Standard Method of Test for

Moisture–Density Relations of Soils Using a 4.54-kg (10-lb) Rammer and a 457-mm (18-in.) Drop

AASHTO Designation: T 180-01

1. SCOPE

1.1. This method of test is intended for determining the relationship between the moisture content and density of soils when compacted in a given mold of a given size with a 4.54-kg (10-lb) rammer dropped from a height of 457 mm (18 in.). Four alternate procedures are provided as follows:

- *Method A*—A 101.60-mm (4-in.) mold: Soil material passing a 4.75-mm (No. 4) sieve Sections 3 and 4.
- *Method B*—A 152.40-mm (6-in.) mold: Soil material passing a 4.75-mm (No. 4) sieve Sections 5 and 6.
- *Method C*—A 101.60-mm (4-in.) mold: Soil material passing a 19.0-mm ($^3/_4$-in.) sieve Sections 7 and 8.
- *Method D*—A 152.40-mm (6-in.) mold: Soil material passing a 19.0-mm ($^3/_4$-in.) sieve Sections 9 and 10.

1.2. The method to be used should be indicated in the specifications for the material being tested. If no method is specified, the provisions of Method A shall govern.

1.3. This test method applies to soils mixtures that have 40 percent or less retained on the 4.75-mm (No. 4) sieve, when Method A or B is used and 30 percent or less retained on the 19.0-mm (¾-in.) sieve, when Method C or D is used. The material retained on these sieves shall be defined as oversize particles (coarse particles).

1.4. If the test specimen contains oversize particles, and the test specimen used for field density compaction control, corrections must be made according to T 224 to compare the total field density with the compacted specimen. The person or agency specifying this method shall specify a minimum percentage of oversize particles below which correction for oversize need not be applied. If no minimum percentage is specified, correction shall be applied to samples with more than five percent by weight of oversize particles.

1.5. If the specified oversized maximum tolerances are exceeded, other methods of compaction control must be used.

Note 1—One method for the design and control of the compaction of such soils is to use a test fill to determine the required degree of compaction and a method to obtain that compaction. Then use a method specification to control the compaction by specifying the type and size of compaction equipment, the lift thickness and the number of passes.

1.6. 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 R 11.

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

2. REFERENCED DOCUMENTS

2.1. *AASHTO Standards:*

- M 92, Wire-Cloth Sieves for Testing Purposes
- M 231, Weighing Devices Used in the Testing of Materials
- R 11, Indicating Which Places of Figures Are to Be Considered Significant in Specified Limiting Values
- T 19/T 19M, Bulk Density ("Unit Weight") and Voids in Aggregate
- T 224, Correction for Coarse Particles in the Soil Compaction Test
- T 265, Laboratory Determination of Moisture Content of Soils

2.2. *ASTM Standards*

- D 2168, Calibration of Laboratory Mechanical-Rammer Soil Compactors

3. APPARATUS

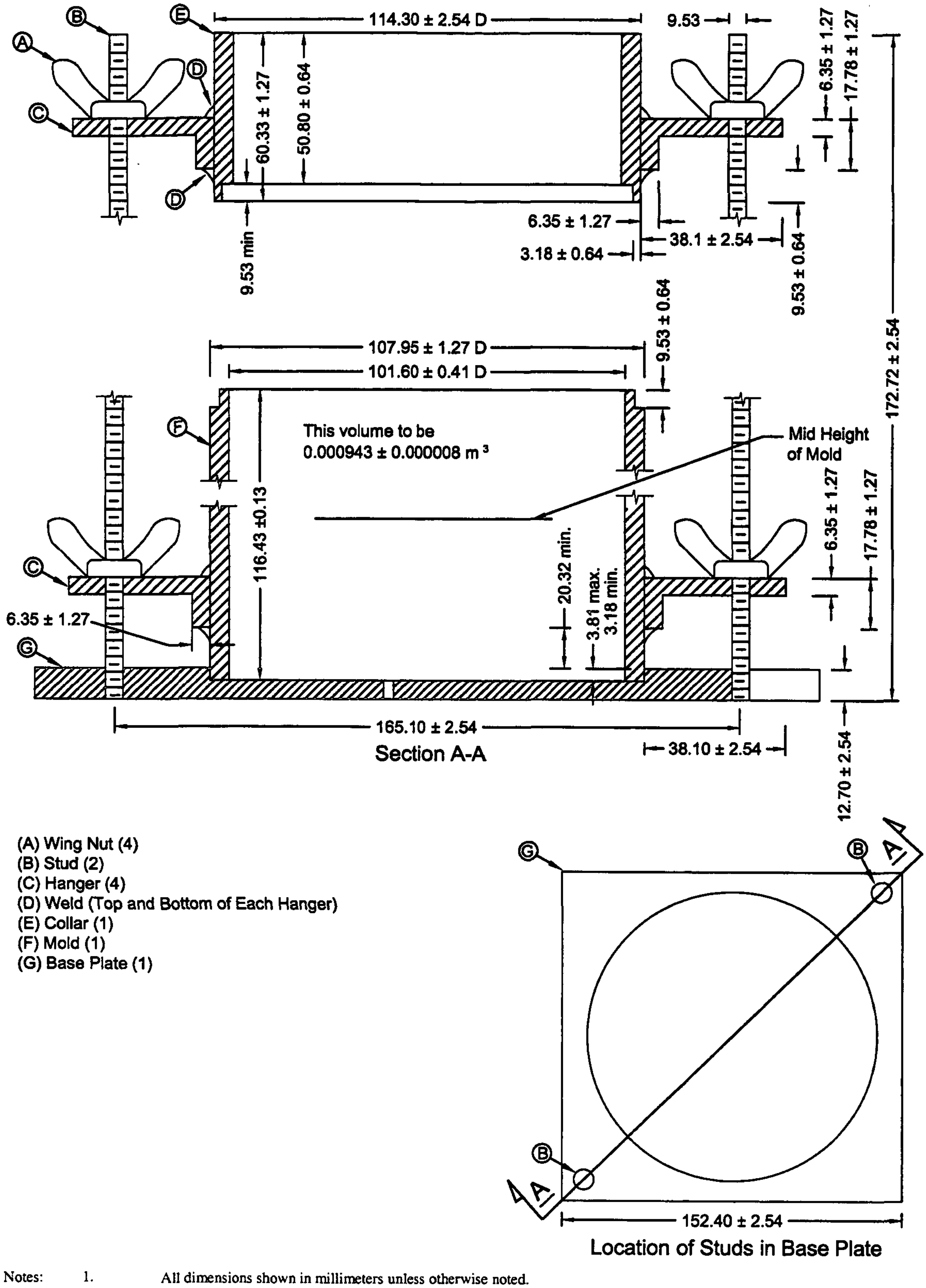
3.1. *Molds*—The molds shall be solid-wall, metal cylinders manufactured with dimensions and capacities shown in Sections 3.1.1 and 3.1.2. They shall have a detachable collar assembly approximately 60 mm ($2^3/_8$ in.) in height, to permit preparation of compacted specimens of soil-water mixtures of the desired height and volume. The mold and collar assembly shall be so constructed that it can be fastened firmly to a detachable base plate made of the same material (Note 2). The base plate shall be plane to 0.13 mm (0.005 in.) as shown in Figures 1 and 2.

Note 2—Alternate types of molds with capacities as stipulated herein may be used, provided the test results are correlated with those of the solid-wall mold on several soil types and the same moisture-density results are obtained. Records of such correlation shall be maintained and readily available for inspection, when alternate types of molds are used.

3.1.1. A 101.6-mm (4-in.) mold having a capacity of 0.000943 ± 0.000008 m^3 ($^1/_{30}$ (0.0333) ± 0.0003 cu ft) with an internal diameter of 101.60 ± 0.41 mm (4.000 ± 0.016 in.) and a height of 116.43 ± 0.13 mm (4.584 ± 0.005 in.) (Figure 1).

3.1.2. A 152.4-mm (6-in.) mold having a capacity of 0.002124 ± 0.000021 m^3 (1/13.33 (0.07500) ± 0.00075 cu ft) with an internal diameter of 152.40 ± 0.66 mm (6.000 ± 0.026 in.) and a height of 116.43 ± 0.13 mm (4.584 ± 0.005 in.) (Figure 2).

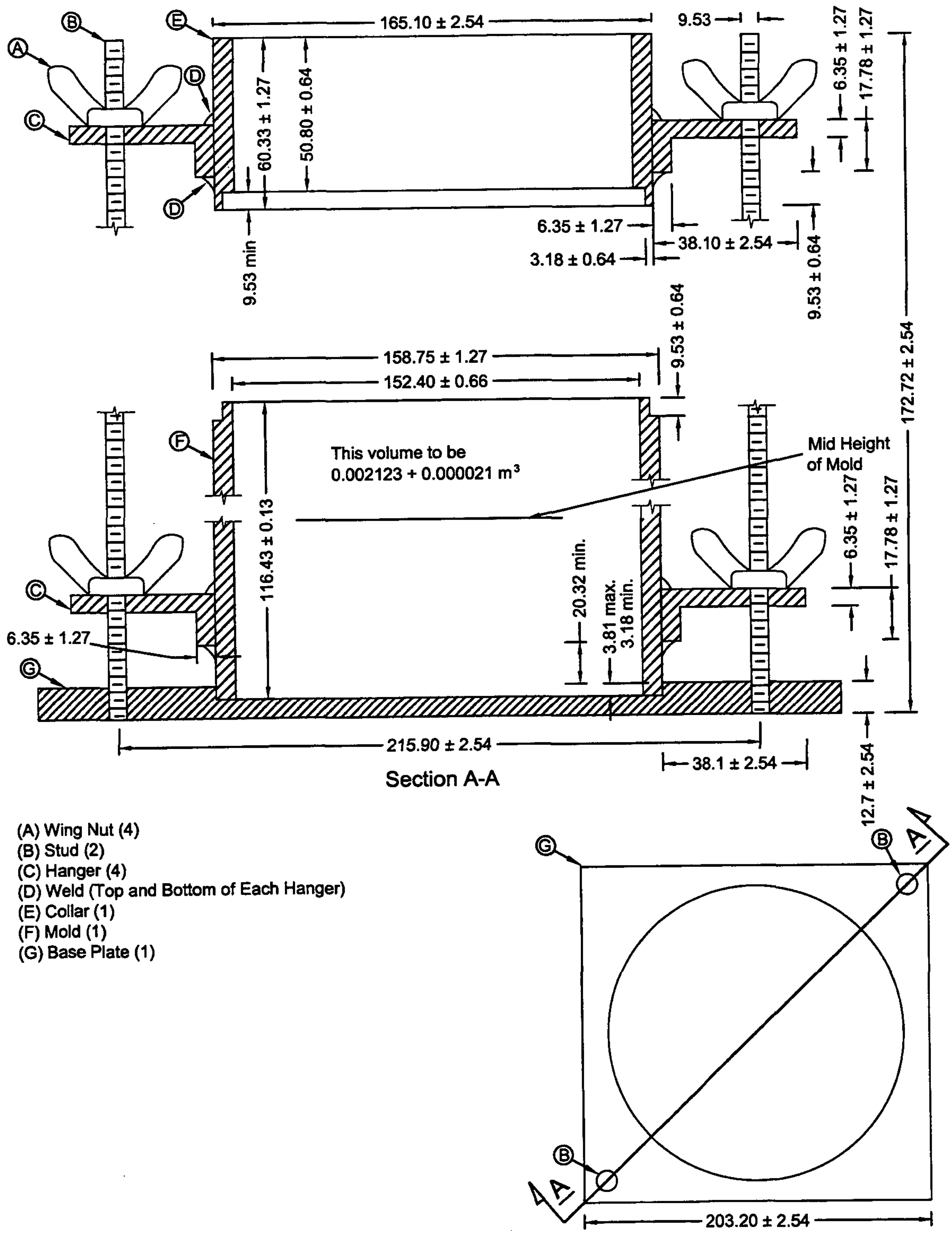
3.1.3. *Molds Out of Tolerance Due to Use*—A mold that fails to meet manufacturing tolerances after continued service may remain in use provided those tolerances are not exceeded by more than 50 percent; and the volume of the mold, calibrated in accordance with T 19/T 19M, is used in the calculations.



Notes:

1. All dimensions shown in millimeters unless otherwise noted.
2. Hanger on the mold portion only cannot extend above the midheight line.
3. Figure 1 is to be used for all compaction molds purchased after the publication o f the 21st edition (HM-21).
4. Not to scale.

Figure 1—Cylindrical Mold and Base Plate (101.60-mm Mold)



Notes:
1. All dimensions shown in millimeters unless otherwise noted.
2. Hanger on the mold portion only cannot extend above the midheight line.
3. Figure 2 is to be used for all compaction molds purchased after the publication of the 21st edition (HM-21).
4. Not to scale.

Figure 2— Cylindrical Mold and Base Plate (152.40-mm Mold)

Dimensional Equivalents for Figure 1

mm	in.	mm	in.	mm	in.
3.18 ± 0.64	0.125 ± 0.025	17.78 ± 1.27	0.700 ± 0.050	107.95 ± 1.27	4.250 ± 0.050
3.81	0.150	20.32	0.800	114.30 ± 2.54	4.300 ± 0.100
6.35 ±1.27	0.250 ± 0.050	38.10 ± 2.54	1.500 ± 0.100	116.43 ± 0.13	4.384 ± 0.005
7.62	0.300	50.80 ± 0.64	2.000 ± 0.025	152.40 ± 2.54	6.000 ± 0.100
9.53 ± 0.64	0.375 ± 0.025	60.33 ± 1.27	2.375 ± 0.050	165.10 ± 2.54	6.500 ± 0.100
12.70 ± 2.54	0.500 ± 0.100	101.60 ± 0.41	4.000 ± 0.016	172.72 ± 2.54	6.800 ± 0.100

0.000943 ± 0.00008 m^3 1/30 ±0.0003 ft^3

Dimensional Equivalents for Figure 2

mm	in.	mm	in.	mm	in.
3.18 ± 0.64	0.125 ± 0.025	17.78 ± 1.27	0.700 ± 0.050	132.40 ± 0.66	6.000 ± 0.026
3.81	0.150	20.32	0.800	132.75 ± 1.27	6.250 ± 0.050
6.35 ±1.27	0.250 ± 0.050	38.10 ± 2.54	1.500 ± 0.100	165.10 ± 2.54	6.500 ± 0.100
7.62	0.300	50.80 ± 0.64	2.000 ± 0.025	172.72 ± 2.54	6.800 ± 0.100
9.53 ± 0.64	0.375 ± 0.025	60.33 ± 1.27	2.375 ± 0.050	203.23 ± 2.54	8.000 ± 0.100
12.70 ± 2.54	0.500 ± 0.100	116.43 ± 0.13	4.384 ± 0.005	215.90 ± 2.54	8.500 ± 0.100

0.000943 ± 0.00008 m^3 1/30 ±0.0003 ft^3

3.2. *Rammer*:

1.1.1. *Manually Operated*—Metal rammer with a mass of 4.536 ± 0.009 kg (10.00 ± 0.02 lb) (Note 3), and having a flat circular face of 50.80 mm (2.000 in.) diameter with a manufacturing tolerance of ±0.25 mm (±0.01 in.). The in-service diameter of the flat circular face shall be not less than 50.42 mm (1.985 in.). The rammer shall be equipped with a suitable guide sleeve to control the height of drop to a free fall 457 ± 2 mm (18.00 ± 0.06 in.) above the elevation of the soil. The guide sleeve shall have at least four vent holes, no smaller than 9.5-mm ($^3/_8$-in.) diameter, spaced approximately 90 degrees (1.57 rad) apart and approximately 19 mm ($^3/_4$ in.) from each end; and shall provide sufficient clearance so the free fall of the rammer shaft and head is unrestricted.

Note 3—The term *weight* is temporarily used in this standard because of established trade usage. The word is used to mean both force and mass and care must be taken to determine which is meant in each case (SI unit for force = newton and for mass = kilogram).

3.2.2. *Mechanically Operated*—A metal rammer which is equipped with a device to control the height of drop to a free fall of 457 ± 2 mm (18.00 ± 0.06 in.) above the elevation of the soil, and uniformly distributes such drops to the soil surface (Note 4). The rammer shall have a mass of 4.536 ± 0.009 kg (10.00 ± 0.02 lb) (Note 2), and have a flat circular face of 50.80 mm (2.000 in.) diameter with a manufacturing tolerance of ±0.25 mm (±0.01 in.). The in-service diameter of the flat circular face shall be not less than 50.42 mm (1.985 in.). The mechanical rammer shall be calibrated by ASTM D 2168 to give the same moisture-density results as with a manually operated rammer.

Note 4—The mechanical rammer apparatus shall be calibrated with several soil types and the mass of the rammer adjusted, if necessary, to give the same moisture-density results as with the manually operated rammer.

It may be impractical to adjust the mechanical apparatus so the free fall is 457-mm (18 in.) each time the rammer is dropped, as with the manually operated rammer. To make the adjustment of free fall, the portion of loose soil to receive the initial blow should be slightly compressed with the rammer to establish the point of impact from which the 457-mm (18-in.) drop is determined; subsequent blows on the layer of soil being compacted may all be applied by dropping the rammer from a height of 457 mm (18 in.) above the initial-setting elevation, or when the mechanical apparatus is designed with a height adjustment for each blow, all subsequent blows should have a rammer free fall of 457 mm (18 in.) measured from the elevation of the soil as compacted by the previous blow. A more detailed calibration procedure for laboratory mechanical rammer soil compactors can be found in ASTM D 2168.

3.2.3. *Rammer Face*—The circular face rammer shall be used but a sector face rammer may be used as an alternative provided the report shall indicate type of face used other than the 50.8-mm (2-in.) circular face and it shall have an area equal to that of the circular face rammer.

3.3. *Sample Extruder (For Solid-Walled Molds Only)*—A jack, lever, frame, or other device adapted for the purpose of extruding compacted specimen from the mold.

3.4. *Balances and Scales*—A balance or scale conforming to the requirements of M 231, Class G 20. Also, a balance conforming to the requirements of M 231, Class G 2.

Note 5—The capacity of the metric balance or scale should be approximately 11.5 kg when used to determine the mass of the 152-mm (6-in.) mold and compacted, moist soil; however, when the 102-mm (4-in.) mold is used, a balance or scale of lesser capacity than 11.5 kg may be used, if the sensitivity and readability is 5 g.

3.5. *Drying Oven*—A thermostatically controlled drying oven capable of maintaining a temperature of 110 ± 5°C (230 ± 9°F) for drying moisture samples.

3.6. *Straightedge*—A hardened steel straightedge at least 250 mm (10 in.) in length. It shall have one beveled edge, and at least one longitudinal surface (used for final trimming) shall be plane within 0.1 percent of the length within the portion used for trimming the soil (Note 6).

Note 6—The beveled edge may be used for final trimming if the edge is true within a tolerance of 0.25 mm per 250 mm (0.1 percent) of length; however, with continued use, the cutting edge may become excessively worn and not suitable for trimming the soil to the level of the mold. The straightedge should not be so flexible that trimming the soil surface with the cutting edge will cause a concave soil surface.

3.7. *Sieves*—50-, 19.0-, and 4.75-mm sieves conforming to the requirements of M 92.

3.8. *Mixing Tools*—Miscellaneous tools such as mixing pan, spoon, trowel, spatula, etc., or a suitable mechanical device for thoroughly mixing the sample of soil with increments of water.

3.9. *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.

METHOD A

4. SAMPLE

4.1. If the soil sample is damp when received from the field, dry it until it becomes friable under a trowel. Drying may be in air or by use of a drying apparatus which is maintained at a temperature not exceeding 60°C (140°F). Then thoroughly break up the aggregation in such a manner as to avoid reducing the natural size of individual particles.

4.2. Sieve an adequate quantity of the representative pulverized soil over the 4.75-mm sieve. Discard the coarse material, if any, retained on the 4.75-mm sieve.

4.3. Select a representative sample, with a mass of approximately 3 kg (7 lb) or more, of the soil prepared as described in Sections 4.1 and 4.2.

Note 7—When developing a compaction 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 sample from the mixing bowl may be preferred in order to determine the amount of moisture available for compaction.

5. PROCEDURE

5.1. Thoroughly mix the selected representative sample with sufficient water to dampen it to approximately four percentage points below optimum moisture content.

5.2. Form a specimen by compacting the prepared soil in the 101.60-mm (4-in.) mold (with collar attached) in five approximately equal layers to give a total compacted depth of about 125 mm (5 in.). Prior to compaction, place the loose soil into the mold and spread into a layer of uniform thickness. Lightly tamp the soil prior to compaction until it is not in a loose or fluffy state, using either the manual compaction rammer or similar device having a face diameter of approximately 50 mm (2 in.). Following compaction of each of the first four layers, any soil adjacent to the mold walls that has not been compacted or extends above the compacted surface shall be trimmed using a knife or other suitable device, and be evenly distributed on top of the layer. Compact each layer by 25 uniformly distributed blows from the rammer dropping free from a height of 457 mm (18 in.) above the elevation of the soil when a sleeve-type rammer is used, or from 457 mm (18 in.) above the approximate elevation of the soil as compacted by the previous blow when a stationary mounted type of rammer is used (Note 8).

Note 8—Each of the following has been found to be a satisfactory base on which to rest the mold during compaction of the soil: A block of concrete, with a mass of not less than 90 kg (200 lb), supported by a relatively stable foundation; a sound concrete floor; and for field application, such surfaces as found in concrete box culverts, bridges, and pavements.

5.2.1. Following compaction, remove the extension collar, carefully trim the compacted soil even with the top of the mold by means of the straightedge, and determine the mass of the mold and moist soil in kilograms to the nearest five grams, or determine the mass in pounds to the nearest 0.01 pounds. For molds conforming to the tolerances given in Section 3.1.1 and masses recorded in kilograms, multiply the mass of the compacted specimen and the mold, minus the mass of the mold, by 1060, and record the result as the wet density, W_1, in kilograms per cubic meter, of compacted soil. For molds conforming to tolerances given in Section 3.1.1 and masses recorded in pounds, multiply the mass of the compacted specimen and the mold, minus the mass of the mold, by 30, and record the result as the wet density, W_1, in pounds per cubic foot of completed soil. For used molds out of tolerance by not more than 50 percent (Section 3.1.3), use the factor for the mold as determined in accordance with T 19/T 19M. During compaction, the mold shall rest firmly on a dense, uniform, rigid, and stable foundation or base. This base shall remain stationary during the compaction process (Note 8).

5.3. Remove the material from the mold and slice vertically through the center. Take a representative sample of the material from one of the cut faces, determine the mass immediately and dry in accordance with T 265, Laboratory Determination of Moisture Content of Soils, to determine the moisture content, and record the results.

5.4. Thoroughly break up the remaining portion of the molded specimen until it will pass a 4.75-mm sieve as judged by eye, and add to the remaining portion of the sample being tested. Add water in sufficient amount to increase the moisture content of the soil by approximately one to two percentage points (water content increments should not exceed 2.5 percent, except when heavy clay soils or organic soils exhibiting flat elongated curves are encountered, the water content increments may be increased to a maximum of four percent), and repeat the above procedure for each increment of water added. Continue this series of determinations until there is either a decrease or no change in the wet unit mass per cubic meter (cubic foot) of the compacted soil (Note 9).

Note 9—This procedure has been found satisfactory in most cases. However, in instances where the soil material is fragile in character and will reduce significantly in grain size due to repeated compaction, and in cases where the soil is heavy-textured, clayey material into which it is difficult to incorporate water, a separate and new sample shall be used in each compaction test. In these cases, separate samples shall be thoroughly mixed with amounts of water sufficient to cause the moisture contents of the samples to vary by approximately two percentage points. The moisture contents selected shall bracket the optimum moisture content, thus providing samples which, when compacted, will increase in mass to the maximum density and then decrease in mass. The samples of soil-water mixtures shall be placed in covered containers and allowed to stand for not less than 12 hours before making the moisture–density test.

5.4.1. In instances where the soil material is fragile in character and will be reduced significantly in grain size by repeated compaction, a separate and new sample shall be used in each compaction test.

METHOD B

6. SAMPLE

6.1. Select the representative sample in accordance with Section 4.3 except that it shall have a mass of approximately 7 kg (16 lb).

7. PROCEDURE

7.1. Follow the same procedure as described for Method A in Section 5, except for the following: Form a specimen by compacting the prepared soil in the 152.40-mm (6-in.) mold (with collar attached) in five approximately equal layers to give a total compacted depth of about 125 mm (5 in.), each layer being compacted by 56 uniformly distributed blows from the rammer. For molds conforming to tolerances given in Section 3.1.2 and masses recorded in kilograms, multiply the mass of the compacted specimen and the mold, minus the mass of the mold by 471, and record the result as the wet density, W_1, in kilograms per cubic meter, of the compacted soil. For molds conforming to tolerances in Section 3.1.2, and masses recorded in pounds, multiply the mass of the compacted specimen and the mold, minus the mass of the mold, by 13.33 and record the result as the wet density, W_1, in pounds per cubic foot, of the compacted soil. For used molds out of tolerance by not more than 50 percent (Section 3.1.3), use the factor for the mold as determined in accordance with T 19/T 19M.

METHOD C

8. SAMPLE

8.1. If the soil sample is damp when received from the field, dry it until it becomes friable under a trowel. Drying may be in air or by use of a drying apparatus which is maintained at a temperature not exceeding 60°C (140°F). Then, thoroughly break up the aggregations in such a manner as to avoid reducing the natural size of individual particles.

8.2. Sieve an adequate quantity of the representative pulverized soil over the 19.0-mm sieve. Discard the coarse material, if any, retained on the 19.0-mm sieve (Note 10).

Note 10—The use of replacement method previously specified, where the oversized particles are replaced with finer particles, to maintain the same percentage of coarse material, is not considered appropriate to compute the maximum density.

8.3. Select a representative sample, with a mass of approximately 5 kg (12 lb), or more, of the soil prepared as described in Sections 8.1 and 8.2.

9. PROCEDURE

9.1. Thoroughly mix the selected representative sample with sufficient water to dampen it to approximately four percentage points below optimum moisture content.

9.2. Form a specimen by compacting the prepared soil in the 101.60-mm (4-in.) mold (with collar attached) in five approximately equal layers to give a total compacted depth of about 125 mm (5 in.). Prior to compaction, place the loose soil into the mold and spread into a layer of uniform thickness. Lightly tamp the soil prior to compaction until it is not in a loose or fluffy state, using either the manual compaction rammer or similar device having a face diameter of approximately 50 mm (2 in.). Following compaction of each of the first four layers, any soil adjacent to the mold walls that has not been compacted or extends above the compacted surface shall be trimmed using a knife or other suitable device, and be evenly distributed on top of the layer. Compact each layer by 25 uniformly distributed blows from a rammer dropping free from a height of 457 mm (18 in.) above the elevation of the soil when a sleeve-type rammer is used, or from 457 mm (18 in.) above the approximate elevation of each finely compacted layer when a stationary mounted type of rammer is used. During compaction, the mold shall rest firmly on a dense, uniform, rigid, and stable foundation or base. This base shall remain stationary during the compaction process. (Note 8).

9.2.1. Following compaction, remove the extension collar, carefully trim the compacted soil even with the top of the mold by means of the straightedge, and determine the mass of the mold and moist soil in kilograms to the nearest 5 grams, or determine the mass in pounds to the nearest 0.01 pounds. For molds conforming to the tolerances given in Section 3.1.1 and masses recorded in kilograms, multiply the mass of the compacted specimen and the mold, minus the mass of the mold, by 1060, and record the result as the wet density, W_1, in kilograms per cubic meter, of compacted soil. For molds conforming to the tolerances given in Section 3.1.1 and masses recorded in pounds, multiply the mass of the compacted specimen and the mold, minus the mass of the mold, by 30, and record the result as the wet density, W_1, in pounds per cubic foot, of compacted soil. For used molds out of tolerance by not more than 50 percent (Section 3.1.3), use the factor for the mold as determined in accordance with T 19/T 19M.

9.3. Remove the material from the mold and slice vertically through the center. Take a representative sample of the material from one of the cut faces, determine the mass immediately and dry in accordance with T 265, and record the results.

9.4. Thoroughly break up the remainder of the material until it will pass a 19.0-mm sieve and 90 percent of the soil aggregations will pass a 4.75-mm sieve as judged by eye, and add to the remaining portion of the sample being tested. Add water in sufficient amounts to increase the moisture content of the soil sample by one or two percentage points, and repeat the above procedure for each increment of water added. Continue this series of determinations until there is either a decrease or no change in the wet unit mass, W_1, per cubic meter (cubic foot) of the compacted soil (Note 9).

METHOD D

10. SAMPLE

10.1. Select the representative sample in accordance with Section 8.3, except that it shall have a mass of approximately 11 kg (25 lb).

11. PROCEDURE

11.1. Follow the same procedure as described for Method C in Section 9, except for the following: Form a specimen by compacting the prepared soil in the 152.40-mm (6-in.) mold (with collar attached) in five approximately equal layers to give a total compacted depth of about 127 mm (5 in.), each layer being compacted by 56 uniformly distributed blows from the rammer. For molds conforming to tolerances given in Section 3.1.2 and masses recorded in kilograms, multiply the mass of the compacted specimen and the mold, minus the mass of the mold, by 471, and record the result as the wet density, W_1, in kilograms per cubic meter, of compacted soil. For molds conforming to tolerances in Section 3.1.2, and masses recorded in pounds, multiply the mass of the compacted specimen and the mold, minus the mass of the mold, by 13.33, and record the result as the wet density, W_1, in pounds per cubic foot of the compacted soil. For used molds out of tolerance by not more than 50 percent (Section 3.1.3), use the factor for the mold as determined in accordance with T 19/T 19M.

CALCULATIONS AND REPORT

12. CALCULATIONS

12.1. Calculate the moisture content and the dry mass of soil as compacted for each trial as follows:

$$w = \frac{A-B}{B-C} \times 100 \qquad (1)$$

and

$$W = \frac{W_1}{w+100} \times 100 \qquad (2)$$

where:

w = percentage of moisture in the specimen,

A = mass of the container and wet soil,

B = mass of the container and dry soil,

C = mass of the container,

W = dry density in kilograms per cubic meter or pounds per cubic foot of compacted soil, and

W_1 = wet density in kilograms per cubic meter or pounds per cubic foot of compacted soil.

13. MOISTURE–DENSITY RELATIONSHIP

13.1. The calculations in Section 12.1 shall be made to determine the moisture content and corresponding oven-dry density (unit mass) in kilograms per cubic meter or pounds per cubic foot for each of the compacted samples. The oven-dry densities of the soil shall be plotted as ordinates and corresponding moisture contents as abscissae.

13.2. *Optimum Moisture Content*—When the densities and corresponding moisture contents for the soil have been determined and plotted as indicated in Section 13.1, it will be found that by connecting the plotted points with a smooth line, a curve is produced. The moisture content corresponding to the peak of the curve shall be termed the "optimum moisture content" of the soil under the above compaction.

13.3. *Maximum Density*—The oven-dry density in kilograms per cubic meter or pounds per cubic foot of the soil at optimum moisture content shall be termed "maximum density" under the above compaction.

14. REPORT

14.1. The report shall include the following:

14.1.1. The method used (Method A, B, C, or D);

14.1.2. The optimum moisture content, as a percentage, to the nearest whole number;

14.1.3. The maximum density in kilograms per cubic meter to the nearest 10 kg/m^3 or in pounds per cubic foot, to the nearest whole number;

14.1.4. In Methods C and D, whether the 19.0-mm material was removed or replaced; and

14.1.5. Type of face if other than 50.8-mm (2-in.) circular.