Transportation Technician Qualification Program

EMBANKMENT & BASE IN-PLACE DENSITY

Workbook

Updated November 2023

Contents

WAQTC Embankment and Base In-Place Density

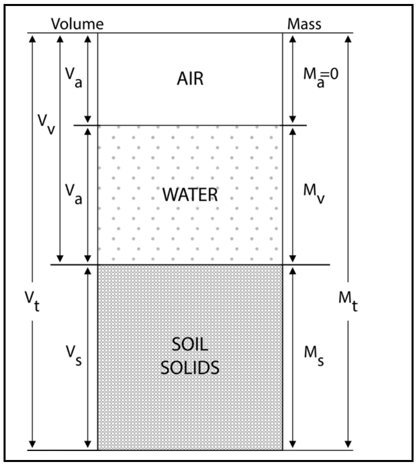
CDOT Soils, Excavation, & Embankment Inspection Manual

TOTAL EVAPORABLE MOISTURE CONTENT OF AGGREGATE BY DRYING FOP FOR AASHTO T 255

LABORATORY DETERMINATION OF MOISTURE CONTENT OF SOILS FOP FOR AASHTO T 265

Significance

01 The amount of water contained in many materials
influences design and construction practices. Road
02 bases are difficult to compact if they are too dry or
too wet. If too dry, water must be added, and the
amount to be added depends on how much is
already present.



Phase diagram

Scope

03 This procedure covers the determination of moisture content of aggregate and soil in accordance with AASHTO T 255-22 and AASHTO T 265-22. It may also be used for other construction materials.

Apparatus

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Overview

05 Moisture content is determined by comparing the wet mass of a sample and the mass of the sample after drying to constant mass. The term constant mass is used to define when a sample is dry.

Constant mass – the state at which a mass does not change more than a given percent, after additional drying for a defined time interval, at a required temperature.

Apparatus

- 06 Balance or scale: capacity sufficient for the principal sample mass, accurate to 0.1 percent of sample mass or readable to 0.1 g., and meeting the requirements of AASHTO M 231
- 07 Container: clean, dry, and capable of being sealed
- 08 Suitable drying container
  - 09 For soils: container requires close-fitting lid
  - For aggregate: container lid is optional

Containers with lids for drying soils

Forced Air Oven

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Infrared Oven

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- Microwave safe container with ventilated lid (for drying aggregate only)
- Heat source, thermostatically controlled, capable of maintaining 110 ± 5°C (230 ± 9°F).
- Forced draft oven (preferred)
- Ventilated oven
- Convection oven
- Heat source, uncontrolled, for use when allowed by the agency, will not alter the material being dried, and close control of the temperature is not required:
  - Infrared heater/heat lamp, hot plate, fry pan, or any other device/method allowed by the agency
  - Microwave oven (900 watts minimum)
- Utensils such as spoons
- Hot pads or gloves

Sample Preparation

Obtain the sample in accordance with the FOP for AASHTO R 90 in its existing condition. If necessary, reduce the sample to moisture content sample size according to the FOP for AASHTO R 76.

For aggregate, the moisture content sample size is based on Table 1 or other information that may be specified by the agency.

15 **TABLE 1**
Sample Sizes for Moisture Content of Aggregate

Nominal Maximum Size* mm (in.)	Minimum Sample Mass g (lb)
150 (6)	50,000 (110)
100 (4)	25,000 (55)
90 (3 1/2)	16,000 (35)
75 (3)	13,000 (29)
63 (2 1/2)	10,000 (22)
50 (2)	8000 (18)
37.5 (1 1/2)	6000 (13)
25.0 (1)	4000 (9)
19.0 (3/4)	3000 (7)
12.5 (1/2)	2000 (4)
9.5 (3/8)	1500 (3.3)
4.75 (No. 4)	500 (1.1)

* One sieve larger than the first sieve to retain more than 10 percent of the material using an agency specified set of sieves based on cumulative percent retained. Where large gaps in specification sieves exist, intermediate sieve(s) may be inserted to determine nominal maximum.

For soil, the moisture content sample size is based on Table 2 or other information that may be supplied by the agency.

16 **TABLE 2**
Sample Sizes for Moisture Content of Soil

Maximum Particle Size mm (in.)	Minimum Sample Mass g
50 (2)	1000
25.0 (1)	500
12.5 (1/2)	300
4.75 (No. 4)	100
0.425 (No. 40)	10

Immediately seal or cover moisture content samples to prevent any change in moisture content or follow the steps in “Procedure.”

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Procedure

Determine and record the sample masses as follows:

18

- For aggregate, determine and record all masses to the nearest 0.1 percent of the sample mass or to the nearest 0.1 g.
- For soil, determine and record all masses to the nearest 0.1 g.

When determining the mass of hot samples or containers or both, place and tare a buffer between the sample container and the balance. This will eliminate damage to or interference with the operation of the balance or scale.

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1. Determine and record the mass of the container.
    a. For soils: the container includes the mass of the close-fitting lid.
    b. For aggregate: the lid is optional unless drying with a microwave then a ventilated lid is required.
2. Place the wet sample in the container.
3. Determine and record the total mass of the container and wet sample.
    a. For oven(s), hot plates, infrared heaters, etc.: Spread the sample in the container.
    b. For microwave oven: Heap sample in the container; cover with ventilated lid.
4. Determine and record the wet mass of the sample (M_W) by subtracting the container mass as determined in Step 1 from the mass of the container and sample in Step 3.
5. Place the sample in one of the following drying apparatuses: 20
    a. For aggregate –
        i. Controlled heat source (oven): at 110 ±5°C (230 ±9°F).
        ii. Uncontrolled heat source (Hot plate, infrared heater, or other heat source as

allowed by the agency): Stir frequently to avoid localized overheating.

b. For soil – controlled heat source (oven): at 110 ±5°C (230 ±9°F).

Note 1: Soils containing gypsum or significant amounts of organic material require special drying. For reliable moisture contents, dry these soils at 60°C (140°F). For more information see AASHTO T 265, Note 2.

6. Dry until sample appears moisture free.
7. Determine mass of sample and container.
8. Determine and record the mass of the sample by subtracting the container mass determined in Step 1 from the mass of the container and sample determined in Step 7.

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Hotplate 22

9. Return sample and container to the heat source for the additional time interval.
   a. Drying intervals for aggregate –
      i. Controlled heat source (oven): 30 minutes
      ii. Uncontrolled heat source (Hot plate, infrared heater, or other heat source as allowed by the agency): 10 minutes
      iii. Uncontrolled heat source (Microwave oven): 2 minutes

Caution: Some minerals in the sample may cause the aggregate to overheat, crack, and explode; altering the aggregate gradation.

   b. Drying interval for soil – controlled heat source (oven): 1 hour

10. Determine mass of sample and container.
11. Determine and record the mass of the sample by subtracting the container mass determined in Step 1 from the mass of the container and sample determined in Step 10. 23
12. Determine percent change by subtracting the new mass determination (M_n) from the previous mass determination (M_p), dividing by the previous mass determination (M_p), and multiplying by 100. 24
13. Continue drying, performing steps 9 through 12, until there is less than a 0.10 percent change after additional drying time.
14. Constant mass has been achieved; sample is defined as dry.
15. Allow the sample to cool. Immediately determine and record the total mass of the container and dry sample.
16. Determine and record the dry mass of the sample (M_D) by subtracting the mass of the container determined in Step 1 from the mass of the container and sample determined in Step 15.
17. 25 Determine and record percent moisture (w) by subtracting the final dry mass determination (M_D) from the initial wet mass determination (M_W), dividing by the final dry mass determination (M_D), and multiplying by 100.

Table 3
Methods of Drying

Aggregat		
Heat Source	**Specific Instructions**	**Drying intervals to achieve constant mass (minutes)**
Controlled: Forced draft (preferred), ventilated, or convection oven	110 ±5°C (230 ±9°F)	30
Uncontrolled:		
Hot plate, infrared heater, or other device/method as allowed by the agency.	Stir frequently	10
Microwave	Heap sample and cover with ventilated lid	2
Soil		
Heat Source	**Specific Instructions**	**Drying interval to achieve constant mass**
Controlled: Forced draft (preferred), ventilated, or convection oven	110 ±5°C (230 ±9°F)	1 hour

Calculation

Constant Mass

Calculate constant mass using the following formula:

$$\% \, Change = \frac{M_p - M_n}{M_p} \times 100$$

Where:

M_p = previous mass measurement

M_n = new mass measurement

Example:

Mass of container:	1232.1 g
Mass of the container and sample after first drying cycle:	2637.2 g
Mass, M_p, of possibly dry sample:	2637.2 g - 1232.1 g = 1405.1 g
Mass of container and sample after second drying cycle:	2634.1 g
Mass, M_n, of sample:	2634.1 g - 1232.1 g = 1402.0 g

$$\% \, Change = \frac{1405.1\,g - 1402.0\,g}{1405.1\,g} \times 100 = 0.22\%$$ 27

0.22 percent is not less than 0.10 percent, so continue drying

Mass of container and sample after third drying cycle: 2633.0 g

Mass, M_n, of sample: 2633.0 g - 1232.1 g = 1400.9 g

$$\% \, Change = \frac{1402.0\,g - 1400.9\,g}{1402.0\,g} \times 100 = 0.08\%$$ 28

0.08 percent is less than 0.10 percent, so constant mass has been reached.

Moisture Content Aggregate and Soils:

Calculate the moisture content, as a percent, using the following formula:

$$w = \frac{M_W - M_D}{M_D} \times 100$$

where:

w = moisture content, percent

M_W = wet mass

M_D = dry mass

Example: 29

Mass of container: 1232.1 g

Mass of container and wet sample: 2764.7 g

Mass, M_W, of wet sample: 2764.7 g - 1232.1 g = 1532.6 g

Mass of container and dry sample **(COOLED)**: 2633.5 g

Mass, M_D, of dry sample: 2633.5 g - 1232.1 g = 1401.4 g

$$w = \frac{1532.6\ g - 1401.4\ g}{1401.4\ g} \times 100 = \frac{131.2\ g}{1401.4\ g} \times 100 = 9.36\% \quad report\ 9.4\%$$

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Report

- On forms approved by the agency
- Sample ID
- M_W, wet mass
- M_D, dry mass
- w, moisture content to the nearest 0.1 percent

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Tips!

- Let the sample cool before determining final dry mass.
- Divide by M_D, not M_W.

REVIEW QUESTIONS

1. What extra care should be taken when using a microwave to dry aggregates?

2. What is the maximum temperature that a sample should be allowed to attain for each of the various types of ovens?

3. How is “constant mass” defined according to this FOP:

   For Aggregate?

   For Soil?

REVIEW QUESTIONS (KEY)

1. What extra care should be taken when using a microwave to dry aggregates?

Heap the sample in the center of a microwave safe container and cover it with a ventilated lid. ***(from AASHTO T 255 / T 265, Procedure, Step 2 (b), page 3-3)***

2. What is the maximum temperature that a sample should be allowed to attain for each of the various types of ovens?

For a controlled heat source *(forced draft, ventilated or convection oven),* maximum temperature allowed is **230º F** *(plus or minus 9). Temperatures for the various uncontrolled ovens and for microwaves will just be as is.*
(from AASHTO T 255 / T 265, Procedure, Step 5 (a & b), page 3-4)

3. How is "constant mass" defined according to this FOP:

For Aggregate?

Less than a 0.10 percent mass change after additional drying time.
(from AASHTO T 255 / T 265, Procedure, Step 13, page 3-5)

For Soil?

Less than a 0.10 percent mass change after additional drying time. Note: *Typically,* a soil sample dried overnight at 230° F is sufficient.
(from AASHTO T 255 / T 265, Procedure, Step 13, page 3-5)

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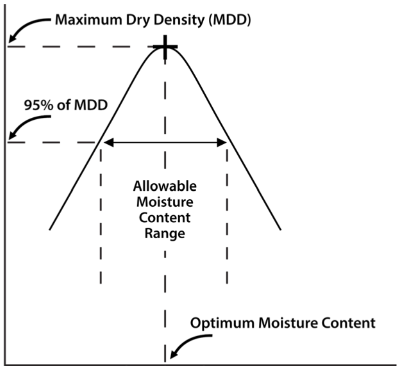
MOISTURE-DENSITY RELATIONS OF SOILS:

USING A 2.5 KG (5.5 LB) RAMMER AND A 305 MM (12 IN.) DROP FOP FOR AASHTO T 99

USING A 4.54 KG (10 LB) RAMMER AND A 457 MM (18 IN.) DROP FOP FOR AASHTO T 180

Steel roller

Adding water



Moisture vs. dry density

Significance

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02 The density or degree of compaction, of soil or soil-
aggregate mixtures has a significant influence on
the stability and durability of roadways. Low
density subgrade, subbase, base, or embankment
will lead to excessive deflection under load or long-
term settlement in an amount higher than
03 anticipated, or both. Obtaining proper density
04 depends on two major factors: compactive effort
and moisture content.

Compactive effort relates to the type and weight of
compaction equipment, along with the thickness of
the "lift" being compacted and the number of times
each lift is passed over by the compaction
05 equipment. Equipment includes static and vibratory
06 rollers, smooth and sheepsfoot steel rollers, and
pneumatic tire rollers of varied weights yielding
many different compactive efforts.

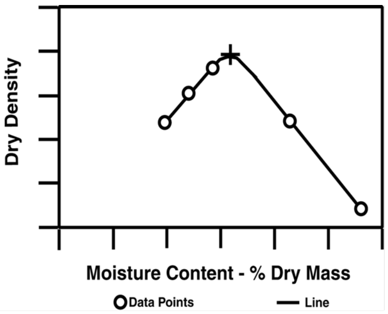
Density also depends upon moisture content. The
moisture content corresponding to maximum dry
07 density of the soil or soil-aggregate mixture under a
given compactive effort is known as optimum water
content. As the water content increases or
08 decreases from this optimum value, the dry density
decreases.

Agency specifications commonly require that a certain percentage of maximum dry density be obtained while the moisture content of the soil or soil-aggregate mixture is held within certain limits. For example, a specification might call for 95 percent of maximum dry density with a moisture content of the optimum value ± 2 percent. For these reasons, it is critical to understand the various test methods and equipment used in determining the moisture-density relations of soil.

Scope

This procedure covers the determination of the moisture-density relations of soils and soil-aggregate mixtures in accordance with two similar test methods:

- 09 AASHTO T 99-22: Methods A, B, C, and D
- AASHTO T 180-22: Methods A, B, C, and D



Optimum water content

This test method applies to soil mixtures having
40 percent or less retained on the 4.75 mm (No. 4)
sieve for methods A or B, or 30 percent or less on
10 the 19 mm (¾ in.) sieve with methods C or D. The
retained material is defined as oversize (coarse)
11 material. If no minimum percentage is specified,
5 percent will be used. Samples containing oversize (coarse) material that meet the percent retained criteria should be corrected by using *Annex A, Correction of Maximum Dry Density and Optimum Moisture for Oversized Particles*. Samples of soil or soil-aggregate mixture are prepared at several moisture contents and compacted into molds of specified size, using manual or mechanical rammers that deliver a specified quantity of compactive energy. The moist masses of the compacted samples are divided by the volume of the mold to determine wet density values. Moisture contents of the compacted samples are determined and used to obtain the dry density values of the same samples. Maximum dry density and optimum moisture content for the soil or soil-aggregate mixture is determined by plotting the relationship between dry density and moisture content.

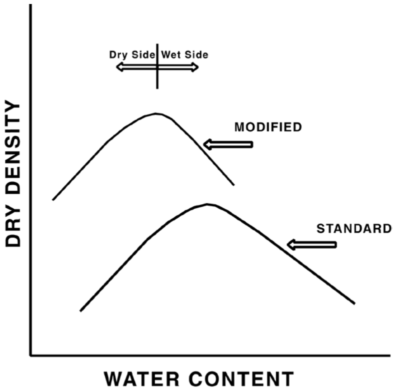
Apparatus

Molds and Rammer

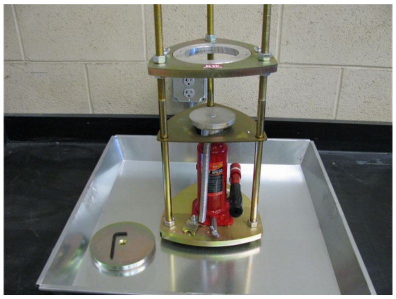
- Mold – Cylindrical mold made of metal with the dimensions shown in Table 1 or Table 2. If permitted by the agency, the mold may be of the "split" type, consisting of two half-round sections, which can be securely locked in place to form a cylinder. Determine the mold volume according to *Annex B*, *Standardization of the Mold*.
- Mold assembly – Mold, base plate, and a detachable collar.

- Rammer – Manually or mechanically operated rammers as detailed in Table 1 or Table 2. A manually operated rammer shall be equipped with a guide sleeve to control the path and height of drop. The guide sleeve shall have at least four vent holes no smaller than 9.5 mm (3/8 in.) in diameter, spaced approximately 90 degrees apart and approximately 19 mm (3/4 in.) from each end. A mechanically operated rammer will uniformly distribute blows over the sample and will be calibrated with several soil types, and shall be adjusted, if necessary, to give the same moisture-density results as with the manually operated rammer. For additional information concerning calibration, see AASHTO T 99 and T 180.

Mechanical Rammer



- Sample extruder – A jack, lever frame, or other device for extruding compacted specimens from the mold quickly and with little disturbance.



Sample extruder

- Balance(s) or scale(s) of the capacity and sensitivity required for the procedure used by the agency.

  A balance or scale with a capacity of 11.5 kg (25 lb) and a sensitivity of 1 g for obtaining the sample, meeting the requirements of AASHTO M 231, Class G 5.

  A balance or scale with a capacity of 2 kg and a sensitivity of 0.1 g is used for moisture content determinations done under both procedures, meeting the requirements of AASHTO M 231, Class G 5.

- Drying apparatus – A thermostatically controlled drying oven, capable of maintaining a temperature of 110 ±5°C (230 ±9°F) for drying moisture content samples in accordance with the FOP for AASHTO T 255/T 265.

- Straightedge – A steel straightedge at least 250 mm (10 in.) long, with one beveled edge and at least one surface plane within 0.1 percent of its length, used for final trimming.

4.75 mm (No. 4) sieve - Straight edge

- Sieve(s) – 4.75 mm (No. 4) and/or 19.0 mm (3/4 in.), meeting the requirements of FOP for AASHTO T 27/T 11.
- Mixing tools – Miscellaneous tools such as a mixing pan, spoon, trowel, spatula, etc., or a suitable mechanical device, for mixing the sample with water.
- Containers with close-fitting lids to prevent gain or loss of moisture in the sample.

Table 1
Comparison of Apparatus, Sample, and Procedure - Metric

	T 99	**T 180**
Mold Volume, m^3	Methods A, C: 0.000943 ±0.000014	Methods A, C: 0.000943 ±0.000014
	Methods B, D: 0.002124 ±0.000025	Methods B, D: 0.002124 ±0.000025
Mold Diameter, mm	Methods A, C: 101.60 ±0.40	Methods A, C: 101.60 ±0.4
	Methods B, D: 152.40 ±0.70	Methods B, D: 152.40 ±0.70
Mold Height, mm	116.40 ±0.50	116.40 ±0.50
Detachable Collar Height, mm	50.80 ±0.64	50.80 ±0.64
Rammer Diameter, mm	50.80 ±0.25	50.80 ±0.25
Rammer Mass, kg	2.495 ±0.009	4.536 ±0.009
Rammer Drop, mm	305 ±2	457 ±2
Layers	3	5
Blows per Layer	Methods A, C: 25	Methods A, C: 25
	Methods B, D: 56	Methods B, D: 56
Material Size, mm	Methods A, B: 4.75 minus	Methods A, B: 4.75 minus
	Methods C, D: 19.0 minus	Methods C, D: 19.0 minus
Test Sample Size, kg	Method A: 3 Method B: 7 Method C: 5 (1) Method D: 11(1)	
Energy, kN-m/m^3	592	2,693

(1) This may not be a large enough sample depending on your nominal maximum size for moisture content samples.

Table 2
Comparison of Apparatus, Sample, and Procedure - English

	T 99	**T 180**
Mold Volume, ft^3	Methods A, C: 0.0333 ±0.0005	Methods A, C: 0.0333 ±0.0005
	Methods B, D: 0.07500 ±0.0009	Methods B, D: 0.07500 ±0.0009
Mold Diameter, in.	Methods A, C: 4.000 ±0.016	Methods A, C: 4.000 ±0.016
	Methods B, D: 6.000 ±0.026	Methods B, D: 6.000 ±0.026
Mold Height, in.	4.584 ±0.018	4.584 ±0.018
Detachable Collar Height, in.	2.000 ±0.025	2.000 ±0.025
Rammer Diameter, in.	2.000 ±0.025	2.000 ±0.025
Rammer Mass, lb	5.5 ±0.02	10 ±0.02
Rammer Drop, in.	12 ±0.06	18 ±0.06
Layers	3	5
Blows per Layer	Methods A, C: 25	Methods A, C: 25
	Methods B, D: 56	Methods B, D: 56
Material Size, in.	Methods A, B: No. 4 minus	Methods A, B: No.4 minus
	Methods C, D: 3/4 minus	Methods C, D: 3/4 minus
Test Sample Size, lb	Method A: 7 Method B: 16 Method C: 12(1) Method D: 25(1)	
Energy, lb-ft/ft^3	12,375	56,250

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(1) This may not be a large enough sample depending on your nominal maximum size for moisture content samples. 19

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Sieve / Mold	4.75 mm (No. 4)	19 mm (3/4")
4"	A	C
6"	B	D

Methods

Sample

If the sample is damp, dry it until it becomes friable under a trowel. Drying may be in air or by use of a drying apparatus maintained at a temperature not exceeding 60°C (140°F). Thoroughly break up aggregations in a manner that avoids reducing the natural size of individual particles.

20 Obtain a representative test sample of the mass required by the agency by passing the material through the sieve required by the agency. See
21 Table 1 or Table 2 for test sample mass and material size requirements.

In instances where the material is prone to degradation, i.e., granular material, a compaction sample with differing moisture content should be prepared for each point.

If the sample is plastic (clay types), it should stand for a minimum of 12 hours after the addition of water to allow the moisture to be absorbed. In this case, several samples at different moisture contents should be prepared, put in sealed containers, and tested the next day.

Note 1: Both T 99 and T 180 have four methods (A, B, C, D) that require different masses and employ different sieves.

Procedure

During compaction, rest the mold firmly on a dense, uniform, rigid, and stable foundation, or base. This base shall remain stationary during the compaction process.

Compacting

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1. Determine the mass of the clean, dry mold. Include the base plate but exclude the extension collar. Record the mass to the nearest 1 g (0.005 lb).
2. Thoroughly mix the selected representative sample with sufficient water to dampen it to approximately 4 to 8 percentage points below optimum moisture content. For many materials, this condition can be identified by forming a cast by hand.
   a. Prepare individual samples of plastic or degradable material, increasing moisture contents 1 to 2 percent for each point.
   b. Allow samples of plastic soil to stand for 12 hrs.

Typical mold

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3. Form a specimen by compacting the prepared soil in the mold assembly in approximately equal layers. For each layer:
   a. Spread the loose material uniformly in the mold.
   b. Lightly tamp the loose material with the manual rammer or other similar device, this establishes a firm surface.

Note 2: It is recommended to cover the remaining material with a non-absorbent sheet or damp cloth to minimize loss of moisture.

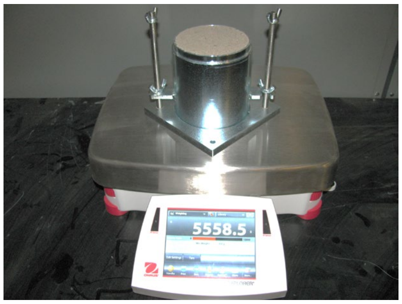
   c. Compact each layer with uniformly distributed blows from the rammer. See Table 1 for mold size, number of layers, number of blows, and rammer specification for the various test methods. Use the method specified by the agency.
   d. Trim down material that has not been compacted and remains adjacent to the walls

of the mold and extends above the compacted surface.

4. Remove the extension collar. Avoid shearing off the sample below the top of the mold. The material compacted in the mold should not be over 6 mm (¼ in) above the top of the mold once the collar has been removed.

Trimming

5. Trim the compacted soil even with the top of the mold with the beveled edge of the straightedge.
6. Clean soil from exterior of the mold and base plate.
7. Determine the mass of the mold, base plate, and wet soil to the nearest 1 g (0.005 lb).



Mass of mold and wet soil

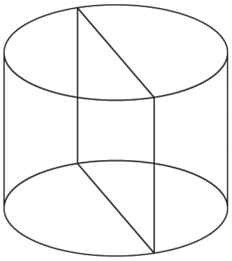
8. Determine the wet mass of the sample by subtracting the mass in Step 1 from the mass in Step 7.
9. Calculate the wet density (ρ_w), in kg/m^3 (lb/ft^3), by dividing the wet mass by the measured volume (V_m).
10. Extrude the material from the mold. For soils and soil-aggregate mixtures, slice vertically through the center and remove one of the cut faces for a representative moisture content sample. For granular materials, a vertical face will not exist. Take a representative sample ensuring that all layers are represented. This sample must meet the sample size requirements of the test method used to determine moisture content.

Extruding the material

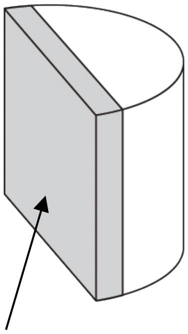
Note 3: When developing a curve for free-draining soils such as uniform sands and gravels, where seepage occurs at the bottom of the mold and base plate, taking a representative moisture content from the mixing bowl may be preferred in order to determine the amount of moisture available for compaction.

11. Determine the moisture content (w) of the sample in accordance with the FOP for AASHTO T 255 / T 265.
12. If the material is degradable or plastic, return to Step 3 using a prepared individual sample. If not, continue with Steps 13 through 15.

13. Thoroughly break up the remaining portion of the molded specimen until it will again pass through the sieve, as judged by eye, and add to the remaining portion of the sample being tested.
14. Add sufficient water to increase the moisture content of the remaining soil by approximately 1 to 2 percentage points and repeat the above procedure.
15. Continue determinations until there is either a decrease or no change in the mass. There will be a minimum of three points on the dry side of the curve and two points on the wet side. For non-cohesive, drainable soils, one point on the wet side is sufficient.



Extruded material



Representative moisture content sample

Calculations

Wet Density

$$\rho_w = \frac{M_w}{V_m}$$

Where:

ρ_w = wet density, kg/m^3 (lb/ft^3)

M_w = wet mass

V_m = volume of the mold, Annex B

Dry Density 35

$$\rho_d = \left(\frac{\rho_w}{w + 100}\right) \times 100 \quad or \quad \rho_d = \frac{\rho_w}{\left(\frac{w}{100}\right) + 1}$$

Where:

ρ_d = dry density, kg/m^3 (lb/ft^3)

w = moisture content, as a percentage

Example for 4-inch mold, Methods A or C 36

Wet mass, M_w = 1.928 kg (4.25 lb)

Moisture content, w = 11.3%

Measured volume of the mold, V_m = 0.000946 m^3 (0.0334 ft^3)

Wet Density

$$\rho_w = \frac{1.928\ kg}{0.000946\ m^3} = 2038\ kg/m^3 \quad \rho_w = \frac{4.25\ lb}{0.0334\ ft^3} = 127.2\ lb/ft^3$$ 37

Dry Density

38

$$\rho_d = \left(\frac{2038\,kg/m^3}{11.3 + 100}\right) \times 100 = 1831\ kg/m^3 \quad \rho_d = \left(\frac{127.2\,lb/ft^3}{11.3 + 100}\right) \times 100 = 114.3\,lb/ft^3$$

Or

$$\rho_d = \left(\frac{2038\,kg/m^3}{\frac{11.3}{100} + 1}\right) = 1831\,kg/m^3 \quad \rho_d = \left(\frac{127.2\ lb/ft^3}{\frac{11.3}{100} + 1}\right) = 114.3\,lb/ft^3$$

Moisture-Density Curve Development 39

When dry density is plotted on the vertical axis versus moisture content on the horizontal axis and the points are connected with a smooth line, a moisture-density curve is developed. The coordinates of the peak of the curve are the maximum dry density, or just “maximum density,” and the “optimum moisture content” of the soil.

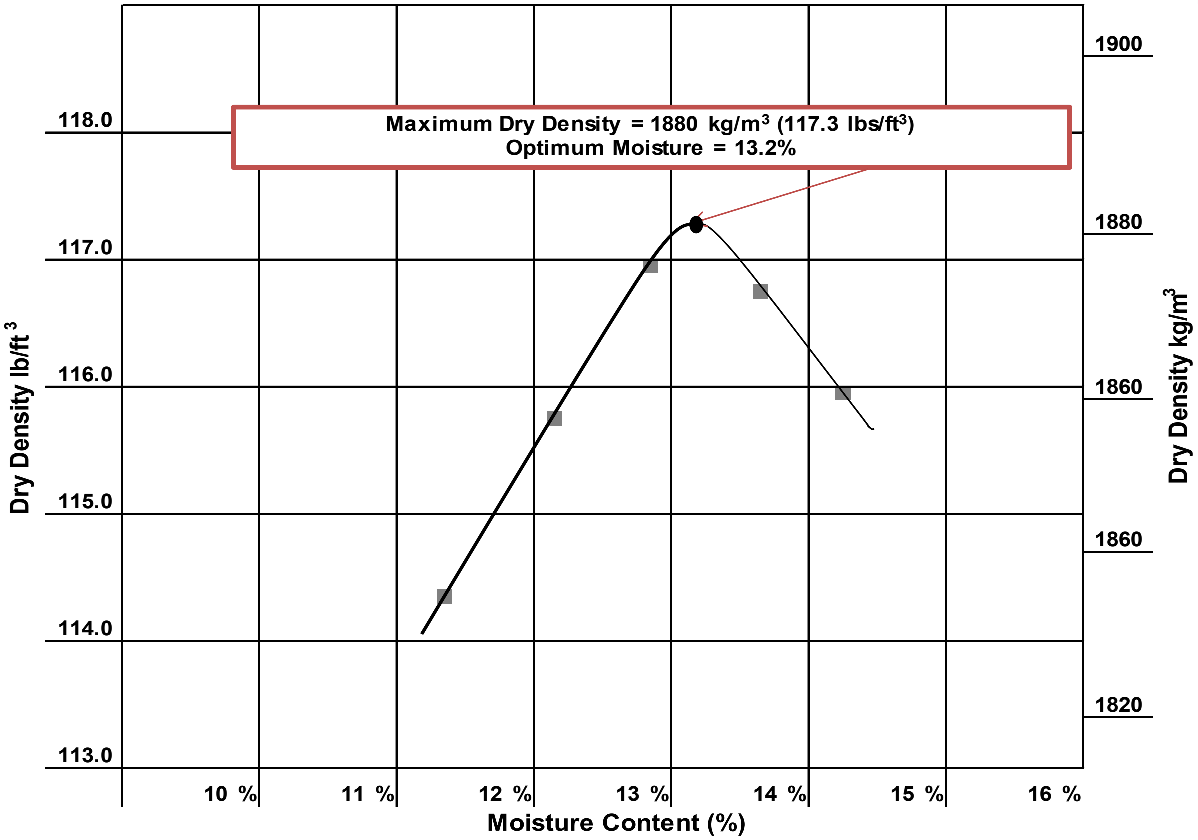
Example

Given the following dry density and corresponding moisture content values, develop a moisture-density relations curve and determine maximum dry density and optimum moisture content.

40

Dry Density,		Moisture Content, %
kg/m^3	lb/ft^3	
1831	114.3	11.3
1853	115.7	12.1
1873	116.9	12.8
1869	116.7	13.6
1857	115.9	14.2

41



In this case, the curve has its peak at: 42

Maximum dry density = 1880 kg/m^3 (117.3 lb/ft^3)

Optimum moisture content = 13.2%

Note that both values are approximate since they are based on sketching the curve to fit the points.

43 Report

- On forms approved by the agency
- Sample ID
- Maximum dry density to the nearest 1 kg/m^3 (0.1 lb/ft^3)
- Optimum moisture content to the nearest 0.1 percent

44 Tips!

- Ideally, obtain 3 dry points and 2 wet points. This produces a reliable moisture-density curve.
- Moisture-density curves are based on dry densities.
- If oversize material exists, corrections must be made.

ANNEX A

CORRECTION OF MAXIMUM DRY DENSITY AND OPTIMUM MOISTURE FOR OVERSIZED PARTICLES

(Mandatory Information)

This section corrects the maximum dry density and moisture content of the material retained on the 4.75 mm (No. 4) sieve, Methods A and B; or the material retained on the 19 mm (¾ in.) sieve, Methods C and D. The maximum dry density, corrected for oversized particles and total moisture content, are compared with the field-dry density and field moisture content.

This correction can be applied to the sample on which the maximum dry density is performed. A correction may not be practical for soils with only a small percentage of oversize material. The agency shall specify a minimum percentage below which the method is not needed. If not specified, this method applies when more than 5 percent by weight of oversize particles is present.

Bulk specific gravity (G_{sb}) of the oversized particles is required to determine the corrected maximum dry density. Use the bulk specific gravity as determined using the FOP for AASHTO T 85 in the calculations. For construction activities, an agency established value or specific gravity of 2.600 may be used.

This correction can also be applied to the sample obtained from the field while performing in-place density.

Procedure

1. Use the sample from this procedure or a sample obtained according to the FOP for AASHTO T 310.
2. Sieve the sample on the 4.75 mm (No. 4) sieve for Methods A and B or the 19 mm (¾ in.) sieve, Methods C and D.
3. Determine the dry mass of the oversized and fine fractions (M_{DC} and M_{DF}) by one of the following:
    a. Dry the fractions, fine and oversized, in air or by use of a drying apparatus that is maintained at a temperature not exceeding 60ºC (140ºF).
    b. Calculate the dry masses using the moisture samples.

To determine the dry mass of the fractions using moisture samples.

1. Determine the moist mass of both fractions, fine (M_{Mf}) and oversized (M_{Mc}):
2. Obtain moisture samples from the fine and oversized material.

3. Determine the moisture content of the fine particles (MC_f) and oversized particles (MC_C) of the material by FOP for AASHTO T 255/T 265 or agency approved method.

4. Calculate the dry mass of the oversize and fine particles.

$$M_D = \frac{M_m}{1 + \mathrm{MC}} \quad 9$$

Where:

M_D = mass of dry material (fine or oversize particles).

M_m = mass of moist material (fine or oversize particles).

MC = moisture content of respective fine or oversized, expressed as a decimal.

5. Calculate the percentage of the fine (P_f) and oversized (P_c) particles by dry weight of the total sample as follows: See Note 2.

$$\mathrm{P_f} = \frac{100 \times M_{DF}}{M_{DF} + M_{DC}} \qquad \frac{100 \ \times 15.4\ lb}{15.4\ lbs + 5.7\ lb} = 73\% \qquad \frac{100 \ \times 6.985\ kg}{6.985\ kg + 2.585\ kg} = 73\% \quad 10$$

And

$$\mathrm{P_c} = \frac{100 \times M_{DC}}{M_{DF} + M_{DC}} \qquad \frac{100 \ \times 5.7\ lb}{15.4\ lbs + 5.7\ lb} = 27\% \qquad \frac{100 \ \times 2.585\ kg}{6.985\ kg + 2.585\ kg} = 27\% \quad 11$$

Or for **P_c**:

$$\mathrm{P_c} = 100 - \mathrm{P_f}$$

Where:

P_f = percent of fine particles, of sieve used, by weight

P_c = percent of oversize particles, of sieve used, by weight

M_{DF} = mass of dry fine particles

M_{DC} = mass of dry oversize particles

Optimum Moisture Correction Equation 12

1. Calculate the corrected moisture content as follows:

$$MC_T = \frac{(MC_F \times \mathrm{P_f}) + (MC_c \times \mathrm{P_c})}{100}$$

13

$$MC_T = \frac{(10.6\% \times 73.0\%) + (2.1\% \times 27.0\%)}{100} = 8.3\%$$

Where:

MC_T = corrected moisture content of combined fines and oversized particles, expressed as a % moisture

MC_F = moisture content of fine particles, as a % moisture

MC_C = moisture content of oversized particles, as a % moisture

Note 1: Moisture content of oversize material can be assumed to be two (2) percent for most construction applications.

Note 2: In some field applications agencies will allow the percentages of oversize and fine materials to be determined with the materials in the wet state.

Density Correction Equation

14

2. Calculate the corrected dry density (ρ_d) of the total sample (combined fine and oversized particles) as follows:

$$\rho_d = \frac{100\%}{\left[\left(\frac{P_f}{\boldsymbol{\rho_f}}\right) + \left(\frac{P_c}{k}\right)\right]}$$ 15

Where:

ρ_d = corrected total dry density (combined fine and oversized particles) kg/m^3 (lb/ft^3)

$\boldsymbol{\rho_f}$ = dry density of the fine particles kg/m^3 (lb/ft^3), determined in the lab

P_c = percent of dry oversize particles, of sieve used, by weight.

P_f = percent of dry fine particles, of sieve used, by weight.

k = Metric: 1,000 * Bulk Specific Gravity (G_{sb}) (oven dry basis) of coarse particles (kg/m^3).

k = English: 62.4 * Bulk Specific Gravity (G_{sb}) (oven dry basis) of coarse particles (lb/ft^3)

Note 3: If the specific gravity is known, then this value will be used in the calculation. For most construction activities, the specific gravity for aggregate may be assumed to be 2.600.

Calculation

Example

- Metric:

Maximum laboratory dry density ($\boldsymbol{\rho_f}$): 1880 kg/m^3

Percent coarse particles (P_c): 27%

Percent fine particles (P_f): 73%

Mass per volume coarse particles (k): (2.697) (1000) = 2697 kg/m^3

$$\rho_d = \frac{100\%}{\left[\left(\frac{P_f}{\boldsymbol{\rho_f}}\right) + \left(\frac{P_c}{k}\right)\right]}$$

$$\rho_d = \frac{100\%}{\left[\left(\frac{73\%}{1880\,kg/m^3}\right) + \left(\frac{27\%}{2697\,kg/m^3}\right)\right]}$$

$$\rho_d = \frac{100\%}{[0.03883\,kg/m^3 + 0.01001\,kg/m^3]}$$

$$\rho_d = 2047.5\,kg/m^3\ report\ \ 2048\,kg/m^3$$

- English:

Maximum laboratory dry density ($\boldsymbol{\rho_f}$): 117.3 lb/ft^3

Percent coarse particles (P_c): 27%

Percent fine particles (P_f): 73%

Mass per volume coarse particles (k): (2.697) (62.4) = 168.3 lb/ft^3

$$\rho_d = \frac{100\%}{\left[\left(\frac{\mathrm{P_f}}{\rho_f}\right)+\left(\frac{\mathrm{P_c}}{k}\right)\right]}\rho_d = \frac{100\%}{\left[\left(\frac{73\%}{117.3 lb/ft^3}\right)+\left(\frac{27\%}{168.3 lb/ft^3}\right)\right]}$$

17

$$\rho_d = \frac{100\%}{[0.6223\, lb/ft^3 + 0.1604\, lb/ft^3]}$$

$$\rho_d = \frac{100\%}{0.7827\, lb/ft^3}$$

$$\rho_d = 127.76\, lb/ft^3 \quad Report\ 127.8\, lb/ft^3$$

19

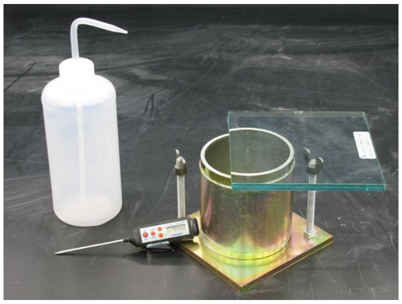
Report

- Results on forms approved by the agency
- Sample ID
- Corrected maximum dry density to the nearest 1 kg/m^3 (0.1 lb/ft^3)
- Corrected optimum moisture to the nearest 0.1 percent

ANNEX B 21
STANDARDIZATION OF THE MOLD

(Mandatory Information)

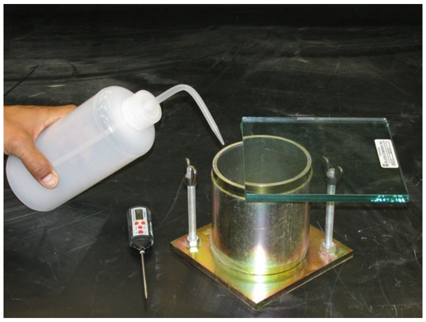
22 Standardization is a critical step to ensure accurate test results when using this apparatus. Failure to perform the standardization procedure as described herein will produce inaccurate or unreliable test results.



Apparatus

Apparatus

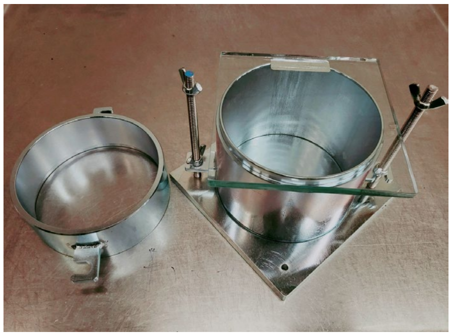
23
- Mold and base plate
- 24 Balance or scale – Accurate to within 45 g (0.1 lb) or 0.3 percent of the test load, whichever is greater, at any point within the range of use.
- Cover plate – A piece of plate glass, at least 6 mm (1⁄4 in.) thick and at least 25 mm (1 in.) larger than the diameter of the mold.
- Thermometers – Standardized liquid-in-glass, or electronic digital total immersion type, accurate to 0.5°C (1°F)



Filling the mold

Procedure

25 1. Create a watertight seal between the mold and base plate.
26 2. Determine and record the mass of the dry sealed mold, base plate, and cover plate.
27 3. Fill the mold with water at a temperature between 16°C and 29°C (60°F and 85°F) and cover with the cover plate in such a way as to eliminate bubbles and excess water.
28 4. Wipe the outside of the mold, base plate, and cover plate dry, being careful not to lose any water from the mold.



Dried filled mold

5. Determine and record the mass of the filled mold, base plate, cover plate, and water.
29 6. Determine and record the mass of the water in the mold by subtracting the mass in Step 2 from the mass in Step 5.

7. Measure the temperature of the water and determine its density from Table B1, interpolating, as necessary.
8. Calculate the volume of the mold, V_m, by dividing the mass of the water in the mold by the density of the water at the measured temperature.

Calculations

31

$$V_m = \frac{M}{\rho_{water}}$$

Where:

V_m = volume of the mold

M = mass of water in the mold

ρ_{water} = density of water at the measured temperature

Example

32

Mass of water in mold	=	0.94367 kg (2.0800 lb)
ρ_{water} at 23°C (73.4°F)	=	997.54 kg/m^3 (62.274 lb/ft^3)

$$V_m = \frac{0.94367\ kg}{997.54\ kg/m^3} = 0.000946\ m^3 \qquad V_m = \frac{2.0800\ lb}{62.274\ lb/ft^3} = 0.0334\ ft^3$$

Table B1
Unit Mass of Water
15°C to 30°C

°C	(°F)	kg/m^3	(lb/ft^3)	°C	(°F)	kg/m^3	(lb/ft^3)
15	(59.0)	999.10	(62.372)	23	(73.4)	997.54	(62.274)
15.6	(60.0)	999.01	(62.366)	23.9	(75.0)	997.32	(62.261)
16	(60.8)	998.94	(62.361)	24	(75.2)	997.29	(62.259)
17	(62.6)	998.77	(62.350)	25	(77.0)	997.03	(62.243)
18	(64.4)	998.60	(62.340)	26	(78.8)	996.77	(62.227)
18.3	(65.0)	998.54	(62.336)	26.7	(80.0)	996.59	(62.216)
19	(66.2)	998.40	(62.328)	27	(80.6)	996.50	(62.209)
20	(68.0)	998.20	(62.315)	28	(82.4)	996.23	(62.192)
21	(69.8)	997.99	(62.302)	29	(84.2)	995.95	(62.175)
21.1	(70.0)	997.97	(62.301)	29.4	(85.0)	995.83	(62.166)
22	(71.6)	997.77	(62.288)	30	(86.0)	995.65	(62.156)

Report

- Mold ID
- Date Standardized
- Temperature of the water
- Volume, V_m, of the mold the nearest 0.000001 m^3 (0.0001 ft^3)

REVIEW QUESTIONS

1. Describe how the plotted data is used to determine optimum moisture content and maximum dry density.

2. How many blows of the rammer are required per lift for the various procedures and methods?

3. Describe how the sample for moisture content is obtained.

4. What sample mass is required for Method A of the T 99 test?

   For Method C of the T 180 test?

5. Describe the purpose of Annex A.

6. The adjustment is based on the mass of material retained on what size sieve?

7. A soil-aggregate mixture has a maximum dry density of 138.6 lb/ft^3 English units and optimum moisture of 6.4 percent. The coarse particles make up 22 percent of the material, having a G_{sb} of 2.631 and 1.7 percent moisture.

   What is the corrected maximum density?

   What is the corrected moisture?

REVIEW QUESTIONS (KEY)

1. Describe how the plotted data is used to determine optimum moisture content and maximum dry density.

When dry density is plotted on the vertical axis versus moisture content on the horizontal axis and the points are connected with a smooth line, a moisture-density curve is developed. The coordinates of the ***peak of the curve*** are the maximum dry density *(max density)* and the optimum moisture content of the soil.
(from AASHTO T 99 / T 180, Moisture-Density Curve Development, page 4-10)

2. How many blows of the rammer are required per lift for the various procedures and methods?

For T99 and T 180, methods A & C, ***25 blows*** are required per lift of material.
For T 99 and T 180, methods B & D, ***56 blows*** are required per lift.
(from AASHTO T 99 / T 180, Table 2, Comparison of Apparatus, Sample and Procedure – English units, page 4-5)

3. Describe how the sample for moisture content is obtained.

Slice vertically through the *"cylinder of soil"* and take a moisture content sample from one of the cut faces, ensuring that all layers are represented.
(from AASHTO T 99 / T 180, Procedure, Step 10, page 4-7)

4. What sample mass is required for Method A of the T 99 test?

7 pound sample ***(from AASHTO T 99 / T 180, Table 2, Comparison of Apparatus, Sample and Procedure – English units, page 4-5)***

For Method C of the T 180 test?

12 pound sample ***(from AASHTO T 99 / T 180, Table 2, Comparison of Apparatus, Sample and Procedure – English units, page 4-5)***

5. Describe the purpose of Annex A.

The purpose of this calculation is to adjust the maximum dry density as determined by the field operating procedure *(FOP)* for AASHTO T 99 / T 180 to compensate for *coarse particles* present in the total sample. ***(from AASHTO T 99 / T 180, Paragraph 1, page 4-13)***

6. The adjustment is based on the mass of material retained on what size sieve?

Retained on the ***No. 4*** or the ***¾ inch*** sieve, depending on the procedure.
(from AASHTO T 99 / T 180, Paragraph 1, page 4-13)

7. A soil-aggregate mixture has a maximum dry density of 138.6 lb/ft^3 English units and an optimum moisture of 6.4 percent. The coarse particles make up 22 percent of the material, having a G_{sb} of 2.631 and 1.7 percent moisture.

What is the corrected maximum density?

$$\rho_d = \frac{100\%}{\left[\left(\frac{P_f}{\rho_f}\right) + \left(\frac{P_c}{k}\right)\right]} = \frac{100}{\frac{78\%}{138.6\,{}^{lb}/_{ft^3}} + \frac{225}{2.361 \times 62.4\,{}^{lb}/_{ft^3}}}$$

$$= \frac{100}{0.56277\,{}^{lb}/_{ft^3} + 0.13400\,{}^{lb}/_{ft^3}}$$

$$= 143.5\ {}^{lb}/_{ft^3}$$

Answer equals ***143.5 pcf***

(from AASHTO T 99/T 180, Adjustment Equation Density, page 4-16 and 4-17)

What is the corrected moisture?

$$MC_T = \frac{(MC_F \times P_f) + (MC_c \times P_c)}{100} \qquad \frac{(6.4\% \times 78.0\%) + (1.7\% \times 22.0\%)}{100} = 5.4\%$$

Answer equals ***5.4%***

(from AASHTO T 99/T 180, Adjustment Equation Optimum Moisture, page 4-15)

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DEVELOPING A FAMILY OF CURVES FOP FOR AASHTO R 75

01 Significance

Soils sampled from one source will have many
02 different moisture-density curves, but if a group of these curves is plotted together, similarities or relationships are usually seen. A family of curves is a group of soil moisture-density relationships that reveal similarities characteristic of the soil type and source. Higher-density soils have curves with steeper slopes and maximum dry densities at lower optimum moisture contents, while the lower-density soils have flatter curves with higher optimum moisture contents.

Mold \ Sieve	4.75 mm (No. 4)	19 mm (3/4”)
4”	A	C
6”	B	D

Methods of T 99 / T 180

Scope

03 This procedure provides a method to develop a
04 family of curves using multiple moisture-density relationships developed using the same method, A, B, C, or D from the FOP for AASHTO T 99/T 180 in accordance with AASHTO R 75-16.

All curves used in a family must be developed using a single Method: A, B, C, or D of a procedure for AASHTO T 99 or T 180. See the FOP for AASHTO T 99/T 180.

05 Terminology

family of curves — a group of soil moisture-density relationships (curves) determined using AASHTO T 99 or T 180, which reveal certain similarities and trends characteristic of the soil type and source.

spine — smooth line extending through the point of maximum density and optimum moisture content of a family of moisture-density curves.

Procedure

1. Sort the curves by Method (A, B, C, or D of the FOP for T 99/T 180). At least three curves are
06 required to develop a family.
2. Select the highest and lowest maximum dry densities from those selected to assist in

determining the desired scale of the subsequent graph.

3. 07 Plot the maximum density and optimum moisture points of the selected curves on the graph.
4. 08 Draw a smooth, “best fit,” curved line through
09 the points creating the spine of the family of curves.
5. Remove maximum density and optimum
10 moisture points that were not used to establish the spine.
6. 11 Add the moisture-density curves associated with the points that were used to establish the spine.
12 It is not necessary to include the portion of the curves over optimum moisture.

13 ***Note 1***—Intermediate curves using slopes similar to those of
14 the original moisture-density curves may be included
15 when maximum density points are more than 2.0 lb/ft^3 apart. Intermediate curves are indicated by a dashed line.

7. 16 Plot the 80 percent of optimum moisture range when desired:
   a. Using the optimum moisture of an existing curve, calculate 80 percent of optimum moisture and plot this value on the curve. Repeat for each curve in the family.
   b. Draw a smooth, “best fit,” curved line connecting the 80 percent of optimum moisture points plotted on the curves that parallel the spine.

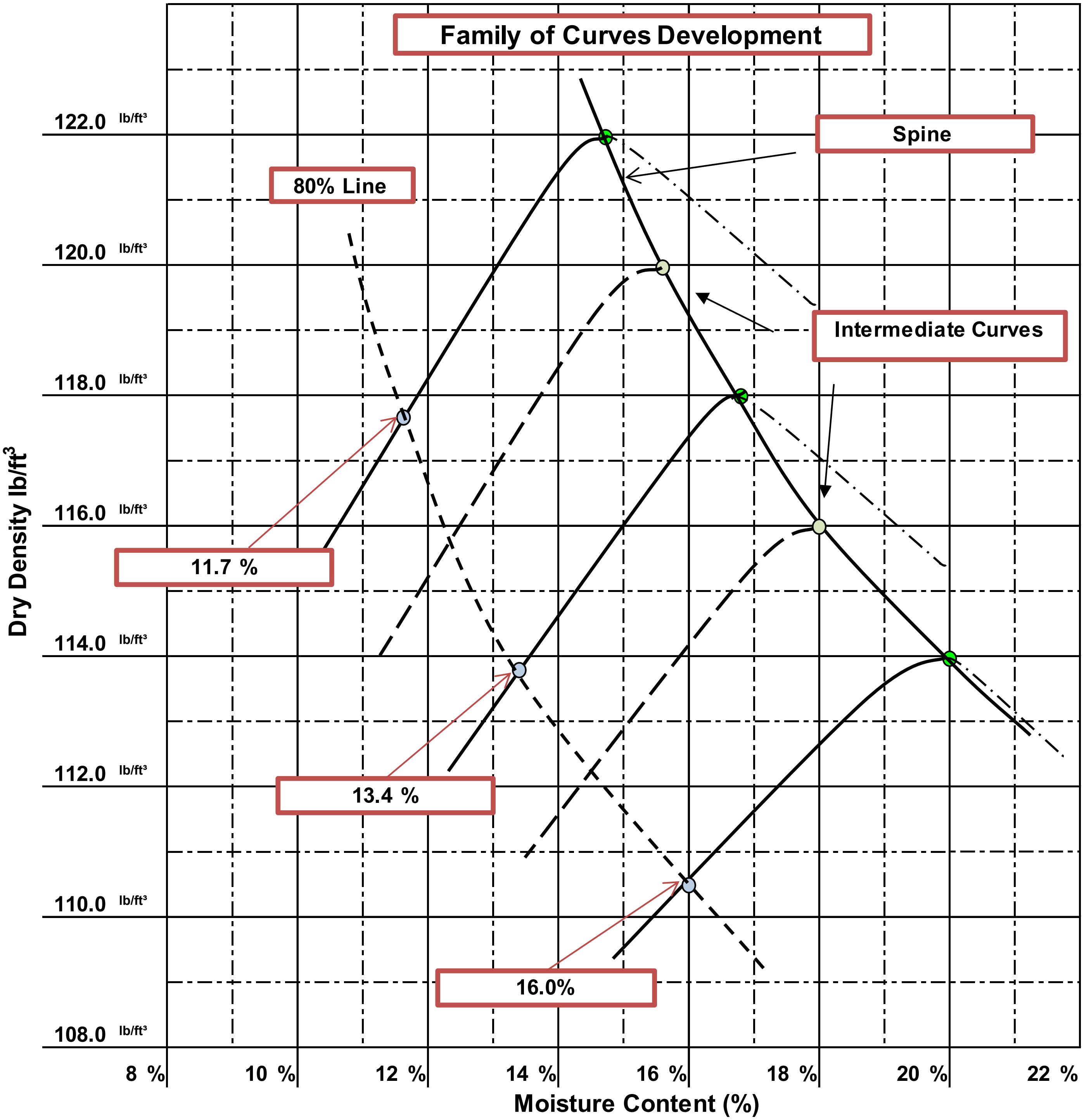
Calculations

Calculate 80 percent of optimum moisture of each curve: 17

Example:

Optimum moisture of the highest density curve = 14.6%

$$80\%\ of\ optimum\ moisture = \frac{80}{100} \times 14.6\% = 11.7\%$$


Family of Curves Development
Spine
80% Line
Intermediate Curves
11.7 %
13.4 %
16.0%
122.0 lb/ft³
120.0 lb/ft³
118.0 lb/ft³
116.0 lb/ft³
114.0 lb/ft³
112.0 lb/ft³
110.0 lb/ft³
108.0 lb/ft³
Dry Density lb/ft³
8 %
10 %
12 %
14 %
16 %
18 %
20 %
22 %
Moisture Content (%)

Tips!

- Make sure that the selected moisture-density relationship curves were developed using the same method from the FOP for AASHTO T 99 / T 180 – A, B, C, or D

REVIEW QUESTIONS

1. To what other procedure(s) is this procedure related?

2. What does the ‘spine’ of the curve mean?

3. Describe the limitations of developing a family of curves.

REVIEW QUESTIONS (KEY)

1. To what other procedure(s) is this procedure related?

AASHTO T99 and T180, and T272.

2. What does the ‘spine’ of the curve mean?

A smooth line extending through the point of maximum density/optimum moisture content of a family of moisture-density curves ***(From AASHTO R75 pg 5-1).***

3. Describe the limitations of developing a family of curves.

- All curves used in a family must be developed using a single Method: A, B, C, or D of a procedure for AASHTO T 99 or T 180.
- At least three curves are required per family.
- Curves must be developed from similar soil types from a source

(From AASHTO R75 pg 5-1 and 5-2).

ONE-POINT METHOD FOR DETERMINING MAXIMUM DRY DENSITY AND OPTIMUM MOISTURE
FOP FOR AASHTO T 272

Significance

Soils sampled from one source will have many different moisture-density curves, but if a group of these curves is plotted together, similarities or relationships are usually seen. A family of curves is a group of soil moisture-density relationships that reveal similarities characteristic of the soil type and source. Higher-density soils have curves with steeper slopes and maximum dry densities at lower optimum moisture contents, while the lower-density soils have flatter curves with higher optimum moisture contents.

In the field, density and moisture content are determined, and a single point is plotted on an individual moisture curve or family of curves graphs.

Scope

This procedure provides for a rapid determination of the maximum dry density and optimum moisture content of a soil sample using a one-point determination in accordance with AASHTO T 272-18. This procedure is related to the FOPs for AASHTO T 99/T 180 and R 75.

One-point determinations are made by compacting the soil in a mold of a given size with a specified rammer dropped from a specified height and then compared to an individual moisture-density curve (FOP for AASHTO T 99 or T 180) or a family of curves (FOP for AASHTO R 75). Four alternate methods – A, B, C, and D – are used and correspond to the methods described in the FOP for AASHTO T 99/T 180. The method used in AASHTO T 272 must match the method used for the reference curve or to establish the family of curves. For example, when moisture-density relationships as determined by T 99 - Method C are used to form the family of curves or an individual moisture density curve, then T 99 - Method C must be used to for the one-point determination.

Apparatus

06 See the FOP for AASHTO T 99/T 180.

Sample

Sample size is determined according to the FOP for AASHTO T 310. In cases where the existing individual curve or family cannot be used, a completely new curve must be developed, and the sample size determined by the FOP for AASHTO T 99/T 180.

07
1. If the sample is damp, dry it until it becomes friable under a trowel. Drying may be in air or by use of a drying apparatus maintained at a temperature not exceeding 60°C (140°F).
2. Thoroughly break up aggregations in a manner that avoids reducing the natural size of individual particles.
3. Pass the material through the appropriate sieve.

Procedure

08

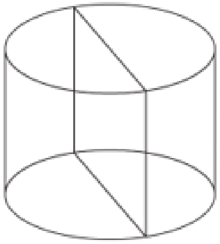
Dense, uniform, rigid foundation

Use the method matching the individual curve or Family of Curves. Refer to Table 1 of the FOP for AASHTO T 99/T 180 for corresponding mold size, number of layers, number of blows, sieve size, and rammer specification for the various test methods. 09

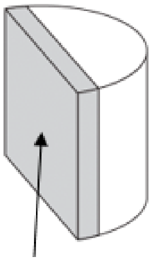
1. Determine the mass of the clean, dry mold. Include the base plate but exclude the extension collar. Record the mass to the nearest 1 g (0.005 lb).
2. Thoroughly mix the sample with sufficient water to adjust moisture content to 80 to 100 percent of the anticipated optimum moisture.
3. Form a specimen by compacting the prepared soil in the mold (with collar attached) in approximately equal layers. For each layer:
    a. Spread the loose material uniformly in the mold.

Note 1: It is recommended to cover the remaining material with a non-absorbent sheet or damp cloth to minimize loss of moisture.

Trim soil



Extruded material



Representative Moisture Content Sample

Mass of mold and wet sample

   b. Lightly tamp the loose material with the manual rammer or other similar device, this establishes a firm surface.
   c. Compact each layer with uniformly distributed blows from the rammer.
   d. Trim down material that has not been compacted and remains adjacent to the walls of the mold and extends above the compacted surface.

4. Remove the extension collar. Avoid shearing off the sample below the top of the mold. The material compacted in the mold should not be over 6 mm (¼ in.) above the top of the mold once the collar has been removed.
5. Trim the compacted soil even with the top of the mold with the beveled side of the straightedge.
6. Clean soil from exterior of the mold and base plate.
7. Determine the mass of the mold and wet soil to the nearest 1 g (0.005 lb).
8. Determine the wet mass of the sample by subtracting the mass in Step 1 from the mass in Step 7.
9. Calculate the wet density (ρ_w) as indicated below under "Calculations."
10. Extrude the material from the mold. For soils and soil-aggregate mixtures, slice vertically through the center and remove one of the cut faces for a representative moisture content sample. For granular materials, a vertical face will not exist. Take a representative sample ensuring that all layers are represented. This sample must meet the sample size requirements of the test method used to determine moisture content.
11. Determine the moisture content (w) of the sample in accordance with the FOP for AASHTO T 255 / T 265.

Calculations

1. Calculate the wet density, in kg/m^3 (lb/ft^3), by dividing the wet mass by the measured volume of the mold (T 19).

   Example – Methods A or C mold: 18

   Wet mass = 2.0055 kg (4.42 lb)

   Measured volume of the mold = 0.0009469 m^3 (0.0334 ft^3)

$$\rho_w = \frac{2.0055\ kg}{0.0009469\ m^3} = 2118\ kg/m^3$$

$$\rho_w = \frac{4.42\ lb}{0.0334\ ft^3} = 132.2\ lb/ft^3$$

Where: 19

ρ_w = Wet density, kg/m^3 (lb/ft^3)

2. Calculate the dry density as follows.

$$\rho_d = \left(\frac{\rho_w}{w+100}\right) \times 100 \quad or \quad \rho_d = \frac{\rho_w}{\left(\frac{w}{100}\right)+1}$$

Where:

ρ_d = Dry density, kg/m^3 (lb/ft^3)

w = Moisture content, as a percentage

Example:

ρ_w = 2118 kg/m^3 (132.2 lb/ft^3)

w = 13.5%

20

$$\rho_d = \left(\frac{2118\ kg/m^3}{13.5+100}\right) \times 100 = 1866\ kg/m^3 \quad \rho_d = \left(\frac{132.2\ lb/ft^3}{13.5+100}\right) \times 100 = 116.5\ lb/ft^3$$

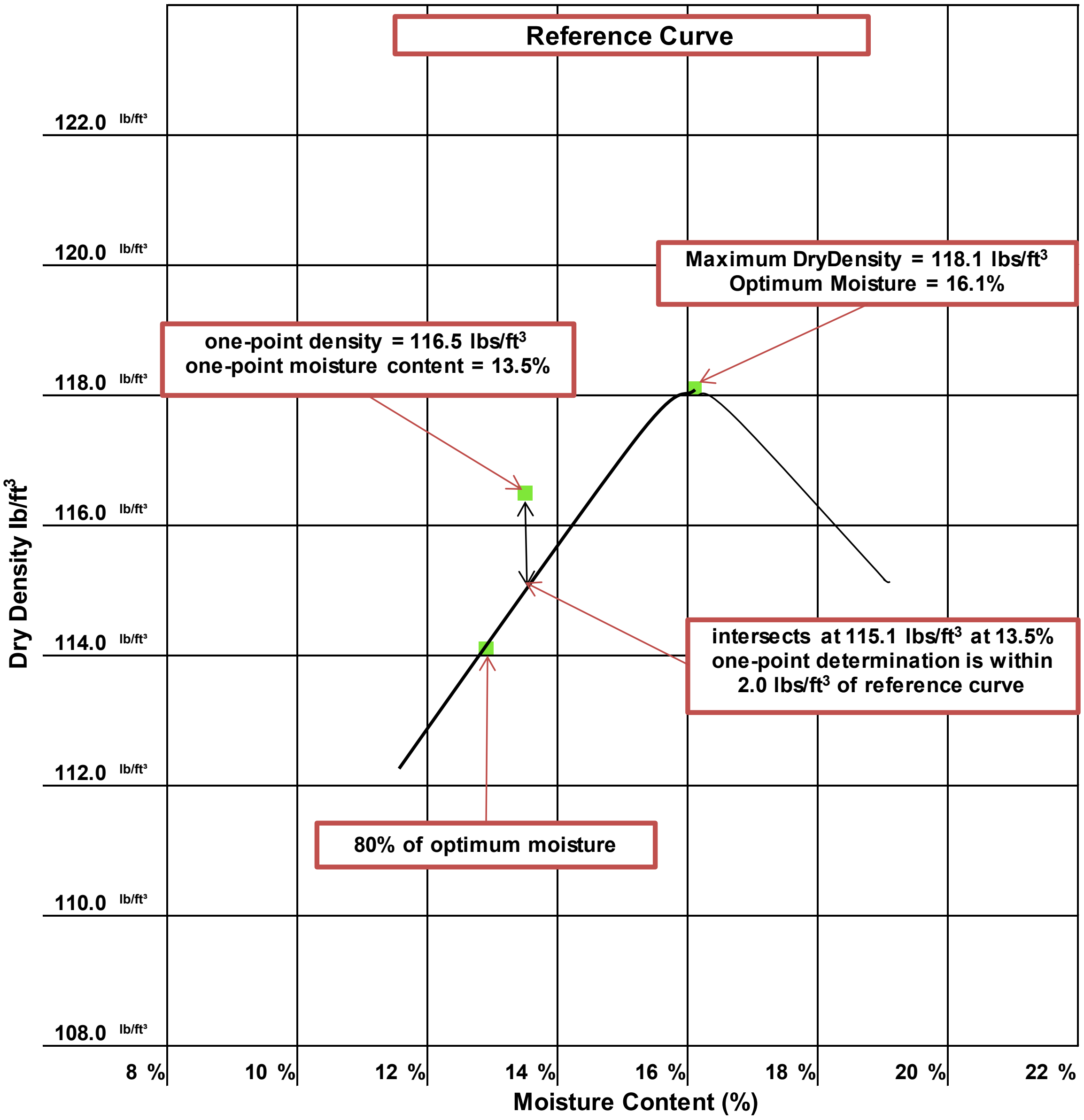
or

$$\rho_d = \left(\frac{2118\ kg/m^3}{\frac{13.5}{100}+1}\right) = 1866\ kg/m^3 \quad \rho_d = \left(\frac{132.2\ lb/ft^3}{\frac{13.5}{100}+1}\right) = 116.5\ lb/ft^3$$

Maximum Dry Density and Optimum Moisture Content Determination Using an Individual Moisture - Density Curve

1. The moisture content must be within 80 to 100 percent of optimum moisture of the reference curve. Compact another specimen, using the same material, at an adjusted moisture content if the one-point does not fall in the 80 to 100 percent of optimum moisture range.
2. 21 Plot the one-point, dry density on the vertical axis and moisture content on the horizontal axis, on the reference curve graph.
3. If the one-point falls on the reference curve or within ±2.0 lb/ft^3, use the maximum dry density and optimum moisture content determined by the curve. 22
4. Use the FOP for AASHTO T 99/T 180 Annex A to determine corrected maximum dry density and optimum moisture content if oversize particles have been removed.
5. 24 Perform a full moisture-density relationship if the one-point does not fall on or within ±2.0 lb/ft^3 of the reference curve at 80 to 100 percent optimum moisture.

Example



Example:

23

The results of a one-point determination were 116.5 lb/ft^3 at 13.5 percent moisture. The point was plotted on the reference curve graph. The point was plotted on the reference curve graph. The one-point determination is within 2.0 lb/ft^3 of the point on the curve that corresponds with the moisture content.

Maximum Dry Density and Optimum Moisture Content Determination Using a Family of Curves

25

1. Plot the one-point, dry density on the vertical axis and moisture content on the horizontal axis, on the reference family of curves graph.
2. If the moisture-density one-point falls on one of the curves in the family of curves, use the maximum dry density and optimum moisture content defined by that curve.

26

3. If the moisture-density one-point falls within the family of curves but not on an existing curve, draw a new curve through the plotted single point parallel and in character with the nearest existing curve in the family of curves. Use the maximum dry density and optimum moisture content as defined by the new curve.

   27

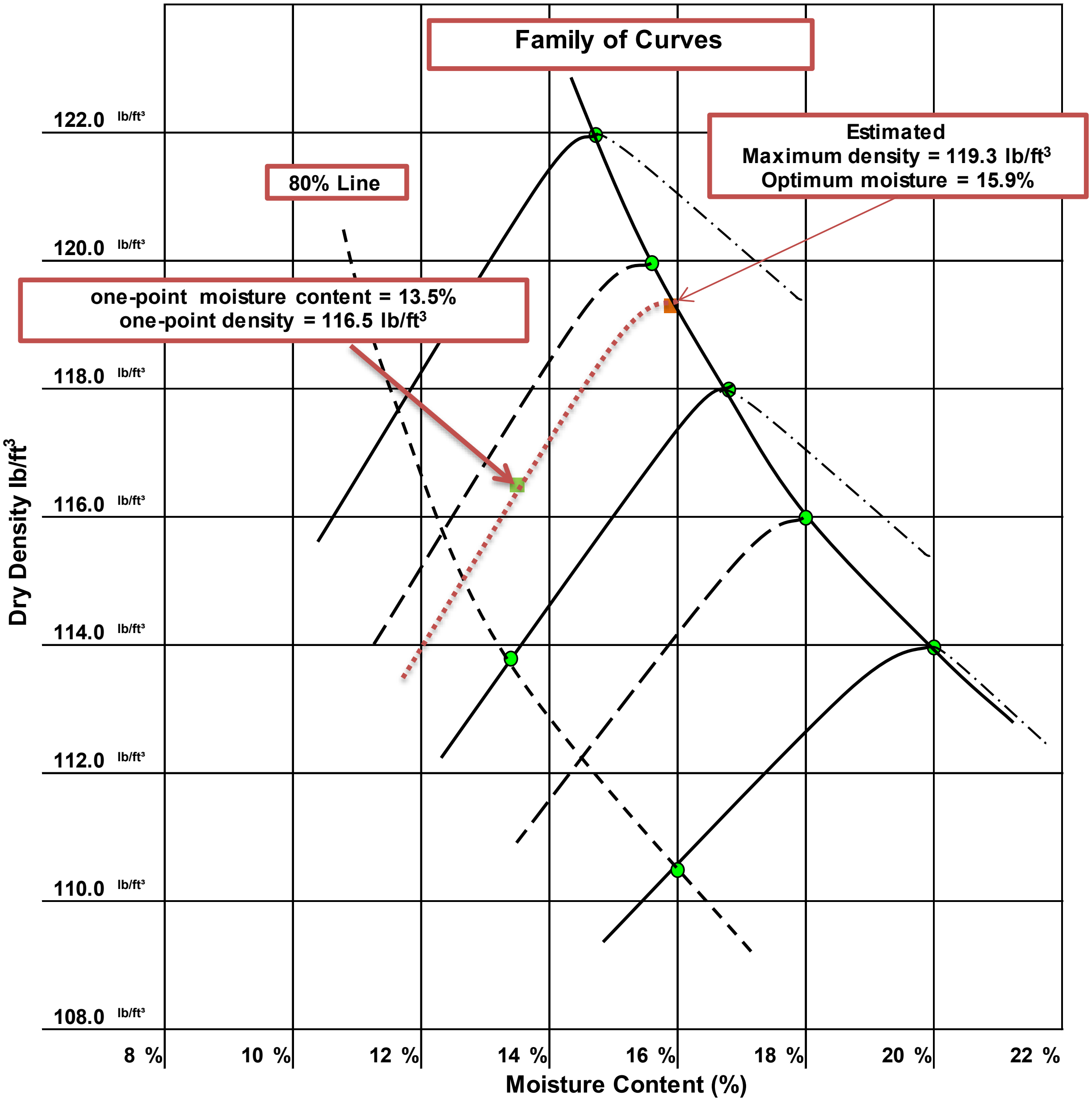
   a. The one-point must fall either between or on the highest or lowest curves. If it does not, then a full curve must be developed.
   b. If the one-point plotted within or on the family of curves does not fall in the 80 to 100 percent of optimum moisture content, compact another specimen, using the same material, at an adjusted moisture content that will place the one-point within this range.

28

4. Use the FOP for AASHTO T 99/T 180 Annex A to determine corrected maximum dry density and optimum moisture content if oversize particles have been removed.
5. If the new curve through a one-point is not well defined or is in any way questionable, perform a full moisture-density relationship to correctly define the new curve and verify the applicability of the family of curves.

Note 2: New curves drawn through plotted single point determinations shall not become a permanent part of the family of curves until verified by a full moisture-density procedure following the FOP for AASHTO T 99/T 180.

EXAMPLE



The results of a one-point determination were 116.5 lb/ft^3 at 13.5 percent moisture. The point was plotted on the reference curve graph. The point was plotted on the appropriate family between two previously developed curves near and intermediate curve.

The “dotted” curve through the moisture-density one-point was sketched between the existing curves. A maximum dry density of 119.3 lb/ft^3 and a corresponding optimum moisture content of 15.9 percent were estimated.

30 Report

- On forms approved by the agency
- Sample ID
- Maximum dry density to the nearest 1 kg/m^3 (0.1 lb/ft^3)
- Corrected maximum dry density (if applicable)
- Optimum moisture content to the nearest 0.1 percent
- Corrected optimum moisture content (if applicable)
- Reference curve or Family of Curves used

31 Tips!

- Make sure that the moisture content of the one-point sample is between 80 and 100 percent of optimum moisture.
- Remember that a full moisture-density procedure shall be made if the curve drawn through the one-point is not well defined or is questionable.

REVIEW QUESTIONS

1. To what other procedure(s) is this procedure related?

2. How are the two procedures used together?

3. Describe the limitations of using the one-point determination with a family of curves.

4. Describe the limitations of using the one-point determination with a single reference curve.

REVIEW QUESTIONS (KEY)

1. To what other procedure(s) is this procedure related?

This procedure is related to AASHTO T 99/ T 180.
(from AASHTO T 272, Scope, page 6-1)

2. How are the two procedures used together?

Follow the procedure outlined for T 99 / T 180 and then use your fabricated *"one point"* to land on a particular family of curves, extracting the maximum dry density and optimum moisture content from the family.
(from AASHTO T 272, Scope, page 6-1)

3. Describe the limitations of using the one-point determination with a family of curves.

The limitations are the following:

1. The soil type and method used must match that of the family of curves.
2. The one point must fall either between or on the *highest* or *lowest* curves on the family. If it does not, than a full curve must be developed.
3. The one point must plot within ***80 to 100 percent*** of the optimum moisture content shown on the family.
4. If the family of curves is such that the new curve through the one point is not well defined or is in any way questionable, a full moisture-density relationship shall be made for the soil. This is done in order to correctly define the new curve and to verify the applicability of the family of curves.
5. New curves drawn through plotted single point determinations ***shall not*** become a permanent part of the family of curves unless verified with an entire single curve.

(from AASHTO T 272, Maximum Dry Density and Optimum Moisture Content Determination, page 6-7)

4. Describe the limitations of using the one-point determination with a single reference curve.

The moisture content must be within 80 to 100 percent of optimum moisture of the reference curve. The one-point does must fall on or within ±2.0 lb/ft^3 of the reference curve at 80 to 100 percent optimum moisture.
(from AASHTO T 272, Maximum Dry Density and Optimum Moisture Content Determination, page 6-5)

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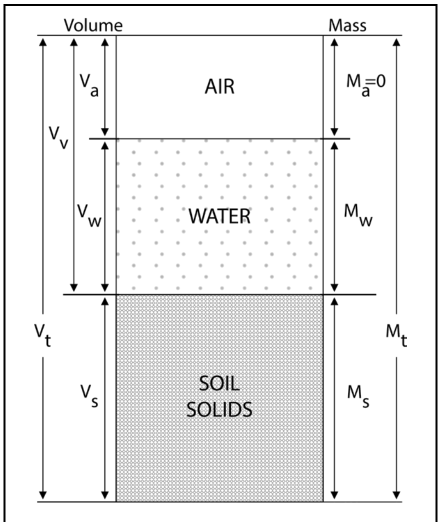
SPECIFIC GRAVITY AND ABSORPTION OF COARSE AGGREGATE FOP FOR AASHTO T 85



Phase diagram

01

Significance

02 03

Bulk specific gravity is a characteristic used for calculating the volume occupied by the aggregate or various mixtures containing aggregate, including Portland Cement Concrete, asphalt mixtures, and other materials that are proportioned or analyzed on an absolute volume basis. Specific gravity is the ratio of the mass of a material to the mass of an equal volume of water. Several categories of specific gravity are used relative to aggregate.

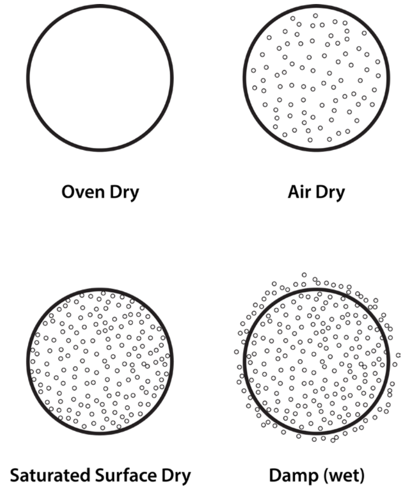
Bulk specific gravity (oven dry), G_{sb}, is used for computations when the aggregate is dry. Bulk specific gravity (saturated surface dry or SSD), G_{sb} SSD, is used if the aggregate is wet. Apparent specific gravity, G_{sa}, is based solely on the solid material making up the constituent particles and does not include the pore space within the particles that is accessible to water.

Absorption values are used to calculate the change in the mass of an aggregate due to water absorbed in the pore spaces within the constituent particles, compared to the dry condition, when it is deemed that the aggregate has been in contact with water long enough to satisfy most of the absorption potential. The laboratory standard for absorption is that obtained after submerging dry aggregate for between 15 to 19 hours in water. Aggregates mined from below the water table may have a higher absorption, when used, if not allowed to dry. Conversely, some aggregates, when used, may contain an amount of absorbed moisture less than the 15-hour-soaked condition. For an aggregate that has been in contact with water and that has free moisture on the particle surfaces, the percentage of free moisture can be determined by deducting the absorption from the total moisture content.

The pores in lightweight aggregates may or may not become filled with water after immersion for 15 hours. In fact, many such aggregates can remain immersed in water for several days without satisfying most of the aggregates' absorption potential. Therefore, this method is not intended for use with lightweight aggregate.

Scope

This procedure covers the determination of specific gravity and absorption of coarse aggregate in accordance with AASHTO T 85-22. Specific
04 gravity may be expressed as bulk specific gravity
(G_{sb}), bulk specific gravity - saturated surface dry (G_{sb} SSD), or apparent specific gravity (G_{sa}). G_{sb} and absorption are based on aggregate after soaking in water. This procedure is not intended for use with lightweight aggregates.



Moisture conditions

Terminology

05 Absorption – the increase in the mass of aggregate
06 due to water being absorbed into the pores of the
07 material, but not including water adhering to the
outside surface of the particles, expressed as a percentage of the dry mass. The aggregate is considered "dry" when it has been maintained at a temperature of 110 ±5°C (230 ±9°F) for sufficient time to remove all uncombined water.

Saturated Surface Dry (SSD) – the condition of an aggregate particle when the permeable voids are filled with water, but no water is present on exposed surfaces.

Specific Gravity – the ratio of the mass, in air, of a volume of a material to the mass of the same volume of gas-free distilled water at a stated temperature.

Apparent Specific Gravity (G_{sa}) – the ratio of the mass, in air, of a volume of the impermeable portion of aggregate to the mass of an equal volume of gas-free distilled water at a stated temperature.

Bulk Specific Gravity (G_{sb}) – the ratio of the mass, in air, of a volume of aggregate (including the permeable and impermeable voids in the particles, but not including the voids between particles) to the mass of an equal volume of gas-free distilled water at a stated temperature.

Bulk Specific Gravity (SSD) (G_{sb} SSD) – the ratio of the mass, in air, of a volume of aggregate, including the mass of water within the voids filled to the extent achieved by submerging in water for 15 to 19 hours (but not including the voids between particles), to the mass of an equal volume of gas-free distilled water at a stated temperature.

Definition: (Specific Gravity Symbols)

G_{sb}

“G” Denotes that this is a **Specific Gravity**

Denotes **Type of Material**

s = soil or “stone”
b = binder
m = mix

Denotes **Type of Specific Gravity**

b = bulk
a = apparent
m = maximum
e = effective

8

Sample container and scale

09

10

Apparatus

- Balance or scale: with a capacity of 5 kg, sensitive to 0.1 g, and meeting the requirements of AASHTO M 231.
- Sample container: a wire basket of 3.35 mm (No. 6) or smaller mesh, with a capacity of 4 to 7 L (1 to 2 gal) to contain aggregate with a nominal maximum size of 37.5 mm (1 1/2 in.) or smaller; or a larger basket for larger aggregates, or both.
- Water tank: watertight and large enough to completely immerse aggregate and basket, equipped with an overflow valve to keep water level constant.
- Suspension apparatus: wire used to suspend apparatus shall be of the smallest practical diameter.
- Sieves: 4.75 mm (No. 4) or other sizes as needed, meeting the requirements of FOP for AASHTO T 27/T 11.
- Large absorbent cloth

Sample Preparation

1. Obtain the sample in accordance with the FOP for AASHTO R 90 (see Note 1). 11
2. Mix the sample thoroughly and reduce to the approximate sample size required by Table 1 in accordance with the FOP for AASHTO R 76.
3. Reject all material passing the appropriate sieve by dry sieving.
4. Thoroughly wash sample to remove dust or other coatings from the surface.
5. Dry the sample to constant mass according to the FOP for AASHTO T 255/T 265 at a temperature of 110 ±5°C (230 ±9°F) and cool in air at room temperature for 1 to 3 hours. 12

Note 1: Where the absorption and specific gravity values are to be used in proportioning concrete mixtures in which the aggregates will be in their naturally moist condition, the requirement for initial drying to constant mass may be eliminated, and, if the surfaces of the particles in the sample have been kept continuously wet until test, the 15-to-19-hour soaking may also be eliminated.

6. Re-screen the sample over the appropriate sieve. Reject all material passing that sieve.
7. The sample shall meet or exceed the minimum mass given in Table 1.

Note 2: If this procedure is used only to determine the G_{sb} of oversized material for the FOP for AASHTO T 99 or T 180, the material can be rejected over the appropriate sieve. For T 99 / T 180 Methods A and B, use the 4.75 mm (No.4) sieve; for T 99 / T 180 Methods C and D, use the 19 mm (3/4 in).

13

Table 1

Nominal Maximum Size*, mm (in.)	Minimum Mass of Sample, g (lb)
12.5 (1/2) or less	2000 (4.4)
19.0 (3/4)	3000 (6.6)
25.0 (1)	4000 (8.8)
37.5 (1 1/2)	5000 (11)
50 (2)	8000 (18)
63 (2 1/2)	12,000 (26)
75 (3)	18,000 (40)

* One sieve larger than the first sieve to retain more than 10 percent of the material using an agency specified set of sieves based on cumulative percent retained. Where large gaps in specification sieves exist, intermediate sieve(s) may be inserted to determine nominal maximum size.

Procedure

1. Immerse the sample in water at room temperature for a period of 15 to 19 hours.

14 *Note 3:* When testing coarse aggregate of large nominal maximum size requiring large samples, it may be more convenient to perform the test on two or more subsamples, and then combine values obtained.

2. Place the empty basket into the water bath and attach to the balance. Inspect the immersion tank to ensure the water level is at the overflow outlet height and basket is fully submerged. Tare the balance with the empty basket attached in the water bath.


SSD Sample

3. 15 Remove the sample from the water and roll it in a large absorbent cloth until all visible films of water are removed. Wipe the larger particles individually. If the sample dries past the SSD condition, immerse in water for 30 min, and then resume the process of surface-drying.

Note 4: A moving stream of air may be used to assist in the drying operation but take care to avoid evaporation of water from aggregate pores.

4. Determine the SSD mass of the sample, and record this and all subsequent masses to the nearest 0.1 g or 0.1 percent of the sample mass,

whichever is greater. Designate this mass as "B."

5. Immediately place the SSD sample in the sample container and weigh it in water maintained at 23.0 ±1.7°C (73.4 ±3°F). Shake the container to release entrapped air before recording the weight. Re-inspect the immersion tank to ensure the water level is at the overflow outlet height and basket is fully submerged. Designate this submerged weight as "C."

Note 5: The container should be immersed to a depth sufficient to cover both it and the sample during mass determination. The wire suspending the container should be of the smallest practical size to minimize any possible effects of a variable immersed length.

Submerged sample in container

16 6. Remove the sample from the basket. Ensure
that all material has been removed and place in
17 a container of known mass.

7. Dry the sample to constant mass according to the FOP for AASHTO T 255/T 265 at 110 ±5°C (230 ±9°F) and cool in air at room temperature for 1 to 3 hours.

8. Determine and record the dry mass. Designate this mass as "A."

Calculations

Perform calculations and determine values using the appropriate formula below.

Bulk specific gravity (G_{sb})

$$G_{sb} = \frac{A}{B - C} \tag{18}$$

Bulk specific gravity, SSD (G_{sb} SSD)

$$G_{sb}SSD = \frac{B}{B - C} \tag{19}$$

Apparent specific gravity (G_{sa})

$$G_{sa} = \frac{A}{A - C} \tag{20}$$

Absorption

$$\text{Absorption} = \frac{B - A}{A} \times 100 \tag{21}$$

Where:

A = oven dry mass, g

B = SSD mass, g

C = weight in water, g

Sample Calculations

Sample	A	B	C	B - C	A - C	B - A
1	2030.9	2044.9	1304.3	740.6	726.6	14.0
2	1820.0	1832.5	1168.1	664.4	651.9	12.5
3	2035.2	2049.4	1303.9	745.5	731.3	14.2

Sample	G_{sb}	G_{sb} SSD	G_{sa}	Absorption
1	2.742	2.761	2.795	0.7
2	2.739	2.758	2.792	0.7
3	2.730	2.749	2.783	0.7

These calculations demonstrate the relationship between G_{sb}, G_{sb} SSD, and G_{sa}. G_{sb} is always lowest since the volume includes voids permeable to water. G_{sb} SSD is always intermediate. G_{sa} is always highest since the volume does not include voids permeable to water. When running this test, check to make sure the values calculated make sense in relation to one another.

22 Report

- On forms approved by the agency
- Sample ID
- Specific gravities to the nearest 0.001
- Absorption to the nearest 0.1 percent

Tips! 23

- Shake the container and sample when weighing in water to release entrapped air.
- Compare G_{sb}, G_{sb} SSD, and G_{sa} to see if they make sense.

REVIEW QUESTIONS

1. What size sample is required for aggregate with a nominal maximum size of 25 mm (1 in.)?

2. When is soaking required? For how long must material be soaked?

3. When, in the process, are dry and SSD masses determined?

REVIEW QUESTIONS (KEY)

1. What size sample is required for aggregate with a nominal maximum size of 25 mm (1 in.)?

Sample size of 4000 grams *(8.8 say, **9 pounds**)* is required.
(from AASHTO T 85, Sample Preparation, Step 7, Table 1, page 7-5)

2. When is soaking required? For how long must material be soaked?

Soaking for a period of ***15 to 19 hours*** is required for this procedure after the sample preparation is complete, once the aggregate sample has reached constant mass and has been allowed to cool to room temperature.
(from AASHTO T 85, Procedure, Step 1, page 7-5)

3. When, in the process, are dry and SSD masses determined?

Three separate masses are needed in order to calculate the specific gravity of coarse aggregate in the lab. **SSD mass** is determined first. The **dry mass** of the sample is determined last. *(The third mass needed is called the **"in water"** weight (or mass). It is determined second of the three.)*
(from AASHTO T 85, Procedure, Step 4 through 7, page 7-6)

IN-PLACE DENSITY AND MOISTURE CONTENT OF SOIL AND SOIL-AGGREGATE BY NUCLEAR METHODS (SHALLOW DEPTH)

FOP FOR AASHTO T 310

Significance

The final in-place density of backfill, roadway embankment, and base is critical to the quality and longevity of a highway project. Low-density material will lead to excessive deflection under load or permanent deformation, or both.

Checking deflection

Performance of this test method in trenches and near structures requires a trench offset correction.

The nondestructive nature of the test allows repetitive measurements to be made at a single test location between roller passes. The procedure is normally suitable from test depths of 50 mm (2 in.) to 300 mm (12 in.).

Scope

Caution!

This procedure covers the determination of density, moisture content, and relative compaction of soil, aggregate, and soil-aggregate mixes in accordance with AASHTO T 310-22. This procedure provides a rapid, nondestructive technique for determining the in-place wet density and moisture content of soil, aggregate, and soil-aggregate mixes. This field operating procedure is derived from AASHTO T 310. The nuclear moisture-density gauge is used in the direct transmission mode.

Apparatus

Gauge, transport case and instruction manual

- Nuclear density gauge with the factory matched standard reference block.
- Drive pin, guide / scraper plate, and hammer for testing in direct transmission mode.
- Transport case for properly shipping and housing the gauge and tools.
- Instruction manual for the specific make and model of gauge.
- Radioactive materials information and calibration packet containing:

  - Daily Standard Count Log
  - 09 Factory and Laboratory Calibration Data Sheet
  - Leak Test Certificate
  - Shippers Declaration for Dangerous Goods
  - 10 Procedure Memo for Storing, Transporting and Handling Nuclear Testing Equipment
  - Other radioactive materials documentation as required by local regulatory requirements
- Sealable containers and utensils for moisture content determinations.

Radiation Safety

- 11 This method does not purport to address all the safety problems associated with its use. The gauge utilizes radioactive materials that may be hazardous to the health of the user unless proper precautions are taken. Users of this gauge must become familiar with the applicable safety procedures and governmental regulations. All operators will be trained in radiation safety prior to operating nuclear density gauges. Some agencies require the use of personal monitoring devices such as a thermoluminescent dosimeter or film badge. Effective instructions together with routine safety procedures such as source leak tests, recording and evaluation of personal monitoring device data, etc., are a recommended part of the operation and storage of this gauge.

Calibration

12 Calibrate the nuclear gauge as required by the agency. This calibration may be performed by the agency using manufacturer's recommended procedures or by other facilities approved by the agency. Verify or re-establish calibration curves, tables, or equivalent coefficients every 12 months.

Standardizing the nuclear density gauge

Standardization

1. Turn the gauge on and allow it to stabilize (approximately 10 to 20 minutes) prior to standardization. Leave the power on during the day's testing.
2. Standardize the nuclear gauge at the construction site at the start of each day's work and as often as deemed necessary by the operator or agency. Daily variations in standard count shall not exceed the daily variations established by the manufacturer of the gauge.

   13 If the daily variations are exceeded after repeating the standardization procedure, the gauge should be repaired and/or recalibrated.
3. Record the standard count for both density and moisture in the Daily Standard Count Log. The exact procedure for standard count is listed in the manufacturer's Operator's Manual. 14

Note 1: New standard counts may be necessary more than once a day. See agency requirements.

Overview

15 There are two methods for determining in-place density of soil / soil aggregate:

- Method A: Single Direction
- Method B: Two Directions

Procedure

16

1. Select a test location(s) randomly and in accordance with agency requirements. Test sites should be relatively smooth and flat and meet the following conditions:
   a) At least 10 m (30 ft.) away from other sources of radioactivity
   b) At least 3 m (10 ft.) away from large objects
   c) The test site should be at least 150 mm (6 in.) away from any vertical projection.
   d) Correct for trench wall effect according to manufacturer's correction procedures if the test site is closer than 600 mm (24 in.) to vertical projection. See Note 2.

Note 2: To perform moisture and density tests in a trench or against a large solid object, it is necessary to perform a trench moisture correction to adjust the gauge or it may read a falsely high moisture content. Moisture present in the walls can thermalize neutrons which return to the gauge and are read as moisture by the detector in the gauge.

2. Remove all loose and disturbed material and remove additional material as necessary to expose the top of the material to be tested.

Prepared area

17

3. Prepare a flat area sufficient in size to accommodate the gauge. Plane the area to a smooth condition to obtain maximum contact between gauge and the material being tested. For Method B, the flat area must be sufficient to permit rotating the gauge 90 or 180 degrees about the source rod.

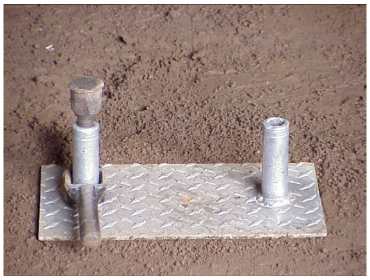
4. Fill in surface voids beneath the gauge with fines of the material being tested passing the 4.75 mm (No. 4) sieve or finer. Smooth the surface with the guide plate or other suitable tool. The depth of the filler should not exceed approximately 3 mm (1/8 in.).

18

Filling surface voids

5. Make a hole perpendicular to the prepared surface using the guide plate and drive pin. The hole shall be at least 50 mm (2 in.) deeper than the desired source rod depth and shall be aligned so that insertion of the source rod will not cause the gauge to tilt from the plane of the prepared area. Remove the drive pin by pulling straight up and twisting the extraction tool.

19



Guide plate and drive pin

6. Place the gauge on the prepared surface so the source rod can enter the hole without disturbing loose material.

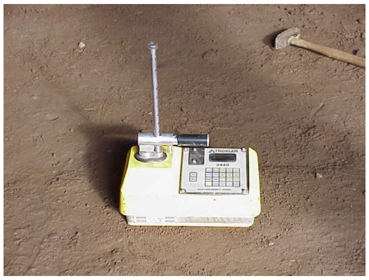
7. Lower the source rod into the hole to the desired test depth using the handle and trigger mechanism.

8. Seat the gauge firmly by partially rotating it back and forth about the source rod. Ensure the gauge is seated flush against the surface by pressing down on the gauge corners and making sure that the gauge does not rock.

9. Pull gently on the gauge to bring the side of the source rod nearest to the scaler / detector firmly against the side of the hole.

10. Perform one of the following as required by agency:

    23 a. **Method A Single Direction**: Take a test consisting of the average of two one-minute readings, and record both density and moisture data. The two wet density readings should be within 32 kg/m^3 (2.0 lb/ft^3) of each other. The average of the two wet densities and moisture contents will be used to compute dry density.



Taking a reading

    22 b. **Method B Two Direction:** Take a one-minute reading and record both density and moisture data. Rotate the gauge 90 or 180 degrees, pivoting it around the source rod. Reseat the gauge by pulling gently on the gauge to bring the side of the source rod nearest to the scaler / detector firmly against the side of the hole and take a one-minute reading. (In trench locations, rotate the gauge 180 degrees for the second test.) Some agencies require multiple one-minute readings in both directions. Analyze the density and moisture data. A valid test consists of wet density readings in both gauge positions that are within 50 kg/m^3 (3.0 lb/ft^3). If the tests do not agree within this limit, move to a new location. The average of the wet density and moisture contents will be used to compute dry density.

Representative sample site

24 11. If required by the agency, obtain a representative sample of the material, 4 kg (9 lb) minimum, from directly beneath the gauge full depth of material tested. This sample will be used to verify moisture content and / or identify the correct density standard. Immediately seal the material to prevent loss of moisture.

The material tested by direct transmission can be approximated by a cylinder of soil approximately 300 mm (12 in.) in diameter directly beneath the centerline of the radioactive source and detector. The height of the cylinder will be approximately the depth of the measurement. When organic material or large aggregate is removed during this operation, disregard the test information, and move to a new test site.

12. To verify the moisture content from the nuclear
gauge, determine the moisture content with a
25 representative portion of the material using the
FOP for AASHTO T 255/ T 265 or other
agency approved methods. If the moisture
content from the nuclear gauge is within
±1 percent, the nuclear gauge readings can be
26 accepted. Moisture content verification is gauge
and material specific. Retain the remainder of
the sample at its original moisture content for a
one-point compaction test under the FOP for
AASHTO T 272, or for gradation, if required.

Note 2: Example: A gauge reading of 16.8 percent moisture and oven dry, or 17.7 percent are within the ±1 percent requirement. Moisture correlation curves will be developed according to agency guidelines. These curves should be reviewed and possibly redeveloped every 90 days because of moisture source decay.

13. Determine the dry density by one of the following methods:
    a. From nuclear gauge readings, compute by subtracting the mass (weight) of the water (kg/m^3 or lb/ft^3) from the wet density (kg/m^3 or lb/ft^3); or compute using the percent moisture by dividing wet density from the nuclear gauge by 1 plus the moisture content expressed as a decimal.
    b. When verification is required and the nuclear gauge readings cannot be accepted, the moisture content is determined by the FOP for AASHTO T 255/T 265, or other agency approved methods. Compute dry density by dividing wet density from the nuclear gauge by 1 plus the moisture content expressed as a decimal.

Percent Compaction

29

- Percent compaction is determined by comparing the in-place dry density as determined by this procedure to the appropriate agency density standard. For soil or soil-aggregate mixes, these are moisture-density curves developed using the FOP for AASHTO T 99 / T 180. When using maximum dry densities developed by the FOP for AASHTO T 99 / T 180 or FOP for AASHTO T 272, it may be necessary to use the Annex in the FOP for AASHTO T 99/T 180 to determine corrected maximum dry density and optimum moisture content.

  For coarse granular materials, the density standard may be density-gradation curves developed using a vibratory method such as AKDOT&PF's ATM 212, ITD's T 74, WAQTC TM 15, or WFLHD's Humphres.

  See appropriate agency policies for use of density standards.

Calculation

Calculate the dry density as follows:

$$\rho_d = \left(\frac{\rho_w}{w + 100}\right) \times 100 \quad or \quad \rho_d = \frac{\rho_w}{\frac{w}{100} + 1}$$ 27

Where:

ρ_d = Dry density, kg/m^3 (lb/ft^3)

ρ_w = Wet density, kg/m^3 (lb/ft^3)

w = Moisture content from the FOPs for AASHTO T 255 / T 265, as a percentage

Calculate percent compaction as follows: 29

$$\% \, Compaction = \frac{\rho_d}{Agency\ density\ standard} \times 100$$

where:

ρ_d = Dry density, kg/m^3 (lb/ft^3)

Agency density standard = Corrected maximum dry density from the FOP from T 99/T 180 Annex

Example:

30

Wet Density readings from gauge:

1948 kg/m^3 (121.6 lb/ft^3)
1977 kg/m^3 (123.4 lb/ft^3)

Avg.: 1963 kg/m^3 (122.5 lb/ft^3)

Moisture readings from gauge: 14.2% and 15.4% = Avg. 14.8% 31

Moisture content from the FOP's for AASHTO T 255 / T 265: 15.9%

Moisture content is greater than 1 percent different so the gauge moisture cannot be used.

Calculate the dry density as follows: 32

$$\rho_d = \left(\frac{1963\, kg/m^3\ or\ 122.5\ lb/ft^3}{15.9 + 100}\right) \times 100\ or\ \ \rho_d = \frac{1963\, kg/m^3\ or\ 122.5\ lb/ft^3}{\frac{15.9}{100} + 1}$$

$$= 1694\ kg/m^3\ or\ 105.7\ lb/ft^3$$

Given:

ρ_w = 1963 kg/m^3 or 122.5 lb/ft^3

w = 15.9%

Calculate percent compaction as follows: 33

$$\% \, Compaction = \frac{105.7 \, lb/ft^3}{111.3 \, lb/ft^3} \times 100 = 95\%$$

Given:

Agency density standard = 111.3 lb/ft^3

Report

- 34 On forms approved by the agency
- Sample ID
- Location of test, elevation of surface, and thickness of layer tested
- Visual description of material tested
- Make, model and serial number of the nuclear moisture-density gauge
- Wet density to the nearest 0.1 lb/ft^3 35
- Moisture content as a percent, by mass, of dry soil mass to the nearest 0.1 percent
- Dry density to the nearest 0.1 lb/ft^3
- Density standard to the nearest 0.1 lb/ft^3
- Percent compaction to the nearest 1 percent
- Name and signature of operator

Tips!

- Check to make sure that:
  - base of gauge is clean prior to testing.
  - shutter block and assembly are free of debris and operating correctly.
  - source rod tip does not have a buildup of material on end.
  - gauge is reading the proper position of the source rod when it is indexed, and that it has been seated correctly.
  - the hole into which the source is lowered is at least 50 mm (2 in.) deeper than the indexed position of the source rod.
  - surface is flat and the gauge does not rock.
  - surface has been properly prepared using filler material.
- Make sure battery is charged before starting work

REVIEW QUESTIONS

1. Describe the calibration and standardization process.

2. What precautions must be taken in selecting a test location?

3. Describe the procedure leading up to the taking of test measurements.

4. What is the difference between Method A and Method B?

5. What is the purpose of determining moisture content by other means than the nuclear gauge?

REVIEW QUESTIONS (KEY)

1. Describe the calibration and standardization process.

Annual calibration on the nuclear gauge is done every 12 months, or as required by the agency.

Standardize the nuclear gauge at the start of each day or when weather conditions change drastically. Warm the gauge up for ***10 to 20 minutes*** and then take standard counts as per the recommendations of the manufacturer. Record both the moisture and density counts in the ***Daily Standard Count Log Book.***
(from AASHTO T 310, Calibration & Standardization, pages 8-2 & 8-3)

2. What precautions must be taken in selecting a test location?

The test location shall be at least **30 feet** away from any other radioactive source *(like another gauge)*, at least **10 feet** away from any large object *(like a pickup truck or a piece of heavy equipment)*, and at least **6 inches** away from any vertical projection *(like a sewer trench wall or raised manhole prior to paving in the middle of a road / street grade)*.
(from AASHTO T 310, Procedure, Step 1 (a, b & c), page 8-3)

3. Describe the procedure leading up to the taking of test measurements.

Remove all loose material from the test site. Prepare a flat area large enough to accommodate the test procedure to be used. Fill the surface voids up to ***1/8 inch*** in depth. Using the guide plate, drive the pin into the surface at least ***2 inches deeper*** than the test to be taken. Remove the pin without damaging the hole. Place the gauge over the hole and lower the pin to the desired test depth without deforming the sides of the hole. Pull the gauge back until it is ***seated*** against the back side of the hole. Check the gauge for being level by placing hands on opposite corners of the gauge to see if it rocks or moves. The nuclear gauge is now ready to begin collecting test data.
(from AASHTO T 310, Procedure, Steps 2 through 9, pages 8-3 & 8-4)

4. What is the difference between Method A and Method B?

Method A is known as the ***single direction*** method. Take two readings in the same direction. Each test lasts for one minute. The allowable tolerance between the two wet density readings from the gauge should be within ***2 pound per cubic foot*** (pcf).

Method B is known as the ***two direction*** method. Take the second reading either **90°** or **180°** from the original reading location. An example of a 180° pivot would be in a trench *(sewer project, etc)*. Each test lasts for one minute. The allowable tolerance between the two wet density readings from the gauge should be within ***3 pcf***.
(from AASHTO T 310, Procedure, Step 10 (a & b), page 8-5)

5. What is the purpose of determining moisture content by other means than the nuclear gauge?

   Moisture content is determined via the field operating procedure *(FOP)* for AASHTO T 255 / T 265 in order to verify the moisture as read from the nuclear gauge. If the two moistures are within ***plus or minus one percent*** of each other, the nuke gauge moisture content may be used.

(from AASHTO T 310, Procedure, Step 12, page 8-6)

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SOILS, EXCAVATION, & EMBANKMENT INSPECTION MANUAL

April, 2023

Contents

Appendix 1: Determining the Liquid Limit of Soils
FOP for AASHTO T89
Determining the Plastic Limit and Plasticity Index of Soils
FOP for AASHTO T90

Appendix 2: AASHTO M-145 Soil Classification Example and Partial Group Index Determination

Appendix 3: Determination of Zero Air Voids Density of Soils with Varying Moisture Content and Specific Gravity

<u>List of acronyms and abbreviations</u>

American Association of State Highway and Transportation Officials	AASHTO
Colorado Department of Transportation	CDOT
Colorado Procedure	CP
Expanded Polystyrene Geofoam	EPS Foam
Mechanistic – Empirical Pavement Design	M-E Pavement Design
Liquid Limit	LL
Non Plastic	NP
No Value	NV
Operational Assurance	OA
Optimum Moisture Content	OMC
Plasticity Index:	PI
Plastic Limit:	PL
Process Control	PC
Western Alliance for Quality Transportation Construction:	WAQTC

Introduction

Inspection and testing during embankment and roadway construction is one method that is used to improve the quality and performance of our highways. This process provides documentation that materials and construction procedures conform to project plans and specifications. The Colorado Department of Transportation (CDOT) qualifies soils and embankment inspectors through the Western Alliance for Quality Transportation Construction (WAQTC) through their Embankment and Base and In-Place Density module. In addition to the WAQTC qualification materials, CDOT desires to have our inspectors familiar with construction practices, geological conditions, testing procedures, and construction specifications that are unique for Colorado.

The goal of this manual is to help familiarize our inspectors with the equipment, testing, and construction practices utilized by CDOT for road and embankment construction. This manual provides background knowledge to help prepare our inspectors to perform their responsibilities during construction. The second portion of CDOT's soils and embankment qualification process includes demonstrating a familiarity of the materials contained in this manual by passing a written exam with questions related to its content. Additional performance exams are also required to demonstrate ability and knowledge to complete other soil tests beyond that which are required to qualify for WAQTC Embankment and Base and In-Place Density certification.

Chapter 1 - Road Construction Basics

Constructing a roadway through a corridor typically requires alternating cut and fill sections to bring the roadway to the specified alignment and grade (Figures 1 and 2). Roadway designers make an attempt to balance cut and fill sections to avoid the need for importing embankment fill materials, and to avoid disposal of excess material derived from cuts after construction is completed.

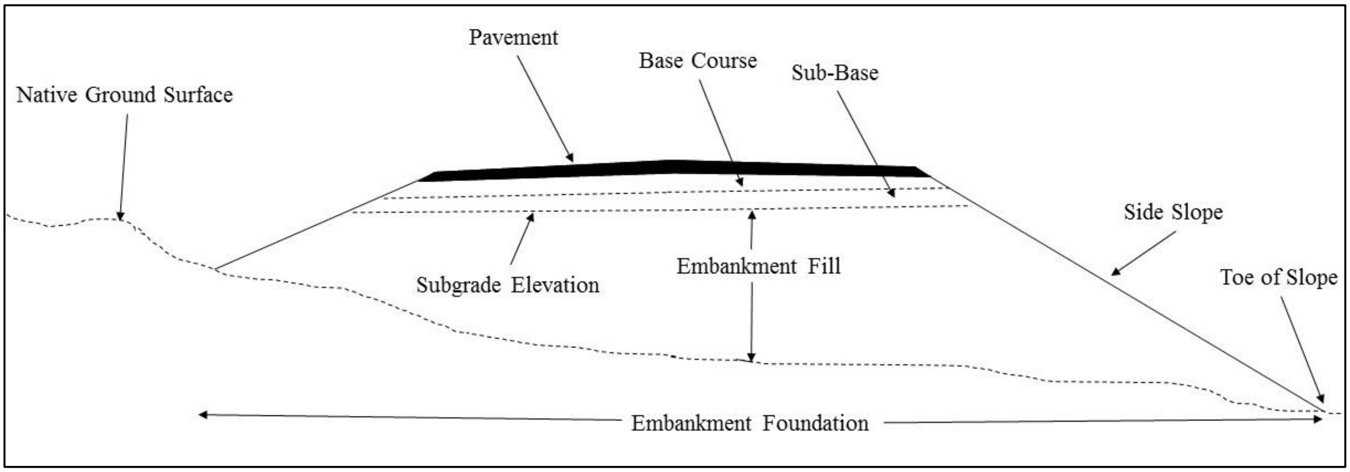


Figure 1: Generalized embankment cross section.

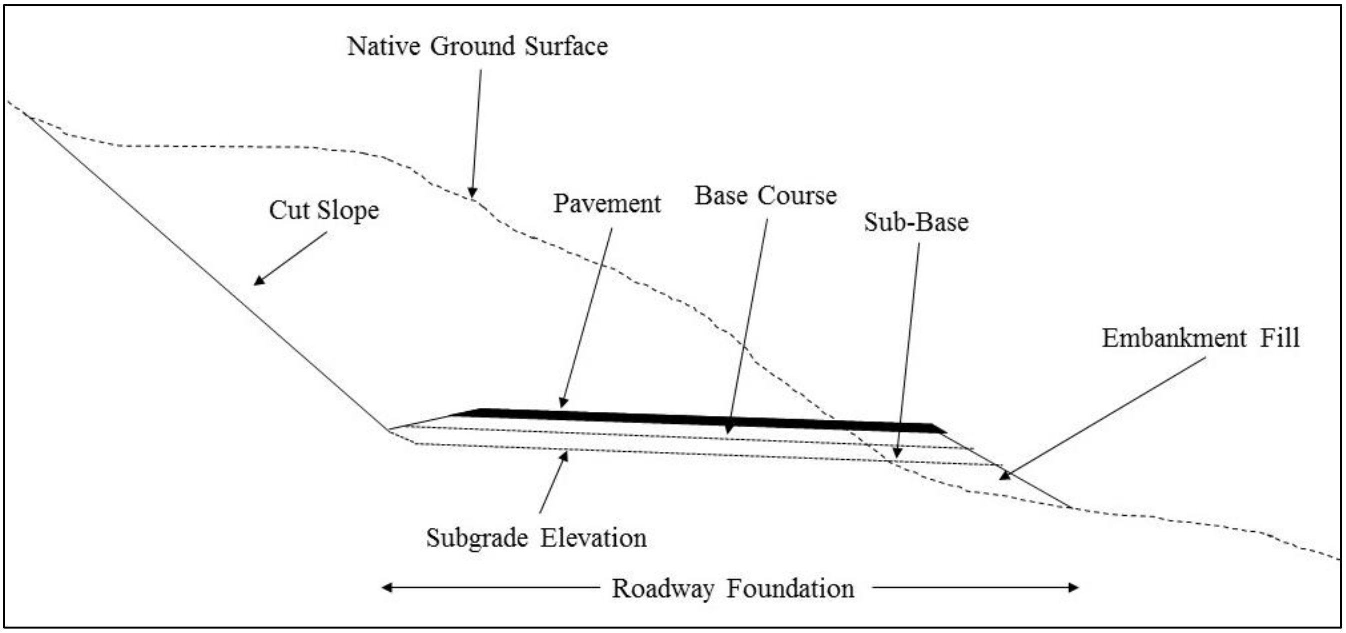


Figure 2: Generalized roadway cut cross section.

Roadway/Embankment Foundation – The native materials onto which a road or embankment is constructed. These materials need to be adequately prepared to provide a stable foundation for the roadway and/or embankment. Preparation at a minimum requires clearing and grubbing, followed by moisture conditioning and compaction. Preparation may also involve in-situ stabilization or even over-excavation and replacement if the materials consist of weak or poor quality soils.

Embankment Fill – The materials used to raise grade to build the roadway up to a specified elevation and to provide support for the roadway and pavement section. Embankment fill material will vary from project to project based on geological conditions (i.e. the material that is locally available), project requirements, specifications, and cost.

Subgrade – The boundary between the top of the embankment fill (in fill sections) or the foundation materials (in cut sections) and the base of the pavement section.

Sub-Base – A layer of aggregate material placed on the subgrade (or completed embankment), onto which the base course layer is placed.

Base Course – A layer of clean sand and gravel that is designed as part of the pavement section to provide strength and increase the life span of the pavement. This layer also provides drainage and separation between the pavement and the underlying fill materials.

Side Slope – The slope formed between the edges of the roadway shoulder and the toe of the embankment. The angle permitted for construction will vary depending on the materials used in the embankment, the quality of the foundation soils, quantity of fill materials available, and the height of the embankments on the project.

Cut Slope – A designed slope that results from removing a high section of topography to accommodate the roadway alignment. The angle permitted for construction will vary depending on materials present within the cut section (i.e. stability), and the need to balance cut and fill quantities (cut slope angles may be increased/decreased to provide the required amount of fill materials for a project).

It is important for the inspector to become familiar with the structure of the roadway, the different soil types that are expected to be encountered in cut slopes and the foundations, and the types of soils that are specified for constructing the embankment and pavement section. Changed conditions or a change in expected materials may require modification of the construction requirements to improve the quality of the finished roadway.

Chapter 2 - Preliminary Investigations

Before roadway or embankment construction even begins, designers and engineers need to become familiar with the types of soils and bedrock that will be encountered on a project. An understanding of groundwater conditions is also necessary. It is necessary to understand foundation conditions for the roadway and embankments, to characterize the materials in cut sections, and to characterize materials in potential borrow source areas. A subsurface investigation is conducted prior to design of any road construction project to gain an understanding of the geological conditions present, and to identify the materials available for construction. These investigations assist engineers in designing embankments and roadways to perform adequately with the materials available and the ground conditions present.

Geotechnical Explorations

General guidelines for geotechnical explorations are presented in Chapter 4 of the Colorado Mechanistic – Empirical (M-E) Pavement Design Manual and Chapter 200 of the CDOT Field Materials Manual: Soil Survey/Preliminary Soil Profile. These manuals provide information on several methods used to characterize the subsurface conditions within a project site or alignment and provide guidelines for collection of soil and bedrock samples for testing and classification. Geotechnical explorations can include drilling soil borings into the subsurface, excavating test pits, and/or the use of geophysical methods to characterize the subsurface conditions. The primary purpose of conducting geotechnical explorations is to identify, delineate, and classify various geological units and soil types through a corridor, and to collect soil samples for laboratory testing.

Photograph 1: Subsurface explorations and soil sampling being conducted with a drill rig.

With this information designers can determine which materials are/are not suitable for use as construction materials, what areas are suitable to build roadways and embankments on, and what areas will require special treatment and stabilization during construction. This information is then conveyed to contractors through the Plans and Specifications that are developed for a project. CDOT soil inspectors need to become familiar with the unique earthwork requirements specified for their given projects.

Chapter 4 of the Colorado M-E Pavement Design Manual and Chapter 200 of the CDOT Field Materials Manual also provide general guidelines for the minimum recommended spacing and depth of geotechnical explorations. For new roadway and embankment construction projects, the following recommendations are given:

- Test holes should not be spaced more than 1,000 feet apart along a corridor alignment through at-grade or fill sections. In continuous cut sections, test holes should not be spaced more than 500 feet apart (Figure 3).

- Subsurface characterization of the upper 10 feet of the subgrade is required for the M-E Pavement Design Methodology (cuts and at-grade sections). Therefore, it is recommended that borings extend a minimum of 10 feet below the final proposed grade (Figure 3).

- For embankments higher than 5 feet, test holes should extend to a minimum depth equal to 2 times the embankment height or into bedrock or similar hard stratum (Figure 3).

- Test holes should extend through the highest portion of a cut section and extend to a minimum depth of 10 feet below the proposed finished grade (Figure 3).

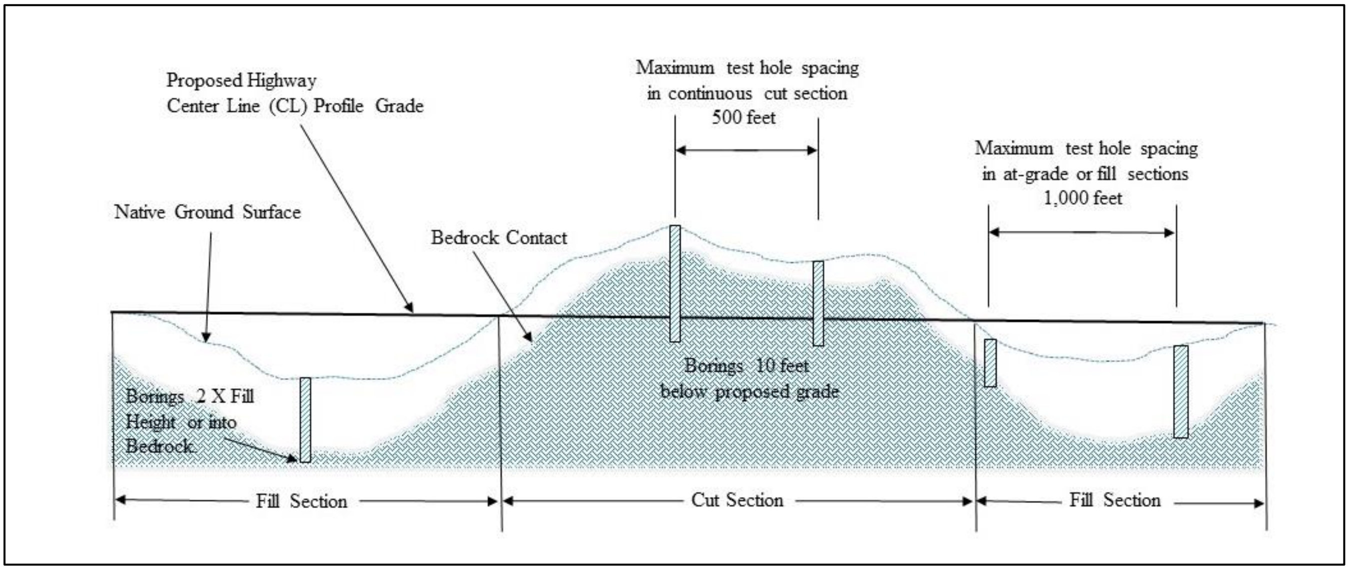


Figure 3: Generalized roadway profile illustrating minimum required geotechnical test hole spacing and depth requirements.

In addition to these requirements, it is recommended that additional explorations be conducted to capture known changes in geological conditions within a corridor. Some projects may require more extensive investigations; in particular high-speed multi-lane facilities in rough terrain or through areas with complex geological conditions.

Borrow Sources

Another purpose of conducting preliminary geotechnical explorations is to identify potential borrow sources for materials that can be used for new highway construction. Borrow pits are permitted areas where approved material is excavated or acquired from stockpiles. If CDOT has the permits to a borrow pit and offers the pit to a contractor it is designated an *available source.* Any borrow sources other than an *available source* is considered a *contractor source*, and it is the contractor's responsibility to obtain any necessary permits and certify that no hazardous materials exist in the source.

Geotechnical explorations are required to identify, sample, and classify potential borrow source areas. Representative soil samples must be submitted to a Region/Central lab for classification and testing before being approved for use in embankment construction. A pit sketch and sampling request must be submitted to the Region Materials Engineer for approval.

Chapter 3 – Basic Soil Mechanics

Soil and embankment inspectors need to understand basic information about soils, testing procedures to classify soils, and how different soil types behave when they are used as an engineered material (i.e compaction, drainage, stability, etc.). This chapter provides a summary of basic soil mechanics and laboratory testing procedures used to determine soil index and engineering properties.

The American Association of State Highway and Transportation Officials (AASHTO) has developed a system for classifying soils into groups based on their different index properties. This classification system is referred to as AASHTO M-145, and is described below. The classification system is based on a soil's grain size distribution and Atterberg limits. These index properties, the tests used determine them, and a summary of the classification system are also described below.

Gradation Analyses

A gradation analysis is a method used to quantitatively determine the distribution of particle sizes in soils, aggregate, or soil-aggregate mixtures. Colorado Procedure (CP) 21, Mechanical Analysis of Soils, describes the procedure to run this test. An oven-dried soil sample that consists of a variety of particle sizes is passed through a series of sieves with different sized openings. The material that is collected or retained on each sieve is then weighed, and the percent mass of each particle size for the soil sample is calculated, then plotted on a grain size curve. The various sieve sizes that are used to classify the grain size distribution of a soil are included in Tables 1 and 2 below. This test is also referred to as a grain size analysis, particle size analysis, or sieve analysis. An example grain size curve is provided in Figure 4.

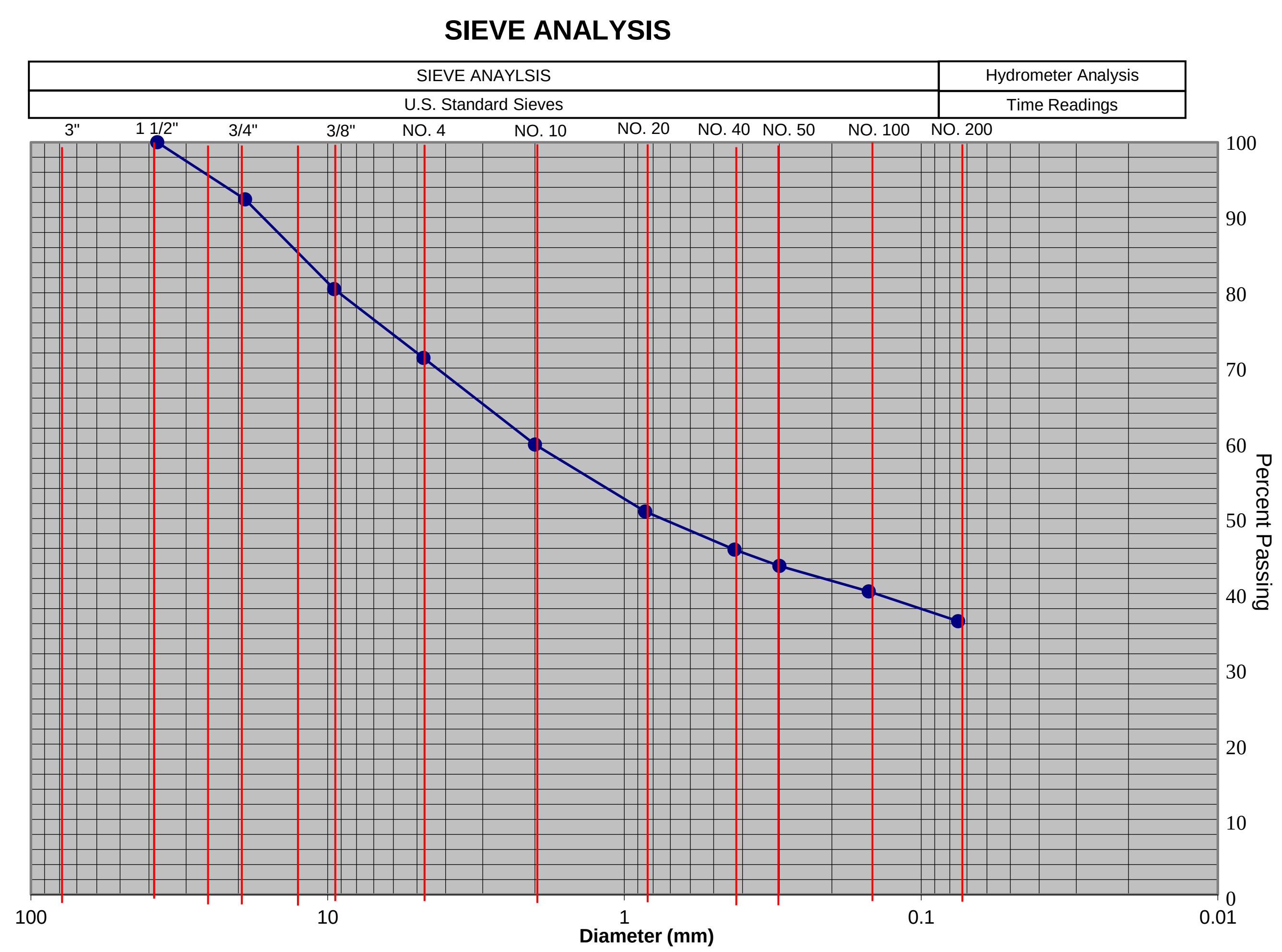
Table 1: Standard Sieve Sizes Used for Gradation Analyses (ASTM Classification)

Sieve Size/Number	Number of Openings per Linear Inch	Soil Type
3-inch	--	Gravel
1-½ -inch	--	
¾-inch	--	
⅜-inch	--	
# 4	4	
# 10	10	Course Sand
# 20	20	
# 40	40	
# 50	50	Fine Sand
# 100	100	
# 200	200	
< # 200	--	Fines (Silt and Clay)

Notes: Cobbles are defined as particle sizes between 3 inches and 12 inches in diameter.
Boulders are defined as particle sizes larger than 12 inches in diameter.

Table 2: Standard Sieve Sizes Used for Gradation Analyses (AASHTO Classification)

Sieve Size/Number	Number of Openings per Linear Inch	Soil Type
3-inch	--	Gravel
1-inch	--	
¾-inch	--	
⅜-inch	--	
# 4	4	
# 10	10	
# 40	40	Coarse Sand
# 200	200	Fine Sand
< # 200	--	Fines (Silt and Clay)



% Gravel: 28.7	% Course Sand: 25.5	% Fines (Silt and Clay): 36.3
	% Fine Sand: 9.5	

Figure 4: Example grain size curve (ASTM Classification).

A sufficient amount of soil needs to be sampled to run a representative gradation test. The minimum mass of material required is dependent on the *Nominal Maximum Size* of aggregate or particle in the sample. CDOT defines the *Nominal Maximum Size* as the smallest sieve opening through which the entire amount of specimen passes. For example, if 100 percent of a specimen passes the 1-½ -inch sieve, and material begins to collect on the next smallest sieve, the nominal maximum size of the sample is 1-½ -inch. Table 3 below summarizes the minimum test sample masses that are required for a gradation test given various nominal maximum particle sizes.

Table 3: Required Test Sample Masses for Gradation Analyses of Aggregate Given Various Nominal Maximum Particle Sizes

Nominal Maximum Size of Aggregate	CDOT Required Minimum Test Sample Masses	
	Pounds	Grams
3-½ -inch	33.0	15,000
3 -inch	27.5	12,500
2-½ -inch	22.0	10,000
2 -inch	16.5	7,500
1-½ -inch	11.0	5,000
1 -inch	5.5	2,500
¾ -inch	4.4	2,000
½ -inch	3.3	1,500
⅜ -inch	2.2	1,000
< ⅜ -inch	0.66	300

Notes: All test sample masses are dry masses.
For gradation analyses of soil, CP-20 requires a minimum of 500 grams (1.1 pound) of material passing the No. 4 sieve for a gradation analysis.

Atterberg Limits

The Atterberg limits define the range of moisture contents in which a soil behaves as a plastic. As the moisture content of a clayey soil increases, the material behavior will change from a dry solid, to plastic, and eventually to a liquid (Figure 5). The specific moisture contents that need to be determined for AASHTO M-145 soil classification are the plastic limit (PL) and the liquid limit (LL). The plastic limit of a soil is the lowest water content at which the soil remains plastic. The liquid limit is the moisture content at which the soil behavior changes from a plastic to a liquid state. The range of moisture contents that a soil behaves as a plastic is referred to as the plasticity index (PI), and is taken as the

difference between the liquid limit and the plastic limit moisture content:
(PI = LL – PL).

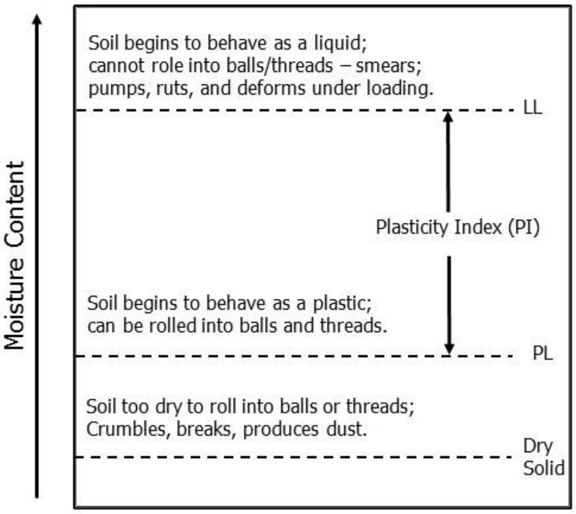


Figure 5: Graphical representation of soil behavior with increased moisture content.

Soils that do not exhibit plastic behavior (clean granular soils) will have a value of zero for the PI, and are referred to as Non Plastic (NP). These soils will have No Value (NV) prescribed for their liquid limit and plastic limit. Soils with higher clay content are characterized by higher liquid limits and higher plasticity indices. If a soil can be rolled into threads after moisture is added, or after the sample is partially dried if it is initially too wet to roll, then the material is considered plastic. If the material cannot be easily rolled, it is likely non-plastic.

The two test procedures used to define the Atterberg limits of a soil are AASHTO T 89, Determining the Liquid Limit of Soils, and AASHTO T 90, Determining the Plastic Limit and Plasticity Index of Soils. These test procedures and the calculations used to determine the liquid limit, plastic limit, and plasticity index are provided in Appendix 1.

AASHTO Soil Classification

The AASHTO Soil Classification system classifies soils into eight major groups based on their grain size distribution and Atterberg limits. These groups are designated A-1 through A-8 (Table 4). Soils that fall within the lower numbered groups are granular (sands and gravels), contain less than 35 percent fines, and tend to be either non-plastic or low plasticity (A-1, A-2, and A-3 soils). Soils that classify within the higher numbered groups have a higher fines content (silt and clay sized particles) and are generally characterized by higher plasticity (A-4, A-5, A-6, and A-7 soils). Peat classifies as an A-8 soil, and this material is characterized by an organic content of 15 percent or more.

Table 4: AASHTO M-145 Soil Classification System
Based on Grain Size Analyses and Atterberg Limit Values

General Classification	Granular Materials (35% or less passing No. 200 Sieve)							Silt and Clay Materials (More than 35% passing No. 200 Sieve)			
Group Classification	A-1		A-3	A-2				A-4	A-5	A-6	A-7
	A-1-a	A-1-b		A-2-4	A-2-5	A-2-6	A-2-7				A-7-5 A-7-6
Sieve Analysis Percent Passing:											
No. 10	50 max	--	--	--	--	--	--	--	--	--	--
No. 40	30 max	50 max	51 min	--	--	--	--	--	--	--	--
No. 200	15 max	25 max	10 max	35 max	35 max	35 max	35 max	36 min	36 min	36 min	36 min
Characteristics of fraction passing No. 40 sieve											
LL (Liquid Limit)	--		--	40 max	41 min	40 max	41 min	40 max	41 min	40 max	41 min
PI (Plasticity Index)	6 max		NP	10 max	10 max	11 min	11 min	10 max	10 max	11 min	11 min
Usual types of significant constituents	Stone fragments, gravel, and sand		Fine sand	Silty or clayey gravel and sand				Silty soils		Clayey soils	
General subgrade rating	Excellent to good					Fair to poor					

Notes: A-8 soils are not included on Table 4, but classify as peat or highly organic soils, and are not suitable for use within embankment foundations or embankment fill.
Plasticity index of A-7-5 subgroup is equal to or less than LL minus 30.
Plasticity index of A-7-6 subgroup is greater than LL minus 30.

To classify a soil using AASHTO M-145, gradation information and the Atterberg limits of a soil must be determined. The sieves used for this classification system are the No. 10, the No. 40, and the No. 200 sieves. To use this classification system, an individual can determine the correct soil classification by process of elimination. An example showing how to classify soils using the AASHTO M-145 system is provided in Appendix 2.

In addition to the major groups and subgroups listed above, additional classification using the liquid limit, plasticity index, and percent fines can be conducted to determine a soils partial group index. The partial group index is a number placed in parentheses after an AASHTO group number: e.g. A-6(5) indicates an A-6 group soil with a partial group index of 5. This number provides an indication of the percent fines a soil contains, the degree of plasticity of the fines, and gives an indication of the quality of the soil as a subgrade material. Higher partial group indices indicate poorer quality soils (i.e. an A-6 with a partial group index of 30 is a poorer quality soil than an A-6 with a partial group index of 5). The procedure to determine the partial group index of a soil is also covered in Appendix 2.

It is important for the inspector to familiarize themselves with this soil classification system. Project specifications will often require specific soil types be used for various types of backfill (i.e. retaining wall backfill, embankment fill, pipe bedding etc.). For example, many projects will require that “Select Material” be used in the upper 2 feet of an embankment prior to placing aggregate base course or pavement. The following AASHTO soil groups qualify as “Select Material”: A-1, A-2-4, and A-3.

Soil Compaction

The foundation soils and the materials used to construct embankments must be properly compacted during construction to improve stability, increase the strength of the soils, reduce the likelihood of post-construction settlement, and increase the long term performance of the roadway. To determine the degree of compaction of an engineered fill, a soil’s optimum moisture content and maximum dry density are used as a reference or benchmark. The following discussion is included to help the inspector understand this concept.

Any soil sample, native or engineered, is composed of solid particles (gravel, sand, silt, and/or clay) and void space/pore space. If the soil is completely dry (zero percent moisture) then the void spaces are filled with air. If a soil is completely saturated, then the void spaces are 100 percent filled with water. Compaction is by definition, the densification of a soil by removal of air/void space through mechanical energy. To adequately compact any soil with conventional construction equipment, water must be added to the soil to increase the degree of compaction that can be achieved. Water acts as a softening agent and allows soil particles to slip over one another and move into a denser configuration.

As water is added to a completely dry soil, the degree of compaction that can be achieved increases. In other words, the density of the soil that can be achieved increases. However, if too much water is added the soil then begins to behave as a liquid. The soil will simply pump or deform with compactive effort, and an increase to densification can no longer be achieved. The moisture content at which the maximum density of a soil can be attained is referred to as the *optimum moisture content*. When a soil is compacted at its optimum moisture content, it can be compacted to its *maximum dry density*.

The test procedures that are used to determine a soil's maximum dry density and optimum moisture content are the Standard and Modified Proctor tests. These tests are described in AASHTO T99 and T180, respectively: Moisture-Density Relations of Soils. A fundamental knowledge of these test procedures and interpretation of the data is already required for WAQTC certification; therefore, the test procedures and data interpretation will not be repeated in this manual.

Zero Air Voids Density

Zero Air Voids Density represents the dry density that would be obtained at various moisture contents if the soil could be compacted to eliminate all air voids present; i.e., when all voids between soil particles are filled with moisture. It is not possible to achieve this level of compaction with conventional construction equipment. At a given moisture content and specific gravity of the soil particles, the zero air voids density represents the maximum density that can be obtained for a given soil. Appendix 3 provides a table summarizing zero air void densities of soils with varying moisture content and specific gravities. Equations to calculate the zero air void densities of soils is also provided in Appendix 3. The maximum dry density of a soil cannot exceed the zero air void or 100% saturation curve for a given soil (Figure 6).

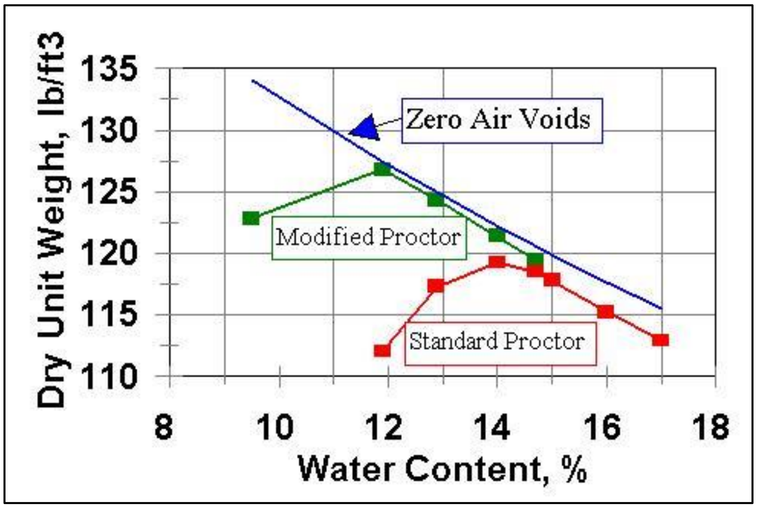


Figure 6: Example zero air voids curve with relation to Standard and Modified Proctor curves shown for a soil.

If the results of a density test fall above the zero air voids line for a soil; then a new proctor curve needs to be developed for the material tested. Similarly, if the results of a density test indicate the percent compaction is greater than 5 percent above the maximum dry density for that soil, then the soil's proctor curve should be verified.

Generalized Soil Properties

There are three divisions of particle sizes that are determined from a gradation analysis: gravel, sand (course and fine), and fines (silt and clay). Sand and gravel are granular soils that are non-cohesive with particles that are visible to the naked eye. Soils composed primarily of sand and gravel have high strength, a high porosity (i.e. good drainage), and are not prone to long-term post-construction settlement. These soils are also easier to work with to gain adequate compaction during construction. Soils composed primarily of sand; however, are highly erodible.

Natural deposits of granular soils are described based on their in-situ density using the following terms: very loose, loose, medium dense, dense, and very dense. The denser the soil deposit, the higher the strength. This information is collected with field tests during a subsurface investigation program.

Silt and clay are classified as "fines", or particles that pass the No. 200 sieve for a gradation analysis. These particles are not distinguishable by the naked eye. Silt is the courser portion of the fines content (particle sizes varying from 0.002 mm to 0.075 mm). Soils composed primarily of silt are non-cohesive and are characterized by low plasticity. Soils composed primarily of silt are also highly erodible, and the same density terms used to describe sand also apply to silty soils.

Clay is cohesive and can have a high variability in plasticity, depending on the mineralogy of the clay particles present. Clay represents particles smaller than 0.002 mm, or 2 microns (μm) in a soil sample. The terms that are used to describe clayey soils refer to their "consistency" or "cohesiveness": very soft, soft, medium stiff, stiff, very stiff, and hard. The cohesion of a clay soil is an indication of its strength, and softer clay soils are characterized by a lower cohesion or lower strength. This information is also collected with field tests during a subsurface investigation program.

Both silt and clay soils are characterized by low permeability (i.e. water does not flow through these soils quickly and they do not drain well). They have lower strength than sand and gravel, and they can be prone to long-term post-construction settlement. These soils are more difficult to work with during construction to achieve adequate compaction. Because of their low permeability, it is more difficult to moisture condition these soils uniformly to achieve near-optimum moisture conditions for adequate compaction. The presence of fines within sandy or gravelly soils results in a decrease in strength, a decrease in permeability, and an increase in the likelihood of post-construction settlement.

Chapter 4: CDOT's Roadway and Embankment Construction Methods

Foundation Preparation and Excavation

The first stage of foundation preparation for embankment and roadway construction is clearing and grubbing. Clearing and grubbing operations involve the removal of trees, shrubs, sod, and other deleterious materials from the construction area. Specifically, clearing refers to the removal of trees, brush, and boulders; and grubbing to the removal of roots and stumps. CDOT specifications require that all sod, trees, bushes, boulders, and organic matter be removed from the foundation area of the roadway prior to the placement of any fill material.

After clearing and grubbing are completed, excavation in cut sections can begin, and the foundations for embankment fill areas are prepared. The cleared ground surface is broken up by plowing, scarifying, or ripping to a minimum depth of 6 inches. This can be accomplished through use of dozers or graders with ripper attachments, or a tractor pulling a disk. Once the ground surface is scarified, it must be moisture conditioned and compacted to the specified embankment density and moisture content.

Photographs 2 and 3: Foundation preparation by means of using a dozer with a ripper attachment or a tractor with a disk to open the subgrade soils.

Excavation in cut areas can be accomplished by a variety of methods. Where soils or rippable bedrock are present in cuts (i.e. very low to low strength bedrock such as claystones, friable sandstones, and shales), dozers and excavators can be used to loosen the material and scrapers can be used to haul the material to fill areas. Where more competent bedrock is present in a cut section, the use of hydraulic hammers, rock pickers, and/or controlled blasting techniques are necessary to excavate the material.

Photographs 4 and 5: Dozer with ripper attachment being used to loosen material in a cut section. Excavator with hydraulic hammer being used to remove competent bedrock from a cut section.

To prepare the foundation area in cut sections, CDOT requires that cuts in bedrock be excavated between 0.5 and 1 foot below the final planned subgrade elevation. Approved embankment fill is then used to bring the excavated areas back to finished grade. Undrained pockets or depressions cannot remain in the excavated area and must be graded to drain.

Excavation is classified in CDOT project specifications using the following terms:

- Unclassified Excavation – the excavation of all materials within the right of way including any materials removed to grade ditches. This can include soil, bedrock, and/or boulders.
- Stripping – the removal of overburden or other material from borrow pits to expose a source material that is intended to be mined and used as embankment fill.
- Removal of Unsuitable Material – the removal of soils and/or mixtures of soil and organic matter that would be detrimental to the roadway or embankment if left in place in its existing condition. This material is removed to a depth determined by an engineer and backfilled to finished grade with approved material properly compacted.
- Rock Excavation – Excavation of competent or durable rock that cannot be removed through the use of rippers attached to a dozer with a minimum flywheel power rating of 235 horsepower (typical of a D-7), or a 48,000 pound excavator (typical of a 320 excavator) utilizing a bucket with rock teeth. Rock excavation typically involves controlled blasting methods, and is generally required for the removal of igneous, metamorphic, and high-strength strongly cemented sedimentary rocks. Rock excavation also includes the removal of boulders having a volume of ½ cubic yard or more.

Embankment Fill

Embankment fill is approved material acquired from excavations or borrow pits that is hauled and placed in fill areas. If the material is obtained from outside of the right of way, it is referred to as "Borrow." Use of material in embankments is contingent upon it meeting specific requirements for the project (i.e. gradation requirements, Atterberg limits, soil classification, and/or strength [R-value/resilient modulus]). The material must also be compacted to the specified density and moisture content.

Any imported fill must meet minimum requirements for corrosivity (sulfate content, chloride content, resistivity and pH) specified in Standard Special Provision 203 – Excavation and Embankment. Contract documents may specify minimum sulfate exposure levels permitted for imported material, and this must be verified through testing. Imported material for backfilling around any pipe structures must also be tested for compatibility with the pipe material specified and meet the minimum corrosion requirements specified in Standard Special Provision 203 – Excavation and Embankment.

CDOT defines three types of embankment fill, described below:

- Soil Embankment – all particle sizes must be less than 6 inches. The material is classified in accordance with AASHTO M 145, and placed and compacted using methods prescribed for the different soil classifications.

- Rock Embankment:
  (1) Contains 50 percent or more retained on the No. 4 sieve.
  (2) Contains > 30 percent retained on the ¾-inch sieve.
  (3) Classifies as an AASHTO A-1 soil type.
  (4) All particle sizes shall be less than 6 inches.
  (5) Particles retained on the No. 4 sieve shall not be composed of non-durable bedrock types.

- Rock Fill:
  (1) A minimum of 50 percent of the material shall be retained on a 4-inch sieve.
  (2) Maximum dimension of any particle permitted is 36 inches.
  (3) Shall be well-graded by visual inspection.
  (4) Shall contain less than 20 percent by volume of material passing the No. 200 sieve based on visual inspection.
  (5) Particles retained on the No. 4 sieve shall not be composed of non-durable bedrock types.

Non-durable bedrock is identified and classified using slake durability testing (CP-L 3104). Materials that break down or degrade to a degree that classifies them as "Non-durable / Soil-like" as described in the procedure are treated as Soil Embankment. Claystone, weakly cemented siltstones or sandstones, and some shales are the most typical types of sedimentary rock that will exhibit slaking behavior.

It is critical for soil inspectors to be aware of the types of embankment fill that are specified for various components of a construction project. If borrow is to be used, the borrow area should be checked to observe if all clearing and grubbing has been completed at the pit site. In addition, soil inspectors need to observe the materials being delivered from a borrow source. The same is true for materials that are excavated from within the project corridor or from within the right of way that are to be used as embankment fill. Geologic materials in their natural state tend to be in layers; therefore, drastic changes in the borrow brought to a project site needs to be noted and monitored. Keeping track of where questionable material is placed can help isolate areas that may require rework. In addition, different material types will have different compaction characteristics, and the correct placement and compaction requirements must be followed in the field. Not all materials derived from cut slopes or from borrow pits may be permitted to be used as embankment fill on the project. Excavation areas where the material is known to be unsuitable for embankment construction will be indicated on the project plans.

Placement and Lift Thickness Requirements

Embankment material is spread through a fill section in layers called lifts. Maintaining exact grade is not required when placing lifts; however, lift thickness must be controlled to achieve adequate compaction. The maximum lift thickness that is permitted is dependent on the material being used to construct the embankment. Before a subsequent lift is placed, each lift must be adequately compacted in accordance with the compaction requirements for the material type being used.

Soil Embankment and Rock Embankment must be placed in loose lifts not to exceed 8 inches. Rock Embankment or Soil Embankment that classifies as an A-1 soil can be placed in lift thickness greater than 8 inches if it is being used to bridge across standing water or swampy ground if approved by the Engineer.

Rock Fill can be placed in a loose lift thickness equivalent to the average particle size, up to a maximum permitted lift thickness of 18 inches. Rocks larger than 18 inches must be separated enough to allow compaction equipment to operate in between, and finer material must be placed to fill in voids between larger stones to avoid nesting. Rock Fill cannot be placed within 2 feet of the final subgrade elevation, and it cannot be placed directly over a structure until 2 feet of compacted Soil/Rock Embankment is initially placed.

Non-durable bedrock must be watered to promote slaking, pulverized, broken down, and processed to 6-inch maximum particle size before being placed as Soil Embankment. Non-durable bedrock particles larger than 6 inches cannot be used in any embankment fill. These materials cannot be used to bridge over standing water or swampy ground within an embankment foundation. These materials also cannot be placed within 2 feet of the final subgrade elevation.

Recycled concrete and asphalt can be incorporated into embankment fill, and the maximum dimension permitted is 24 inches for concrete and 12 inches for asphalt. These materials shall be processed, placed, and compacted using appropriate methods dependent on the overall classification of the embankment material once the recycled material is incorporated. Rebar shall not extend more than one inch beyond the edges of recycled concrete particles. Recycled concrete or asphalt shall not be permitted in the upper 2 feet of the final subgrade elevation or within 2 feet of the final finished side slopes unless otherwise noted in the Contract.

Regardless of the type of material being placed, frozen materials shall not be used in the construction of embankments. Embankment fill other than A-1 soil types cannot be placed within standing water, and the embankment surface must be maintained to provide surface drainage at all times.

Where embankments are to be placed on existing slopes steeper than 4-horizontal-to-1-vertical (4H:1V), the embankment layers must be continually benched into the existing slope as it is built. A two-foot deep key must be excavated at the base of the slope and backfilled with approved and compacted embankment material, and the benches are constructed upwards from the key (Figure 7).

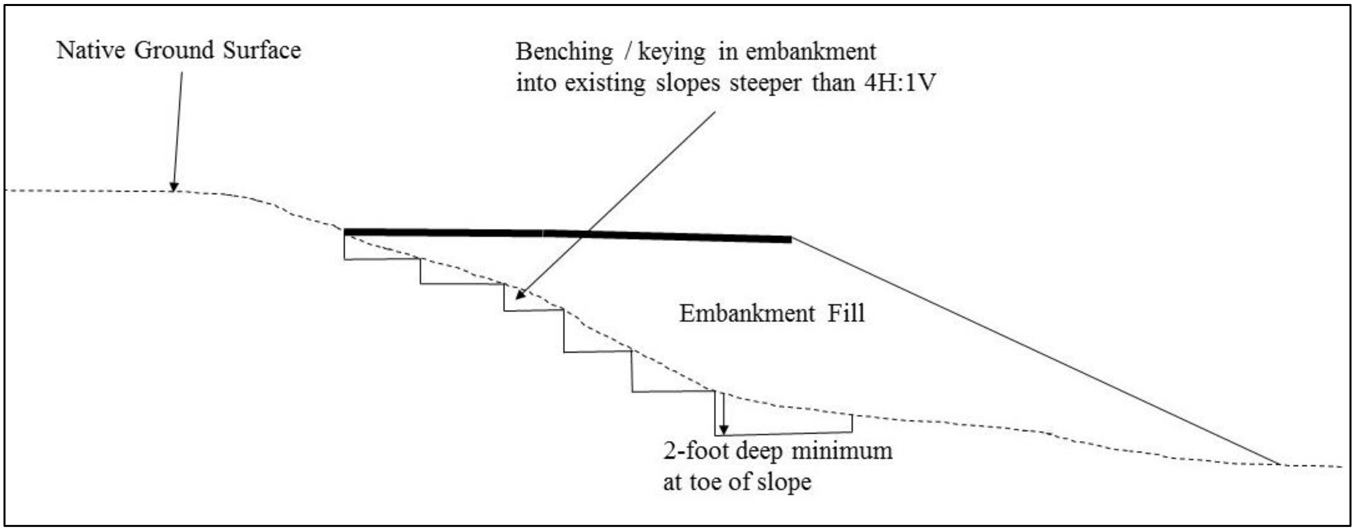


Figure 7: Generalized embankment cross section illustrating proper benching requirements when a new embankment is constructed onto an existing slope steeper than 4H:1V.

Embankment side slopes are to be built a minimum of 12 inches beyond the final grade shown in the plans to allow for compaction equipment to compact the outer edges of the embankment. Once the specified level of compaction is achieved, the side slopes are trimmed back to final grade, and the excess material can be used in subsequent lifts as the embankment is built to subgrade elevation.

Moisture Conditioning and Compaction Requirements

Compaction requirements for embankment fill are dependent on the type of embankment fill being placed (Soil Embankment vs. Rock Embankment vs. Rock Fill). Soil Embankment is further divided into different groups, which are assigned different compaction criteria and methods dependent on the overall classification of the material. Compaction is achieved in the field through control of lift thickness, and through the use of appropriate compaction equipment for the materials being placed. Moisture conditioning may be required, which requires the use of water trucks if the material is too dry. To achieve the desired effect for compaction, the spray bars on the water trucks should distribute water evenly over the material that is to be compacted. If the material is too wet to achieve compaction, then it must be disked or scarified, then allowed to aerate to reduce the moisture content.

Photograph 6: Water truck being used to moisture condition soils in preparation for compaction.

Samples of embankment fill are to be collected for classification (gradation and Atterberg limit testing), corrosion testing (sulfate content, chloride content, resistivity, and pH), moisture density relations as required for the material type (AASHTO T 99/T 180 modified by CP 23), and slake durability testing as required for the material type (CP-L 3104) at the frequencies prescribed in the Field Materials Manual or as specified in the Contract. The following sections summarize compaction requirements for each of the embankment fill types.

Soil Embankment with less than or equal to 30 percent retained on the ¾-inch sieve:

- A-1, A-2-4, A-2-5, and A-3 soils are compacted at +/- 2 percent of optimum moisture content and to at least 95 percent of maximum dry density determined in accordance with AASHTO T 180, modified by CP 23.
- All other soil types are compacted to 95 percent of maximum dry density determined in accordance with AASHTO T 99, modified by CP 23.
  - Soils with 35 percent fines or less are compacted at +/- 2 percent of optimum moisture content.
  - Soils with more than 35 percent fines are compacted at a moisture content equal to or above optimum to achieve stability of the compacted lift; which is defined as the absence of rutting or pumping. If the soils prove to be unstable when compacted at or above optimum moisture content, the moisture required for compaction can be reduced below optimum as approved by the Engineer.

Compaction control will be tested using nuclear density gauges (AASHTO T 310) at the frequencies prescribed in the Field Materials Manual or as specified in the Contract. A one-point moisture/density verification test (CP 25-13) shall be performed at the frequency required in the Field Materials Manual to verify the use of the correct moisture/density curve. The test sites should be selected randomly, and should be representative of the materials placed in the surrounding areas.

Soil Embankment with greater than 30 percent retained on the ¾-inch sieve:

- The contractor must construct a test strip to the dimensions specified, which can be incorporated into the final embankment.
- The contractor is responsible for determining the moisture conditioning, the type of equipment, and number of passes that are needed to achieve adequate compaction; however, compression-type or vibratory rollers are required for granular materials, and sheepsfoot rollers are required for cohesive soils.
- Adequate compaction will be demonstrated by the absence of rutting, pumping, or deflection during a proof roll of the test strip using a piece of construction equipment that exerts a minimum 18-kip per axle load.
- Once the test strip passes a proof roll, the contractor can resume embankment construction with the material using the same moisture conditioning and compaction methods that were used to construct the test strip.
- Changes in material type require construction of a new test strip followed by a proof roll.
- Placement, moisture conditioning, and compaction of every lift will be observed by the Contractor's Process Control (PC) Representative, and accepted by the Engineer. Adequate

compaction of each lift will be demonstrated as the absence of rutting, pumping, or deflection as construction equipment is routed over a lift following the compactive efforts that were used and accepted for the respective test strip.

- The Engineer may request a proof roll at any time to document the condition of a lift.

Non-durable bedrock within soil embankment:

- These materials must be compacted using a tamping foot roller weighing at least 30 tons. The projections shall extend at least 4 inches from the drum.
- A minimum of 4 passes is required, and the roller speed shall not exceed 3 miles per hour.
- Additional roller passes may be required to achieve adequate compaction.

Rock Embankment and Rock Fill:

- Contractor must construct a test strip to the dimensions specified, which can be incorporated into the final embankment.
- The contractor is responsible for determining the moisture conditioning necessary to achieve adequate compaction.
- Vibratory or compression-type rollers are required. Compression rollers must weight a minimum of 20 tons. Vibratory roller must exert a minimum dynamic force of 30,000 pounds of impact per vibration, and achieve a minimum of 1,000 vibrations per minute.
- A minimum of 4 passes over the entire width of each lift is required. Compression type rollers cannot be operated at speeds over 3 miles per hour, and the speed of vibratory rollers cannot exceed 1.5 miles per hour.
- Adequate compaction will be demonstrated by the absence of rutting, pumping, or deflection during a proof roll of the test strip using a piece of construction equipment that exerts a minimum 18-kip per axle load.
- Once the test strip passes a proof roll, the contractor can resume Rock Fill or Rock Embankment construction with the material using the same moisture conditioning and compaction methods that were used to construct the test strip.
- Changes in material type require construction of a new test strip followed by a proof roll.
- The contractor can deviate from the minimum equipment and compactive efforts specified; but every lift placed for the first 2,000 cubic yards of fill must pass a proof roll.
- Placement, moisture conditioning, and compaction of every lift will be observed by the Contractor’s PC Representative, and accepted by the Engineer. Adequate compaction of each lift will be demonstrated as the absence of rutting, pumping, or deflection as construction equipment is routed over a lift following the compactive efforts that were used and accepted for the respective test strip. Finer material shall be placed between larger stones of a rock fill.

- The Engineer may request a proof roll at any time to document the condition of a lift.

Compaction Equipment:

Steel vibratory rollers either have single or dual drums with control over the amplitude and frequency of vibrations. The drums must be filled with ballast, and the vibration may need to be adjusted to achieve the desired compaction. If the amplitude or frequency is set incorrectly, the material being compacted may be pushed away or forced in front of the drums rather than being directed downward to densify the material. This is referred to as a “roll front” and is an indication that compaction is not being achieved.

Compression-type/pneumatic rollers have rubber, air-filled tires used for compaction. The tires should be smooth without tread, and should all be uniformly inflated. The tire pressure influences the degree of compaction that can be achieved. In addition, the weight of pneumatic rollers can be adjusted by adding water or sand to the ballast box to adjust the compactive effort achieved.

Photographs 7 and 8: Dual drummed steel vibratory roller and rubber-tired pneumatic roller.

Sheepsfoot compactors are used to compact fill materials composed of cohesive (clayey) soils and clay-rich non-durable bedrock. These compactors roll on steel metal drums with long, steel projections. The weight of these compactors can also be adjusted by adding sand or water to the ballast box on the compactor.

Photograph 9: Sheepsfoot compactor.

Instead of relying on vibration to achieve compaction, sheepsfoot rollers accomplish compaction through a kneading action of clay soils. When clay soils are compacted at the appropriate moisture content, the projections will sink into the material and penetrate into the preceding lift that was placed. As the soil is densified with multiple passes from the compactor, the projections will penetrate less until the roller begins to ride on top of the compacted lift. This is referred to as "walking out" (Figure 8).

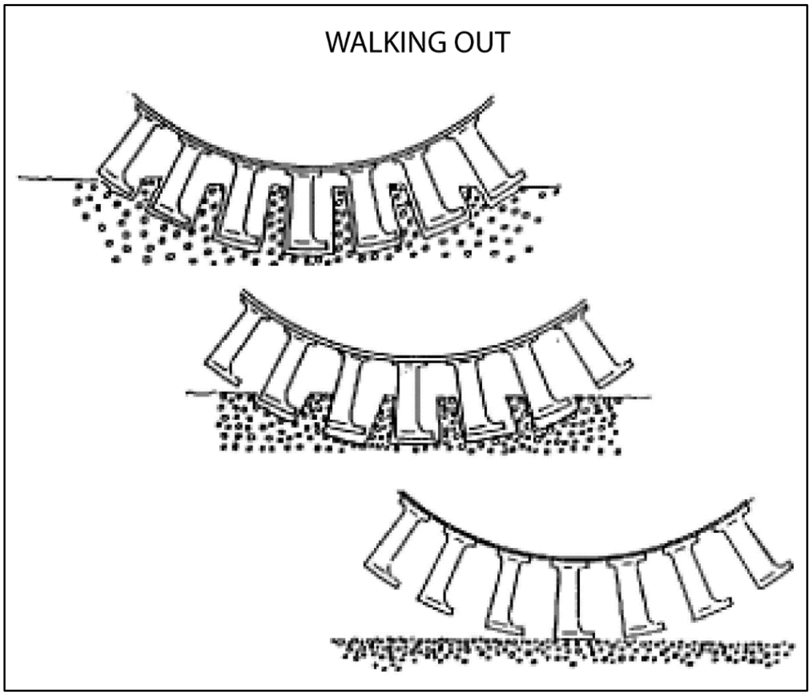


Figure 8: Diagram illustrating proper penetration and eventual "walking out" of the projections from a sheepsfoot compactor following multiple passes.

If clay soils are too wet, the soils will either pump or begin to collect between the roller projections, and compaction will not be achieved. Similarly, if clay soils are too dry the projections will not penetrate into the lift adequately, and compaction of the base of the lift will not be achieved.

Grade Control and Proof Rolling

As cuts and fills progress during a road construction project, the grade and slopes should be checked periodically. Grade and elevations should be checked at known stations by referring to cross sections in the project plan sets. If the final lift of the embankment is to be select material, the proceeding lift will be rolled with a sheepsfoot to leave the top 2 inches rough. If no select material is required, the contractor will bring the embankment to final grade prior to placing sub-base (if required) and base course (if required). The final surface will be fine-bladed with a grader, and rolled smooth with a steel drum roller to seal the surface of the top lift and provide protection against weather and construction traffic. Variations in the final grade elevations in both cut and fill sections shall not be more than 0.08 foot (1 inch). Where asphalt or concrete pavement are to be placed, the final grade plane shall not vary by more than 0.04 foot (1/2-inch).

Prior to placing any sub-base, base course, or pavement (if pavement is to be placed directly on the prepared subgrade), the completed surface is proof rolled with pneumatic tire equipment. Proof rolling is required after the required compaction of the embankment/subgrade has been achieved and it has been built to the required grade. A minimum axle load of 18 kips per axle is required, and a weigh ticket must be submitted to prove this requirement is met. Proof rolling must be performed within 48 hours prior to placing any sub-base, base course, or pavement; or if the condition of the final surface changes due to weather or other circumstances. Soft spots can be identified by non-uniform deflection in localized areas during the proof rolling operations. These areas must be ripped, dried or wetted as necessary, and recompacted to the appropriate density.

Photograph 10: Proof rolling operation being completed by a filled water truck.

Chapter 5 – Common Soil Problems in Colorado That Can Effect Construction

Geological conditions may exist within a corridor that lead to difficult highway and embankment construction. In addition to making construction difficult, some soil deposits, if they go unnoticed or are left untreated, can contribute to post-construction problems such as differential movement of the embankments that support a roadway, or even failure of the pavement structure and/or the embankments. This chapter provides a brief overview of common soil problems that need to be addressed during design or construction to improve the quality of the finished roadways. Basic information for how these soil problems are addressed or mitigated are also included. Problem soils require special attention beyond the generalized earthwork preparation and compaction specifications found in CDOT’s Standard Specifications. A project will have Special Provisions written into the specifications to address soil problems that are expected to be encountered within a corridor.

Soft Clay Deposits – Consolidation and Stability

Thick deposits of soft clay within an embankment foundation can pose a number of problems during construction. Soft clays in Colorado can be encountered in stream flood plains, wetland areas, and in areas where claystone bedrock is capped by a thick weathered layer referred to as “residual soil.” Soft clays will generally have a high moisture content (some in excess of the liquid limit), and as a result, may not have the strength or cohesion to adequately support a roadway or a new embankment.

A major issue that soft clays pose if fully saturated is consolidation, which can lead to post-construction settlement if mitigation is not implemented during construction. Consolidation is the process where a saturated clay deposit is placed under a surcharge load (i.e. adding 20 feet of fill material for construction of an embankment), and the increased load results in an expulsion of pore water from the clay. As the pore water is expelled, the clay deposit and anything built over top of it begins to settle and deform. Because clays have a very low permeability, this process takes a significant amount of time; in some instances several years, and settlement of the overlying embankment and roadway occurs gradually but continually. If the thickness or strength of a clay deposit varies beneath a long stretch of embankment, differential settlement can occur. In other words, thicker sections will settle a higher magnitude and over a longer time duration than thinner deposits; resulting in uneven rates and magnitudes of deformation to the overlying embankment and roadway structure.

Photographs 11 and 12: Resultant pavement damage due to differential settlement caused by consolidation of saturated clays beneath a high embankment.

Consolidation can be mitigated through a process known as accelerated embankment consolidation. A combination of strategies can be implemented to pre-consolidate a clay deposit to a desired magnitude before the pavement structure is built:

- Constructing an excess surcharge to pre-load the deposit. In other words, if a 20-foot embankment is to be built, additional material can be placed to increase the load on the deposit, and accelerate the consolidation process before the road is constructed. Once the predicted/desired amount of settlement is achieved (this is monitored through time with survey and instrumentation); the surcharge is removed and the final pavement structure is built
- Installation of wick drains into the deposit, which decreases the flow paths for pore water expulsion, thus accelerating the process.
- Time: whether using wick drains or surcharging or if both procedures are used, time is required to allow settlement to occur before the roadway structure is built.

Photographs 13 and 14: Accelerated consolidation being achieved through the use of surcharging and wick drains.

If the deposit is near the ground surface and not too thick to be removed cost effectively, the material can also simply be removed from the embankment foundation and replaced with an approved fill material. This process is known as over-excavation and replacement. Another option that can be used to reduce the effects of consolidation is to reduce the surcharge of the embankment through the use of Expanded Polystyrene Geofoam blocks (EPS foam) in place of soil or rock fill.

Photograph 15: Light-weight EPS foam blocks being used to bridge over soft clay deposits for new embankment construction.

Soft clays also pose stability problems for new embankment construction. If a high embankment is placed over a soft clay deposit, and the material is loaded beyond its shear strength, bearing capacity failures of the embankment or a landslide can result. These issues may not manifest during construction, but can come into play months or years down the road if the deposit becomes overly saturated with an excessive amount of rainfall or snow melt.

Photograph 16: Landslide that developed as a result of embankment construction over a weak clay deposit.

Mitigation of soft clay deposits that can lead to embankment stability problems can be addressed using a variety of methods that are dependent on a number of factors including but not limited to cost, construction access, subsurface conditions, and material properties. Drains can be installed in the material, buttresses can be constructed at the toe of an embankment to prevent movement (i.e. slope flattening), the embankment can be constructed of light-weight fill materials to reduce the load on the deposit (EPS foam), the soil can be treated to improve its strength (deep soil mixing, grout injection), or reinforcement elements can be installed to increase the stability of the ground such as geotextiles, piles, drilled shafts, or ground anchors.

Swelling Soil and Heaving Bedrock

Swelling soils are clay-rich soils that exhibit a volume change with increases or decreases to their moisture content. These soils are very common in Colorado, and are derived from weathering of certain claystone bedrock formations. Heaving bedrock operates by the same mechanism; but is differentiated because the swelling occurs from intact bedrock layers rather than from unconsolidated soil deposits. Swelling soils and heaving bedrock contain clay particles with a specific mineral referred to as montmorillonite. This mineral is characterized by a platy or layered structure that absorbs water, causing the individual layers to expand. This expansion can increase the volume of a deposit by more than 20 percent; and the swelling action can exert thousands of pounds of force onto overlying structures.

Once a pavement or structure is placed over these soils; natural evaporation is restricted, which can cause moisture to build up in the subsurface. In addition, if pavement cracks develop through time and allow water infiltration into the subsurface, an increase in moisture content can occur. The underlying soils then expand, and buckling and differential heave can occur to the overlying structures.

Photographs 17 and 18: Damage to asphalt pavement and separation along a concrete construction joint as a result of swelling soils.

Problems due to swelling soils and heaving bedrock most often occur in cut areas, where dry claystone bedrock or residual soils can be exposed, and in transitions from cut to fill areas. However, swelling soils can also result in problems in fill areas if clay soils with expansion potential are used as embankment fill. CDOT requires that soils with more than 35 percent fines be compacted at a moisture content at or above optimum moisture to help reduce the magnitude of swell that can occur post-construction.

Remedial measures to address swelling soil generally involve reducing the likelihood of water infiltration; as an increase in moisture content is required to initiate swell. The crown of the roadway is generally sloped to promote runoff and eliminate ponding water. In addition, drainage ditches are constructed below the subgrade level in low areas and are graded to allow rapid runoff of surface water.

Other methods to mitigate swelling soil include over-excavation and replacement; where potential expansive layers are removed to a specified depth and replaced with non-expansive material compacted to the appropriate density. Chemical treatment of the subgrade soils with lime, flyash, or combinations of these materials have also been used to successfully reduce the swell potential of these soils.

Photograph 19: Mixing a lime slurry into subgrade soils to reduce the swell potential.

It should be noted that chemical soil treatment by the use of lime or other cement agents can result in a different type of heave for soils characterized by a high sulfate content. Sulfate can react with the lime (or other calcium based products) resulting in the growth of ettringite and/or thaumasite crystals in the soil. The growth of these crystals in the soil also results in a volume expansion and heave to overlying structures.

The soil inspector needs to be aware if swelling soils are encountered within a corridor; and what, if any, mitigation measures were specified to address these soils during construction.

Collapsible Soils

Collapsible soils (also known as hydrocompactive soils) are typically dry, fine-grained soils with a honeycomb skeletal fabric with open pore spaces between the individual soil particles. The soil is typically characterized by a high dry strength and can support loading conditions from overburden stresses in addition to structures. However, once the soil becomes wet, a water content threshold can be reached which can dissolve or weaken the soil binding agents, resulting in rapid densification of the soil particles into the open void structure, and subsequent settlement.

Contrary to consolidation, soil collapse can occur relatively rapidly. However, a thick deposit of collapsible soil may experience continued collapse for several years as the subsurface moisture content slowly increases with time. Similar to consolidation and swelling soils, the magnitude and time frame of soil collapse is rarely uniform across a deposit. Therefore, differential settlement often occurs to structures and roadways built over these deposits if mitigation was not implemented during construction.

Photograph 20: Sinkhole development as a result of collapsible soil deposits settling at depth.

Proactive mitigation techniques for collapsible soils include pre-wetting and/or pre-densification; or over-excavation and replacement. Pre-wetting involves intentionally saturating the soil deposits prior to construction by sprinkler irrigation, flood irrigation, trenching, ponding water, or pumping water into the subsurface through the use of injection wells. Pre-densification can be used alone, or in combination with pre-wetting. For shallow deposits, dynamic compaction with construction equipment can be conducted. For deep deposits; injection of compaction grout in combination with pre-wetting is one method that has successfully treated collapsible soils. Compaction grout is a stiff, high-slump grout that is injected at high pressures to actively displace and densify soils at depth.

Passive mitigation techniques include measures to reduce water infiltration into the subsurface where these deposits may exist through the use of surface and subsurface drainage systems. The use of low-permeability fill materials (clay) can also reduce surface water infiltration.

Unsuitable Materials

CDOT's specification requires removal of materials that can have a detrimental effect to the roadway or embankment if left in place in their current condition. If these materials can be moisture conditioned and compacted following the specifications, they can be reused. However, soils that contain organics or soils that cannot be moisture conditioned and compacted in accordance with the specifications must be removed and replaced with approved fill.

Soils containing a high organic content pose a problem for embankment foundations and are not permitted to remain in place or be incorporated into embankment fill. These soils are typically very low strength, and are not suitable as a subgrade or foundation material to build new embankments or pavement structures on. Continued decomposition of organic materials can result in voids being formed in the deposit, which can lead to differential settlement and stability problems post-construction. These soils are typically dark in color and smell of rotting vegetation. This material can be found in low-lying flood plains adjacent to stream channels and in wetland areas. Typically these soils will be addressed during construction by over-excavation and replacement with approved material. When organic soils are expected to be encountered on a project or are identified during a subsurface exploration program, the project plan sheets will delineate areas where removal is required. This material must be removed to the depth and extents indicated in the plans and specifications. It may be possible for deposits to vary in depth and extent than what is shown on the plans. Soil inspectors must observe the areas being excavated and document whether or not all of the poor quality soil has been removed from an embankment foundation.

Photograph 21: Organic soils being excavated from a project site.

Geosynthetics for Problem Soil Treatment

In some situations, poor subgrade conditions may be present within a corridor where either a demanding schedule or high cost prohibits remedial measures such as over-excavation and replacement, or deep soil treatment. Geosynthetics are a cost-effective means to address soft and low-strength subgrade soils and can be installed relatively quickly on a construction project. These materials can also be used to bridge an embankment over standing water where high ground water conditions cannot be economically dealt with through grading or drainage construction.

Geosynthetics include a variety of materials that are used for different applications. Products common to embankment construction and their applications are included in Table 6 below:

Table 6: Common Applications for Geosynthetics in Embankment Construction

Applications	Geotextiles	Geogrids	Geocomposites
Separators	X		X
Reinforcement	X	X	X
Filtration	X		X
Drainage	X	X	X

Geotextiles consist of synthetic fibers that are either woven or matted together in a random, non-woven fashion. Some are also knitted. The woven materials are characterized by a higher tensile strength. The use of synthetic fibers increases their durability for permanent use in earthwork construction. Geotextiles are porous and allow water to flow across their plane.

Geogrids are polymers formed into an open, grid-like pattern. These materials are stretched in the manufacturing process to improve their physical properties (tensile strength and deformation characteristics). While they can be used as a drainage medium, geogrids are almost exclusively used as reinforcement to improve the strength of soils.

Geocomposites consist of a combination of geotextiles and geogrids (or other geotextiles that are not listed here) to provide a material with a variety of properties for multiple applications.

Figure 9: Photographs of various types of geosynthetics. From left to right: woven geotextiles, geogrid, and geocomposite.

A separator may be needed where the embankment fill specified for a project is composed of a different gradation characteristic than the foundation soils (i.e. placing a granular fill over a soft clay layer). If high ground water conditions and a soft clay deposit exists within an embankment foundation, it is necessary to install a drainage layer at the base of the embankment (i.e. a clean granular soil such as gravel). However; if the clay is very soft, an excessive amount of gravel may be required to bridge over the deposit; as the gravel may sink into the clay with repeated construction loading. In this example, a geotextile fabric or geocomposite can be placed as a separator over the clay subgrade soils to eliminate this problem and avoid excessive costs associated with hauling and placing excess gravel until it finally bridges over top the poor subgrade soils.

The use of geosynthetics over soft subgrade soils is also a method to reinforce or increase the strength of the embankment foundation. Certain types of geotextiles and geogrids are manufactured to have a high tensile strength to resist deformation from settlement or subgrade failure in the form of a bearing capacity failure. The installation of a layer at the base of an embankment acts as a rigid layer to resist movement or deformation of the subgrade soils.

Photograph 22: Geotextile installation over soft, unstable subgrade soils.

Drainage and filtration would be required where a roadway is constructed into a slope that is characterized by high ground water conditions or springs (Figure 10). A drainage fabric can be installed to intercept a seep and direct the water flow beneath the embankment to discharge at the toe. Similarly, a drainage layer such as gravel can be used for this application; however, the material may need to be wrapped in a geotextile to prevent fines from infiltrating and plugging the gravel; reducing the permeability and life of the drainage material (i.e. filtration).

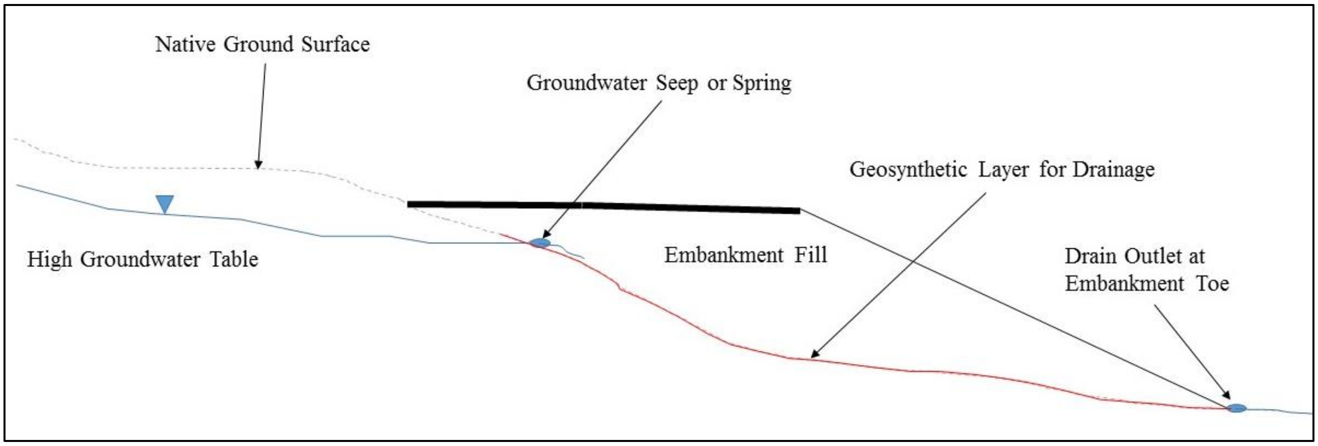


Figure 10: Geosynthetic application for drainage and filtration to direct groundwater flow beneath an embankment.

If geosynthetics are specified and included on a roadway and embankment construction project, the CDOT soils inspector must be familiar with the properties of the material specified and its application. CDOT uses the New York DOT’s Approved Products List for geosynthetic approval on projects. It is important to document that the materials that arrive on site have the properties (i.e. drainage characteristics, tensile strength, etc.) that are required in the specifications. The inspector also must document whether the Contractor installed the materials in accordance with either the project specifications or with the manufacturers recommendations.

Appendix 1:

Determining the Liquid Limit of Soils – FOP for AASHTO T89

Determining the Plastic Limit and Plasticity Index of Soils – FOP for AASHTO T90

**(For accessibility requirements of the materials in this appendix,
contact AASHTO Publications at 800-231-3475)**

Standard Method of Test for

Determining the Liquid Limit of Soils

AASHTO Designation: T 89-13 (2021)

Technically Revised: 2013 **Reviewed but Not Updated: 2021** **Editorially Revised: 2021**

Technical Subcommittee: 1a, Soil and Unbound Recycled Materials

American Association of State Highway and Transportation Officials
555 12th Street NW, Suite 1000
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AASHTO Designation: T 89-13 (2021)

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Technical Subcommittee: 1a, Soil and Unbound Recycled Materials

1. SCOPE

1.1. The liquid limit of a soil is that water content, as determined in accordance with the following procedure, at which the soil passes from a plastic to a liquid state.

1.2. The following applies to all specified limits in this standard: For the purposes of determining conformance with these specifications, an observed value or a calculated value shall be rounded off "to the nearest unit" in the last right-hand place of figures used in expressing the limiting value, in accordance with ASTM E29.

1.3. *The quality of the results produced by this standard are dependent on the competence of the personnel performing the procedure and the capability, calibration, and maintenance of the equipment used. Agencies that meet the criteria of R 18 are generally considered capable of competent and objective testing/sampling/inspection/etc. Users of this standard are cautioned that compliance with R 18 alone does not completely assure reliable results. Reliable results depend on many factors; following the suggestions of R 18 or some similar acceptable guideline provides a means of evaluating and controlling some of those factors.*

2. REFERENCED DOCUMENTS

2.1. *AASHTO Standards*:

- M 231, Weighing Devices Used in the Testing of Materials
- R 18, Establishing and Implementing a Quality Management System for Construction Materials Testing Laboratories
- R 58, Dry Preparation of Disturbed Soil and Soil–Aggregate Samples for Test
- R 74, Wet Preparation of Disturbed Soil Samples for Test
- T 265, Laboratory Determination of Moisture Content of Soils

2.2. *ASTM Standards*:

- D4318, Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils
- E29, Standard Practice for Using Significant Digits in Test Data to Determine Conformance with Specifications

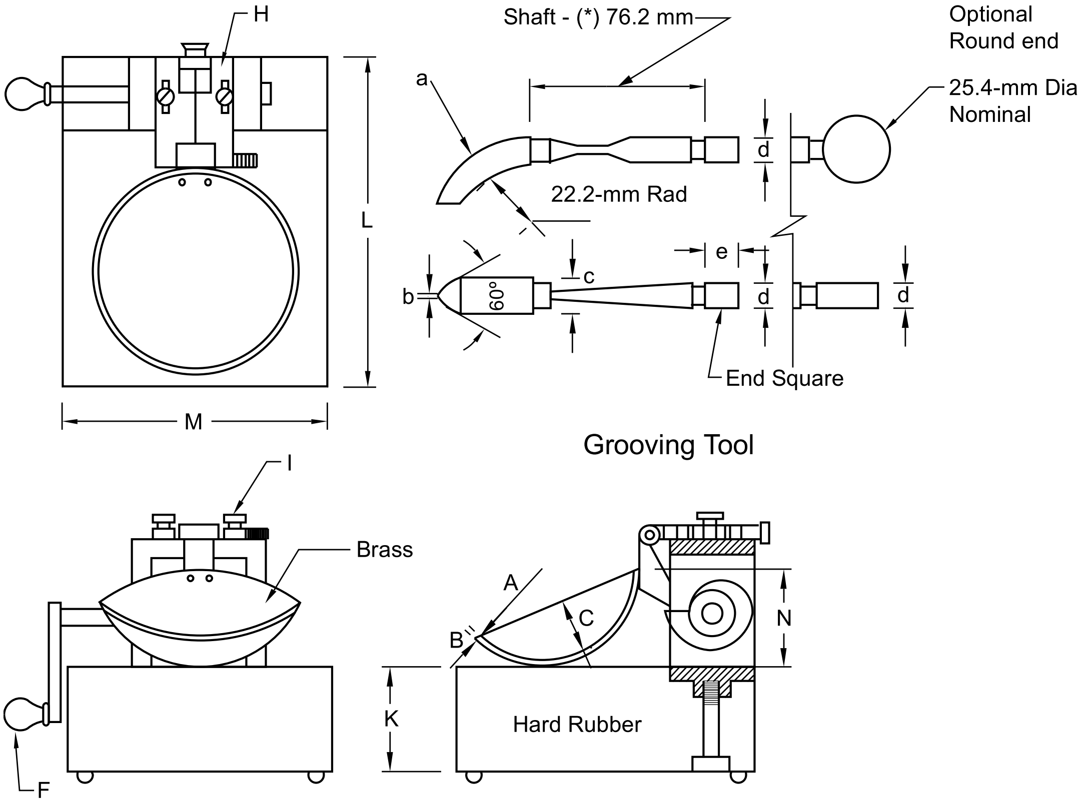
3. APPARATUS

3.1. *Dish*—A porcelain dish, preferably unglazed, or similar mixing dish, about 115 mm in diameter.

3.2. *Spatula*—A spatula or pill knife having a blade about 75 to 100 mm in length and about 20 mm in width.

3.3. *Liquid Limit Device*:

3.3.1. *Manually Operated*—A device consisting of a brass dish and carriage, constructed according to the plan and dimensions shown in Figure 1 (see Note 1).



	Liquid Limit Device							Grooving Tool				
	Cup Assembly				Base			Curved End			Gauge	
Dimension	A	B	C	N	K	L	M	a	b	c	d	e*
Description	Radius of Cup	Thickness of Cup	Depth of Cup	Cup at Cam Follower to Base	Thickness	Length	Width	Thickness	Cutting Edge	Width	Depth	Length
Metric, mm	54	2.0	27	47	50	150	125	10.0	2.0	13.5	10.0	15.9
Tolerance, mm	2	0.1	1	1.5	5	5	5	0.1	0.1	0.1	0.2	—

Note: Plate "H" may be designed for using one (1) securing screw (I).
An additional wear tolerance of 0.1 mm shall be allowed for dimension "b" for used grooving tools.
Feet for base shall be of resilient material.
(*) Nominal dimensions.
All tolerances specified are plus or minus (±) except as noted above.

Figure 1—Manual Liquid Limit Device

3.3.2. *Mechanically Operated*—A motorized device equipped to produce the rise and rate of shocks to a brass cup as described in Sections 5.2 and 6.3 of this procedure, respectively. The cup and the critical dimensions of the device shall conform to those shown in Figure 1 of this procedure. The device shall give the same liquid limit values as obtained with the manually operated device (Note 1).

Note 1—The base of the liquid limit device should have a resilience of at least 80 percent and not more than 90 percent when determined in accordance with the procedure given in the Appendix.

3.4. *Grooving Tool*:

3.4.1. *Curved Grooving Tool*—A grooving tool conforming to the critical dimensions shown in Figure 1. The gauge need not be part of the tool.

3.4.2. *Flat Grooving Tool (Alternate)*—A grooving tool made of plastic or noncorroding metal conforming to the critical dimensions shown in ASTM D4318, Figure 3. The gauge need not be part of the tool (Note 2).

Note 2—The flat grooving tool should not be used interchangeably with the curved grooving tool. There are some data that indicate that the liquid limit is slightly increased when the flat tool is used instead of the curved tool.

3.5. *Gauge*—A gauge, whether attached to the grooving tool or separate, conforming to the critical dimension "d" shown in Figure 1 of this test method or "K" in Figure 3 of ASTM D4318, and may be, if separate, a metal bar 10.0 ± 0.2 mm thick and approximately 50 mm long.

3.6. *Containers*—Suitable containers made of material resistant to corrosion and not subject to change in mass or disintegration on repeated heating and cooling. Containers shall have close-fitting lids to prevent loss of moisture from samples before initial mass determination and to prevent absorption of moisture from the atmosphere following drying and before final mass determination. One container is needed for each moisture content determination.

3.7. *Balance*—The balance shall have sufficient capacity and conform to M 231, Class G 1.

3.8. *Oven*—A thermostatically controlled drying oven capable of maintaining temperatures of 110 ± 5°C for drying moisture samples.

METHOD A

4. SAMPLE

4.1. A sample with a mass of about 100 g shall be taken from the thoroughly mixed portion of the material passing the 0.425-mm sieve that has been obtained in accordance with R 58 or R 74; for structural analysis use R 74, Method B.

5. ADJUSTMENT OF LIQUID LIMIT DEVICE

5.1. The Liquid Limit Device shall be inspected to determine that the device is in good working order; that the pin connecting the cup is not worn sufficiently to permit side play; that the screws connecting the cup to the hanger arm are tight; that the points of contact on the cup and base are not excessively worn; that the lip of the cup is not excessively worn; and that a groove has not been worn in the cup through long usage. The grooving tool shall be inspected to determine that the critical dimensions are as shown in Figure 1 of this test method or ASTM D4318, Figure 3.

Note 3—Wear is considered excessive when the point of contact on the cup or base exceeds approximately 13 mm in diameter, or when any point on the rim of the cup is worn to approximately one half of the original thickness. Although a slight groove in the center of the cup is noticeable, it is not objectionable. If the groove becomes pronounced before other signs of wear appear, the cup should be considered excessively worn. Excessively worn cups shall be replaced. A base that is excessively worn may be refinished as long as the thickness does not exceed the tolerance shown in Figure 1 of this test method by more than –2.5 mm and the distance between the cup at the cam follower and the base is maintained within the tolerances specified in Figure 1.

5.2. Adjust the height of drop of the cup so that the point on the cup that comes in contact with the base rises to a height of 10.0 ± 0.2 mm. See Figure 2 for proper location of the gauge relative to the cup during adjustment. Check the height of drop of the cup prior to each day's testing.

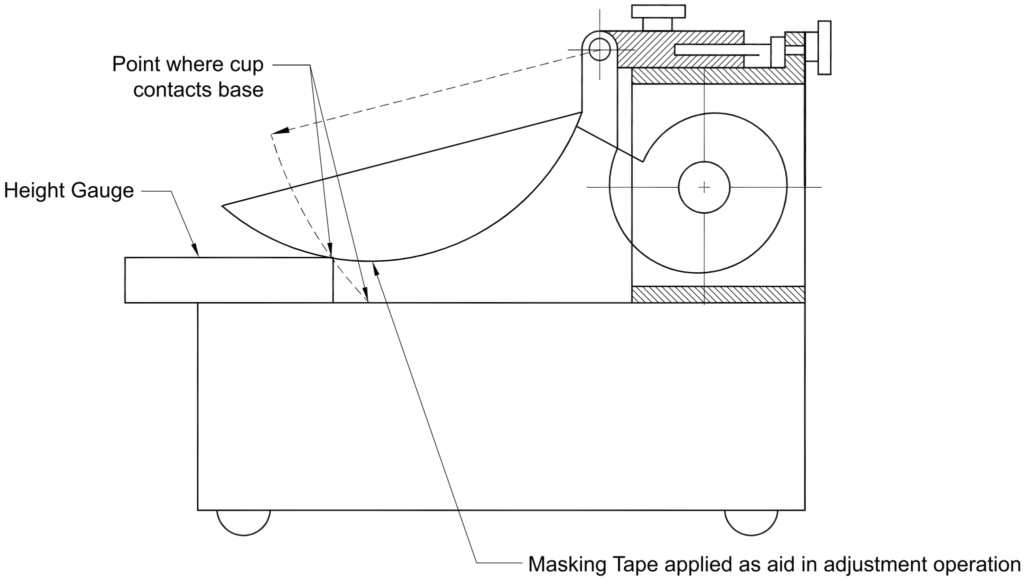


Figure 2—Calibration for Height of Drop

Note 4—A convenient procedure for adjusting the height of drop is as follows: place a piece of masking tape across the outside bottom of the cup parallel with the axis of the cup hanger pivot. The edge of the tape away from the cup hanger should bisect the spot on the cup that contacts the base. For new cups, placing a piece of carbon paper on the base and allowing the cup to drop several times will mark the contact spot. Attach the cup to the device and turn the crank until the cup is raised to its maximum height. Slide the height gauge under the cup from the front, and observe whether the gauge contacts the cup or the tape (see Figure 2). If the tape and cup are both contacted, the height of drop is approximately correct. If not, adjust the cup until simultaneous contact is made. Check adjustment by turning the crank at two revolutions per second while holding the gauge in position against the tape and cup. If a ringing or clicking sound is heard without the cup rising from the gauge, the adjustment is correct. If no ringing is heard or if the cup rises from the gauge, readjust the height of drop. If the cup rocks on the gauge during this checking operation, the cam follower pivot is excessively worn and the worn parts should be replaced. Always remove tape after completion of adjustment operation.

6. PROCEDURE USING THE CURVED GROOVING TOOL

6.1. The soil sample shall be placed in the mixing dish and thoroughly mixed with 15 to 20 mL of distilled or demineralized water by alternately and repeatedly stirring, kneading, and chopping with a spatula. Further additions of water shall be made in increments of 1 to 3 mL. Each increment of water shall be thoroughly mixed with the soil as previously described before another increment of water is added. Once testing has begun, no additional dry soil should be added to the moistened soil. The cup of the Liquid Limit Device shall not be used for mixing soil and water. If too much moisture has been added to the sample, the sample shall either be discarded, or mixed and kneaded until natural evaporation lowers the closure point into an acceptable range.

Note 5—Some soils are slow to absorb water; therefore, it is possible to add the increments of water so fast that a false liquid limit value is obtained. This can be avoided if more mixing and/or time is allowed. Tap water may be used for routine testing if comparative tests indicate no differences in results between using tap water and distilled or demineralized water. However, referee or disputed tests shall be performed using distilled or demineralized water.

When sufficient water has been thoroughly mixed with the soil to form a uniform mass of stiff consistency, a sufficient quantity of this mixture shall be placed in the cup above the spot where the cup rests on the base and shall be squeezed and spread with the spatula to level and at the same time trimmed to a depth of 10 mm at the point of maximum thickness. As few strokes of the spatula as possible shall be used, care being taken to prevent the entrapment of air bubbles within the mass. The excess soil shall be returned to the mixing dish and covered to retain the moisture in the sample. The soil in the cup of the device shall be divided by a firm stroke of the grooving tool along the diameter through the centerline of the cam follower so that a clean sharp groove of the proper dimensions will be formed as shown in Figure 3. To avoid tearing of the sides of the groove or slipping of the soil cake on the cup, up to six strokes from front to back or from back to front counting as one stroke, shall be permitted. The depth of the groove should be increased with each stroke and only the last stroke should scrape the bottom of the cup.

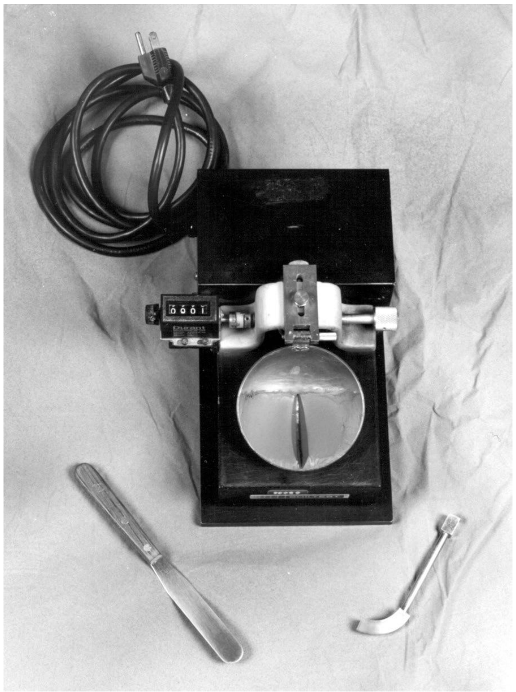


Figure 3—Liquid Limit Device with Soil Sample in Place

6.2. The cup containing the sample prepared as described in Section 6.2 shall be lifted and dropped by turning the crank F at the rate of approximately two revolutions per second until the two sides of the sample come in contact at the bottom of the groove along a distance of about 13 mm. The number of shocks required to close the groove this distance shall be recorded. The base of the machine shall not be held with the free hand while the crank F is turned.

Note 6—Some soils tend to slide on the surface of the cup instead of flowing. If this occurs, more water should be added to the sample and remixed, then the soil–water mixture placed in the cup, a groove cut with the grooving tool and Section 6.2 repeated. If the soil continues to slide on the cup at a lesser number of blows than 25, the test is not applicable and a note should be made that the liquid limit could not be determined.

6.3. 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 that portion of the groove in which the soil flowed together, shall be removed and placed in a suitable container. The soil in the container shall be dried in accordance with T 265 to determine the moisture content, and the results recorded.

6.4. The soil remaining in the cup shall be transferred to the mixing dish. The cup and grooving tool shall then be washed and dried in preparation for the next trial.

6.5. Repeat the foregoing operations, adding sufficient water to bring the soil to a more fluid condition. Obtain the first sample in the range of 25 to 35 shocks, the second sample in the range of 20 to 30 shocks, and the third sample in the range of 15 to 25 shocks. The range of the three determinations shall be at least 10 shocks.

7. ALTERNATE PROCEDURE USING THE FLAT GROOVING TOOL

7.1. The procedure shall be the same as prescribed in Sections 6.1 through 6.6, except for the procedure in Section 6.2 for forming the groove. Form a groove in the soil pat in accordance with Section 11.2 of ASTM D4318.

8. CALCULATION

8.1. The water content of the soil shall be expressed as the moisture content in percentage of the mass of the oven-dried soil and shall be calculated as follows:

$$\text{percentage moisture} = \frac{\text{mass of water}}{\text{mass of oven-dried soil}} \times 100 \qquad (1)$$

8.1.1. Calculate the percentage of moisture to the nearest whole percent.

9. PREPARATION OF FLOW CURVE

9.1. A "flow curve" representing the relation between moisture content and corresponding number of shocks shall be plotted on a semilogarithmic graph with the moisture contents as abscissae on the arithmetical scale, and the number of shocks as ordinates on the logarithmic scale. The flow curve shall be a straight line drawn as nearly as possible through the three or more plotted points.

10. LIQUID LIMIT

10.1. The moisture content corresponding to the intersection of the flow curve with the 25-shock ordinate shall be taken as the liquid limit of the soil. Report this value to the nearest whole number.

METHOD B

11. SAMPLE

11.1. A sample with a mass of about 50 g shall be taken as described in Section 4.1.

12. PROCEDURE

12.1. Using the curved grooving tool (Section 6) or the flat grooving tool (Section 7) the procedure shall be the same as prescribed in Sections 6.1 through 6.5 except that the initial amount of water to be added in accordance with Section 6.1 shall be approximately 8 to 10 mL and the moisture sample taken in accordance with Section 6.4 shall be taken only for the accepted trial.

12.2. For accuracy equal to that obtained by the standard three-point method, the accepted number of blows for groove closure shall be restricted to between 22 and 28 blows. After obtaining a preliminary closure in the acceptable blow range, immediately return the soil remaining in the cup to the mixing dish and, without adding any additional water, repeat as directed in Sections 6.2 and 6.3. If the second closure occurs in the acceptable range (22 to 28, inclusive) and the second closure is within two (2) blows of the first closure, secure a water content specimen as directed in Section 6.4.

12.3. Groove closures between 15 and 40 blows may be accepted if variations of ±5 percent of the true liquid limit are tolerable.

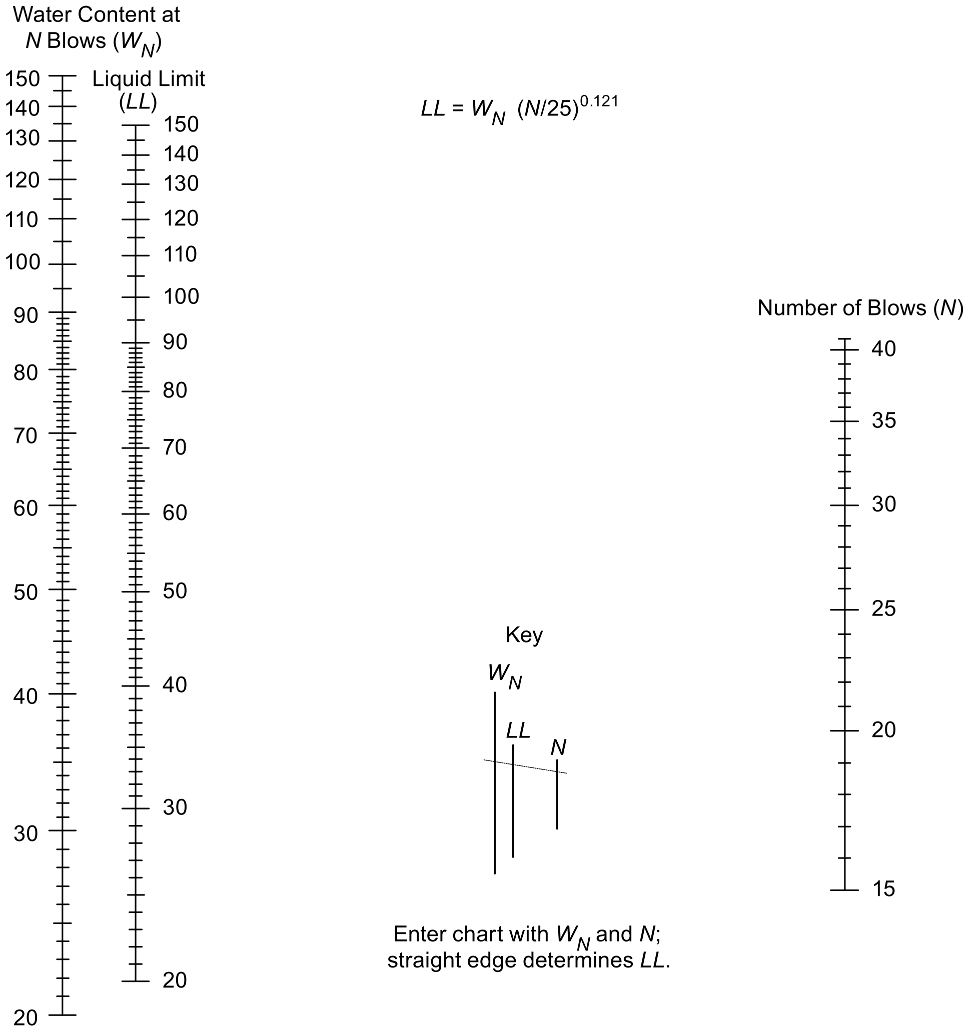
13. CALCULATION

13.1. The water content of the soil at the time of the accepted closure shall be calculated in accordance with Section 8.1.

14. LIQUID LIMIT

14.1. The liquid limit shall be determined by one of the following methods: the nomograph, Figure 4; the correction factor method, Table 1; or by any other method of calculation that produces equally accurate liquid limit values. The standard three-point method shall be used as a referee test to settle all controversies.

14.2. The key in Figure 4 illustrates the use of the nomograph (mean slope).



$LL = W_N\ (N/25)^{0.121}$

Enter chart with W_N and N; straight edge determines LL.

Figure 4—Nomographic Chart Developed by the Waterways Experiment Station, Corps of Engineers, U.S. Army, to Determine Liquid Limit Using Mean Slope Method

14.3. The correction factor method, Table 1, uses the moisture content of the liquid limit sample multiplied by a factor (k) of the second closure blow count. Figure 5 was developed for the Calculation of the Liquid Limit.

$$LL = W_N(N/25)^{0.121} \qquad (2)$$

or

$$LL = kW_N \qquad (3)$$

where:

N = number of blows causing closure of the groove at water content,

LL = liquid limit corrected for closure at 25 blows,

W_N = water content, and

k = factor given in Table 1.

Table 1—Factors for Obtaining Liquid Limit from Water Content and Number of Blows Causing Closure of the Groove

Number of Blows, *N*	Factor for Liquid Limit, *k*
22	0.985
23	0.990
24	0.995
25	1.000
26	1.005
27	1.009
28	1.014

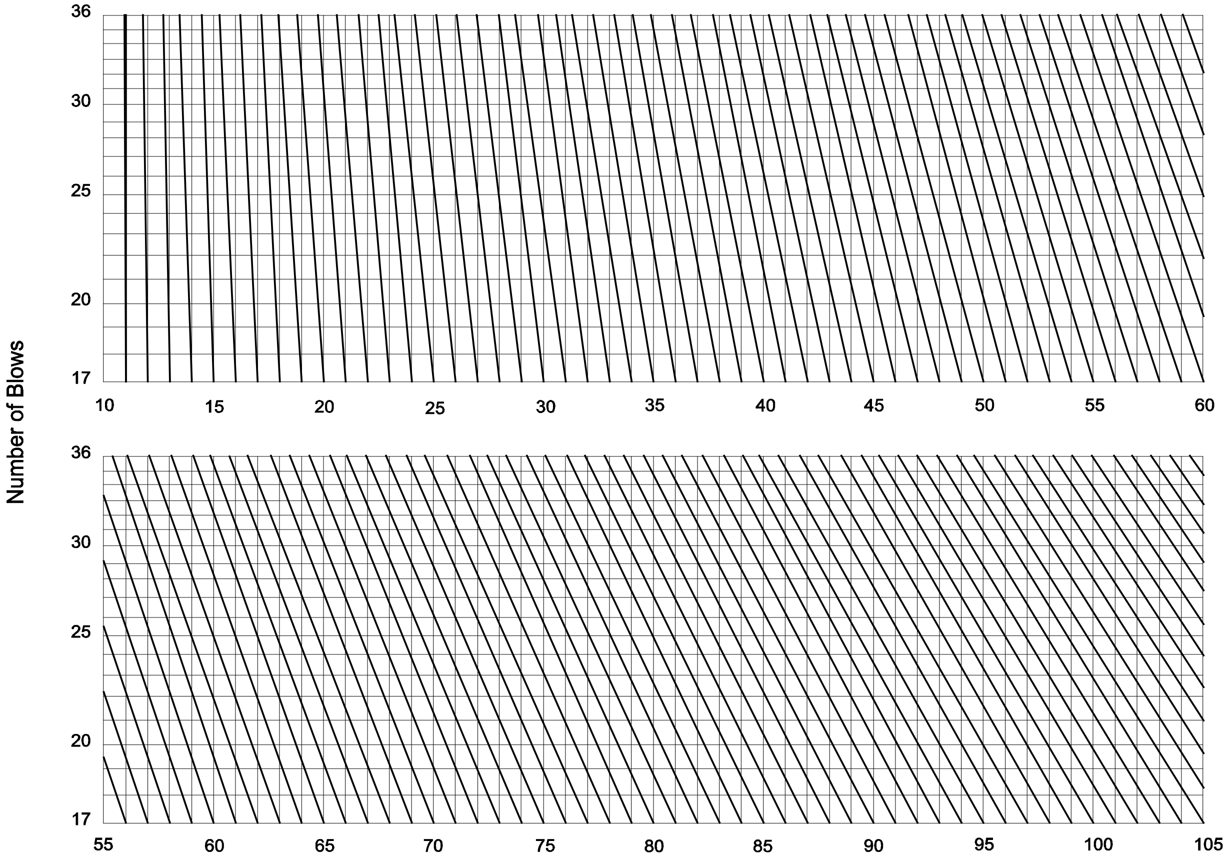


Figure 5—Chart Developed by Washington State Highway Department for the Calculation of the Liquid Limit

CHECK OR REFEREE TESTS

15. METHOD TO BE USED

15.1. Method A, using the curved grooving tool procedure (Section 6), shall be used in making check or referee tests. The results of liquid limit tests are influenced by:

15.1.1. The time required to make the test;

15.1.2. The moisture content at which the test is begun; and

15.1.3. The addition of dry soil to the seasoned sample.

16. PROCEDURE

16.1. Therefore, in making the liquid limit test for check or referee purposes, the following time schedule shall be used:

16.1.1. *Mixing of soil with water*—5 to 10 min, the longer period being used for the more plastic soils;

16.1.2. *Seasoning in the humidifier*—30 min;

16.1.3. *Remixing before placing in the brass cup*—add 1 mL of water and mix for 1 min;

16.1.4. *Placing in the brass cup and testing*—3 min; and

16.1.5. *Adding water and remixing*—3 min.

16.2. No trial requiring more than 35 blows or fewer than 15 blows shall be recorded. In no case shall dried soil be added to the seasoned soil being tested.

17. PRECISION STATEMENT

17.1. This precision statement applies to soils having a liquid limit range from 21 to 67.

17.2. *Repeatability (Single Operator)*—Two results obtained by the same operator on the same sample in the same laboratory using the same apparatus, and on different days, should be considered suspect if they differ by more than 7 percent of their mean.

17.3. *Reproducibility (Multilaboratory)*—Two results obtained by different operators in different laboratories should be considered suspect if they differ from each other by more than 13 percent of their mean.

18. KEYWORDS

18.1. Atterberg; clay soil; liquid limit; plasticity index.

APPENDIX

(Nonmandatory Information)

X1. MEASURING THE RESILIENCE OF LIQUID LIMIT DEVICE BASES

X1.1. A device for measuring the resilience of liquid limit device bases is shown in Figure X1.1 and Table X1.1. The device consists of a clear acrylic plastic tube and cap, an 8-mm diameter polished steel ball, and a small bar magnet. The cylinder may be cemented to the cap or threaded as shown.

The small bar magnet is held in the recess of the cap, and the steel ball is fixed into the recess in the underside of the cap with the bar magnet. The cylinder is then turned upright and placed on the top surface of the base to be tested. Hold the tube lightly against the liquid limit device base with one hand, and release the ball by pulling the magnet out of the cap. Use the scale markings on the outside of the cylinder to determine the highest point reached by the bottom of the ball. Repeat the drop at least three times, placing the tester in a different location for each drop. The average rebound of the steel ball, expressed as a percent of the total drop, equals the resilience of the liquid limit device base. Tests should be conducted at room temperature.

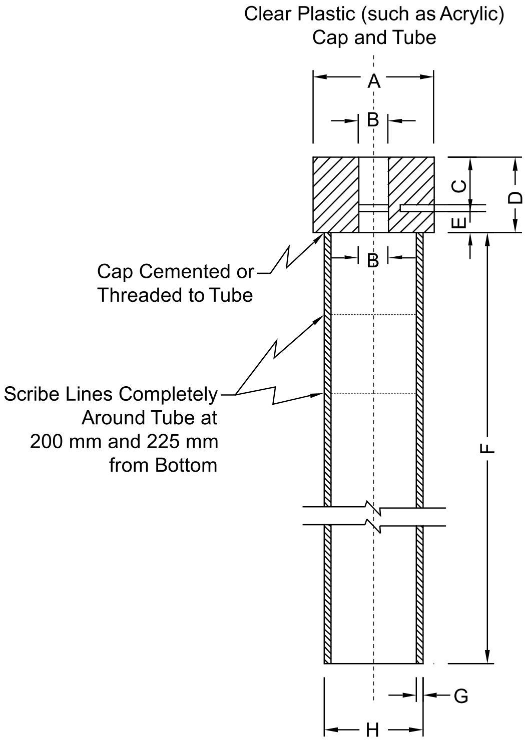


Figure X1.1—Resilience Tester

Table X1.1—Table of Measurements for Resilience Tester[a]

Dimension	Description	Metric, mm
A	Diam. of cap	38.0^b
B	Diam. of hole	9.0^b
C	Depth of hole	18.0^b
D	Height of cap	25.5^b
E	Depth of hole	8.0
F	Length of tube	250.0
G	Wall thickness	3.2^b
H	O.D. of tube	31.8^b
Scribed lines from bottom	Upper 90%	225.0
	Lower 80%	200.0

[a] Tube stands plumb.

[b] These dimensions are not critical in the performance of the test.

Standard Method of Test for

Determining the Plastic Limit and Plasticity Index of Soils

AASHTO Designation: T 90-20

Technically Revised: 2020 **Editorially Revised: 2021**

Technical Subcommittee: 1a, Soil and Unbound Recycled Materials

**American Association of State Highway and Transportation Officials
555 12th Street NW, Suite 1000
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Standard Method of Test for

Determining the Plastic Limit and Plasticity Index of Soils

AASHTO Designation: T 90-20

Technically Revised: 2020 **Editorially Revised: 2021**

Technical Subcommittee: 1a, Soil and Unbound Recycled Materials

1. SCOPE

1.1. The plastic limit of a soil is the lowest moisture content at which the soil remains plastic. The plasticity index of a soil is the range in moisture content, expressed as a percentage of the mass of the oven-dried soil, within which the material is in a plastic state. The plasticity index is calculated as the numerical difference between the liquid limit and plastic limit of the soil.

1.2. The following applies to all specified limits in this standard: For the purpose of determining conformance with these specifications, an observed value or a calculated value shall be rounded off "to the nearest unit" in the last right-hand place of figures used in expressing the limiting value, in accordance with ASTM E29.

1.3. Two procedures for rolling out soil samples are provided in this method: the Hand Rolling Method and the Plastic Limit Device Method. The Hand Rolling Method shall be used as the referee procedure.

1.4. This test method is often conducted in conjunction with T 89, which is used to determine the liquid limit of soils.

1.5. *The quality of the results produced by this standard are dependent on the competence of the personnel performing the procedure and the capability, calibration, and maintenance of the equipment used. Agencies that meet the criteria of R 18 are generally considered capable of competent and objective testing/sampling/inspection/etc. Users of this standard are cautioned that compliance with R 18 alone does not completely assure reliable results. Reliable results depend on many factors; following the suggestions of R 18 or some similar acceptable guideline provides a means of evaluating and controlling some of those factors.*

2. REFERENCED DOCUMENTS

2.1. *AASHTO Standards*:

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- R 61, Establishing Requirements for Equipment Calibrations, Standardizations, and Checks
- R 74, Wet Preparation of Disturbed Soil Samples for Test

- T 89, Determining the Liquid Limit of Soils
- T 265, Laboratory Determination of Moisture Content of Soils

2.2. *ASTM Standard*:

- E29, Standard Practice for Using Significant Digits in Test Data to Determine Conformance with Specifications

3. APPARATUS

3.1. *Dish*—A porcelain evaporating dish or similar mixing dish about 115 mm in diameter.

3.2. *Spatula*—A spatula or pill knife having a blade about 75 mm in length and about 20 mm in width.

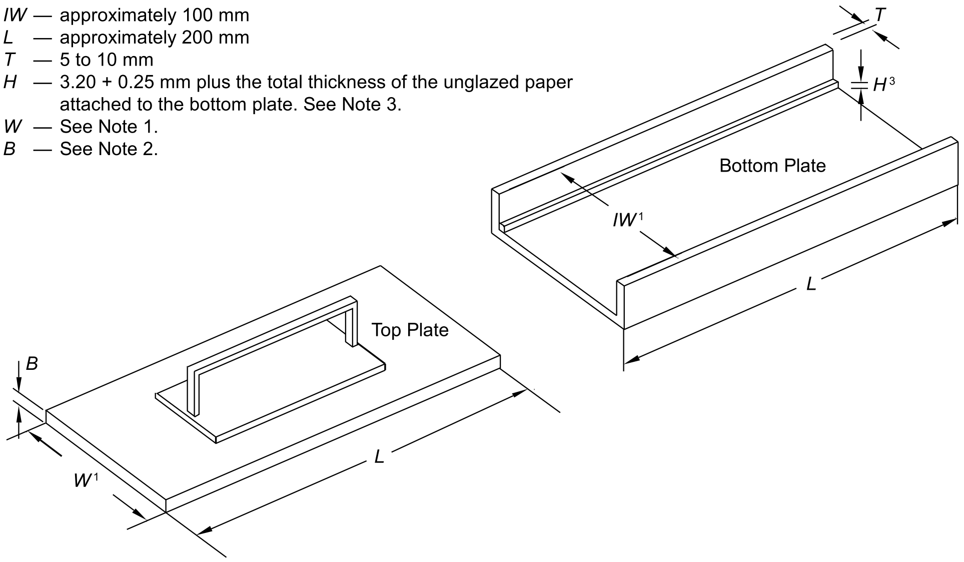
3.3. *Surface for Rolling*—Shall consist of one of the following:

3.3.1. A ground glass plate or piece of smooth, unglazed paper on which to roll the sample. Paper, if used, shall not add foreign matter (fibers, paper fragments, etc.) to the soil during the rolling process and shall lay flat on a smooth horizontal surface.

3.3.2. *Plastic Limit Rolling Device*[1,2]—A device made of acrylic conforming to the dimensions shown in Figure 1.

Dimensions:

IW — approximately 100 mm
L — approximately 200 mm
T — 5 to 10 mm
H — 3.20 + 0.25 mm plus the total thickness of the unglazed paper attached to the bottom plate. See Note 3.
W — See Note 1.
B — See Note 2.



Notes:

1. The tolerance between the width of the top plate (*W*) and the inside width of the bottom plate *(IW)* shall be such that the top plate slides freely on the rails without wobbling.
2. The top plate shall be rigid enough so that the thickness of the soil threads is not influenced by flexure of the top plate.
3. The width of the side rails shall be between 3 and 6 mm.

Figure 1—Plastic Limit Rolling Device

3.3.2.1. *Paper for Rolling Device*—Unglazed paper that does not add foreign matter (fibers, paper fragments, etc.) to the soil during the rolling process. Attach the unglazed paper to the top and bottom plates of the device either by a spray-on adhesive or by use of a self-adhesive backing.

Note 1—Take special care to remove the adhesive that remains on the plastic limit rolling device after testing. Repeated tests without such removal will result in a buildup of the residual adhesive and a decreased soil thread diameter.

3.4. *Moisture Content Container*—Made of material resistant to corrosion and not subject to change in mass or disintegration on repeated heating and cooling. The container shall have a close-fitting lid to prevent loss of moisture from samples before initial mass determination and to prevent absorption of moisture from the atmosphere following drying and before final mass determination. One container is needed for each moisture content determination.

3.5. *Balance*—A class G1 balance meeting the accuracy requirements of M 231.

3.6. *Oven*—Thermostatically controlled and capable of maintaining temperatures of 110 ± 5ºC for drying samples.

4. CALIBRATIONS, STANDARDIZATIONS, AND CHECKS

4.1. Unless otherwise specified, follow the requirements and intervals for equipment calibrations, standardizations, and checks in R 18.

4.2. Follow the procedures for performing equipment calibrations, standardizations, and checks found in R 61.

5. SAMPLE

5.1. *If only the plastic limit is to be determined*—Take a quantity of soil with a mass of about 20 g from the thoroughly mixed portion of the material passing the 0.425-mm (No. 40) sieve, obtained in accordance with R 58 or R 74. Place the air-dried soil in a mixing dish and thoroughly mix with distilled, demineralized, or de-ionized water until the mass becomes plastic enough to be easily shaped into a ball (Notes 2 and 3). Take a portion of this ball with a mass of about 10 g for the test sample.

Note 2—Tap water may be used for routine testing if comparative tests indicate no differences in results between using tap water and distilled, demineralized, or de-ionized water. However, use distilled, demineralized, or de-ionized water for referee or disputed tests.

Note 3—The objective is to add enough moisture to a plastic soil sample so that the 3-mm thread described in Section 6 does not crumble on the first roll. For a nonplastic soil, this will not be possible.

5.2. *If the plasticity index (both liquid and plastic limit) is to be determined*—Take a test sample with a mass of about 10 g from the thoroughly wet and mixed portion of the soil prepared in accordance with T 89. Take the sample at any stage of the mixing process at which the mass becomes plastic enough to be easily shaped into a ball without sticking to the fingers excessively when squeezed. If the sample is taken before completion of the liquid limit test, set it aside and allow to season in air until the liquid limit test has been completed. If the sample taken during the liquid limit test is too dry to permit rolling to a 3-mm thread as described in Section 6, add more water and remix (Note 3).

6. PROCEDURE

6.1. Determine and record the mass of the moisture content container.

6.2. Select a 1.5- to 2.0-g portion from the 10-g mass of soil prepared in accordance with Section 5. Form the selected portion into an ellipsoidal mass.

6.3. Use one of the following methods to roll the soil mass into a 3-mm-diameter thread at a rate of 80 to 90 strokes per minute, counting a stroke as one complete motion of the hand forward and back to the starting position again.

6.3.1. *Hand Rolling Method*—Roll the mass between the palm or fingers and the ground-glass plate or unglazed paper with just sufficient pressure to roll the mass into a thread of uniform diameter throughout its length. Deform the thread further on each stroke until its diameter reaches 3 mm. Take no more than 2 min to roll the soil mass to the 3-mm diameter.

Note 4—The amount of hand or finger pressure required will vary greatly, according to the soil. Fragile soils of low plasticity are best rolled under the outer edge of the palm or at the base of the thumb.

6.3.2. *Alternate Procedure, Plastic Limit Device Method*—Place the soil mass on the bottom plate. Place the top plate in contact with the soil mass. Simultaneously apply a slight downward force and back and forth motion to the top plate so the plate comes in contact with the side rails within 2 min. During this rolling process, do not allow the soil thread to contact the side rails.

Note 5—In most cases, more than one soil mass (thread) can be rolled simultaneously in the plastic limit rolling device.

6.4. The soil shall roll to a thread diameter of 3 mm at least one time to be considered plastic. When the diameter of the thread reaches 3 mm, squeeze the thread between the thumb and fingers and form the mass back into a roughly ellipsoidal shape. Repeat the rolling and re-forming process as described in Section 6.3 until the soil can no longer be rolled into a thread and begins to crumble. The crumbling may occur when the thread has a diameter greater than 3 mm, provided the soil has been previously rolled into a thread 3 mm in diameter (Note 6). This is considered a satisfactory end point. If unsure a satisfactory end point has been reached, verify by attempting to reform the soil into an ellipsoidal mass and, if possible, repeat the rolling process until the soil can no longer hold a thread shape when a slight amount of pressure is applied to the ellipsoidal mass. Do not attempt to produce failure at an exact 3-mm diameter by purposely reducing the rate of rolling or the hand pressure, or both (Note 7).

Note 6—The crumbling will manifest itself differently with various types of soil. Some soils fall apart in numerous small aggregations of particles; others may form an outside tubular layer that starts splitting at both ends. The splitting may progress toward the middle, and the thread may finally fall apart in many small platy particles. Heavy clay soils require much pressure to deform the thread, particularly as they approach the plastic limit. These types of soils may break into a series of barrel-shaped segments each about 6 to 9 mm in length.

Note 7—For feebly plastic soils, it may be necessary to reduce the total amount of deformation by making the initial diameter of the ellipsoidal-shaped mass nearer to the required 3-mm final diameter.

6.5. Gather the portions of the crumbled soil together and place in the moisture content container. Immediately cover the container with a close-fitting lid to prevent additional loss of moisture.

6.6. Repeat the operations described in Sections 6.3 through 6.5 until the entire 10-g specimen is tested. Place all of the crumbled portions into the same moisture content container.

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

7. CALCULATIONS

7.1. The plastic limit of the soil is the moisture content determined in Section 6.7, expressed as a percentage of the oven-dry mass, and determined in accordance with T 265. Report the plastic limit to the nearest whole number.

7.2. If applicable, calculate the plasticity index of a soil as the difference between its liquid limit and its plastic limit, as follows:

$$\text{plasticity index} = \text{liquid limit} - \text{plastic limit} \tag{1}$$

7.3. Report the results as calculated in Section 7.2 as the plasticity index, except under the following conditions:

7.3.1. When the liquid limit or plastic limit cannot be determined, report the plasticity index as NP (nonplastic).

7.3.2. When the plastic limit is equal to, or greater than, the liquid limit, report the plasticity index as NP.

8. PRECISION STATEMENT

8.1. This precision statement applies to soils with a plastic limit range between 15 and 32, tested using the hand rolling method.

8.2. *Repeatability (Single Operator)*—Two results obtained by the same operator on the same sample in the same laboratory using the same apparatus should be considered suspect if they differ by more than 10 percent of their mean.

8.3. *Reproducibility (Multilaboratory)*—Two results obtained by different operators in different laboratories should be considered suspect if they differ from each other by more than 18 percent of their mean.

9. KEYWORDS

9.1. Atterberg; clay soil; plastic limit; plasticity index.

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[1] The plastic limit rolling device is covered by a patent (U.S. Patent No. 5,027,660). Interested parties are invited to submit information regarding the identification of an alternative(s) to this patent to AASHTO Headquarters. Your comments will receive careful consideration at a meeting of AASHTO Technical Section 1a on Soil Materials Tests.

[2] Bobrowski, L. J., Jr. and D. M. Griekspoor, "Determination of the Plastic Limit of a Soil by Means of a Rolling Device," *Geotechnical Testing Journal*, GTJODJ, Vol. 15, No. 3, September 1992, pp. 284–287.

Appendix 2:

AASHTO M-145 Soil Classification Example and Partial Group Index Determination

AASHTO M-145 Soil Classification System

General Classification	Granular Materials (35% or less passing No. 200 Sieve)							Silt and Clay Materials (More than 35% passing No. 200 Sieve)			
Group Classification	A-1		A-3	A-2				A-4	A-5	A-6	A-7
	A-1-a	A-1-b		A-2-4	A-2-5	A-2-6	A-2-7				A-7-5 A-7-6
Sieve Analysis Percent Passing:											
No. 10	50 max	--	--	--	--	--	--	--	--	--	--
No. 40	30 max	50 max	51 min	--	--	--	--	--	--	--	--
No. 200	15 max	25 max	10 max	35 max	35 max	35 max	35 max	36 min	36 min	36 min	36 min
Characteristics of fraction passing No. 40											
LL (Liquid Limit)	--		--	40 max	41 min	40 max	41 min	40 max	41 min	40 max	41 min
PI (Plasticity Index)	6 max		NP	10 max	10 max	11 min	11 min	10 max	10 max	11 min	11 min
Usual types of significant constituents	Stone fragments, gravel, and sand		Fine sand	Silty or clayey gravel and sand				Silty soils		Clayey soils	
General subgrade rating	Excellent to good					Fair to poor					

<u>EXAMPLE</u>: What is the classification of the soil with the following index properties?

Gradation (% Passing):

#10 = 72.1
#40 = 53.3
#200 = 38.2

Liquid Limit = 33
Plastic Index = 8

Use a process of elimination to determine the soil classification. In this example, the percent passing the number 200 sieve is greater than 35. All A-1, A-2, and A-3 soils can be eliminated:

General Classification	Granular Materials (35% or less passing No. 200 Sieve)							Silt and Clay Materials (More than 35% passing No. 200 Sieve)			
Group Classification	A-1		A-3	A-2				A-4	A-5	A-6	A-7
	A-1-a	A-1-b		A-2-4	A-2-5	A-2-6	A-2-7				A-7-5 A-7-6
Sieve Analysis Percent Passing:											
No. 10	50 max	--	--	--	--	--	--	--	--	--	--
No. 40	30 max	50 max	51 min	--	--	--	--	--	--	--	--
No. 200	15 max	25 max	10 max	35 max	35 max	35 max	35 max	36 min	36 min	36 min	36 min
Characteristics of fraction passing No. 40											
LL (Liquid Limit)	--		--	40 max	41 min	40 max	41 min	40 max	41 min	40 max	41 min
PI (Plasticity Index)	6 max		NP	10 max	10 max	11 min	11 min	10 max	10 max	11 min	11 min
Usual types of significant constituents	Stone fragments, gravel, and sand		Fine sand	Silty or clayey gravel and sand				Silty soils		Clayey soils	
General subgrade rating	Excellent to good					Fair to poor					

The Plastic Index of this soil is below 11; therefore, all A-6 and A-7 soils can also be eliminated:

General Classification	Granular Materials (35% or less passing No. 200 Sieve)							Silt and Clay Materials (More than 35% passing No. 200 Sieve)			
Group Classification	A-1		A-3	A-2				A-4	A-5	A-6	A-7
	A-1-a	A-1-b		A-2-4	A-2-5	A-2-6	A-2-7				A-7-5 A-7-6
Sieve Analysis Percent Passing:											
No. 10	50 max	--	--	--	--	--	--	--	--	--	--
No. 40	30 max	50 max	51 min	[illegible]	--	--	--	--	--	--	--
No. 200	15 max	25 max	10 max	35 max	35 max	35 max	35 max	36 min	36 min	36 min	36 min
Characteristics of fraction passing No. 40											
LL (Liquid Limit)			--	40 max	41 min	40 max	41 min	40 max	41 min	40 max	41 min
PI (Plasticity Index)	6 max		NP	10 max	10 max	11 min	11 min	10 max	10 max	11 min	11 min
Usual types of significant constituents	Stone fragments, gravel, and sand		Fine sand	Silty or clayey gravel and sand				Silty soils		Clayey soils	
General subgrade rating	Excellent to good					Fair to poor					

Finally, the Liquid Limit is less than 41; therefore, the A-5 Soil Group can also be eliminated:

General Classification	Granular Materials (35% or less passing No. 200 Sieve)							Silt and Clay Materials (More than 35% passing No. 200 Sieve)			
Group Classification	A-1		A-3	A-2				A-4	A-5	A-6	A-7
	A-1-a	A-1-b		A-2-4	A-2-5	A-2-6	A-2-7				A-7-5 A-7-6
Sieve Analysis Percent Passing:											
No. 10	50 max	--	--	--	--	--	--	--	--	--	--
No. 40	30 max	50 max	51 min	--	--	--	--	--	--	--	--
No. 200	15 max	25 max	10 max	35 max	35 max	35 max	35 max	36 min	36 min	36 min	36 min
Characteristics of fraction passing No. 40											
LL (Liquid Limit)	--		--	40 max	41 min	40 max	41 min	40 max	41 min	40 max	41 min
PI (Plasticity Index)	6 max		NP	10 max	10 max	11 min	11 min	10 max	10 max	11 min	11 min
Usual types of significant constituents	Stone fragments, gravel, and sand		Fine sand	Silty or clayey gravel and sand				Silty soils		Clayey soils	
General subgrade rating	Excellent to good					Fair to poor					

Gradation (% Passing):
#10 = 72.1
#40 = 53.3
#200 = 38.2

Liquid Limit = 33
Plastic Index = 8

The resulting soil classification is A-4.

AASHTO M-145 Soil Classification System

General Classification	Granular Materials (35% or less passing No. 200 Sieve)							Silt and Clay Materials (More than 35% passing No. 200 Sieve)			
Group Classification	A-1		A-3	A 2				A-4	A-5	A-6	A-7
	A-1-a	A-1-b		A-2-4	A-2-5	A-2-6	A-2-7				A-7-5 A-7-6
Sieve Analysis Percent Passing:											
No. 10	50 max	--	--	--	--	--	--	--	--	--	--
No. 40	30 max	50 max	51 min	--	--	--	--	--	--	--	--
No. 200	15 max	25 max	10 max	35 max	35 max	35 max	35 max	36 min	36 min	36 min	36 min
Characteristics of fraction passing No. 40 sieve											
LL (Liquid Limit)	--		--	40 max	41 min	40 max	41 min	40 max	41 min	40 max	41 min
PI (Plasticity Index)	6 max		NP	10 max	10 max	11 min	11 min	10 max	10 max	11 min	11 min
Usual types of significant constituents	Stone fragments, gravel, and sand		Fine sand	Silty or clayey gravel and sand				Silty soils		Clayey soils	
General subgrade rating	Excellent to good					Fair to poor					

🟨	A-1, A-3, A-2-4, and A-2-5 Soils: Compacted +/- 2% OMC to 95% max. dry density via T 180 modified by CP 23. Use vibratory or pneumatic rollers.
🟩	A-2-6 and A-2-7 Soils: Compacted +/- 2% OMC to 95% max. dry density via T 99 modified by CP 23. Use vibratory, pneumatic, or sheepsfoot rollers.
🟧	A-4, A-5, A-6, and A-7 Soils: Compacted at or above OMC to 95% max. dry density via T 99 modified by CP 23 if soils are stable. If unstable, compact below OMC with Engineer’s approval. Use sheepsfoot rollers.

Soil Embankment with greater than 30 percent retained on the ¾-inch sieve: The contractor must construct a test strip to the dimensions specified, which can be incorporated into the final embankment.

Partial Group Index Determination

A soil's Liquid Limit, Plasticity Index, and percent passing the No. 200 sieve are used to determine the partial group index. The liquid limit partial group number, and the plasticity index partial group number are determined separately, then added together and rounded to a whole number to determine the partial group index for a soil.

The liquid limit partial group number is determined by the liquid limit and the percent passing the No. 200 sieve. The equation to calculate the liquid limit partial group number is:

$(F-35)[0.2+0.005(LL-40)]$

where: F = % passing the No. 200 sieve
LL = Liquid Limit of the soil

If the% passing the # 200 sieve is $\leq$ 35%, then the LL partial group index will be 0.

The plasticity index partial group number is determined by the plasticity index and the % passing the No. 200 sieve. The equation to calculate the plasticity index partial group number is:

$0.01[(F-15)(PI-10)]$

where: F = % passing the No. 200 sieve
PI = Plasticity Index of the soil

Partial Group Index = LL Partial Group Number + Plasticity Index Partial Group Number
(Rounded to the nearest whole number)

Example Problem:

What is the partial group index of the soil with the following characteristics?

$F = 45.1\%$
$LL = 38$
$PI = 26$

The initial soil classification for the soil is an A-6.

For Liquid Limit Partial Group Number:

$= (F-35)\ [0.2+0.005(LL-40)]$

$= (45.1-35)\ [0.2+0.005(38-40)]$

$= (10.1)\ [0.2+(-0.01)]$

$= (10.1)\ [.19]$

$= 1.92$

For Plasticity Index Partial Group Number:

$= 0.01[(F-15)\ (PI-10)]$

$= 0.01[(45.1-15)\ (26-10)$

$= 0.01[(30.1)\ (16)]$

$= 0.01[481.6]$

$= 4.82$

Answer: LL partial group number = 1.92

PI partial group number = 4.82

Partial Group Index = 1.92 + 4.82 = 6.74 = 7

Completed classification is A-6(7)

Appendix 3:

Determination of Zero Air Voids Density of Soils with Varying Moisture Content and Specific Gravity

The zero air voids density (Dz) for a soil at a given moisture content is calculated using the equation below. The specific gravity of the soil particles must be known to calculate the zero air voids density that can be achieved at a specific moisture content. The zero air voids curve is typically plotted on the proctor curve at each percent moisture point to provide a reference for checking relative compaction in the field. This curve is also referred to as the *100% saturation curve*.

$$Dz = \frac{(S.G.soil)(62.4\ lb/ft^3)}{1 + \left(\frac{(S.G.soil)(\%\ Moisture\ of\ proctor\ point)}{100}\right)}$$

Where: S.G. = Specific Gravity of the soil
Dz = Zero Air Voids Density at a specific moisture content

<u>Example:</u>
S.G. soil = 2.650
Percent moisture = 11.2%

$$Dz = \frac{(2.650)(62.4\ lb/ft^3)}{1 + \left(\frac{(2.650)(11.2)}{100}\right)}$$

$$Dz = \frac{(165.4\ lb/ft^3)}{(1.296)}$$

Dz = 127.6 lbs/ft^3 at 11.2% Moisture

The Zero Air Voids Density Tabulation shown on the next page provides a quick reference to determine the zero air voids density that would be obtained at various moisture contents given typical specific gravity values for soil. When a specific gravity test is not conducted for a soil; this table can be used to estimate the zero air voids density. For sands, specific gravity is typically 2.65. For clays, specific gravity can range from 2.70 to 2.75.

Table A-1:
Zero Air Voids Density Tabulation Given Various Moisture Contents and Common Specific Gravities for Soils

Moisture Content (Percent of dry weight)	Zero Air Void Dry Densities		
	At 2.65 Specific Gravity (lb / ft^3)	At 2.70 Specific Gravity (lb / ft^3)	At 2.75 Specific Gravity (lb / ft^3)
9.0	133.5	135.5	137.6
9.5	132.1	134.1	136.1
10.0	130.7	132.7	134.6
10.5	129.4	131.3	133.2
11.0	128.0	129.9	131.7
11.5	126.7	128.6	130.4
12.0	125.5	127.3	129.0
12.5	124.2	126.0	127.7
13.0	123.0	124.7	126.4
13.5	121.8	123.5	125.1
14.0	120.6	122.3	123.9
14.5	119.5	121.1	122.7
15.0	118.3	119.9	121.5
15.5	117.2	118.8	120.3
16.0	116.1	117.7	119.2
16.5	115.1	116.6	118.0
17.0	114.0	115.5	116.9
17.5	113.0	114.4	115.8
18.0	112.0	113.4	114.8
18.5	111.0	112.4	113.7
19.0	110.0	111.4	112.7
19.5	109.0	110.4	111.7
20.0	108.1	109.4	110.7
20.5	107.2	108.5	109.7
21.0	106.2	107.5	108.8
21.5	105.3	106.6	107.8
22.0	104.5	105.7	106.9
22.5	103.6	104.8	106.0
23.0	102.7	103.9	105.1

Table A-1 Continued:
Zero Air Voids Density Tabulation Given Various Moisture Contents and Common Specific Gravities for Soils

Moisture Content (Percent of dry weight)	Zero Air Void Dry Densities		
	At 2.65 Specific Gravity (lb / ft^3)	At 2.70 Specific Gravity (lb / ft^3)	At 2.75 Specific Gravity (lb / ft^3)
23.5	101.9	103.1	104.2
24.0	101.1	102.2	103.4
24.5	100.3	101.4	102.5
25.0	99.5	100.6	101.7
25.5	98.7	99.8	100.9
26.0	97.9	99.0	100.1
26.5	97.1	98.2	99.3
27.0	96.4	97.4	98.5
27.5	95.7	96.7	97.7
28.0	94.9	95.9	96.9
28.5	94.2	95.2	96.2
29.0	93.5	94.5	95.5
29.5	92.8	93.8	94.7
30.0	92.1	93.1	94.0
30.5	91.4	92.4	93.3
31.0	90.8	91.7	92.6
31.5	90.1	91.0	91.9
32.0	89.5	90.4	91.3
32.5	88.8	89.7	90.6
33.0	88.2	89.1	90.0
33.5	87.6	88.5	89.3
34.0	87.0	87.8	88.7
34.5	86.4	87.2	88.1
35.0	85.8	86.6	87.4
35.5	85.2	86.0	86.8