



**Washington State
Department of Transportation**

Materials Manual

M 46-01.47

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Engineering and Regional Operations
State Materials Laboratory

Foreword

The *Materials Manual* continues to use AASHTO, ASTM, WAQTC, and WSDOT test methods. The strategic direction for the Materials Laboratory is to continue to expand the use of AASHTO and ASTM standards whenever possible.

The manual has retained its dual unit format. However, English units predominate with metric units in parenthesis. WSDOT is using English units. The manual reflects the Quality System concerns of an AASHTO accredited organization and is organized by numerical test order. It also features two contents and an index.

The manual reflects a continuing policy of adopting “consensus” standards wherever practical. Adoption of these, in the form of AASHTO, ASTM, WAQTC, or other nationally recognized standards eliminates much of the previous text, which merely recopied the national documents. By adopting these standards, we provide a common standard that can be used by neighboring states and other laboratories or organizations. Contractors who work in more than one state also benefit by having to conform with fewer unique tests.

The concept of Field Operating Procedures (FOP) is continued to support the work of Materials Testers at the Field or Project level. Full procedures are provided when WSDOT Test Methods apply, or when a consensus standard (AASHTO, ASTM, or WAQTC) has been adapted to an FOP. The FOP provides the essential performance elements for the field technician.

When not specified by the test procedure, test reports will be generated through the Materials Testing System (MATS) or by the use of forms approved by the State Materials Engineer.

The WSDOT Materials Laboratory is responsible for establishing and managing all test procedures. For technical information or suggested changes to test methods or procedures, contact the WSDOT Materials Laboratory Quality Systems Manager through the departmental mail system at MS 47365; by mail at PO Box 47365, Olympia, WA 98504-7365; by email at mawdslr@wsdot.wa.gov; by telephone at 360-709-5497; or by fax at 360-709-5588, physically located at 1655 South Second Avenue, Tumwater, WA 98512. Please use this physical address for all communications other than U.S. Postal Service mail.

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WSDOT Errata to WAQTC TM 15

Laboratory Theoretical Maximum Dry Density of Granular Soil and Soil/Aggregate

WAQTC TM 15 has been adopted by WSDOT with the following changes:

Apparatus

Replace with below:

- **Small Mold Assembly:** includes mold, mold base, and mold follower.
 - **Small Mold:** ASTM 513 DOM Steel Tubing; volume approximately 0.003 m³ (0.1 ft.³); 165 mm (6.500 in.) O.D. nominal, 6.4 mm (0.250 in.) wall thickness, I.D. 152.4 ± 0.8 mm (6 ± 0.032 in.); Height 203.2 ± 1.6 mm (8 ± 0.064 in.). In-service molds not to exceed a I.D. of 153.9 mm (6.064 in.).
 - **Small Mold Base:** Removable from mold, 15.9 mm (0.625 in.) nominal plate steel. Both surfaces ground to between 15.8 to 13.6 mm (0.624 to 0.536 in.) thick.
 - **Small Mold Follower:** Plate Steel with an edge thickness of 12.7 mm ± 1.6 mm (0.500 ± 0.064 in.). New follower diameter tolerance of - 0.8 mm to - 1.6 mm (- 0.032 to - 0.064 in.) of the diameter of the matching small mold. In-service follower shall not exceed - 3.2 mm (- 0.125 in.).
- **Large Mold Assembly:** includes mold, mold base, and mold follower.
 - **Large mold:** ASTM 513 DOM Steel Tubing; 267 mm (10.500 in.) O.D. nominal, 6.4 mm (0.250 in.) wall thickness, I.D. 254.0 ± 0.8 mm (10 ± 0.032 in.); Internal Height 254.0 ± 1.6 mm (10 ± 0.064 in.). In- service molds not to exceed a I.D. of 255.6 mm (10.064 in.).
 - **Large Mold Base:** 6.3 to 9.5 mm (0.250 to 0.375 in.) plate steel. Skip welded or fully welded to the mold
 - **Large Mold Follower:** Plate Steel with an edge thickness of 12.7 mm ± 1.6 mm (0.500 ± 0.064 in.). New follower diameter tolerance of - 0.8 mm to - 1.6 mm - (0.032 in. to 0.064 in.) of the diameter of the matching mold. In-service follower shall not exceed - 3.2 mm (- 0.125 in.).

Sample Preparation

Replace step one with below:

1. Obtain a representative sample according to Table 3 below.

Table 3 TM15 Sample Size		
	Minimum Mass lb (kg)	
If no more than 15 percent by weight of aggregate exceeds 19 mm (¾ in.)	210	95
If 15 percent or more by weight of aggregate exceeds 19 mm (¾ in.)	330	150

Theoretical Maximum Density Curve Development

Replace with below:

WSDOT Employees – Enter laboratory data into MATS to develop the maximum density chart and maximum density curve.

Non-WSDOT Employees – Enter laboratory data into WAQTC spreadsheet to develop the maximum density chart and maximum density curve. Spreadsheet available at

<http://waqtc.org/library/library.cfm>

LABORATORY THEORETICAL MAXIMUM DRY DENSITY OF GRANULAR SOIL AND SOIL/ AGGREGATE WAQTC TM 15

Scope

This method is used to establish the theoretical maximum dry density of granular and non-granular soil-aggregate. Use Procedure 1 for material with more than 30 percent retained on the 4.75 mm (No. 4) sieve or Procedure 2 for material with more than 30 percent retained on the 19.0 mm (¾ in.) sieve.

Terminology

- Fine aggregate portion – material passing the 4.75 mm (No. 4) Sieve.
- Coarse aggregate portion – material retained on the 4.75 mm (No. 4) sieve.

Significance

A theoretical maximum dry density chart and curve are developed by determining a laboratory maximum dry density of a representative sample of material passing the 4.75 mm (No. 4) and the material retained on the 4.75 mm (No. 4), and their respective apparent specific gravities (G_{sa}). The theoretical maximum dry density chart and curve address the range of theoretical maximum dry densities due to fluctuations in coarse and fine aggregate of a given material.

To determine the laboratory maximum dry density of the fine aggregate portion, this method allows for use of the FOP for AASHTO T 99/T 180 or by vibratory compactor covered in the method.

This method is for use on granular materials having 30 to 70 percent passing the 4.75 mm (No. 4) or 19.0 mm (¾ in.) sieve.

Apparatus

- A vibratory spring-loaded compactor – D G Parrott & Son Humphres Maximum Density machine, or equivalent.
- Small Mold Assembly: includes mold, mold base, and mold follower.
 - Mold: approximately 0.003 m³ (0.1 ft.³) volume. Made of steel tubing meeting ASTM A513 with a 165 mm (6.500 in.) nominal outside diameter, 6 mm (0.250 in.) wall thickness, 152 ±1 mm (6 ±0.03 in.) inside diameter, and a height of 203 ±1 mm (8 ±0.032 in.). For in-service molds, do not to exceed 15 mm (6.060 in.) inside diameter.
 - Mold Base: 16 mm (0.625 in.) steel plate separate from the mold. Grind both surfaces to 15 ±1 mm (0.600 ±0.030 in.) thickness.

- Mold Follower: Steel plate, with a 12 ± 1 mm (0.460 ± 0.03 in.) edge thickness fitting inside the mold with 1.5 mm (0.063 in.) maximum space between mold follower and mold wall. For new followers, the diameter tolerance is -1 mm to -2 mm (-0.031 in. to -0.063 in.) of the inside diameter of the matching mold.
- Large Mold Assembly: includes mold, mold base, and mold follower
 - Mold: approximately 0.014 m³ (0.5 ft.³) volume. Made of steel tubing meeting ASTM A513 with a 267 mm (10.500 in.) nominal outside diameter, 6 mm (0.250 in.) wall thickness, 254 ± 1 mm (10 ± 0.032 in.) inside diameter, and a height of 254 ± 1 mm (10 ± 0.032 in.). For in-service molds, do not to exceed 256 mm (10.060 in.) inside diameter.
 - Mold Base: 6 to 8 mm (0.250 to 0.312 in.) steel plate skip welded or fully welded to the mold.
 - Mold Follower: Steel plate, with 14 ± 1 mm (0.550 ± 0.030 in.) edge thickness fitting inside the mold with 1.5 mm (0.063 in.) max. space between mold follower and mold wall. For new followers, the diameter tolerance is -1 mm to -2 mm (-0.031 in. to -0.063 in.) of the inside diameter of the matching mold.
- Manually operated rammer: 2.5 kg (5.5 lb.) rammer meeting the requirements of the FOP for AASHTO T 99/T 180.
- Measuring device: minimum length 150 mm (6 in.), accurate and readable to 0.25 mm (0.01 in.)
- Sieves: 75 mm (3 in.), 19 mm ($\frac{3}{4}$ in.), and a 4.75 mm (No. 4) conforming to the FOP for AASHTO T 27/T 11
- Balance or Scale: Capacity sufficient for the principal sample mass, readable to 0.1 percent or 0.1 g, and meeting the requirements of AASHTO M 231
- Tamping rod: straight steel, 16 mm ($\frac{5}{8}$ in.) in diameter and approximately 400 mm (24 in.) long having at least one end rounded to a hemispherical tip
- Straight edge: at least 25 mm (1 in.) longer than the diameter of the mold
- A stopwatch or timer readable to 1 second
- Miscellaneous tools including pans, spoon, trowel, mechanical mixer (optional), etc.

Laboratory Maximum Dry Density

Select the proper method for determining the laboratory maximum dry density of the fine aggregate portion of the sample, refer to Table 1, or as directed by the agency.

Select the proper method for determining the laboratory maximum dry density of the coarse aggregate portion of the sample, refer to Table 2.

Table 1
Fine Aggregate Portion Laboratory Maximum Dry Density Method

Estimated Soil Type	Recommended Test Method
Sandy, non-plastic, permeable soil or non-cohesive soil.	WAQTC TM 15 Vibratory Compactor
Silt, some plasticity, low permeability.	FOP for AASTHO T 99/T 180, T 99 Method A
Sandy/silt, some plasticity, permeable.	WAQTC TM 15 and FOP for AASTHO T 99/T 180, T 99 Method A (use highest results)

Table 2
Coarse Aggregate Portion Laboratory Maximum Dry Density Method

Coarse Aggregate Amount	Test Method
No more than 15 percent by weight of the original aggregate specimen exceeds 19 mm ($\frac{3}{4}$ in.)	WAQTC TM 15 Vibratory Compactor Procedure 1
15 percent or more by weight of the original aggregate specimen is greater than 19 mm ($\frac{3}{4}$ in.) but does not exceed 75 mm (3 in.)	WAQTC TM 15 Vibratory Compactor Procedure 2

Sample Preparation

1. Obtain a representative sample according to the FOP for AASTHO R 90, minimum 180 kg. (400 lbs.).
2. Reduce according to the FOP for AASTHO R 76 to a sufficient size to yield amounts required in steps 7 and 8.
3. If the sample is damp, dry 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).
4. Thoroughly break up aggregations in a manner that avoids reducing the natural size of individual particles.

5. Remove the material retained on the 75 mm (3 in.) sieve.
6. Separate into coarse and fine aggregate portions by passing the remainder of the sample through the 4.75 mm (No. 4) sieve.
7. Fine aggregate:
 - a. Obtain a representative sample as described in the FOP for AASHTO T 99/T 180, T 99 Method A.

Or
 - b. Obtain at least three representative test samples of approximately 6 kg (13 lb.) each for the fine aggregate vibratory compactor method.
 - c. Obtain a representative sample of the remaining material and determine the apparent specific gravity (G_{sa}) according to AASHTO T 84 or Annex B.
8. Coarse aggregate:
 - a. Obtain a representative sample of 19 mm ($\frac{3}{4}$ in) to 4.75 mm (No. 4) of approximately 5 kg (11 lb.) for coarse aggregate vibratory compactor Procedure 1.

Or
 - b. Obtain a representative sample of 75 mm (3 in) to 4.75 mm (No. 4) of approximately 20 kg (45 lb.) for coarse aggregate vibratory compactor Procedure 2.
 - c. Obtain a representative sample of the remaining material and determine the apparent specific gravity (G_{sa}) according to FOP for AASHTO T 85 or Annex B.

Laboratory Maximum Dry Density of Fine Aggregate Portion

Determine laboratory maximum dry density of the fine aggregate portion according to the FOP for AASHTO T 180/T 99, T 99 Method A, or the following vibratory compactor method. Refer to Table 1.

Vibratory Compactor Method

1. Determine and record the mass of the clean dry small mold assembly to the nearest 5 g (0.01 lb.). Designate this mass as the M_m .
2. Add enough water to one of the fine aggregate portions to saturate the sample, approximately optimum moisture. Do not over saturate (Note 1).

Note 1: The sample is considered saturated when one to two drops of free water are visible at the base of the mold assembly at the end of the first 2-minute load cycle, Table 3. Refer to Step 11.

3. Mix until homogenous.

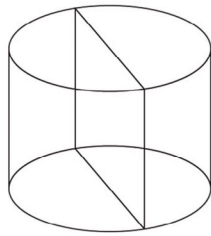
4. Place approximately one third of the sample in the mold with mold base attached.
5. Consolidate with 25 strokes of the tamping rod, distribute evenly over the surface, and 25 blows of the manually operated rammer.
6. Repeat Steps 4 and 5 for two subsequent lifts. The surface of the top lift should be finished as level as possible.
7. Place the follower on top of the molded specimen and mount the mold assembly on the jack platform in the compactor. Use spacers between the load spring assembly and follower to adjust the elevation of the mold assembly so the hammers strike near the center of the mass of material in the mold assembly.
8. Elevate the mold assembly with the jack until the load spring assembly seats on top of the follower and apply an initial seating load of approximately 100 lb_f on the sample.
9. Start the compactor hammers. Continue to elevate the mold assembly, applying the load gradually over the time stated in the Table 3.

Table 3
Load Application Rate

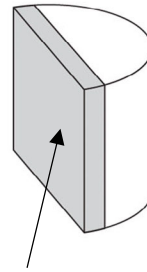
Load lb _f	Time
0 to 500	1 min.
500 to 1,000	30 sec.
1,000 to 2,000	30 sec.

10. Upon reaching 2,000 lb_f at the end of the 2-minute cycle, stop the hammer, release the load on the jack, and return to zero pressure.
11. Determine apparent moisture.
 - a. If the material is pumping around the mold follower or excessive amounts of water are seeping from between the mold and mold base, prepare a new sample and begin the test again at Step 1.
 - b. If the base of the mold is dry or there is a small amount of water, repeat Steps 7 through 10, four additional times.
12. Remove the mold assembly from the compactor.
13. Measure the height of the compacted specimen.
 - a. Lay the straight edge across the top of the mold assembly.

- b. Using the measuring device, measure from the bottom of the straight edge to the top of the follower and spacers to the nearest 0.1 mm (0.01 in.). Designate as D.
 - c. Calculate and record the height of the compacted specimen, h_s , by subtracting D and T (thickness of the follower) from the height of the mold h_m . See Annex A..
14. Determine and record the mass of the mold assembly and specimen, M_{ms} , to the nearest 5 g (0.01 lb.).
 15. Determine and record the mass of the specimen, M_s , by subtracting M_m from M_{ms} .
 16. Remove the specimen from the mold assembly.
 17. Use the entire specimen for a moisture content sample or obtain a representative sample by slicing vertically through the center of the specimen. Obtain at least 500 g (1.1 lb.) from one of the cut faces, ensuring that all the layers are represented. If a vertical face does not exist, take a representative sample.



Slice through the center



Representative moisture content sample

18. Determine and record the moisture content, w , according to the FOP for AASHTO T 255/T 265.
19. Calculate and record the wet density, ρ_w , of the fine aggregate portion.
20. Calculate and record the laboratory dry density, ρ_d , of the fine aggregate portion.

Laboratory Maximum Dry Density of the Coarse Portion

Vibratory Compactor Method

Note 2: Procedure 1 uses the small mold assembly, this procedure is not recommended for material with aggregate larger than 9.3 mm (3/4 in.).

Procedure 1

1. Determine and record the mass of the small mold assembly to the nearest 5 g (0.01 lb.). Designate this mass as the M_m .

2. Determine and record the mass of the coarse aggregate portion to the nearest 5 g (0.01 lb.). Designate this mass as the M_s . See Note 3.

Note 3: If all the coarse aggregate portion does not fit in the mold assembly or there is some indication that material may have been lost, perform alternate Step 16 to determine M_s .

3. Determine amount of water to add to the coarse aggregate portion by multiplying the mass determined in Step 2 by 0.025 (2.5 percent).
4. Add water to coarse aggregate portion, mix thoroughly.
5. Place approximately one third of the sample in the mold with mold base attached.
6. Tamp the surface lightly with the manually operated rammer to consolidate material and achieve a level surface.
7. Repeat Steps 5 and 6 for two subsequent lifts. Ensure all the coarse aggregate portion is placed in the mold.
8. Place the follower on top of the molded specimen and mount the mold assembly on the jack platform in the compactor. Use spacers between the load spring assembly and follower to adjust the elevation of the mold assembly so the hammers strike near the center of the mass of material in the mold assembly.
9. Elevate the mold assembly with the jack until the loading spring assembly seats on top of the follower and spacers.
10. Apply an initial seating load of approximately 100 lbf on the sample.
11. Start the compactor hammers. Continue to elevate the mold, applying the load gradually over the time stated in the Table 3.
12. Upon reaching the 2,000 lbf load at the end of the 2-minute cycle, stop the hammer, release the load on the jack, and return to zero pressure.
13. Repeat Steps 10 through 12 four additional times.
14. Remove the mold assembly from the compactor.
15. Measure the height of the compacted specimen.
 - a. Lay the straight edge across the top of the mold assembly.
 - b. Using the measuring device, measure from the bottom of the straight edge to the top of the follower and spacers to the nearest 0.1 mm (0.01 in.). Designate as D .
 - c. Calculate and record the height of the compacted specimen, h_s , by subtracting D and T (thickness of the follower) from the height of the mold h_m . See Annex A.

16. Alternate method of determining M_s
 - a. Remove the specimen from the mold assembly.
 - b. Determine the dry mass according to the FOP for AASHTO T 255. Designate as M_s .
17. Calculate and record the laboratory dry density, ρ_d , of the coarse aggregate portion.

Procedure 2

1. Determine and record the mass of the large mold assembly to the nearest 5 g (0.01 lb.). Designate this mass as the M_m .
2. Determine and record the mass of the coarse aggregate portion to the nearest 5 g (0.01 lb.). Designate this mass as the M_s .

Note 4: If all the coarse aggregate portion does not fit in the mold or there is some indication that material may have been lost, perform alternate Step 13 to determine M_s .

3. Place approximately one fifth of the sample in the large mold with mold base.
4. Tamp the surface lightly with the manually operated rammer to consolidate material and achieve a level surface.
5. Place the follower on top of the molded specimen and mount the mold assembly on the jack platform in the compactor. Use spacers between the load spring assembly and follower to adjust the elevation of the mold assembly so the hammers strike near the center of the mass of material in the mold assembly.
6. Elevate the mold assembly with the jack until the loading spring assembly seats on top of the follower.
7. Apply an initial seating load of approximately 100 lbf on the sample.
8. Start the compactor hammers. Continue to elevate the mold assembly, applying the load gradually over the time stated in the Table 3.
9. Upon reaching the 2,000 lbf load at the end of the 2-minute cycle, stop the hammer, release the load on the jack, and return to zero pressure.
10. Repeat Steps 3 through 9 four additional times. Ensure all the coarse aggregate portion is placed in the mold on the final lift.
11. Remove the mold assembly from the compactor.
12. Measure the height of the compacted specimen.
 - a. Lay the straight edge across the top of the mold assembly.

- b. Using the measuring device, measure from the bottom of the straight edge to the top of the follower and spacers to the nearest 0.1 mm (0.01 in.). Designate as D.
- c. Calculate and record the height of the compacted specimen, h_s , by subtracting D and T (thickness of follower) from the height of the mold, h_m . See Annex A.

13. Alternate method of determining M_s

- a. Remove the specimen from the mold assembly.
- b. Determine the dry mass of the specimen according to the FOP for AASHTO T 255. Designate as M_s .

14. Calculate and record the laboratory dry density, ρ_d , of the coarse aggregate portion.

Calculations

Height of specimen in mold (fine or coarse aggregate portion)

$$h_s = h_m - D - T$$

where:

- h_s = height of specimen in mold, 0.1 mm (0.01 in.)
 h_m = height of mold, 0.1 mm (0.01 in.), Annex A
D = measured distance from the mold top to the follower, 0.1 mm (0.01 in.)
T = thickness of the follower, 0.1 mm (0.01 in.), Annex A

Volume of the specimen in the mold (fine or coarse aggregate portion)

$$V_s = \frac{h_s \times \pi \times \left(\frac{d}{2}\right)^2}{1e^9 \text{ mm}^3 / \text{m}^3 \text{ or } 1728 \text{ in}^3 / \text{ft}^3}$$

where:

- V_s = volume of specimen in mold m^3 (ft^3)
d = inside diameter of the mold, 0.1 mm (0.01 in.), Annex A

Mass of fine aggregate portion in the mold assembly

$$M_s = M_{ms} - M_m$$

where:

- M_s = mass of specimen in mold assembly, 0.005 kg (0.01 lb.)
 M_{ms} = mass of mold assembly and specimen, 0.005 kg (0.01 lb.)
 M_m = mass of mold assembly, 0.005 kg (0.01 lb.)

Wet Density of fine aggregate portion

$$\rho_w = \frac{M_s}{V_s}$$

Where:

- ρ_w = wet density, kg/m³ (lb/ft³)
 M_s = mass of specimen in the mold assembly, 0.005 kg (0.01 lb.)
 V_s = volume of specimen in mold m³ (ft³)

Laboratory maximum dry density fine aggregate portion

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

Where:

- ρ_d = dry density, kg/m³ (lb/ft³)
 w = moisture content, as a percentage (FOP for AASHTO T 255)

Laboratory maximum dry density of coarse aggregate portion

$$\rho_d = \left(\frac{M_s}{V_s} \right) \times 100$$

Where:

ρ_d	=	dry density, kg/m ³ (lb/ft ³)
M_s	=	mass of specimen in the mold assembly, 0.005 kg (0.01 lb.)
V_s	=	volume of specimen in mold m ³ (ft ³)

Example**Example for small mold fine aggregate portion**

Wet mass, M_w	=	6.470 kg (14.26 lb)
Moisture content, w	=	11.3%
Height of mold, h_m	=	203.7 mm (8.02 in.)
Inside diameter of mold, d	=	153.4 mm (6.04 in.)
Measurement from top of mold to follower, D	=	44.5 mm (1.75 in.)
Thickness of the follower, T	=	3.6 mm (0.14 in.)
Mass of specimen and mold assembly, M_{ms}	=	6.400 kg (14.11 lb)
Mass of mold assembly, M_m	=	0.280 kg (0.62 lb)

Height of fine aggregate portion in mold

$$h_s = h_m - D - T$$

$$h_s = 203.7 \text{ mm} - 44.5 \text{ mm} - 3.6 \text{ mm} = 155.6 \text{ mm}$$

$$h_s = 8.02 \text{ in.} - 1.75 \text{ in.} - 0.14 \text{ in.} = 6.13 \text{ in.}$$

Volume of the fine aggregate in the mold

$$V_s = \frac{h_s \times \pi \times \left(\frac{d}{2}\right)^2}{1e^9 \text{ mm}^3 / \text{m}^3 \text{ or } 1728 \text{ in}^3 / \text{ft}^3}$$

$$V_s = \frac{155.6 \text{ mm} \times \pi \times \left(\frac{153.4 \text{ mm}}{2}\right)^2}{1,000,000,000 \text{ mm}^3 / \text{m}^3} = 0.002876 \text{ m}^3$$

Or

$$V_s = \frac{6.13 \text{ in.} \times \pi \times \left(\frac{6.04 \text{ in.}}{2}\right)^2}{1728 \text{ in}^3 / \text{ft}^3} = 0.1016 \text{ ft}^3$$

Mass of fine aggregate portion in the mold

$$M_s = M_{ms} - M_m$$

$$M_s = 6.400 \text{ kg} - 0.280 \text{ kg} = 6.119 \text{ kg}$$

$$M_s = 14.11 \text{ lb} - 0.62 \text{ lb} = 13.49 \text{ lb}$$

Wet density of fine aggregate portion

$$\rho_w = \frac{M_s}{V_s}$$

$$\rho_w = \frac{6.119 \text{ kg}}{0.002876 \text{ m}^3} = 2128 \text{ kg/m}^3$$

$$\rho_w = \frac{13.49 \text{ lb}}{0.1016 \text{ ft}^3} = 132.8 \text{ lb/ft}^3$$

Laboratory maximum dry density of the fine aggregate portion

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

$$\rho_d = \left(\frac{2128 \text{ kg/m}^3}{11.3\% + 100} \right) \times 100 = 1912 \text{ kg/m}^3 \quad \rho_d = \left(\frac{132.8 \text{ lb/ft}^3}{11.3\% + 100} \right) \times 100 = 119.3 \text{ lb/ft}^3$$

Or

$$\rho_d = \left(\frac{2128 \text{ kg/m}^3}{\frac{11.3\%}{100} + 1} \right) = 1912 \text{ kg/m}^3 \quad \rho_d = \left(\frac{132.8 \text{ lb/ft}^3}{\frac{11.3\%}{100} + 1} \right) = 119.3 \text{ lb/ft}^3$$

Example for small mold coarse aggregate portion (Procedure 1)

Calculations will be the same for Procedure 2

Height of mold assembly, h_m	=	203.7 mm (8.02 in.)
Inside diameter of mold, d	=	153.4 mm (6.04 in.)
Measurement from top of mold assembly to follower, D	=	42.4 mm (1.67 in.)
Thickness of the follower, T	=	3.6 mm (0.14 in.)
Mass of coarse aggregate in the mold assembly, M_s	=	4.985 kg (10.99 lb)

Height of coarse aggregate portion in mold

$$h_s = h_m - D - T$$

$$h_s = 203.7 \text{ mm} - 42.4 \text{ mm} - 3.6 \text{ mm} = 157.7 \text{ mm}$$

$$h_s = 8.02 \text{ in.} - 1.67 \text{ in.} - 0.14 \text{ in.} = 6.21 \text{ in.}$$

Volume of the coarse aggregate portion in the mold

$$V_s = \frac{h_s \times \pi \times \left(\frac{d}{2}\right)^2}{1e^9 \text{ mm}^3 / \text{m}^3 \text{ or } 1728 \text{ in}^3 / \text{ft}^3}$$

$$V_s = \frac{157.7 \text{ mm} \times \pi \times \left(\frac{153.4 \text{ mm}}{2}\right)^2}{1,000,000,000 \text{ mm}^3 / \text{m}^3} = 0.002915 \text{ m}^3$$

$$V_s = \frac{6.21 \text{ in.} \times \pi \times \left(\frac{6.04 \text{ in.}}{2}\right)^2}{1728 \text{ in}^3 / \text{ft}^3} = 0.1030 \text{ ft}^3$$

Laboratory maximum dry density of coarse aggregate portion

$$\rho_d = \left(\frac{M_s}{V_s} \right) \times 100$$

$$\rho_d = \left(\frac{4.985 \text{ kg}}{0.002915 \text{ m}^3} \right) \times 100 = 1710 \text{ kg/m}^3$$

$$\rho_d = \left(\frac{10.99 \text{ lb}}{0.1030 \text{ ft}^3} \right) \times 100 = 106.7 \text{ lb/ft}^3$$

Theoretical Maximum Density Curve Development

Enter the following data into an approved spreadsheet to develop the maximum density chart and maximum density curve.

- Laboratory maximum dry density, ρ_d , of the coarse aggregate portion to the nearest 1 kg/m^3 (0.1 lb/ft^3)
- Laboratory maximum dry density, ρ_d , of the fine aggregate portion to the nearest 1 kg/m^3 (0.1 lb/ft^3)
- Optimum moisture content to the nearest 0.1 percent if the FOP for AASTHO T 99/T 180, T 99 Method A was used for the fine portion.
- Coarse aggregate apparent specific gravity, G_{sa} , to the nearest 0.001
- Fine aggregate portion apparent specific gravity, G_{sa} , to the nearest 0.001

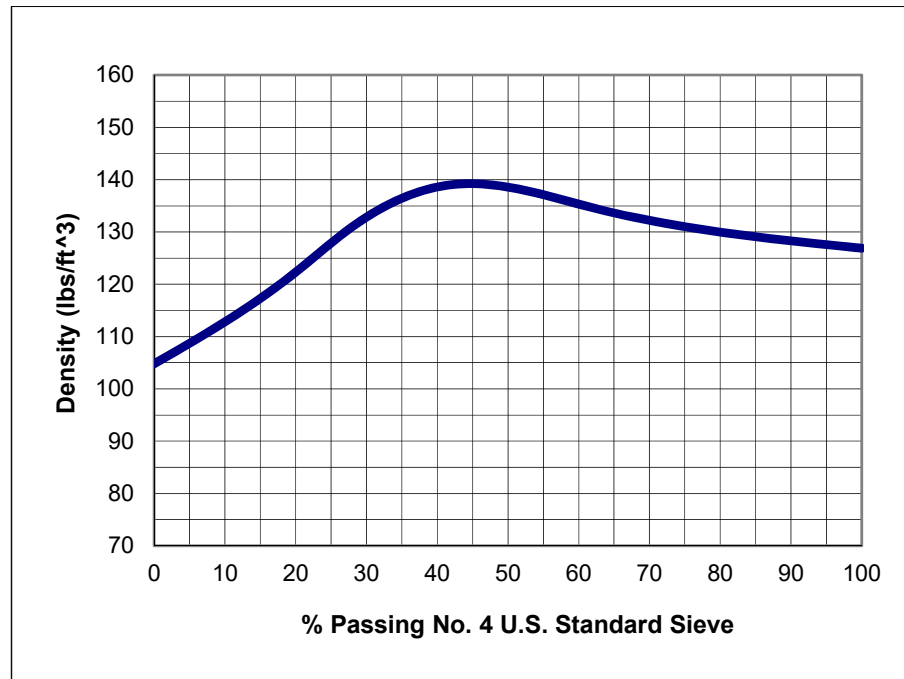
Example

Theoretical Maximum Dry Density Chart

Density Curves				Density Curves			
Pass #4	Maximum	Pass #4	Maximum	Pass #4	Maximum	Pass #4	Maximum
0.0	104.8	31.0	133.7	62.0	134.6	82.0	129.6
1.0	105.6	32.0	134.5	63.0	134.3	83.0	129.4
2.0	106.4	33.0	135.2	64.0	134.0	84.0	129.3
3.0	107.1	34.0	135.8	65.0	133.6	85.0	129.1
4.0	107.9	35.0	136.4	66.0	133.3	86.0	128.9
5.0	108.7	36.0	137.0	67.0	133.1	87.0	128.8
6.0	109.5	37.0	137.5	68.0	132.8	88.0	128.6
7.0	110.3	38.0	137.9	69.0	132.5	89.0	128.4
8.0	111.1	39.0	138.3	70.0	132.2	90.0	128.3
9.0	112.0	40.0	138.6	71.0	132.0	91.0	128.1
10.0	112.8	41.0	138.9	72.0	131.7	92.0	128.0
11.0	113.7	42.0	139.0	73.0	131.5	93.0	127.9
12.0	114.5	43.0	139.2	74.0	131.2	94.0	127.7
13.0	115.4	44.0	139.2	75.0	131.0	95.0	127.6
14.0	116.4	45.0	139.2	76.0	130.8	96.0	127.4
15.0	117.3	46.0	139.2	77.0	130.6	97.0	127.3
16.0	118.2	47.0	139.1	78.0	130.4	98.0	127.2
17.0	119.2	48.0	139.0	79.0	130.2	99.0	127.0
18.0	120.2	49.0	138.8	80.0	130.0	100.0	126.9
19.0	121.3	50.0	138.6	81.0	129.8		
20.0	122.3	51.0	138.3				
21.0	123.4	52.0	138.1				
22.0	124.5	53.0	137.8				
23.0	125.6	54.0	137.5				
24.0	126.8	55.0	137.1				
25.0	127.9	56.0	136.8				
26.0	129.0	57.0	136.4				
27.0	130.0	58.0	136.0				
28.0	131.0	59.0	135.7				
29.0	132.0	60.0	135.3				
30.0	132.8	61.0	135.0				

Control Points for Density Curves		
Pass #4	Maximum	Loose
0.0	104.8	87.6
20.5	122.8	99.6
27.4	130.4	103.8
42.5	139.1	105.4
61.1	134.9	96.7
100.0	126.9	81.9

Theoretical Maximum Dry Density Curve



Report

- Results on standard agency forms
- Sample ID
- Laboratory maximum dry density of the coarse aggregate portion to the nearest 1 kg/m³ (0.1 lb/ft³)
- Laboratory maximum dry density of the fine aggregate portion to the nearest 1 kg/m³ (0.1 lb/ft³)
- Optimum moisture content to the nearest 0.1 percent (when using the FOP for AASTHO T 99/T 180, T 99 Method A for the fine aggregate portion)
- Coarse aggregate apparent specific gravity (G_{sa}) to the nearest 0.001
- Fine aggregate apparent specific gravity (G_{sa}) to the nearest 0.001
- Theoretical maximum dry density chart
- Theoretical maximum dry density curve

ANNEX A STANDARDIZATION OF THE MOLD ASSEMBLY

(Mandatory Information)

Apparatus

- Calipers having a range sufficient to measure the diameter of the measure being checked and readable to at least 0.1 mm (0.01 in.)
- Inside diameter caliper, 300 mm (12 in.) range
- Straight edge at least 25 mm (1 in.) larger than the mold
- Ruler readable to 0.1 mm (0.01 in.)

Procedure**Determine the height of the mold (h_m)**

1. Place the straight edge across the top of the mold with mold base.
2. Using the caliper measure from the bottom of the straight edge to the center mold with base to the nearest 0.1 mm (0.01 in.)
3. Turn the straight edge 90 degrees.
4. Repeat Step 2.
5. Average the two measurements.
6. Designate as h_m

Determine the thickness of the mold follower and spacers (T)

1. Place follower and spacers inside the mold with mold base.
2. Place the straight edge across the top of the mold.
3. Using the caliper measure from the bottom of the straight edge to the center of the top of the follower to the nearest 0.1 mm (0.01 in.).
4. Turn the straight edge 90 degrees.
5. Repeat Step 3.
6. Average the two measurements.
7. Subtract the average measurement from h_m
8. Designate as T.

Determine the inside diameter of the mold (d)

1. Using the caliper measure the inside diameter of the mold to the nearest 0.1 mm (0.01 in.).
2. Turn the mold 90 degrees.
3. Repeat Step 1.
4. Average the two measurements.
5. Designate as d.

ANNEX B APPARENT SPECIFIC GRAVITY (G_{sb}) DETERMINATION

(Mandatory Information)

This procedure covers the determination of apparent specific of coarse and fine aggregate by means of a pycnometer. When the soil is composed of material both larger and smaller than the 4.75 mm (No. 4) sieve, the sample is separated on the 4.75 mm (No. 4) sieve.

Apparatus

- Pycnometer: A flask or other suitable container in which the volume can be reproduced within ± 0.1 ml. The volume of the flask shall be at least 50 percent greater than required for the test sample.
- Pycnometer / volumetric flask cover: A glass plate or a metal or plastic cover with a vented opening
- Balance: A balance of sufficient capacity, readable to 0.1 g. Meeting AASHTO M 231, Class G2.
- Oven: Capable of maintaining a temperature of $110 \pm 5^\circ\text{C}$ ($230 \pm 9^\circ\text{F}$) for drying the specimens to a constant mass.
- Vacuum lid: A transparent lid with a suitable vacuum connection, with a vacuum opening to be covered with a fine wire mesh
- Vacuum: Capable of evacuating air from the container to a partial vacuum of 13.33 kPa (100 mmHg) or less absolute pressure
- Manometer or vacuum gauge: Capable of measuring the vacuum being applied at the source of the vacuum
- Water bath: A constant-temperature water bath (optional)
- Thermometers: Thermometric devices accurate to 0.5°C (1°F)
- Bleeder valve to adjust vacuum
- Timer

Sample Preparation

1. Sample and reduce the aggregate in accordance with the FOPs for AASHTO R 90 and R 76.
2. Dry the sample sufficiently to obtain a clean separation of fine and coarse material in the sieving operation.
3. Sieve the sample in accordance with the FOP for AASHTO T 27/ T 11 over the 4.75 mm (No. 4) sieve.

Coarse test sample

- a. Split or quarter approximately 1000 g of material from the portion retained on the 4.75 mm (No. 4) sieve.
- b. Dry to constant mass according to the FOP for AASHTO T 255 at $110 \pm 5^{\circ}\text{C}$ ($230 \pm 9^{\circ}\text{F}$).
- c. Cool to room temperature.

Fine test sample

- a. Split or quarter approximately 500 g of material from the portion passing the 4.75 mm (No. 4) sieve.
- b. Dry to constant mass according to the FOP for AASHTO T 255/T 265 at $110 \pm 5^{\circ}\text{C}$ ($230 \pm 9^{\circ}\text{F}$).
- c. Cool to room temperature.

Procedure

The procedure is performed on fine and coarse aggregate separately.

1. Determine and record the mass of the dry test sample. Designate as A.
2. Place the test sample in the pycnometer.
3. Add water at approximately 20°C (68°F) until the pycnometer is about $\frac{3}{4}$ full.
4. Connect the pycnometer to the vacuum system.
5. Apply partial vacuum, 30 mmHg or less absolute pressure, for 20 ± 1 min.
6. Agitate the pycnometer and contents, either continuously by mechanical device or manually by vigorous shaking, at 2-minute intervals. This agitation facilitates the removal of entrapped air.
7. Release vacuum and disconnect the hoses.
8. Fill the pycnometer with water without reintroducing air. Water temperature should be maintained as close to $20 \pm 0.5^{\circ}\text{C}$ ($68 \pm 1^{\circ}\text{F}$) as possible throughout the procedure.

Note 1: It may be necessary to place the pycnometer in a water bath for 10 minutes after the release of vacuum to stabilize at $20 \pm 0.5^{\circ}\text{C}$ ($68 \pm 1^{\circ}\text{F}$).

- a. Metal pycnometer (coarse test sample only) – Fill the pycnometer with $20 \pm 0.5^{\circ}\text{C}$ ($68 \pm 1^{\circ}\text{F}$) water according to manufacturer's instructions and dry the outside.
 - b. Glass pycnometer (fine or coarse test samples) – Completely fill the pycnometer with $20 \pm 0.5^{\circ}\text{C}$ ($68 \pm 1^{\circ}\text{F}$) water, slide the calibrated glass plate over the mouth of the pycnometer making sure there are no air bubbles trapped under the plate. Dry the outside.
9. Determine and record the mass of the pycnometer, sample, and water. Designate as C.

Calculation

Calculate the G_{sa} to three decimal places as follows:

$$G_{sa} = \frac{A}{A + B - C}$$

Where:

- A = Mass of dry sample in air, g
- B = Mass of pycnometer filled with water at 20°C (68°F), g, determined during the Standardization of Pycnometer procedure
- C = Mass of pycnometer, water, and the test sample at to 20 ±0.5°C (68 ±1°F), g

Coarse example:

$$G_{sa} = \frac{2200.3 \text{ g}}{2200.3 \text{ g} + 7502.5 \text{ g} - 8812.0 \text{ g}} = 2.470$$

Given:

- A = 2200.3 g
- B = 7502.5 g
- C = 8812.0 g

Report

- Report on standard agency forms.
- Report apparent specific gravities, G_{sa} , to the nearest 0.001

Standardization of Pycnometer

The pycnometer shall be standardized periodically in conformance with procedures established by the agency.

1. Fill the pycnometer with water at approximately 20°C (68°F).
2. Place the metal or plastic cover, or a glass plate on the pycnometer and eliminate all air.

Note B1: When using a metal pycnometer and cover, place the cover on the pycnometer and push down slowly, forcing excess water out of the hole in the center of the cover. Use care when filling the pycnometer to avoid reintroducing air into the water.

3. Stabilize the pycnometer at $20 \pm 0.5^\circ\text{C}$ ($68 \pm 1^\circ\text{F}$) for 10 ± 1 min.
4. Towel dry the outside of the pycnometer and cover.
5. Determine and record the mass of the pycnometer, water, and lid.
6. Repeat Steps 2 through 5 two more times for a total of three determinations.
7. If the variation of the three masses is within 0.3 g, average the three masses. Designate as “B.”
8. If the variation of the masses is greater than 0.3 g, take corrective action and perform the “Standardization of Pycnometer” again.

Performance Exam Checklist

WAQTC TM 15

Laboratory Theoretical Maximum Dry Density of Granular Soil and Soil/Aggregate

Participant Name: _____ Exam Date: _____

Record the symbols "P" for passing or "F" for failing on each step of the checklist.

Procedure Element	Trial 1	Trial 2
1. The tester has a copy of the current procedure on hand?	_____	_____
2. All equipment is functioning according to the test procedure, and if required has the current calibration/standardization/check and maintenance tags present?	_____	_____
Sample Preparation Element		
3. A minimum of 180 kg. (400 lbs.) representative sample material obtained according to FOP for AASHTO R 90?	_____	_____
4. Representative sample reduced according to FOP for AASHTO R 76 to yield the sample sizes for testing?	_____	_____
5. If damp, sample dried at a temperature not exceeding 60°C (140°F)?	_____	_____
6. Material retained on the 75 mm (3 in.) sieve removed?	_____	_____
7. Coarse and fine aggregate portions separated through the 4.75 mm (No. 4) sieve?	_____	_____
Fine Aggregate Portion Element		
8. Proper test method selected based on Table 1?	_____	_____
9. Mass of clean dry small mold determined to the nearest 5 g (0.01 lb.)?	_____	_____
10. Enough water added to saturate sample and mixed until homogenous?	_____	_____
11. Each lift consolidated with 25 strokes of tamping rod and 25 blows of manually operated rammer?	_____	_____
12. Top lift finished as level as possible?	_____	_____
13. Mold cap placed and spacers utilized so the hammers strike near the center of mass in the mold?	_____	_____
14. Initial seating load of approximately 100 lbf applied?	_____	_____
15. Compaction begun and load application rate per Table 3 followed?	_____	_____
16. Based on the determination of apparent moisture, compaction cycle repeated four additional times or a new sample is prepared and test restarted from Step 1.?	_____	_____
17. Height of compacted specimen determined and recorded?	_____	_____
18. Mass of specimen determined and recorded?	_____	_____
19. Moisture content determined and recorded?	_____	_____
20. Dry density determined?	_____	_____

Procedure Element	Trial 1	Trial 2
Coarse Aggregate Portion Element		
21. Proper test method selected based on Table 2?	_____	_____
Procedure 1 Element		
22. Mass of clean dry small mold determined to the nearest 5 g (0.01 lb.)?	_____	_____
23. Mass of coarse aggregate portion (Ms) determined to the nearest 5 g (0.01 lb.)?	_____	_____
24. Coarse aggregate mass multiplied by 0.025 to determine mass of water to be added?	_____	_____
25. Water and coarse aggregate mixed thoroughly?	_____	_____
26. Each lift tamped lightly with manually operated rammer?	_____	_____
27. Mold cap placed and spacers utilized so the hammers strike near the center of mass in the mold?	_____	_____
28. Initial seating load of approximately 100 lbf applied?	_____	_____
29. Compaction begun and load application rate per Table 3 followed?	_____	_____
30. Compaction cycle repeated four additional times?	_____	_____
31. Height of compacted specimen determined and recorded?	_____	_____
32. If all the coarse aggregate did not fit into the mold the alternate method of determining Ms followed?	_____	_____
33. Dry density determined?	_____	_____
Procedure 2 Element		
34. Mass of clean dry large mold determined to the nearest 5 g (0.01 lb.)?	_____	_____
35. Mass of coarse aggregate portion (Ms) determined to the nearest 5 g (0.01 lb.)?	_____	_____
36. Approximately one fifth of the sample place in mold?	_____	_____
37. Lift tamped lightly with manually operated rammer to consolidate and level?	_____	_____
38. Mold cap placed and spacers utilized so the hammers strike near the center of mass in the mold?	_____	_____
39. Initial seating load of approximately 100 lbf applied?	_____	_____
40. Compaction begun and load application rate per Table 3 followed?	_____	_____
41. Aggregate placement and compaction cycle repeated four additional times?	_____	_____
42. Height of compacted specimen determined and recorded?	_____	_____
43. If all the coarse aggregate did not fit into the mold the alternate method of determining Ms followed?	_____	_____
44. Dry density determined?	_____	_____

Procedure Element	Trial 1	Trial 2
Apparent Specific Gravity of the Fine and Coarse Portions According to Annex B		
45. Appropriate amount of coarse and fine aggregate portions obtained, dried, and cooled?	_____	_____
46. Mass of dry test sample(s) determined and recorded?	_____	_____
47. Test sample(s) placed in pycnometer and 20°C (68°F) water added to about ¾ full?	_____	_____
48. Partial vacuum applied to pycnometer and contents for 20 ± 1 min. and agitated by mechanical device or manually?	_____	_____
49. Vacuum released and pycnometer filled with water without reintroducing air?	_____	_____
50. Water stabilized at 20 ±0.5°C (68 ±1°F), pycnometer cover positioned, and outside dried?	_____	_____
51. Mass of pycnometer, sample, and water determined and recorded?	_____	_____
52. Specific Gravity determined?	_____	_____

Comments: First Attempt: Pass _____ Fail _____ Second Attempt: Pass _____ Fail _____

Examiner Signature: _____ WAQTC #: _____

