded until failure.

Calculations: If software is used, the calculations are performed concurrently with testing

The calculations performed in T 297 are commonly performed using computer software.

Total Test Time: 2–5 days

### **Apparatus**

- Axial Loading Device – The rate of advance of the loading device shall not deviate by more than 1% from the selected value.
- Axial Load-Measurement Device – The axial load-measurement loading device shall be capable of measuring the axial load to an accuracy of within 1% of the axial load at failure.
- Triaxial Compression Chamber – The triaxial chamber shall have a working chamber pressure equal to the sum of the effective consolidation stress and the back pressure. The base plate shall have an inlet through which the pressure liquid is supplied to the chamber. The base plate shall have inlets leading to the specimen base and provide connection to the cap to allow saturation and drainage of the specimen when required. The top plate shall have a vent valve for air to be forced out of chamber as it is filled.

- Axial Load Piston – The piston passing through the top of the chamber and its seal must be designed so the variation in axial load due to friction does not exceed 0.1 % of the axial load at failure.
- Pressure and Vacuum-Control Devices – The chamber pressure and back-pressure control devices shall be capable of applying and controlling pressures to within 62 kPa (0.25 lbf/in.2) for effective consolidation pressures less than 200 kPa (28 lbf/in.2) and to within 1 % for effective consolidation pressures greater than 200 kPa. The vacuum-control device shall be capable of applying and controlling partial vacuums to within 2 kPa.
- Pressure- and Vacuum-Measurement Devices – The chamber pressure-, back pressure-, and vacuum-measuring devices shall be capable of measuring pressures or partial vacuums.
- Pore-Water Pressure-Measurement Device – The specimen pore-water pressure shall also be measured.
- Volume Change Measurement Device – The volume of water entering or leaving the specimen shall be measured with an accuracy of within 0.05 % of the total volume of the specimen.
- Deformation Indicator – The vertical deformation of the specimen is usually determined from the travel of the piston acting on the top of the specimen. The piston travel shall be measured with an accuracy of at least 0.25% of the initial specimen height. The deformation indicator shall have a range of at least 15% of the initial height of the specimen.
- Specimen Cap and Base – The specimen cap and base shall be designed to provide drainage from both ends of the specimen.
- Porous Discs – Two rigid porous disks shall be used to provide drainage at the ends of the specimen.
- Filter-Paper Strips and Disks – Filter-paper strips are used by many laboratories to decrease the time required for testing. Filter-paper disks of a diameter equal to that of the specimen may be placed between the porous disks and specimen to avoid clogging of the porous disks.
- Rubber Membrane – The rubber membrane used to encase the specimen shall provide reliable protection against leakage.
- Valves – Changes in volume due to opening and closing valves may result in inaccurate volume change and pore-water pressure measurements. For this reason, valves in the specimen drainage system shall be of the type that produce minimum volume changes due to their operation.

- Specimen-Size Measurement Devices – Devices used to determine the height and diameter of the specimen shall be constructed such that their use will not disturb/deform the specimen.
- Sample Extruder – The sample extruder shall be capable of extruding the soil core from the sampling tube at a uniform rate in the same direction of travel as the sample entered the tube and with minimum disturbance of the sample.
- Water De-aeration Device – The amount of dissolved gas (air) in the water used to saturate the specimen shall be decreased by boiling, by heating and spraying into a vacuum, or by any other method that will satisfy the requirement for saturating the specimen within the limits imposed by the available maximum back pressure and time to perform the test.
- Testing Environment – The consolidation and shear portion of the test shall be performed in an environment where temperature fluctuations are less than 4 °C (7.2 °F) and there is no direct contact with sunlight.

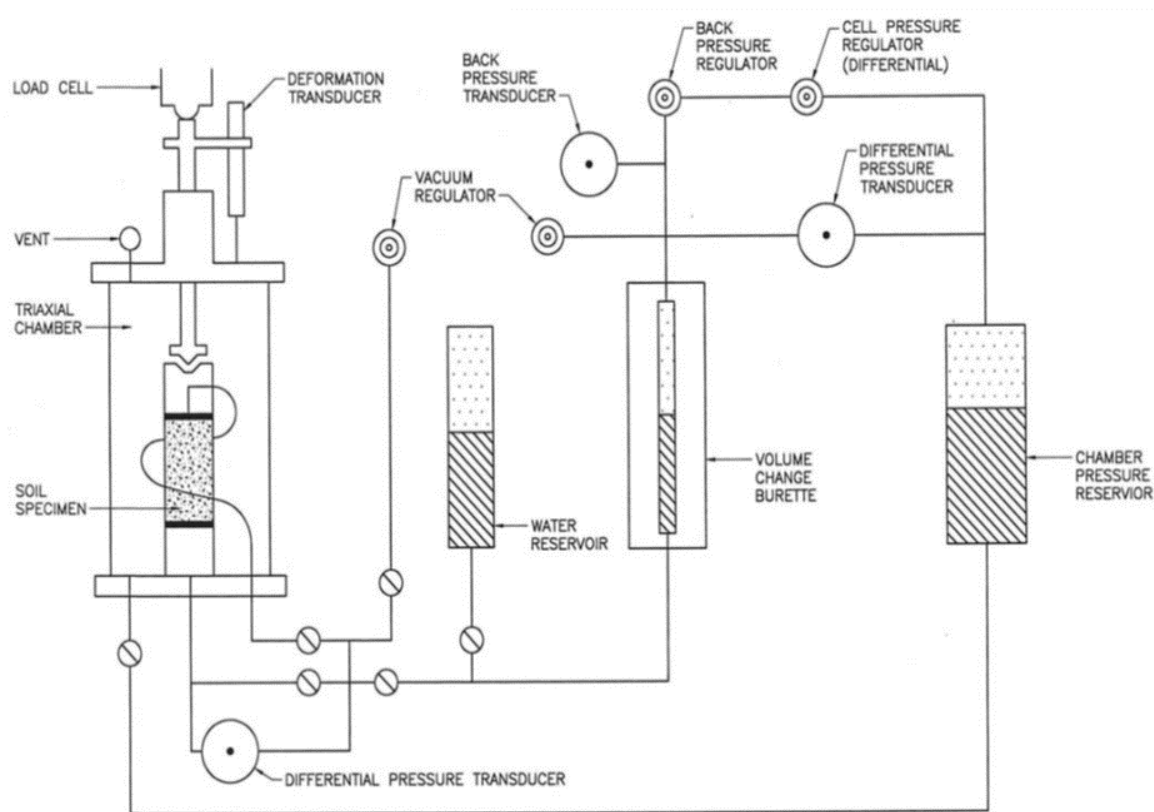


Figure 20: Schematic Diagram of a Typical Consolidated Undrained Triaxial Apparatus

## Sample Preparation

### Specimen Size

The specimen shall be cylindrical, with a minimum diameter of 33 mm (1.3 in.). The average height to diameter ratio shall be between 2 and 2.5. The largest particle shall be smaller than  $1/6$  of the specimen diameter.

### Intact Specimen

Prepare intact specimens from large intact samples or from samples secured in accordance with ASTM D1587 or other acceptable intact tube sampling procedures.

### Reconstituted Specimens

Soil required for reconstituted specimens shall be thoroughly mixed with sufficient water to produce the desired water content. If water is added to the soil, store the material in a covered container for at least 16 hours prior to compaction.

### Mounting Specimen

#### *Wet Mounting*

Fill the specimen drainage lines and pore pressure measurement device with de-aired water. Saturate porous stones by boiling them in water for at least 10 minutes and allow to cool to room temperature. Saturate filter paper with water prior to placement. Place saturated porous stones on specimen base. Place filter paper disk on top of porous stone. Place specimen on top of filter disk. Place another filter disk on top of specimen. Place porous disk and specimen cap on top of filter paper. If filter paper strips or a filter paper cage are to be used, saturate the paper prior to placement on the specimen.

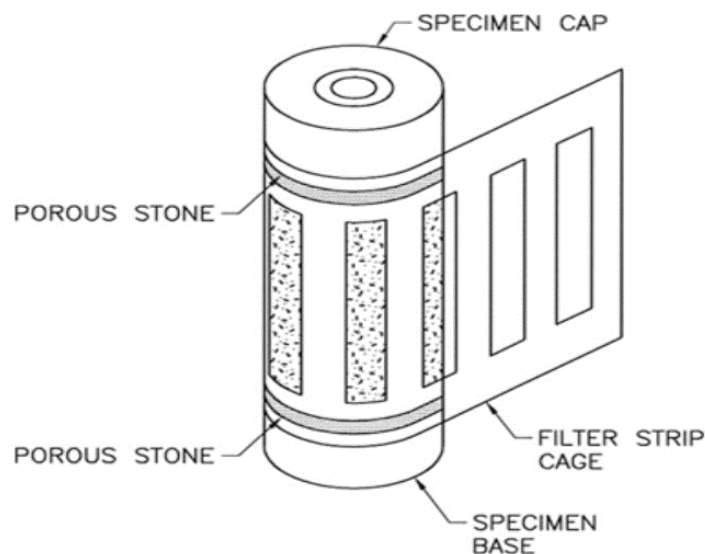


Figure 21: Filter Strip Cage



*Dry Mounting*

Dry the specimen drainage system. This may be accomplished by allowing the dry air to flow through the system. Dry the porous disk in an oven and then place the disk in a desiccator to cool to room temperature prior to mounting the specimen. Place dry porous stones on specimen base. Place specimen on top of porous disk. Place porous disk and specimen cap on top of specimen. If filter paper strips or a filter paper cage are to be used, the cage or strips may be held in place with a small piece of tape at the top and bottom.

**Note: If desired, dry filter paper disk may be placed between the porous disk and specimen.**

For both mounting procedures, place the rubber membrane around the specimen and seal it at the cap and base with two rubber O-rings or other positive seal at each end. A thin coating of silicon grease on the vertical surfaces of the cap and base will aid in sealing the membrane. If filter-paper strips or a filter-paper cage are used, do not apply grease to surfaces in contact with the filter-paper.

Attach the top drainage line and check the alignment of the specimen and the specimen cap. If the dry mounting method has been used, apply a partial vacuum of approximately 35 kPa (5 psi)—not to exceed the consolidation stress—to the specimen through the top drainage line prior to checking the alignment. If there is any eccentricity, release the partial vacuum, realign the specimen and cap, and then reapply the partial vacuum.

**Procedure – Saturation****Step 1**

Assemble the triaxial chamber.

**Step 2**

Bring the axial load piston into contact with specimen cap several times to permit proper seating and alignment without exceeding load of 0.5% of estimated load at failure.

**Step 3**

Record the reading on the deformation indicator when the piston is brought into contact the final time.

**Step 4**

Carefully fill the chamber to avoid trapping air inside the chamber.

**Step 5**

Accomplish saturation without undesirable pre-stressing or swelling of specimen.

**Step 6**

Specimen considered adequately saturated if “B” value > 0.95 or if a plot of “B” versus back pressure indicates no further increase in “B” with increasing back pressure.

**Step 7**

“B” calculated as change in pore pressure divided by change in chamber pressure:

$$\frac{\Delta u}{\Delta \sigma_3}$$

$\Delta u$  = change in the specimen pore pressure that occurs as a result of change in the chamber pressure when the specimen drainage valves are closed.

$\Delta \sigma_3$  = change in the chamber pressure.

**Procedure – Consolidation****Step 1**

Bring axial load piston into contact with specimen cap and record deformation.

**Step 2**

Take care not to exceed axial load of 0.5% of estimated axial load at failure.

**Step 3**

Raise piston a small distance above the cap and lock it in place.

**Step 4**

With drainage valves closed, hold maximum back pressure constant while chamber pressure is increased until the difference between the chamber and back pressure equals the desired effective consolidation pressure.

**Note: Increasing the chamber pressure is allowed over a period of up to 10 minutes with the drainage valves open. Volume change readings then begin immediately after total pressure is reached.**

**Step 5**

Perform the consolidation in stages if the effective consolidation stress is greater than 40 kPa (5.8 psi) and filter strips used, with a load increment ratio not exceeding 2 (stress not more than doubled each increment).

**Step 6**

Record the initial volume change, with the drainage valves opened to allow the specimen to drain from both ends.

**Note: Volume change readings are typically obtained from a burette, but other systems are allowable.**

**Step 7**

Record volume changes at increasing intervals of elapsed time, such as 0.1, 0.2, 0.5, 1, 2, 4, 8, 15 and 30 minutes, 1, 2, 4 and 8 hours, etc.

**Note: Times with easy square roots, or other intervals, may be used.**

**Step 8**

After the 15-minute volume change reading, couple the piston with the specimen cap and record deformation readings.

**Step 9**

Plot the volume change and deformation readings versus the logarithm or square root of elapsed time.

**Step 10**

Continue the consolidation for at least one log cycle of time or one overnight period after 100% primary consolidation has been reached.

**Note: A marked deviation between slopes of volume change readings and deformation curves toward the end of consolidation (based on deformation readings) indicates fluid leakage from chamber into the specimen, and the test should be terminated.**

**Step 11**

Determine the time for 50% primary consolidation ( $t_{50}$ ).

**Note: If the specimen swells or does not consolidate, check for equipment malfunction. If a similar specimen is being tested at a higher effective consolidation stress, the  $t_{50}$  from that test can be used instead. If there is no other data available, use a strain rate of 1% per hour.**

**Procedure – Prior to Axial Loading****Step 1**

Isolate the specimen by opening or closing appropriate valves so pore-water pressure will be measured by pore-pressure measurement device and no drainage will occur during shear.

**Step 2**

Bring the axial load piston into contact with the specimen cap.

**Step 3**

Record the initial pore-pressure to the nearest 0.7 kPa (0.1 psi) immediately prior to the piston contact on the cap.

**Procedure – Axial Loading****Step 1**

Apply the axial load at a rate to produce equalization of pore pressures throughout the specimen at failure.

**Note: Strain rate is preferably determined by dividing expected strain at failure percent (such as 4%) by 10 times the value of  $t_{50}$ .**

**Step 2**

Record the load, deformation, and pore-water pressure values at increments of 0.1% to 1% strain.

**Note: The increments listed here should be considered minimums. Additional readings are acceptable.**

**Step 3**

Record load and deformation values recorded and record pore-water pressure values to the nearest 0.7 kPa (0.1 psi).

**Step 4**

Record the values at every 1% and sufficient readings taken to define stress-strain curve.

**Step 5**

Continue the loading until 15% strain

**Note: Loading may be stopped when principal stress difference (deviator stress) has dropped 20%, or when 5% additional axial strain occurs after peak in principal stress difference (deviator stress).**

**Procedure – Removing Specimen****Step 1**

Remove the axial load, and reduce the chamber and back pressures to zero.

**Step 2**

Remove the specimen quickly with the drainage valves remaining closed.

**Step 3**

Remove the rubber membrane (and filter-paper strips or cage, if used), blot-free water on specimen, and determine the water content of total specimen.

**Note: If specimen is to be used for index tests, specimen should be weighed prior to removing material for index property tests and a representative portion of the specimen should be used to determine final water content.**

**Step 4**

Sketch a picture or take a photograph of the specimen, showing mode of failure, prior to placing the specimen in the oven.

**Calculations**

Due to the complexity, calculations and graphs associated with this standard are primarily completed using computer software.

**Reporting the Test Results and Data Sheets**

The reporting and collecting of this data is normally performed by computer software.

**Interpreting and Utilizing the Test Results**

Data from testing can be substantial. The interpretation and utilization of the results are performed by the engineer assigned to the project.

**Common Errors**

- Data collection system was not sufficient.
- Loading piston was not backed off of specimen cap before consolidation.
- Testing environment was exposed to sunlight.
- The specimen extruder did not extrude at a smooth and uniform rate.
- Vacuum system was not presented and/or operational.

## **AASHTO T 307, Standard Method of Test for Determining the Resilient Modulus of Soils and Aggregate Materials**

### **Background Information**

Resilient modulus (MR) is widely used in pavement design and analysis of multilayered systems to predict cracking, rutting, faulting, and other undesirable pavement behaviors.

### **Significance and Use**

Resilient modulus is a measure of the stiffness of the soil at a particular depth in the pavement and at a specific stress level. This method applies to undisturbed samples of natural and compacted subgrade soils, and to disturbed samples of subgrade soils and untreated (unbound) base/subbases prepared for testing by compaction in the laboratory.

During the test, the specimen is subjected to a cyclic stress and a static confining stress using a triaxial pressure chamber. Total resilient axial deformation is measured and used to determine the resilient modulus of the material. Resilient modulus values are used to calculate the pavement structural response to wheel loads, and with pavement design procedures, such as the AASHTO Mechanistic-Empirical Pavement Design Guide (MEPDG), to design pavement structures.

### **Related Tests and Specifications**

- AASHTO T 265, Laboratory Determination of Moisture Content of Soils

### **Timeline for Completion**

Preparation Time: 1 hour

A cylindrical soil specimen is cut from a tube sample or remolded from loose material. The specimen is mounted in a triaxial chamber.

Test Time: 1 hour

The sample is conditioned using 500 to 1,000 repetitions of a small load. The sample is then subjected to a loading scheme of up to 1,500 load application cycles at varying confining pressures, causing a total permanent vertical strain of 5% or less. The specimen is then sheared under axial strain. The moisture content of the sample is determined at the end of the test.

Calculations: Data is collected and the calculations are performed using automated computer software.

Total Test Time: 2 hours

### Apparatus

- Triaxial Pressure Chamber – A triaxial testing chamber pressurized with air, set up to allow deformation to be measure externally using two LVDTs. The pressure shall be monitored to an accuracy of at least 0.7 kPa.
- Loading Device – Either a top-loading, closed loop, electrohydraulic, or electropneumatic testing machine with a function generator capable of applying a haversine-shaped load pulse.
- Load Measuring Equipment – An electronic load cell located between the actuator and the chamber piston rod of sufficient capacity for the size of the sample being tested.
- Axial Deformation Measuring Equipment – Two spring-loaded LVDTs fixed to opposite sides of the piston rod outside the test chamber, with sufficient range for the size of the sample being tested. The LVDTs shall be wired so that data from each one can be read and reviewed independently and the results averaged for the calculations.
- Specimen Preparation Equipment – Appropriate to the type of samples used for testing.
- Sample Trimming Equipment – Such as a miter box, wire cutter, etc. as specified in AASHTO T296.

System calibration and periodic checks: The entire system (transducer, conditioning, and recording devices) shall be calibrated every 2 weeks or after every 50 resilient modulus tests. The LVDTs shall also be checked daily.

### Sample Preparation

1. There are several methods of sample preparation. Undisturbed tube samples are preferred for cohesive materials. Samples may also be laboratory-compacted or reconstituted samples.
2. To be suitable for testing, the specimen length shall be at least twice the diameter. The sample shall be free of defects such as cracks, gouges, broken corners that cannot be repaired during preparation, presence of particles much larger than typical for the material, and foreign material.
3. The sample preparation method shall be chosen to closely emulate the wet density, moisture content, and density gradient (if any) for the *in-situ* material.

**Note: The resilient modulus value is very dependent on the moisture content of the material being tested. Every effort should be made to ensure that the sample simulates the field conditions.**

4. The annex of the method provides specific guidance for reconstituting samples to the proper moisture content and density.

## Procedure

There are two material types defined in the method.

Type 1 – All soils with less than 70% passing the 2.00 mm (#10) sieve and less than 20% passing the 75- $\mu$ m (#200) sieve, and that have a plasticity index of 10 or less. Soils classified as Type 1 will be molded in a 150 mm diameter mold.

Type 2 – Includes all soils not meeting the criteria for material Type 1. Thin-walled tube samples of untreated subgrade soils fall into this Type 2 category.

### Step 1

Assemble the sample with moist filter papers, moist porous stones, cap, and base. Cover the specimen with a triaxial membrane and seal it to the cap and base using O rings or other pressure seal.

### Step 2

Connect the specimen's bottom drainage line to the vacuum source through the bubble chamber. Apply a 7 kPa vacuum to check for membrane leakage. Bubbles visible in the bubble chamber indicate the specimen is not completely sealed. If no bubbles are present, disconnect the vacuum from the sample.

### Step 3

Assemble the triaxial chamber. Insert the load piston and obtain a firm connection with the load cell. Slide the assembled apparatus into position under the axial loading device. Couple the loading device to the triaxial chamber piston rod.

### Step 4

Open all drainage valves leading into the specimen to atmospheric pressure to simulate drained conditions.

### Step 5

Resilient Modulus Testing - Connect the air pressure supply line to the triaxial chamber and apply the specified pre-conditioning confining pressure. Maintain a contact stress of  $10\% \pm 0.7$  kPa of the maximum applied axial stress during each sequence number.

### Step 6

Conditioning - Apply a minimum of 500 repetitions of the load. If the sample height is still decreasing after 500 repetitions, continue up to 1,000 repetitions. If the total vertical



permanent strain reaches 5% during conditioning, cease the conditioning process terminated determine the cause of the problem.

#### Step 7

Apply the appropriate loading sequence from the table, adjusting the confining pressure and axial stress as specified.

#### Step 8

If the total vertical permanent strain did not exceed 5% during the testing and if strength information is desired, shear the specimen at an axial strain rate of 1% per minute.

#### Step 9

Quick Shear Test – an axial load is applied until the specimen reaches failure.

#### Step 10

Reduce the confining pressure to zero, take the membrane off of the sample, and use the entire specimen to determine the moisture content according to T 265.

**Note: The axial and cyclic stress loads used for resilient modulus testing, conditioning and quick shear testing and are dependent upon on the soil being tested (subgrade versus base/subbase).**

### Calculations

#### Step 1

The data is recorded by the computer and arranged in a table.

#### Step 2

The axial strain for the past five load cycles is averaged for each sequence.

#### Step 3

The resilient modulus is calculated as:

$$\text{resilient modulus} = \frac{\text{amplitude of repeated axial stress}}{\text{amplitude of resultant recoverable axial strain}}$$

#### Step 4

The results of the quick-shear procedure are reported if applicable.

### Reporting the Test Results

The data is typically calculated and reported using computer software.

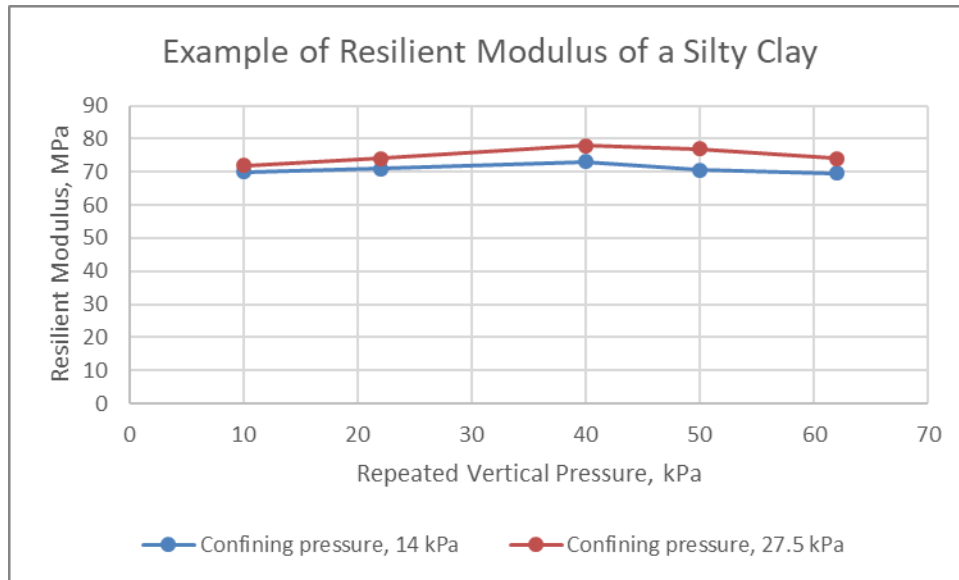


Figure 22: Example of Resilient Modulus of a Silty Clay

### Interpreting and Utilizing the Test Results

The results of the resilient modulus test are typically derived using software based on the MEPDG or other layered elastic analysis (LEA) programs. The MEPDG uses project-specific traffic, climate, layer thickness, and materials data to estimate damage accumulation over a specified pavement service life. The resilient modulus is one of many pieces of data used to optimize pavement design using such programs.

### Common Errors

- Sample preparation errors are the most common problems with this method. The moisture content and stress conditions of the sample must be very similar to the material in the field in order for the data to be valid. Using samples created by different methods can also affect test results.

## Appendix A: Lab Materials

### HMEC Module B Soils Tests

Wednesday, January 27, 2016

Please review Page 2 for your grouping and team assignments.

<b>Times</b>	<b>Group A</b>	<b>Group B</b>	<b>Group C</b>	<b>Group D</b>
TBD	Prep Session	Prep Session	Prep Session	Prep Session
TBD	Station 1	Station 2	Station 3	Station 4
TBD	Station 2	Station 3	Station 4	Station 1
TBD	Station 3	Station 4	Station 1	Station 2
TBD	Station 4	Station 1	Station 2	Station 3
TBD	Station 5	Station 5	Station 5	Station 5
TBD	Debrief Session	Debrief Session	Debrief Session	Debrief Session

#### Station 1

- AASHTO T 216 One-Dimensional Consolidation Properties of Soils

#### Station 2

- AASHTO T 208 Unconfined Compressive Strength of Cohesive Soil
- AASHTO T 296 Unconsolidated, Undrained Triaxial Compressive Strength of Cohesive Soils
- AASHTO T 297 Consolidated, Undrained Triaxial Compressive Strength of Cohesive Soils

#### Station 3

- AASHTO R 58 Dry Preparation of Disturbed Soil and Soil-Aggregate Samples for Test
- AASHTO T 88 Particle Size Analysis of Soils
- AASHTO T 89 Determining the Liquid Limit of Soils
- AASHTO T 90 Determining the Plastic Limit and Plasticity Index of Soils
- AASHTO T 100 Specific Gravity of Soils
- AASHTO M145, ASTM D2487 and D2488 - Soil Classification Methods

#### Station 4

- AASHTO T 99 Moisture-Density Relations of Soils (Standard Method)
- AASHTO T 180 Moisture-Density Relations of Soils (Modified Method)

Station 5

- AASHTO T 307 Resilient Modulus of Soils and Aggregate Materials

Debrief Session

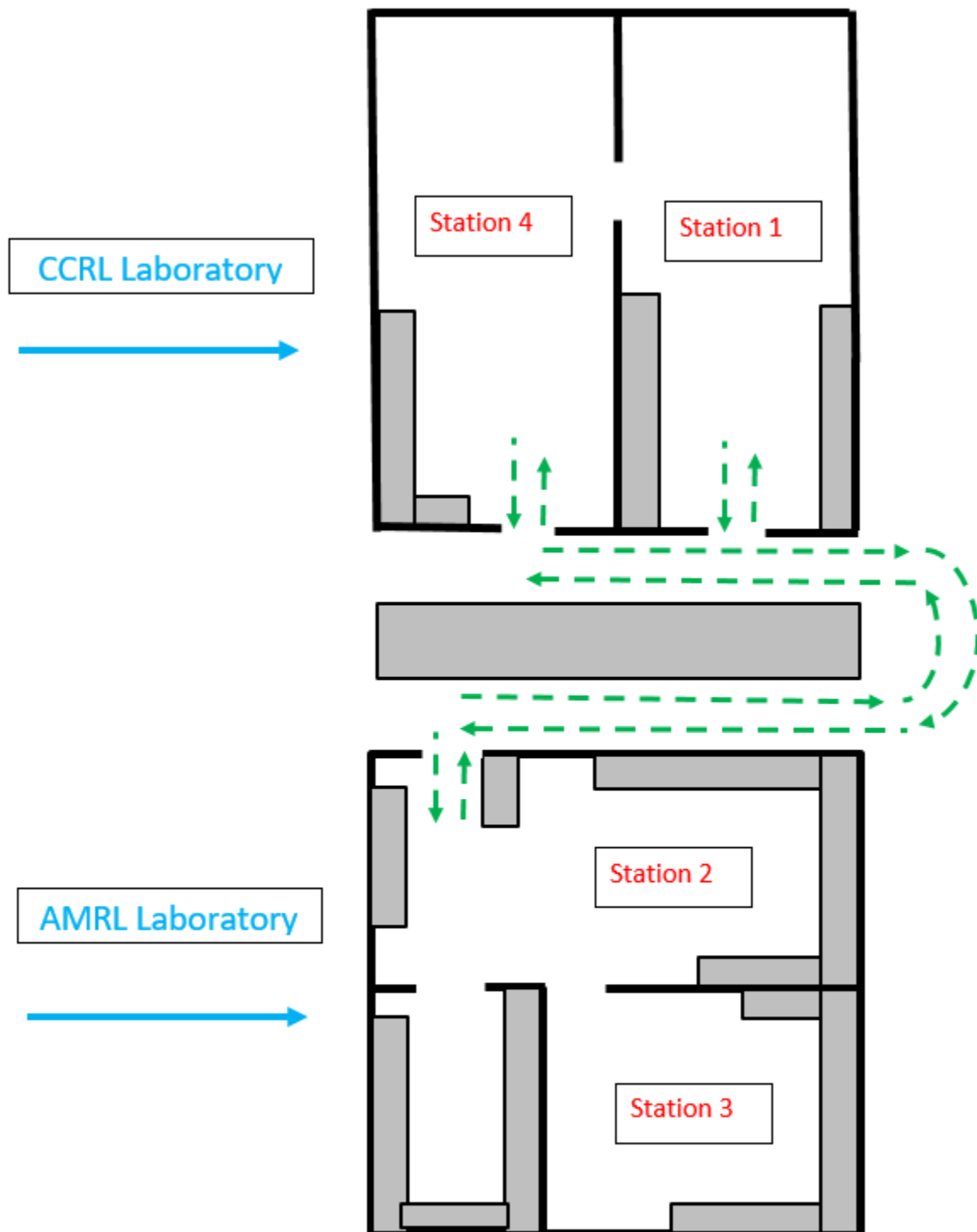
Stations 1 and 4 will be performed in the CCRL Laboratory

Stations 2 and 3 will be performed in the AMRL Laboratory

Station 5 and the prep and de-brief sessions will be held in the upstairs classroom

### **Team Assignments**

To be determined.

**AMRL Laboratory Layout for Module B (Soils)**

### Station 1: AASHTO T 216 One-Dimensional Consolidation of Soil

(1) Measure and weigh the empty consolidation ring.

Weight (lbs) =   
 Height (in) =   
 Diameter (in) =   
 Radius (in) =   
 Area (in<sup>2</sup>) =

(2) Calculate the area of the specimen ring.

(3) Obtain a sample by extruding one from a shelby tube.

(4) Cut the specimen with the consolidation ring.

(5) Weigh the consolidation ring with soil.

Weight (lbs) =

(6) Determine the average height of the specimen with at least four measurements.

Reading 1 (in)	Reading 2 (in)	Reading 3 (in)	Reading 4 (in)
<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>

(7) Determine a water content in an oven using some of the trimmings.

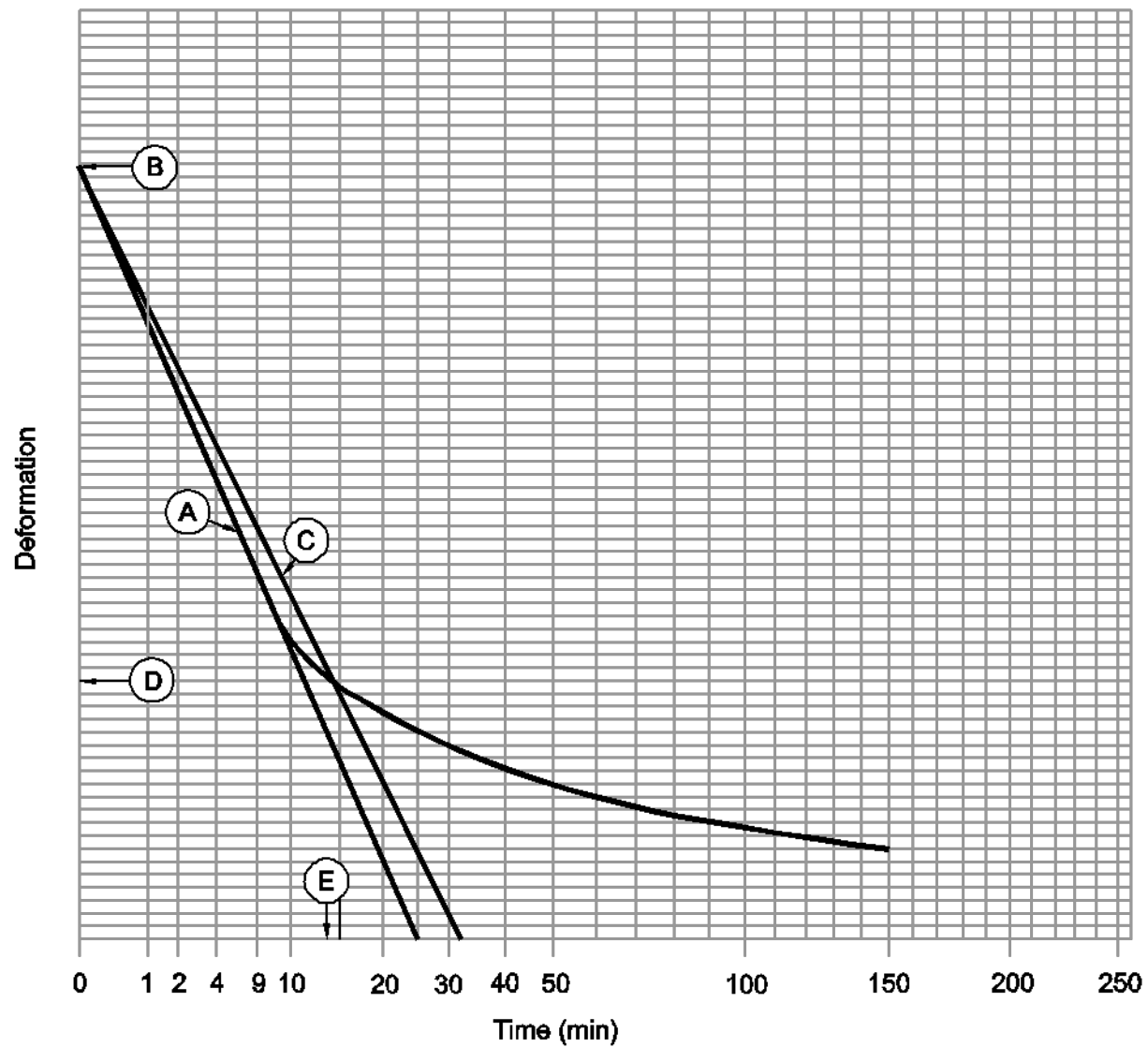
% water content =

Avg height (in) =   
 Volume (in<sup>3</sup>)  
 $v = \pi r^2 h$

Loading increment =  TSF

Loading or unloading?

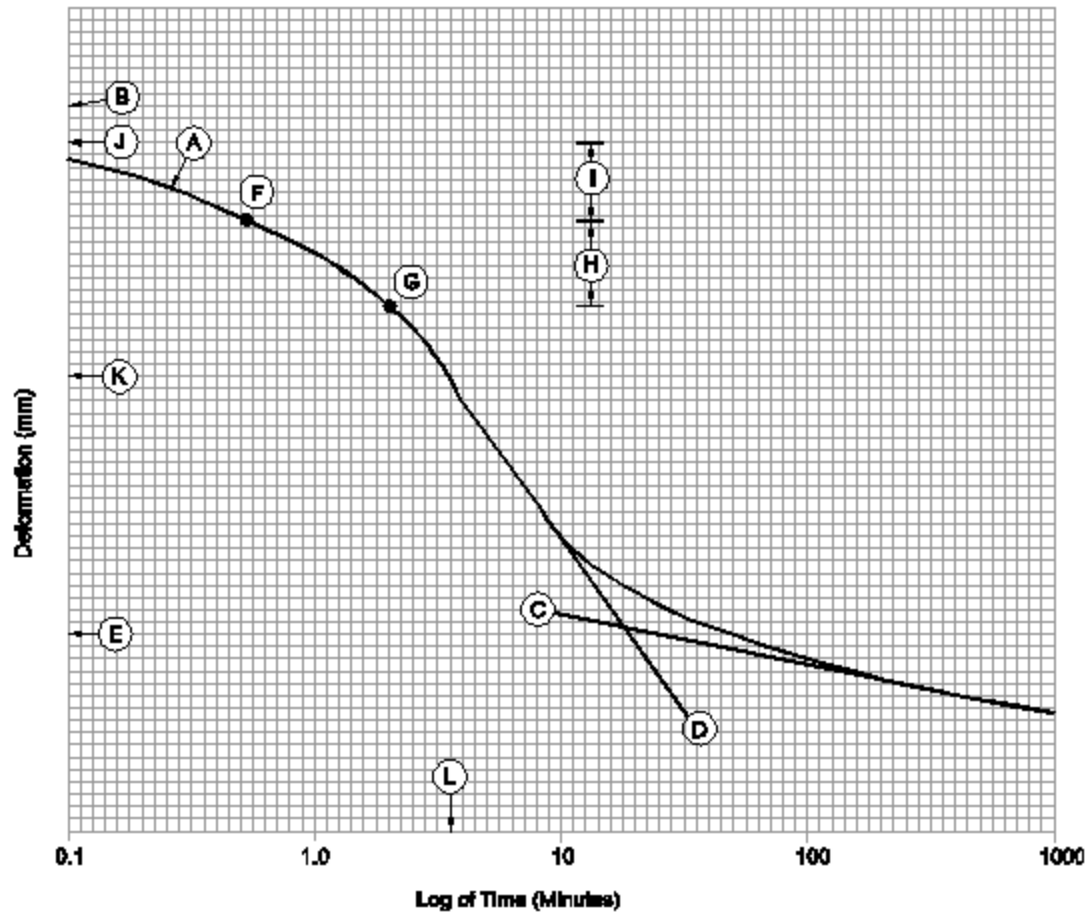
Date	actual time of reading	Gauge reading (in)	Elapsed time (min)
			0
			0.1 0.06sec
			0.25 15sec
			0.5 30sec
			0.75 45sec
			1 60sec
			1.5 90sec
			2 min
			4 min
			6 min
			8 min
			10 min



- A Time deformation curve from data points
- B  $d_0$  extension of initial linear portion of curve A to time = 0 min
- C Construction lines with slope—1.15 times initial linear portion of curve A
- D  $d_{90}$  deformation at point where curve A crosses line C
- E  $t_{90}$  time at point where curve A crosses line C

*Square Root of Time*





- A Time-deformation curve from data points
- B Deformation at time—0 minutes
- C Extension of final linear portion of curve
- D Extension of steepest linear portion of curve
- E  $d_{100}$  deformation at intersection of lines C and D
- F  $t_1$  selected point in time
- G  $t_2$  time at four times  $t_1$  (deformation at time  $t_2$  should be less than 50% and larger than 25% of the total deformation for load increment)
- H Increment of deformation between times  $t_1$  and  $t_2$
- I Increment of deformation equal to F
- J  $d_0$  calculated initial deformation
- K  $d_{50}$  mean of  $d_0$  and  $d_{100}$
- L  $t_{50}$  time at  $d_{50}$

*Log of Time*

**Station 2: AASHTO T 208 Unconfined Compressive Strength of Cohesive Soil**

Technician name		Date	
Job number		Location	
Boring number		Sample number	
Description of sample		Optimum Moisture %	

Moisture content	Before testing	After testing	Optional
Tare #			
Wet soil + tare + lid	(g)	(g)	(g)
Dry soil + tare + lid	(g)	(g)	(g)
Tare + lid	(g)	(g)	(g)
Moisture Content	%	%	%

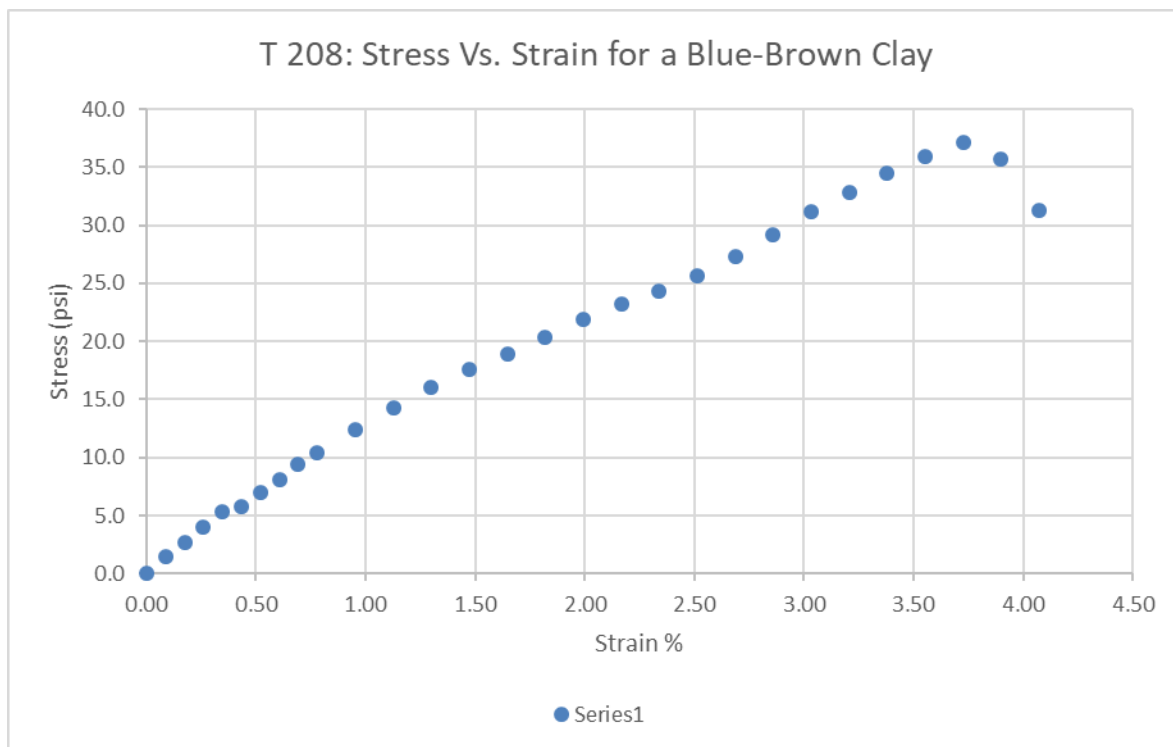
Specimen diameter	At 1/4 height	At 1/2 height	At 3/4 height
Diameter	(in)	(in)	(in)
Average diameter	(in)		

Specimen height	At 0° rotation	At 120° rotation	At 240° rotation
Height	(in)	(in)	(in)
Average height	(in)		
0.5% axial strain / min.	(in/min.)	2% axial strain / min.	(in/min.)
Sample mass before testing	(g)		

Strain rate selected for testing:

Reading	Strain (in)	Load	Reading	Strain (in)	Load
0	0.0		12	.36	
1	.03		13	.39	
2	.06		14	.42	
3	.09		15	.45	
4	.12		16	.48	
5	.15		17	.51	
6	.18		18	.54	
7	.21		19	.57	
8	.24		20	.60	
9	.27		21	.63	
10	.30		22	.66	
11	.33		23	.69	

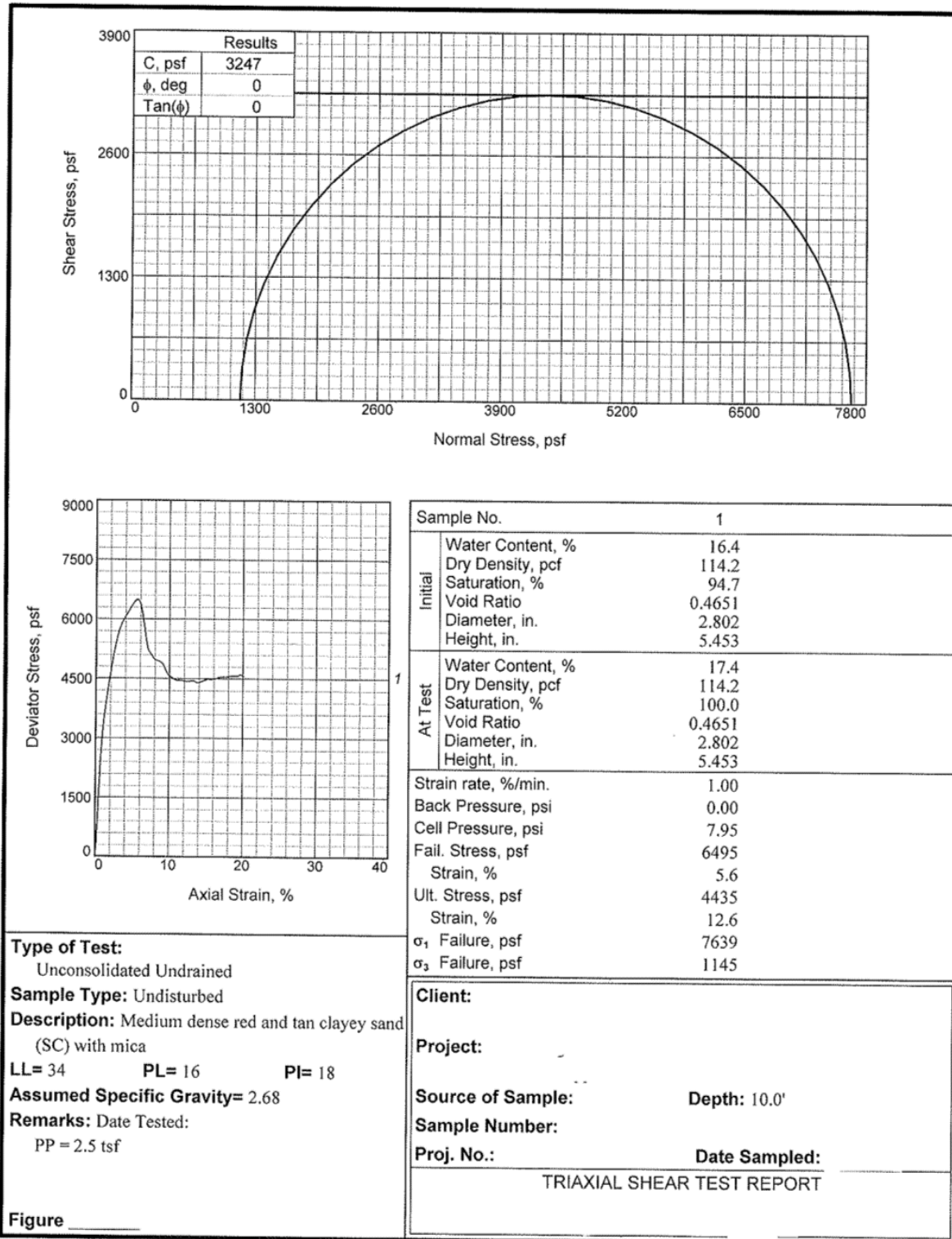
Graph the relationship between compressive stress and axial strain. Report the maximum value of compressive stress, or the compressive stress at 15% axial strain, whichever is secured first, and report it as the unconfined compressive strength.



## Station 2: AASHTO T296 Unconsolidated-Undrained Compressive Strength

						Test No.:		
						Before Test	After Test	
Date: _____	Top Dia.: _____ in.	Ht. @ 120° _____ in.				Tare No.		
Boring No.: _____	Mid Dia.: _____ in.	Ht. @ 240° _____ in.				Wet Wt.+ T.		
Sample No.: _____	Bot. Dia.: _____ in.	Ht. @ 360° _____ in.				Dry Wt.+ T.		
Depth, ft.: _____	Avg. Dia.: _____ in.	Avg. Ht.: _____ in.				Tare Wt.		
PP, tsf _____	Wet Wt.: _____ gms.	PP Top _____				Wt. Water		
LL, % _____		See Frame: _____	See Photo			Wet Soil		
PL, % _____		PP Bot _____	For Failure			Dry Soil		
PI, % _____	Material: _____					Water %		
File Name: _____	Job No. _____	Sp.Gr.: _____	Cell No.: _____	Load	Rate of Strain, % / min.: _____			
						Test No.:		
						Before Test	After Test	
Date: _____	Top Dia.: _____ in.	Ht. @ 120° _____ in.				Tare No.		
Boring No.: _____	Mid Dia.: _____ in.	Ht. @ 240° _____ in.				Wet Wt.+ T.		
Sample No.: _____	Bot. Dia.: _____ in.	Ht. @ 360° _____ in.				Dry Wt.+ T.		
Depth, ft.: _____	Avg. Dia.: _____ in.	Avg. Ht.: _____ in.				Tare Wt.		
PP, tsf _____	Wet Wt.: _____ gms.	PP Top _____				Wt. Water		
LL, % _____		See Frame: _____	See Photo			Wet Soil		
PL, % _____		PP Bot _____	For Failure			Dry Soil		
PI, % _____	Material: _____					Water %		
File Name: _____	-uu -	Sp.Gr.: _____	Cell No.: _____	Load	Rate of Strain, % / min.: _____			
						Test No.:		
						Before Test	After Test	
Date: _____	Top Dia.: _____ in.	Ht. @ 120° _____ in.				Tare No.		
Boring No.: _____	Mid Dia.: _____ in.	Ht. @ 240° _____ in.				Wet Wt.+ T.		
Sample No.: _____	Bot. Dia.: _____ in.	Ht. @ 360° _____ in.				Dry Wt.+ T.		
Depth, ft.: _____	Avg. Dia.: _____ in.	Avg. Ht.: _____ in.				Tare Wt.		
PP, tsf _____	Wet Wt.: _____ gms.	PP Top _____				Wt. Water		
LL, % _____		See Frame: _____	See Photo			Wet Soil		
PL, % _____		PP Bot _____	For Failure			Dry Soil		
PI, % _____	Material: _____					Water %		
File Name: _____	-uu -	Sp.Gr.: _____	Cell No.: _____	Load	Rate of Strain, % / min.: _____			
						Overburden per foot of depth, lbs.: _____		
Remarks: _____								

Tested By: \_\_\_\_\_ Reduced By: \_\_\_\_\_ Checked By: \_\_\_\_\_ Date of Recap.: \_\_\_\_\_



## Station 2: AASHTO T297 Consolidated-Undrained Compressive Strength

Humboldt Scientific, Inc.		Consolidated Undrained Triaxial Test (ASTM D4767)																																																																																																																									
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Checked By:																																																																																																																											
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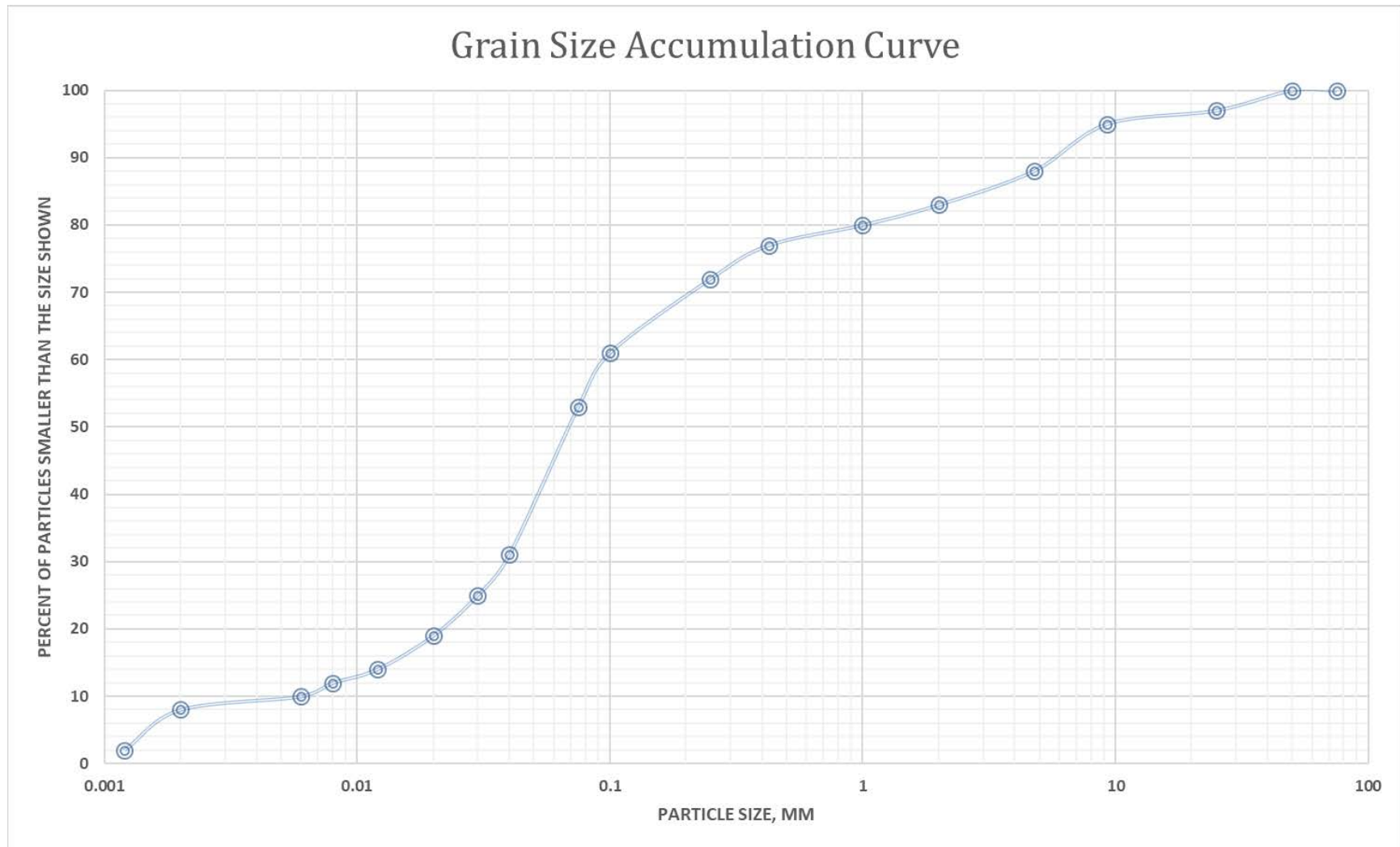
## Station 3: AASHTO T88 Particle Size Analysis of Soils

Hydrometer: 152HMass Coarse Material: 710.70 gPercentage Retained on #10: 11.81%

Hydroscopic Moisture Determination	
Mass of Dish (g)	36.1 g
Mass of Dish and Air Dry Soil (g)	47.0 g
Mass of Air Dry Soil (g)	10.9 g
Mass of Dish and Oven Dry Soil (g)	46.9 g
Mass of Oven Dry Soil (g)	10.8 g
Mass of Moisture Lost (g)	0.1 g
Hygroscopic Moisture (%)	0.93 %

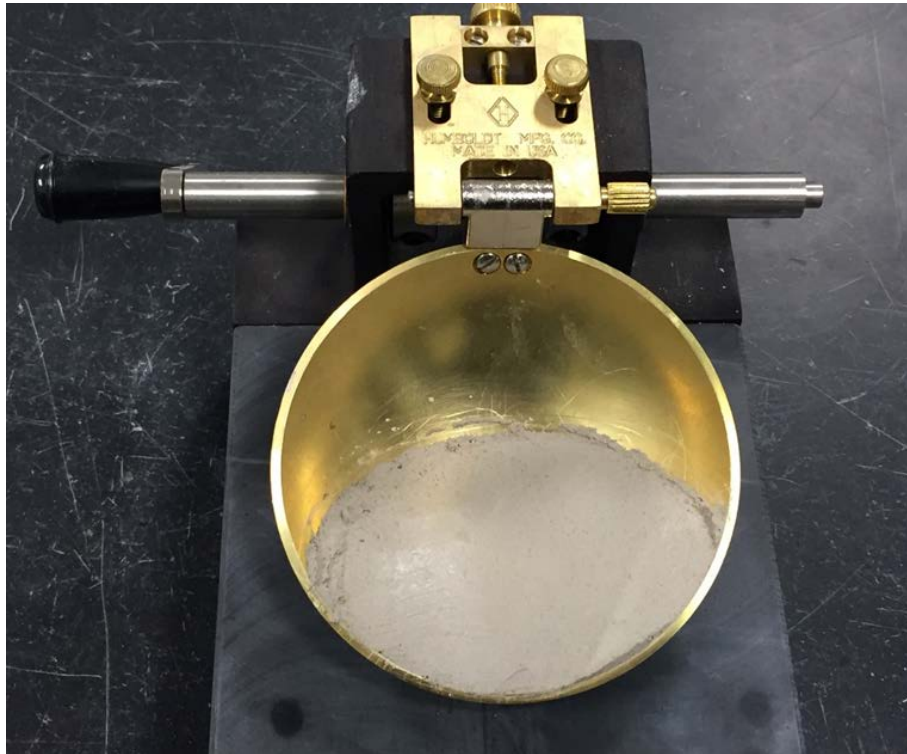
Sample Mass Determination	
Specific Gravity [T100], G	2.75
Specific Gravity Constant, a	0.98
Air-Dry Mass Without Hydroscopic Moisture, (g)	704.09 g
Corrected Mass of Hydrometer Sample, (g)	99.02 g

Hydrometer Test									
Time (min.)	Hydrometer Reading	Temp (°C)	Composite Correction Reading	Temp (°C)	Corrected Reading (R)	Effective Depth (L)	K	D	P
2	40	19.9	56	19.7	37	102	0.0041954	0.029961	63.97%
5	37	19.9	56	19.7	34	107	0.0041954	0.019408	58.40%
15	32	19.9	56	19.7	29	115	0.0041954	0.011617	50.06%
30	30	20.0	56	19.7	28	117	0.0041900	0.008275	45.90%
60	26	20.5	56	19.8	23	125	0.0042155	0.006085	39.00%
250	23.5	22.0	56	20.0	20.5	129.5	0.0040920	0.002945	34.99%
1440	20	21.0	56	19.0	17	135	0.0041390	0.001267	29.32%





**Station 3: AASHTO T89 Liquid Limit**



*Liquid Limit material spread in the brass cup*



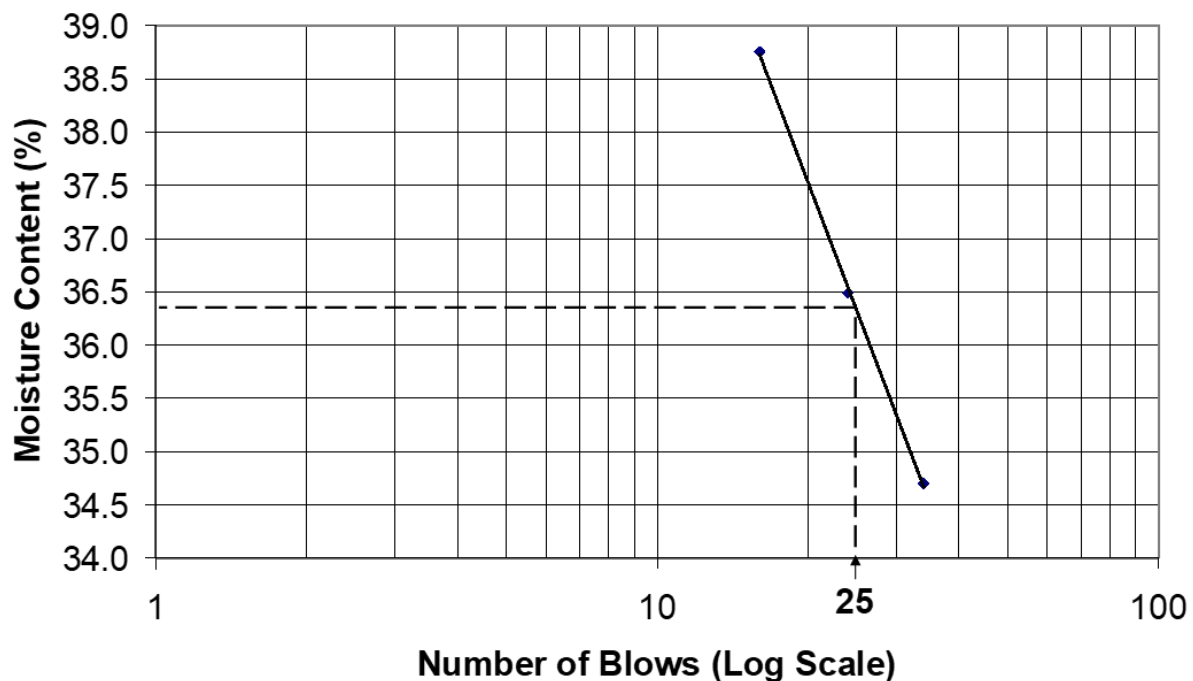
*Closure of soil cake (about 1/2 inch)*

## Liquid Limit Data

Container Number	1	2	3
Number of Shocks	27	22	17
Mass of Empty Container (A)	22.59g	23.22g	17.13g
Mass of Container + Wet Soil (B)	29.81g	34.18g	26.26g
Mass of Container + Dry Soil (C)	27.95g	31.25g	23.71g
Mass of Wet Soil (D = B-A)	7.22g	10.96g	9.13g
Mass of Dry Soil (E = C-A)	5.36g	8.03g	6.58g
Moisture Content ( $[(D-E)/E \times 100]$ )	35%	36%	39%

Liquid Limit = 36.3 (determined by the water content corresponding to the closure at 25 blows)

## Flow Curve of Moisture Content Vs. Number of Shocks



**Station 3: AASHTO T90 Plastic Limit**

*Crumbled soil at its plastic limit*

**Plastic Limit Data**

<b>Container Number</b>	1
<b>Mass of Empty Container (A)</b>	22.59g
<b>Mass of Container + Wet Soil (B)</b>	29.81g
<b>Mass of Container + Dry Soil (C)</b>	27.95g
<b>Mass of Wet Soil (D = B-A)</b>	7.22g
<b>Mass of Dry Soil (E = C-A)</b>	5.36g
<b>Moisture Content (<math>[(D-E)/E \times 100]</math>)</b>	35%

$$\text{Plasticity Index} = \text{LL (36)} - \text{PL (22)}$$

$$\text{Plasticity Index} = 14$$

**Station 3: AASHTO T100 Soil Specific Gravity****Example Calculations**

$$T_x = 26.1^\circ\text{C}$$

$$W_o = 24.89 \text{ g}$$

$$W_a = 351.53 \text{ g}$$

$$W_b = 367.15 \text{ g}$$

$$\text{Specific gravity, } T_x/T_x = 24.89/[24.89 + (351.53 - 367.15)]$$

$$\text{Specific gravity, } T_x/T_x = 2.685$$

$$\text{Specific gravity } T_x/20^\circ\text{C} = 0.9986 \times 2.685$$

$$\text{Specific gravity } T_x/20^\circ\text{C} = 2.681$$

Temperature in °C	Relative Density of Water	Correction Factor <i>K</i>
18	0.9986244	1.0004
19	0.9984347	1.0002
20	0.9982343	1.0000
21	0.9980233	0.9998
22	0.9978019	0.9996
23	0.9975702	0.9993
24	0.9973286	0.9991
25	0.9970770	0.9989
26	0.9968156	0.9986
27	0.9965451	0.9983
28	0.9962652	0.9980
29	0.9959761	0.9977
30	0.9956780	0.9974

**Station 4: AASHTO T99 Moisture-Density Relations of Soils (Standard Effort)**

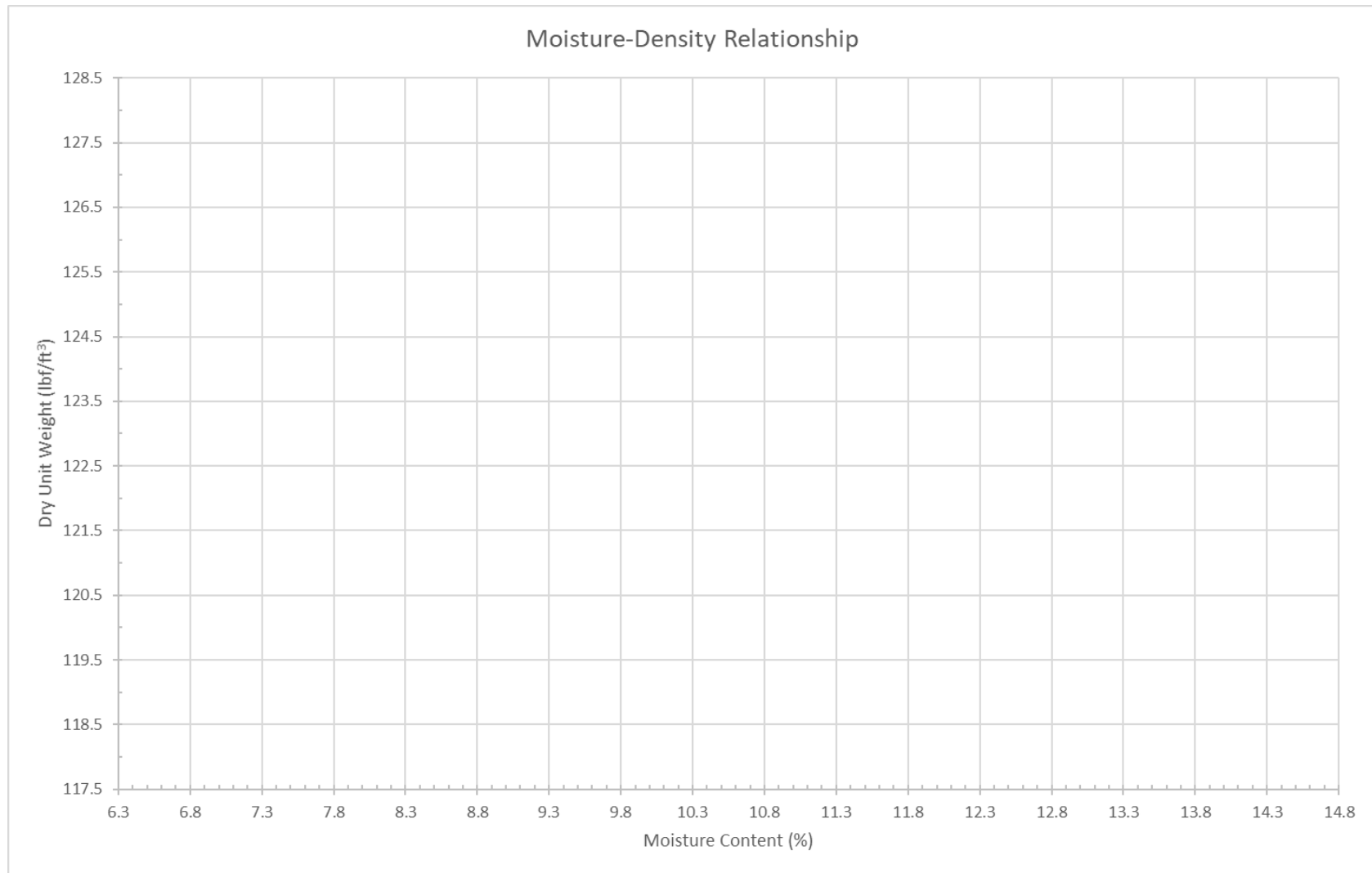
Optimum Moisture Content: \_\_\_\_\_

Max. Dry Density: \_\_\_\_\_

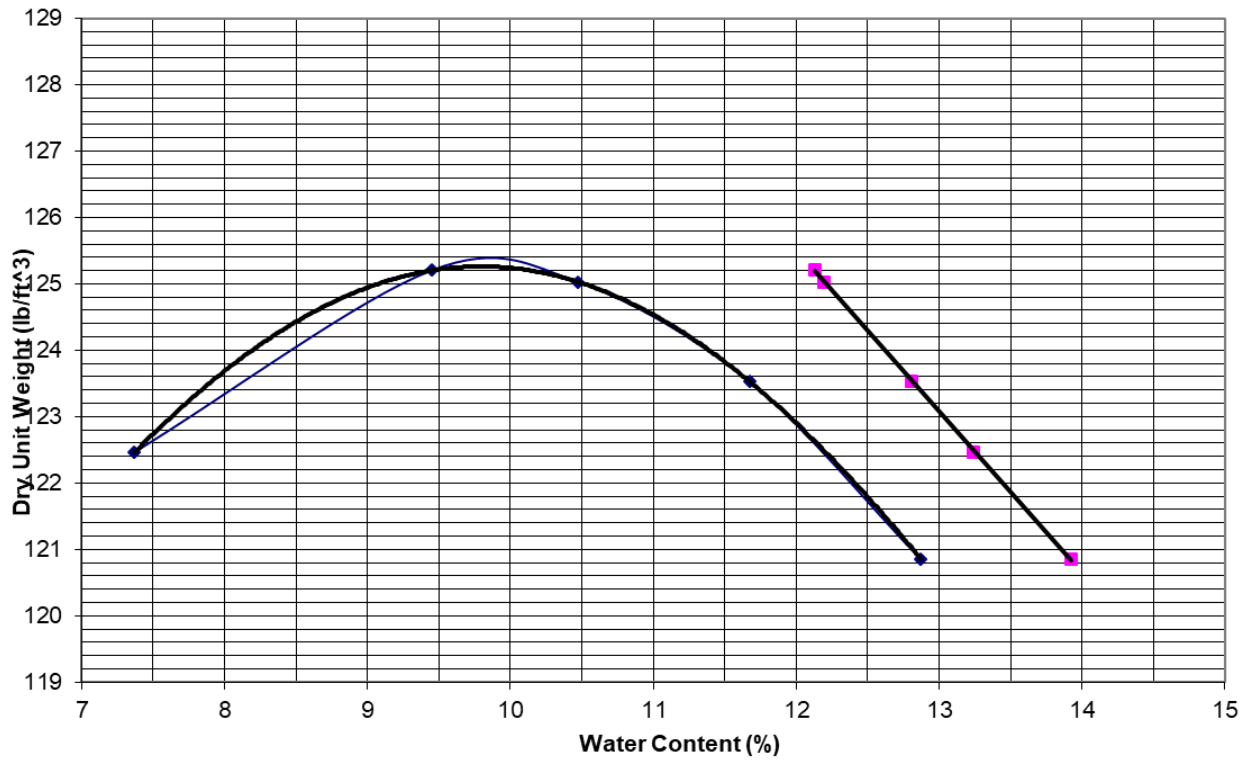
	Point #	1	2	3	4	5
	Mold ID					
V	Volume of Mold (ft <sup>3</sup> )	1/30	1/30	1/30	1/30	1/30
B	Mass of Mold (lb)					
A	Mass of Mold & Specimen (lb)					
M <sub>g</sub>	Mass of Specimen (lb) [A-B]					
W <sub>1</sub>	Wet Density (lb/ft <sup>3</sup> )					
W <sub>lb</sub>	Dry Density (lb/ft <sup>3</sup> )					

	Point #	1	2	3	4	5
	Container ID	1	2	3	4	5
C	Mass of Container & Lid (lb)	0.3011	0.3007	0.3003	0.3016	0.3014
D	Mass of Container, Lid, & Wet Specimen (lb)	0.8953	0.7449	0.8327	1.0459	1.1365
E	Mass of Container, Lid, & Dry Specimen (lb)	0.8545	0.7066	0.7822	0.9680	1.0412
F	Mass of Water (lb) [D-E]	0.0408	0.0383	0.0505	0.0779	0.0953
G	Mass of Dry Sample (lb) [E-C]	0.5534	0.4059	0.4819	0.6664	0.7398
w	Percent Water Content (%)	7.4	9.4	10.5	11.7	12.9

Wet Calculated as follows:  $W_1 = (A - B)/V$ Dry Density Calculated as follows:  $W_{lb} = \frac{W_1}{w+100} \times 100$



Moisture Density Method A and C




## Appendix B: Lab Presentations

Slide 1

[illegible]




# Slide 2




## Lesson Introduction – Resilient Modulus

By the end of this lesson, you will be able to:

- Explain the importance of resilient modulus and its application in pavement design
- Discuss the difference between the strength of a material and the stiffness of a material layer
- Identify factors that influence resilient modulus
- Compare the benefits of direct testing for resilient modulus vs. estimation from other soil properties

 This lesson will take approximately 30 minutes to complete.

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MODULE B

RESILIENT MODULUS

LAB

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[illegible]

Slide 3

## What is Resilient Modulus

- Resilient Modulus ( $M_R$ ) is a measurement of material stiffness
  - Is the primary material property used to characterize roadbed soil for flexible pavements
  - Key information for layered elastic analysis (LEA)
  - Used in the AASHTO Mechanistic-Empirical Pavement Design Guide (MEPDG) to predict pavement performance

[illegible]

# Slide 4

## Strength of materials

- In engineering, we often talk about the strength of a material
  - Strength is measured as a pressure  
 $\text{Strength} = \text{Force} / \text{Area}$
  - Strength is a characteristic of the material
    - For isotropic materials (materials that have the same properties in every direction, such as steel), the shape of the material does not affect its strength
    - For example: if one wire can support a certain load without breaking, adding a second identical wire will double the load that can be supported

[illegible]

Slide 5

## Stiffness of materials

- Stiffness is different from strength in that it depends on factors such as the shape of the material.
- $\text{Stiffness} = \text{Force} / \text{deflection}$  (for a given shape)
- Some shapes deflect more easily in a certain direction
- For example, consider trying to bend a thin metal ruler:
  - If bent in the flat direction, the ruler bends easily. It is not very stiff.
  - If bent across the thickness it will resist strongly
- A stiff object will not deflect very much before it fails

[illegible]

Slide 6

### Two springs example

- Two springs, made from the same material, will have different deflections under a certain load. Even though the strength of the material is the same, the springs have different stiffness.



Slide 7

## Stiffness of pavements

- Strength can predict when something will break or fail
- Stiffness is a useful measurement for pavements because it describes the behavior of the material before it breaks
- Repeated loading and unloading can cause damage and permanent deformation to a material over time (fatigue)
- Resilient modulus measures the elastic properties of building materials and includes information about non-linear behavior for rapidly-applied loads

[illegible]

Slide 8

## Factors that affect stiffness

- Shape is not the only factor that affects stiffness
- Other factors include:
  - Temperature / climate
  - Particle size
  - Moisture content
  - Total stress or confinement pressure
  - Position in pavement layer
- The resilient modulus should be measured for the range of conditions the road will experience during service

[illegible]

Slide 9



## Ice-cream sandwich example

- Think of a pavement system as an ice-cream sandwich. How stiff will the system be at 30°F compared to at 100°F? Which layer will deform the most?




[illegible]



Slide 10

## Pavement layers diagram

- Different pavement layers have varying stiffness



Layer	Stiffness
Surface	High
Base	Medium-High
Subbase	Medium-Low
Subgrade	Low

[illegible]


Slide 11

## Layer analysis

- Most pavement systems will consist of multiple layers
- The interaction between the layers and the stress applied by vehicular traffic is complex
- Resilient Modulus ( $M_R$ ) makes predicting the suitability of a pavement system easier through computer modeling
- Variations in design can be modeled to see which design is best suited for the conditions at the site

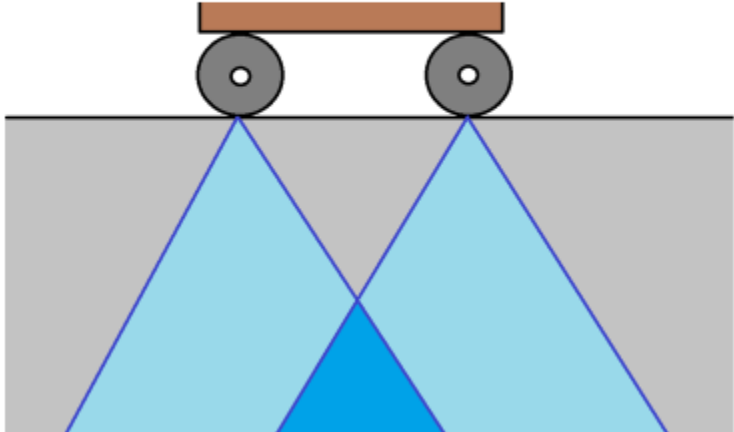
[illegible]

Slide 12



## Position in pavement changes stress

- A vehicle applies a brief load to the pavement as it travels. The stress between the axles is greater than in other areas.



[illegible]

Slide 13

## Resilient Modulus definition

- Resilient Modulus is a measurement of stiffness
- Defined as **Resilient Modulus ( $M_R$ )** =  $\frac{\text{deviator stress}}{\text{resilient strain}}$
- Resilient Modulus is determined by applying a cyclic load to a specimen
- This cyclic load creates the **deviator stress**
- The amount the specimen rebounds is the **resilient strain**

[illegible]

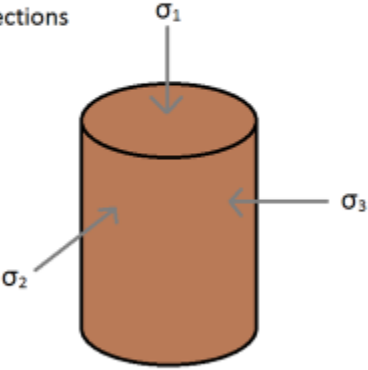
## Slide 14

### Stress states


- Consider a section of soil beneath the surface under some confining force:

Equal force all directions  
 $\sigma_1 = \sigma_2 = \sigma_3$

- In this case,  $\sigma_3$  is the same as  $\sigma_1$  or  $\sigma_2$
- The confining force simulates soil conditions



Confining pressure or Bulk stress,  $\Theta = (\sigma_1 + \sigma_2 + \sigma_3) / 3$



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MODULE B

RESILIENT MODULUS

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## Slide 15

### Deviator stress

- A cyclic load is applied, represented as the deviator stress,  $\sigma_d$
- Total axial stress,  $\sigma_1 = \sigma_d + \sigma_3$
- Deviator stress,  $\sigma_d = \sigma_1 - \sigma_3$
- The deviator stress simulates loading and unloading due to traffic

Cyclic load applied to specimen

New bulk stress,  $\Theta = (\sigma_d + 3\sigma_3) / 3$

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MODULE B

RESILIENT MODULUS

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Slide 16

## Strain

- Strain is how much a material deforms under a load
- $\text{Strain} = \Delta \text{ length} / \text{original length}$

Original length

Change in length  
due to deviator stress

$\sigma_d$

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RESILIENT MODULUS

LAB

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[illegible]

## Slide 17

### Resilient strain

- Resilient strain is how much the material rebounds
- Also termed recoverable axial strain

Original length

Change in length due to deviator stress

$\sigma_d$

Resilient strain is how much length the specimen recovers when the force is removed

recovered length

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MODULE B

RESILIENT MODULUS

LAB

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Slide 18

## Methods that measure Resilient Modulus

- Several test methods can be used to determine  $M_R$ :
  - Indirect tension test for bituminous mixtures
  - Vane shear testing for in-place soil
  - Triaxial testing for soil materials
- This presentation will focus on triaxial testing, AASHTO T 307

[illegible]

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## Overview of AASHTO T 307



- A cylindrical soil sample is placed in a triaxial testing chamber
- A confining pressure is applied to the sample
- The sample is conditioned with 500 or 1000 repetitions of a small vertical load
- A cyclic vertical load is applied to the sample and the resulting change in height is measured using an LVDT system
- Load sequences applied varying the confining pressure and maximum axial stress, so that the resilient modulus can be determined for different conditions
- Testing ends if the sample exceeds 5% permanent deformation

Slide 20

### Sample preparation




- The most common in-lab sample prep is the two plungers method. Uses a solid mold and static load to make a sample.
  - Standard contains 3 Annexes about sample preparation for different soil types
- 




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## Prepared sample

- Sample must be free of gouges and discontinuities
- Take 3 measurements of diameter and of height





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
[illegible]

Slide 22



## Sample preparation is key

- Moisture content can change the results drastically
- It is vital to prepare the soil to the target moisture content
- Goal is to create a uniform sample at the correct moisture content



Moisture content can change the results drastically.

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[illegible]

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## T 307 Equipment

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- Triaxial testing cell
- Two LVDTs









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- Triaxial testing cell
- Two LVDTs



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## LVDTs must agree

- LVDTs are checked at the beginning of the test to see if they give the same results
- Misalignment is a common problem
  - Make every effort to get the LVDTs to agree within 10%
  - Agreeing within 30% is acceptable error
  - If the LVDTs are not within 30%, test must be discontinued and alignment fixed.

[illegible]

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### Assembled triax cell

- Assembled like any triax sample
- Covered with a membrane and sealed with O-rings





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## T 307 sample conditioning

- After the sample is loaded in the triaxial chamber the conditioning procedure is performed
- Same idea as a seating load for a normal triaxial test
  - Small load compared to later testing
  - Checks that equipment is aligned before starting test
  - Establishes the “initial height” of the specimen
  - 500 to 1000 repetitions of load

The HVE logo consists of a blue circle containing the white letters "HVE". A black pencil icon is positioned at the bottom right of the circle.

A vertical ruler with markings from 1 to 15 inches. The numbers are printed in black along the right edge of the ruler.

The U.S. Department of Transportation logo features a stylized circular emblem with a road winding through it.

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[illegible]

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## Compression device

- Sample is loaded using a special compression device



[illegible]

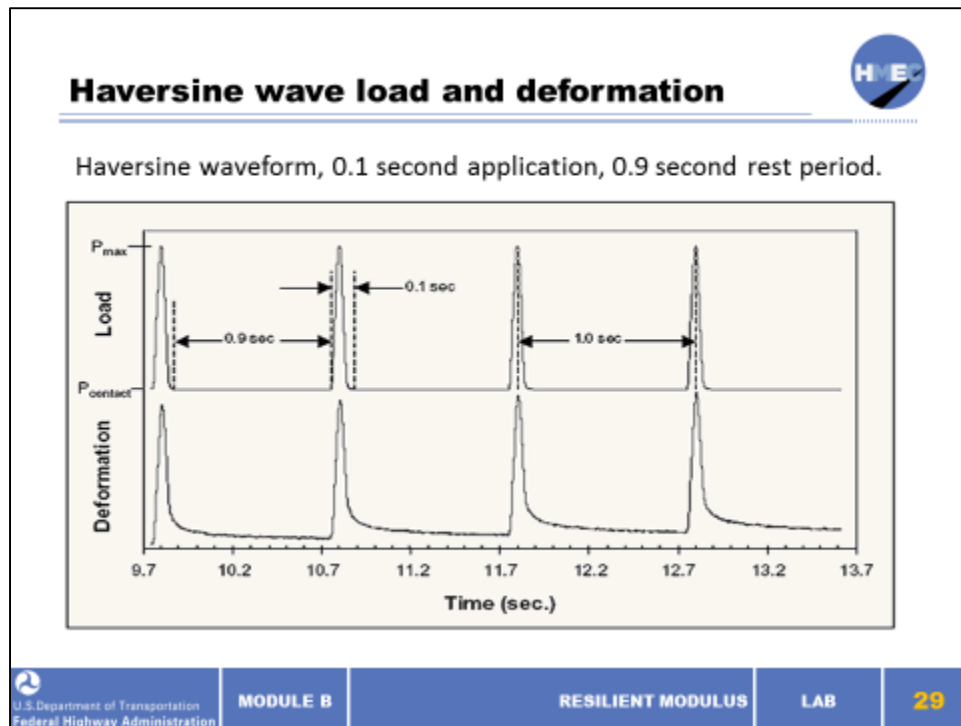
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## Cyclic load applied

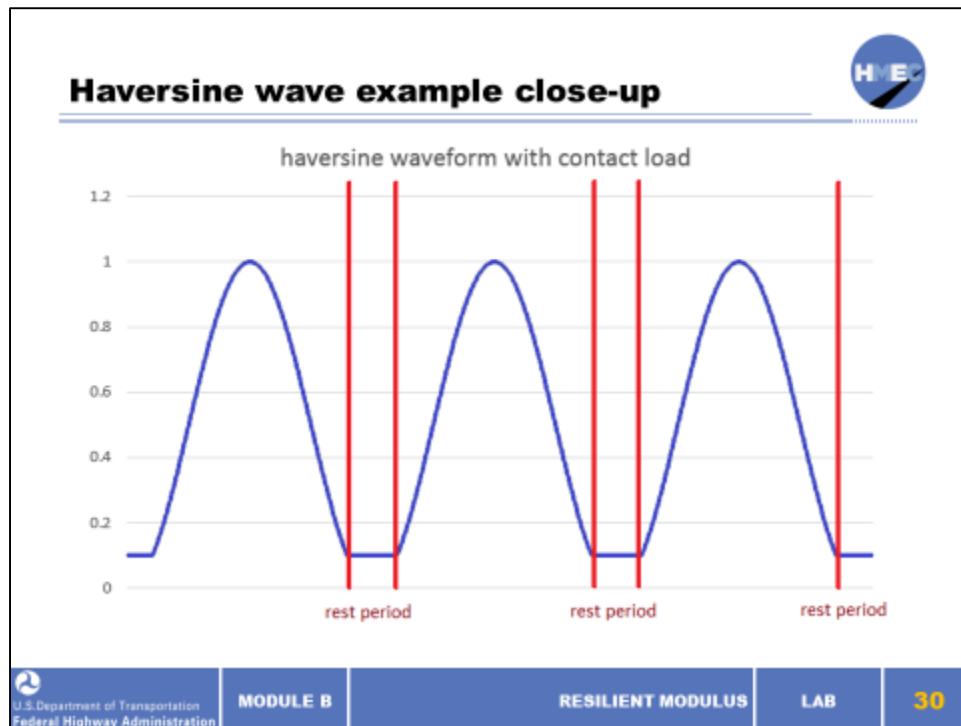
- Haversine waveform load applied to sample
  - Load duration 0.1 seconds
  - Rest period 0.9 seconds
  - Load on sample is not zero during rest period, “contact load” equal to 10% of max load is always maintained
  - Load repeated 100 times
- Soil change in height monitored by LVDTs

[illegible]

## Slide 29




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## Slide 31

### Loading sequence

- After applying load 100 times, continue to next load sequence
- Each load sequence tests different axial stress and confining pressure conditions
- Load applied 100 times during each sequence
- ~ 800,000 data points in 40 minutes



Sequence	Confining pressure (psi)	Max axial stress (psi)
1	6	2
2	6	4
3	6	6
4	6	8
5	6	10
6	4	2
7	4	4
8	4	6
9	4	8
10	4	10
11	2	2
...	...	...

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## Permanent vertical strain

- This test is determining recoverable vertical strain
- If the sample stops recovering, then useful data can no longer be obtained
- If permanent vertical strain exceeds 5% of specimen height, the test ends
- If not, quick shear test takes specimen to 5% strain

[illegible]

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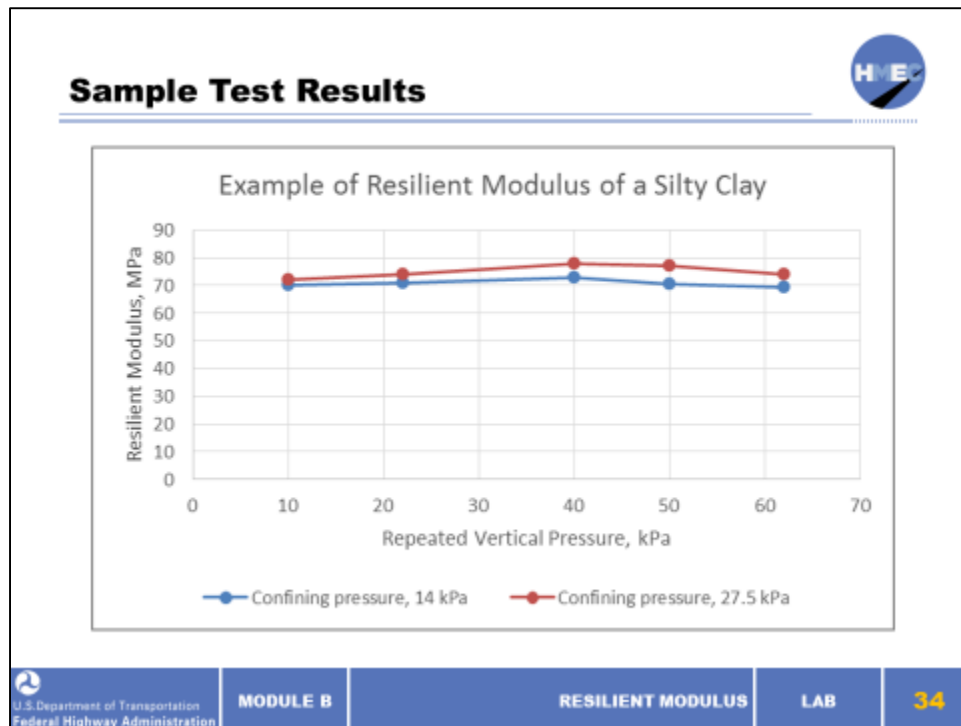
## Calculate $M_R$

- Resilient Modulus ( $M_R$ ) = deviator stress / resilient strain
- Deviator stress determined from load sequence
- Resilient strain determined from LVDT data
- Test performed on more samples to determine effects of different moisture contents
- Typical  $M_R$  values for unbound aggregate base range from 15,000 to 60,000 psi

[illegible]



## Slide 34



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## Usefulness of $M_R$




- Resilient modulus can be used in layered elastic analysis
- Used to predict strain at the bottom of HMA layer
  - Excess strain on bottom of HMA causes “fatigue cracking”
- Used to predict vertical stress at the top of subgrade
  - Excess stress at top of subgrade causes rutting
- Excellent resource for iterative pavement design

[illegible]

Slide 36

## Measurement vs. Estimation

- Many agencies recommend estimation of  $M_R$  for some designs because the T307 test for  $M_R$  is
  - Time-consuming
  - Uses expensive equipment
  - Requires lots of sample material



[illegible]


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## Equations for estimation of $M_R$

- There are many equations used to estimate  $M_R$
- Most estimation equations are only valid for a small range of materials (Ex: fine grained soils with  $CBR < 20$ )
- Example: based on California Bearing Ratio (CBR)
  - $M_R \text{ (psi)} = 2555 \text{ (CBR)}^{0.64}$
- Example: Hveem R-value is used by the AASHTO Mechanistic-Empirical Pavement Design Guide (MEPDG)
  - $M_R \text{ (psi)} = 1155 + 555 * R\text{-value}$


[illegible]

## Slide 38



### Estimation issues

- Variation between estimated and measured value is often 20% or more
- If  $M_R$  is estimated in a design, a higher factor of safety should be used to compensate

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## **Best practices for $M_R$**

- Typical testing plan:
  - Test according to T 307 for resilient modulus on a variety of local samples
  - Use T 307 results to validate a correlation equation
  - Test for the correlated property on the majority of samples and estimate  $M_R$

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[illegible]


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## Lesson Summary

You are now able to:

- Explain the importance of resilient modulus and its application in pavement design
- Discuss the difference between the strength of a material and the stiffness of a material layer
- Identify factors that influence resilient modulus
- Compare the benefits of direct testing for resilient modulus vs. estimation from other soil properties

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