MARYLAND DEPARTMENT OF TRANSPORTATION

STATE HIGHWAY ADMINISTRATION

Office of Materials Technology
Soils and Aggregate Field Technician
Study Guide

Soils and Aggregate Technology Division
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Table of Contents

PART 1

Introduction

1.1 Introduction and overview of soils school

1.1.1 Licensing, audits, and renewal

- Certificate is valid for five years.
- Minimum three independent assurance audits for renewal.
- Mid-Atlantic Region Technician Certification Program (MARTCP) website: https://roads.maryland.gov/mdotsha/pages/Index.aspx?PageId=53

1.2 Introduction to soils and compaction

1.2.1 Types of soils

- Inorganic
- Organic

1.2.2 Sieve and Grain Sizes

- Cobbles and Boulders – stone or gravel particles larger than 3".
- Gravel- rounded particles of rock that will pass 3" sieve and be retained on #10 sieve.
- Stone – crushed or naturally angular particles of rock that will pass 3" sieve and be retained on #10 sieve.
- Sand, sieve size:
    - Coarse – passing #10 sieve and be retained on #40 sieve.
    - Fine - passing #40 sieve and be retained on #200 sieve.
- Fines (silt and clay) – passing #200 sieve.

1.2.3 Soil classification systems

- **USCS (United Soil Classification System)**
- It is an all-purpose system. USCS does not attempt to rank soils from good to bad, because specific soils may be excellent for some purposes and poor for others. SHA OMT primarily uses USCS for **clay core** soil properties determination. Table 1.1 and Figure 1.1 show USCS.

Table 1.1 Unified Soil Classification System

Unified Soil Classification System					
Major Division		Group Symbol	Laboratory Classification Criteria		Soil Description
			Percentage finer than 0.075 mm (No.200) sieve	Supplementary Requirements	
Coarse-grained (over 50% by weight retained on the 0.075 mm(No 200) sieve)	Gravelly Soils (over half of coarse fraction retained on #4 sieve)	GW	0 to 5	Cu greater than 4; Cc between 1 and 3	Well- graded gravels, sandy gravels
		GP	0 to 5	Not meeting above gradation requirements for GW	Gap-graded or uniform gravels, sandy gravels
		GM	12 or more	PI less than 4 or below A-line	Silty gravel, silty sandy gravels
		GC	12 or more	PI greater than 7 and above A-line	Clayey gravels, clayey sandy gravels
	Sandy soils (over half of coarse fraction passing on #4 sieve)	SW	0 to 5	Cu greater than 4; Cc between 1 and 3	Well-graded, gravelly sands
		SP	0 to 5	Not meeting above gradation requirements for SW	Gap-graded or uniform sands, gravelly sands
		SM	12 or more	PI less than 4 or below A-line	Silty sands, silty gravelly sands
		SC	12 or more	PI greater than 7 and above A-line	Clayey sands, clayey gravelly sands
Fine-grained (over 50% by weight retained on the 0.075 mm(No 200) sieve)	Low compressibility (liquid limit less than 50)	ML	Plasticity Chart		Silts, very fine sands, silty or clayey fine sands, micaceous silts
		CL	Plasticity Chart		Low plasticity clays, sandy or silty clays
		OL	Plasticity Chart, organic odor or color		Organic silts and clays of low plasticity
	High compressibility (liquid limit less than 50)	MH	Plasticity Chart		Micaceous silts, diatomaceous silts, volcanic ash
		CH	Plasticity Chart		Highly plastic clays and sandy clays
		OH	Plasticity Chart, organic odor or color		Organic silts and clays of high plasticity
Soils with fibrous organic matter		Pt	Fibrous organic matter; will char, burn or glow		Peat, sandy peats and clayey peat

* Note: For soils having 5 to 12 percent passing the 0.075 mm (No. 200) sieve, use dual symbol (e.g GW-GC)

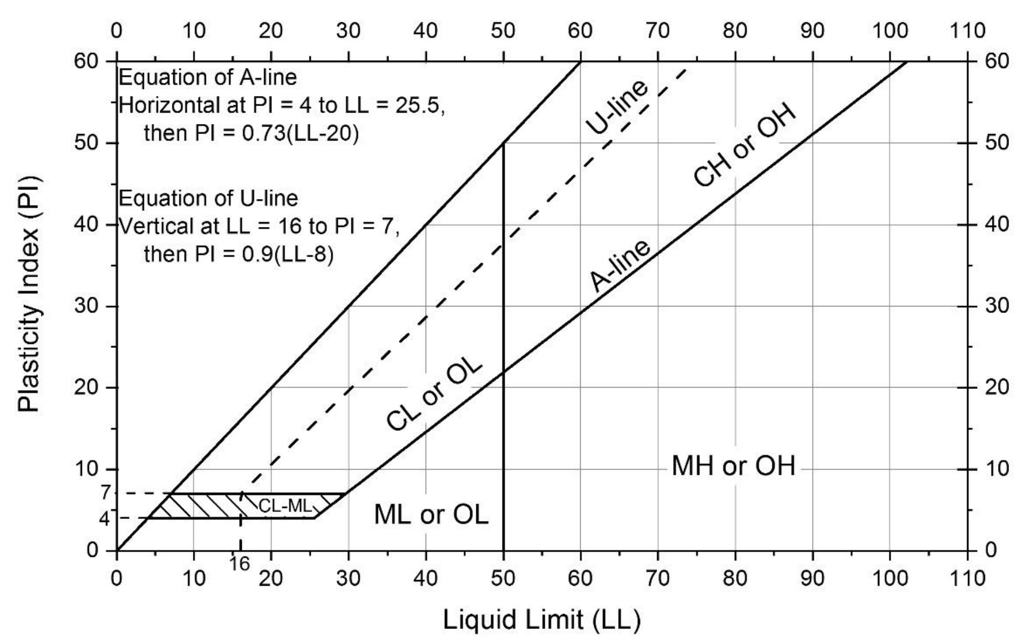

Figure 1.1 Plasticity Chart

- **USDA (U.S. Department of Agriculture) classification system**
  - Developed for agricultural purposes.
  - OMT SHA uses USDA for subsoil, topsoil, and BSM. Figure 1.2 shows USDA classification system.

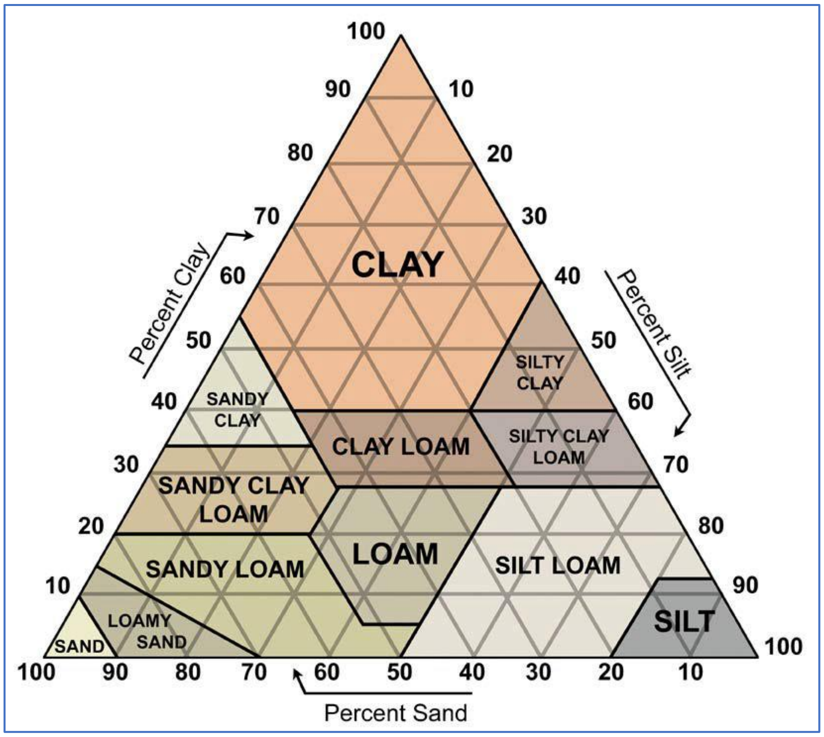

Figure 1.1 USDA Classification System

- **AASHTO (American Association of State Highway and Transportation Officials)**
  - It rates soils according to their suitability for support of roadway pavements.
  - SHA OMT classifies borrow soils based on AASHTO classification system (Table 1.2).

Table 1.2 AASHTO Classification System

AASHTO Classification of Soils and Soil-Aggregate Mixtures											
General Classification	Granular Materials (35 percent or Less Passing 0.075 mm (No. 200) Sieve)							Silt-Clay Materials (More than 35 Percent Passing 0.075 mm (No. 200Sieve))			
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				
Sieve analysis, percent passing											
2.00 mm (No. 10)	50 max	-	-	-	-	-	-	-	-	-	-
0.425 mm (No. 40)	30 max	50 max	51 min	-	-	-	-	-	-	-	-
0.075 mm (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 0.425 mm (No. 40)											
Liquid limit	-	-	40 max	41 max	40 max	41 min	41 min	40 max	41 min	40 max	41 min
Plasticity Index	6 max	N.P.	10 max	10 max	11 min	11 min	11 min	10 max	10 max	11 min	11 min
Usual types of significant constituent materials	Stone fragments, gravel, and sand	Fine Sand	Silty or clayey gravel and sand					Silty soils		Clayey soils	
General Rating as subgrade	Excellent to Good							Fair to Poor			

1.3 Compaction of Soil and Mixture of Soil and Aggregates

1.3.1 Definition of Compaction

Compaction is a process in which a stress (energy input) applied to soil expels the air from soil’s voids and creates the following changes in the materials:

- Increase of unit weight
- Decrease in permeability
- Decrease in compressibility
- Resistance to erosion

Moisture in soil and aggregates is extremely important for the proper compaction of these materials. The moisture plays the role of a lubricant between the particles and helps with their rearrangement in the process. The dryer the soil, the more resistant will be to compaction efforts. If the soil is too wet, the water will push the particles apart and will prevent their proper compaction. Each type of soils has its own optimum moisture content at which the soil will reach maximum dry density.

1.3.2 Percent Relative Compaction (percent compaction)

- Percent relative compaction is obtained from a field compaction test and compared to the laboratory proctor test. (See **5.4** for example)

$$RC,\% = \frac{D_{dry}}{D_{lab}} \times 100$$

where: RC, % = Percentage of relative compaction
D_{dry} = Dry density of tested material, lb./ft^3
D_{lab} = Laboratory maximum dry density lb./ft^3 per AASHTO T99 or T180

1.3.3 SHA Construction Specifications

As per MDOT SHA specifications, compaction requirements for embankment and subgrade are as follows:

- 1 ft below the top of subgrade, the compaction level shall meet at least 92 percent of the maximum dry density and +/- 2 percent of optimum moisture as per (T180).
- Top 1 ft of subgrade, the compaction level shall meet at least 97 percent of the maximum dry density and +/- 2 percent of optimum moisture as per (T180).

As per MDOT SHA specifications, compaction requirements for pavement base materials are as follows:

- Graded Aggregate Base – The compaction level shall meet 97 percent of maximum dry density and +/- 2 percent of optimum moisture as per (T180).
- Stabilized Graded Aggregate Base – The compaction level shall meet 95 percent of maximum dry density and +/- 2 percent of optimum moisture as per (T180).

Determine the in-place density as per MSMT 350 (AASHTO T 191) or MSMT 352 (AASHTO T 310). Compaction equipment used on-site is following:

- Sheepsfoot roller – best for compacting silty and clayey soils
- Smooth steel drum vibratory roller – good for sand and gravel compaction
- Trench roller, plate tamper, other

1.4 Density, %MC, Dry / Wet Density Relation, and Optimum Moisture:

Maximum Dry Density and optimum moisture content are obtained through a Proctor test (AASHTO T99 or T180)

1.4.1 Density:

Density is defined as mass (weight) divided by volume.

$$D = \frac{W}{V}.$$

Where: D = Density, lb./ft^3
W = weight of soil sample
V = volume of soil sample

The more closely pressed together the individual particles of a quantity of material are, the denser it is. Soil and aggregate densification is obtained by the expelling the air between the material particles. MDOT SHA specification will require that the field earthwork be compacted to a specified percent of a target density called maximum density. The nuclear gauge and sand cone apparatus are two devices that are used to determine if the earthwork in the field has met this requirement (in-place density). To determine the dry density of a soil in-place, it is necessary to also determine the moisture content of the soil.

1.4.2 Percent Moisture Content:

Moisture Content is an amount of moisture present in a material. Calculate the moisture content for each compacted sample by dividing the water content (loss between wet mass and dry mass of moisture sample) by the dry mass of the sample and multiplying by 100 (see 5.3 for example calculation).

$$\boldsymbol{w}\% = \frac{\boldsymbol{W}_{wet} - \boldsymbol{W}_{dry}}{\boldsymbol{W}_{dry}} * 100$$

Where: $w\%$ = percent moisture,
W_{wet} = weight of wet aggregate and container (g or lb.),
W_{dry}= weight of dry aggregate and container (g or lb.),

1.4.3 Dry Density & Wet Density Relations:

The following formula is for finding the dry density of a soil sample at its current moisture present (see 5.4 for example calculation)

$$D_{dry} = \frac{D_{wet}}{1 + (\frac{w\%}{100})}$$

Where: D_{dry} = dry density of material lb/ft^3
D_{wet} = wet density of material, lb/ft^3
w = percentage moisture content (%)

1.4.4 Optimum Moisture Content (OMC):

Optimum moisture is the percentage moisture when the material has reached its maximum dry density. Any more or any less moisture in the material would result in a lower dry density. Maximum Dry Density (MDD) of a material corresponds to the peak of the moisture density curve where the density of the material reaches its maximum at optimum moisture content.

1.5 Measurement Accuracy and Rounding Procedure

1.5.1 Significant figure recording for different measurements:

	UNITS
• Moistures to the Tenth = .1	gram
• All Density readings to the Tenth = .1	PCF
• All Weight readings to the Hundredth = .01	lb.
• All Volumes to the Ten Thousandths = .0001	cu. Ft.

1.5.2 Rounding procedure

This method addresses rounding-off of numbers from test results and calculations.

If the number following the last number to be retained is less than 5, the last number to be retained is left unchanged and the numbers(s) following the last number to be retained is/are discarded.

- Example: Round 1.43 to the tenth = 1.4

If the number following the last number to be retained is larger than 5, increase the last number to be retained by 1 and discard the number(s) following the last number to be retained.

- Example: Round 2.68 to the tenth = 2.7

If the number following the last number to be retained is 5, and there are no numbers beyond 5 or only zeros, the last number to be retained is increased by 1 if odd, or left unchanged if even, and the number(s) following the last number to be retained is/are discarded.

- Example: Round 3.5 to a whole number = 4
- Example: Round 6.650 to the tenth = 6.6

If the number(s) following the last number to be retained is 5 and there is/are number(s) following the 5, the last number to be retained is increased by one regardless of being odd or even. The number(s) following the last number to be retained is/are discarded.

- Example: Round 3.52 to a whole number = 4

1.6 OMT Forms

Forms	
27B	Soil Test Report
31	Compaction report for embankment and subgrade
34	Compaction report for GAB (Sand Cone test)
161	MSHA Nuclear D/M Compaction Report

PART 2

Moisture - Density Relations of Soils

AASHTO T 99, T 180 – Moisture-Density Relationship of Soils and Soil-Aggregate Mixture (Proctor Compaction Test)
MSMT 351 (AASHTO T272) - Moisture-Density Relationship of Soils and Soil-Aggregate Mixture (One Point Proctor Compaction Test)
MSMT 251 (AASHTO T 255) – Field Moisture Content Determination
FAMILY OF CURVES

2.1 AASHTO T 99/T 180 – Moisture-Density Relationship of Soils and Soil-Aggregate Mixture

2.1.1 Procedure methods

The step-by-step procedures for AASHTO T 99 and T 180 are essentially the same. The differences in the two procedures are indicated in Table 2.1.

Table 2.1 Moisture-Density Methods and Associated Mold Sizes

Moisture-Density Methods and Associated Mold Sizes				
	Method A	Method B	Method C	Method D
Mold Size	101.60 mm (4 in.)	152.40 mm (6 in.)	101.60 mm (4 in.)	152.40 mm (6 in.)
Material Size	Passing 4.75 mm (No. 4)	Passing 4.75 mm (No. 4)	Passing 19.0 mm (3/4 in.)	Passing 19.0 mm (3/4 in.)
Blows per Layer	25	56	25	56
Standard (T 99)	3 Layers using 2.495 kg (5.5 lb.) rammer, 305 mm (12 in.) drop			
Modified (T 180)	5 Layers using 4.536 kg (10 lb.) rammer, 457 mm (18 in.) drop			

2.1.2 Equipment

Before beginning any procedure, you must first assemble all the equipment you will need to perform the test. You will need the following equipment per AASHTO T 99/T 180 as shown in Figure 2.1 below and as indicated above.

- **Rammers:** The difference between the two procedures (standard and modified) is the mass and freefall of the rammer used to compact the soil or soil and aggregate mixture in the mold and the number of layers placed into the compaction mold for compaction.
  - Note: **Mechanical compacting ram**: If a mechanical compacting ram is used, it must be calibrated to produce results repeatable with the manual moisture density determination methods using ASTM method D2168.

- **Compaction (concrete) block**, with a mass not less than 90 kg (200 lb.)
- **Molds:** Depending on the method, either a 101.6 mm (4 in.) or a 152.4 mm (6 in.) mold, solid wall metal cylinder, with dimensions and capacities as shown in Table 2.1.
- **Scales and balances:** Meeting state requirements.
- **Oven, stove or other drying device:** Meeting state requirements.
- **Straightedge:** At least 250 mm (10 in.) length, made of hardened steel with one beveled edge. The straightedge is used to plane the surface of the soil even with the top of the mold. The straightedge should not be so flexible that it leaves a concave surface when trimming the soil from the top of the compacted sample.
- **Sieves:** 50.0 mm (2 in.), 19.0 mm (3/4 in.), and a 4.75 mm (No. 4) conforming to the requirements of AASHTO M92.
- **Mixing Tools:** Sample pans, spoons, scoops, trowels, used for mixing the sample with water.
- **Containers:** Corrosion resistant with close fitting lids to retain moisture content of prepared soil samples.
- **Graduated cylinders:** For adding water.

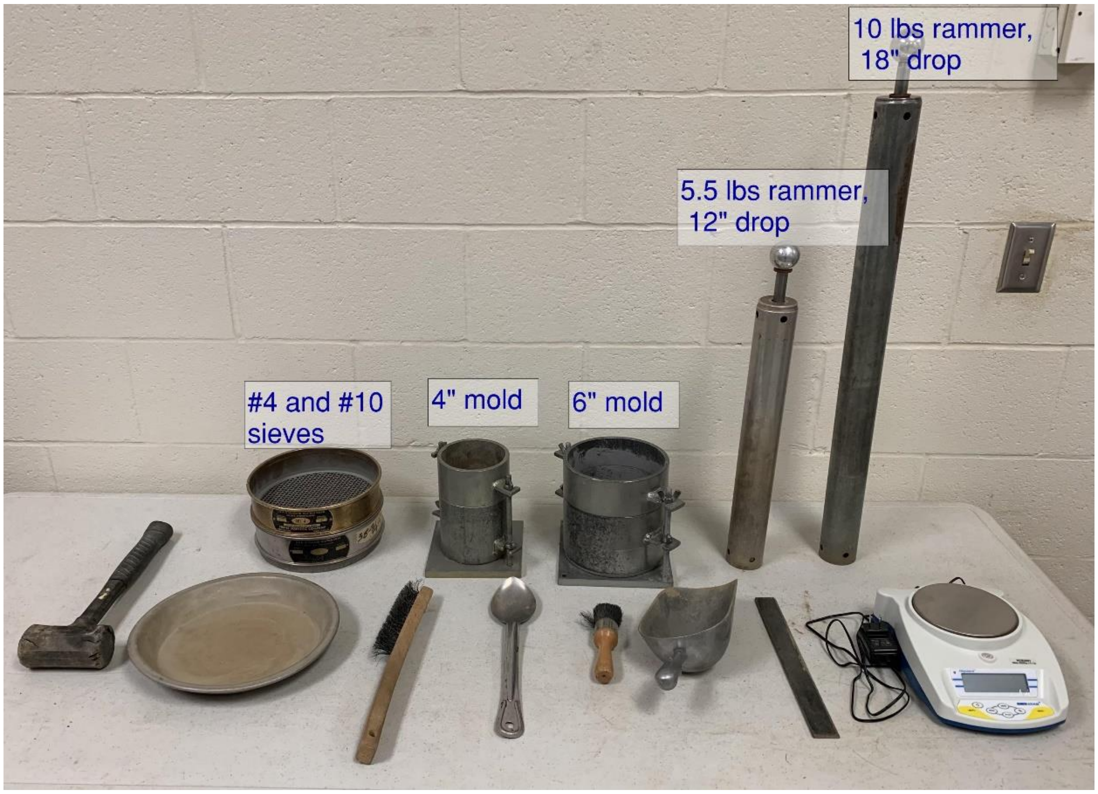

Figure 2.1 ASHTO T-99 and T-180 equipment

2.1.3 Sample preparation and procedure

Procedures for AASHTO T99 and T180 differ in the number of layers, rammer weight, and freefall height (see Table 2.1).
Select procedure (AASHTO T99 or T 180)
Select method to be used (A, B, C, or D) as per Table 2.1.

- If the sample is wet, dry it until it becomes friable under a trowel. Aggregations in a friable soil sample will break apart easily. Avoid breaking apart the natural particles when breaking up the soil aggregations.

- Sieve the sample over the specified sieve size to find for the moisture – density relationship method being performed. Discard any oversize material retained on the specified sieve.

- Thoroughly mix the remaining sample. Obtain at least enough material to fill the mold when compacted. There should be enough extra material for determination of moisture content and increase in density as more water is added.

NOTE: This method uses the same soil or soil-aggregate sample for each "point" on the density curve. If the soil or soil-aggregate mixture to be tested is a clayey material which will not easily mix with water, or where the soil material is fragile and will break apart from the repeated blows of the compaction rammer, it may be necessary to prepare individual portions for each density point. In most cases enough material should be sampled from the field to permit five individual "points" starting 4% to 8% below the anticipated optimum moisture content, and then each subsequent "point" increased by 2% moisture. Optimum moisture content should be clearly defined on the moisture-density curve. To achieve that, start by plotting the results from the moisture density test. Once the series of determination points indicate decrease or no change of the wet density perform one more determination. After all the points have been plotted, connect them to form a curve on which the maximum wet density value will indicate the optimum water content for that sample.

- Prepare the sample(s) and mix with water to produce the desired moisture content.
- **For example** - See Part 5 (5.2).

2.1.4 Typical Test Results

Typical maximum density and optimum moisture that can be expected as the result of a standard compaction test (AASHTO T 99) are given below (Table 2.2). A modified compaction test (AASHTO T 180) will yield 10 to 15 percent higher maximum densities and 20 to 30 percent lower optimum moisture than AASHTO T 99 due to the greater compactive effort used.

Table 2.2 Typical Values of Maximum Density and Optimum Moisture

Typical Values of Maximum Density and Optimum Moisture for Common Types of Soil (using AASHTO T 99)			
Unified Soil Classification	Soil Description	Range of Max. Densities (lb./ft^3)	Range of Optimum Moisture (%)
CH	Highly Plastic Clays	75-105	19-36
CL	Silty Clays	95-120	12-24
ML	Silts and Clayey Silts	95-120	12-24
SC	Clayey Sands	105-125	11-19
SM	Silty Sands	110-125	11-16
SP	Poorly graded Sands	100-120	12-21
SW	Well graded Sands	110-130	9-16
GC	Clayey Gravel w/sands	115-130	9-14
GP	Poorly graded gravels	115-125	11-14
GW	Well graded Gravels	125-135	8-11

2.1.5 Common Testing Errors:

- The soil is not thoroughly mixed to achieve uniform moisture.
- The wrong mold is used for the test.
- The mold is out of calibration tolerances.
- The compaction block is not of sufficient mass.
- The compaction block is unstable.
- The wrong rammer is used for the test.
- The drop of the rammer is incorrect.
- The manual rammer is not lifted to the full stroke.
- The manual rammer is not held vertically when the blows are delivered.
- The rammer is not properly cleaned between uses.
- The mechanical rammer is out of calibration.
- The wrong number of blows is delivered with the rammer.
- The mechanical rammer has the wrong compaction face.
- The layers during compaction process vary in thickness.
- The straightedge may become worn with use.
- The sample is not properly dried, or the moisture content sample is improperly taken.
- The points are not plotted correctly on the graph.

2.1.6 Summary of Procedure

This procedure determines the moisture-density relationship of soils and soil-aggregate mixtures. It is sometimes referred to as the standard proctor or the modified proctor test. A quantity of soil or soil and aggregate mixture is prepared at a desired moisture content and compacted in a standard mold using a manual or mechanical rammer. The wet mass of this compacted sample is divided by the volume of the mold to determine the wet density. Once the moisture content of the compacted sample is determined, then it is used to calculate the dry density of the material by using dry-wet densities relationship formula. This procedure is repeated at varied moisture contents.

2.2 MSMT 351(AASHTO T272) – Field Determination of Moisture Density Relations of Soils (One Point Method and Family of Curves)

2.2.1 Material Sampling

Minimum sample size:

- Method "A" – 7 lb. (3.2 kg)
- Method "B" – 16 lb. (7 kg)
- Method "C" – 11 lb. (5 kg)
- Method "D" – 24 lb. (11 kg)

Note: Moisture content of the sample should not exceed the anticipated optimum water content for that type of soil/aggregate, otherwise it will void the test result.

2.2.2 Equipment

Refer to T 99/180 equipment (see Table 2.1)

2.2.3 Scope and Summary of Testing

The wide variety of soils encountered in any geographical area makes it difficult for the inspector who performs the in-place density test to identify the soil and relate it to the proper laboratory maximum density test. To fill up that need, the one-point method has been developed to enable a field soils inspector to determine the wet density of a soil in the field and use the family of curves to determine the soil's maximum dry density and optimum moisture content.

AASHTO T 272 one-point method corresponds to AASHTO T99 or AASHTO T180. It is important to note which method (T99 or T180) is used. For example, if T180 is done using method C for determination of moisture -density relationship and to create the family of curves, then the same method must be used for the one-point determination.

The Family of Curves conversion tool has been developed to provide maximum dry density and optimum moisture for soils commonly used in highway construction. The curves created in the laboratory settings represent the moisture/density relationships of various soils or soils containing aggregate. Once the wet density and moisture content of a soil is known, its maximum dry density and optimum moisture can be read from the curve for that specific soil.

2.2.4 SOP for performing MSMT 351 (AASHTO T272) - One Point Method for Determining Soil Maximum Density and Optimum Moisture based on T 180 Modified Proctor Test and filling up form OMT 031

Note: This SOP is for AASHTO T180 – C (4" mold, ¾" sieve). The step-by-step procedure for all (A, B, C, and D) methods is the same except for the equipment, layers, and number blows as outlined in Table 2.1.

1. Preparing the material sample (Ref Section 2.1.3)

a) Obtain a representative sample material for the test (See section 2.2.1)
b) Sieve it through ¾" (19mm) sieve and discard the material retained in the sieve.
c) Reduce the sieved material to a mass of 11 lb.
d) Thoroughly mix the sample material

2. Compacting the sample in the mold

Note: Use form **OMT 031** for all Line # entries and calculations

a) Weigh the mold empty (without the collar). Record the weight in lbs. on **Line 14** of the form.
b) Place the collar on the mold, tighten it, and place the assembled mold on a concrete block with a **minimum weight of 200 lb.**
c) Scoop the soil to place first layer lightly tapping it, so it is not in a loose state.
d) Place the rammer vertically in the mold and compact the layer with 25 uniformly distributed blows. For each blow, the rammer shall drop from its highest point in the sleeve (18" above the soil layer) in a free fall.
e) If a plug of soil appears in the sleeve of the rammer during the test, remove it and either discard it or place it back into the mold. After removing the plug, continue with the blow count until reaching 25 blows.
f) Repeat steps c) to e) for all five layers of soil.
g) Upon completion of the compaction, remove the mold collar. The fifth layer shall be slightly above the rim of the mold (approximately 5" depth of compacted soil for all five layers).
h) Use a straightedge to level the soil with the edge of the mold.
i) Weight the mold with the compacted soil in it. Record the weight on **Line 13.**
j) Calculate the weight of the soil in the mold by subtracting **Line 14** from **Line 13**. Record the result in lb. on **Line 15.**
k) Calculate the wet density of the soil in the mold by using the formula on **Line 16** and record the result in lb/ft^3.

3. Moisture determination test of a field test sample

Note: Use form **OMT 031** for all Line # entries and calculations

a) Extrude the sample from the mold. The mold collar and the rammer may be used to do so.
b) Obtain a representative sample from the middle of the sample. The moisture sample at minimum shall be 500 grams.
c) Weigh a sample of the material in grams and record it (without tare) on **Line 18** of the form.
d) Place the sample on a gas stove or hot plate using a low flame/heat setting. Mix the sample continuously to expedite the drying process and prevent the burning of particles. Always use a low flame or heat setting. Extreme/concentrated heat may cause over burning and loss of material.
e) When the sample looks dry, remove it from the stove, allow for it to cool, and weigh it. Afterwards, return the sample back to the heating element, continue drying for another two to three minutes, cool, and re-weigh. When a constant weight has been achieved (**less than 0.1 % difference between the weights**), the sample is dry. Record the net weight of the dry sample on **Line 19** of the form.

Note: Care must be taken to avoid losing any of the sample

Calculate % difference in moisture using the following formula:

$$\% \, \boldsymbol{difference} = \frac{\boldsymbol{W}_{\boldsymbol{weight\ of\ wet\ material}} - \boldsymbol{W}_{\boldsymbol{weight\ of\ dry\ material}}}{\boldsymbol{W}_{\boldsymbol{weight\ of\ dry\ material}}} * \mathbf{100}$$

Calculate final % moisture using the following formula:

$$\boldsymbol{w} \, \%_{\boldsymbol{percent\ moisture}} = \frac{\boldsymbol{W}_{\boldsymbol{initial\ weight\ of\ wet\ material}} - \boldsymbol{W}_{\boldsymbol{final\ weight\ of\ dry\ material}}}{\boldsymbol{W}_{\boldsymbol{final\ weight\ of\ dry\ material}}} * \mathbf{100}$$

f) Calculate weight of the moisture in the sample by subtracting weight of the dry material from weight of the wet material (**Line 18 – Line 19**) and record it on **Line 20** of the form.
g) Record % moisture from the sample by dividing the weight of moisture by weight of dry material and multiply the result by 100 as shown on **Line 21.**

4. Finding OMC and Maximum Dry Density using Family of Curves

A family of curves is created in a lab for a specific project based on soil samples taken from the project area. In the following example, the family of curves is based on five soil samples.

If the one-point proctor falls on one of the curves in the Family of Curves, the maximum dry density and optimum moisture content defined by that curve shall be used. If the one-point falls within the family of curves but not on a curve, a new curve shall be drawn through the plotted one-point and parallel to nearest curve of the family in the same general shape, the maximum dry mass and optimum moisture content as defined by that new curve shall be used. If the one-point plotted within or on the family of curves does not fall in the range of 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 that range.

For example – See Part 5 (5.3)

2.2.5 Common Testing Errors

Refer to T 99/180 common testing errors (see 2.1.5)

2.2.6 Typical test results

This test provides the same results as an AASHTO T 99 and T 180 Moisture – Density Relations of Soils Using 2.5 kg (5.5 lb.)/ 4.5 kg (10 lb.) Rammer and a 305 mm (12 in.)/ 457 mm (18 in.) drop.

2.3 MSMT 251 (ASTM D4959-16) – Determination of Water Content by Direct Heating

2.3.1 Scope

The moisture content of a material influences its ability or inability to be excavated, consolidated, moved, screened, weighed, dried out, or reabsorbed. Moisture content calculations used for soils and aggregates are determined by dividing the weight of the water in the material by the weight of the dry material. The moisture content is used to calculate a variety of properties, including density, plasticity, permeability etc.

2.3.2 Equipment

- An electric hot plate or a gas burner.
- Scale or balance conforming to AASHTO M 231 Class G100 and G2.
- Metal container, such as a large frying pan or equivalent.
- Pointing trowel or large spoon.

2.3.3 Test Procedure

- Select a representative quantity of material.
  All soils and aggregate moisture content sample sizes must be a minimum of 500 grams.
  MDOT GAB moisture samples must be a minimum of 6000 grams.
- Weigh a clean dry container.
- Place the sample in the container and weigh.
- Place the container on the stove or hot plate and, while drying, mix the sample continuously to expedite drying and prevent burning of the aggregate. Always use a low flame or heat setting.
- When the sample looks dry, remove it from the stove, cool, and weigh. Put sample back on the stove, continue drying for another two to three minutes, cool, and re-weigh. When a constant weight has been achieved, the sample is dry. Record the weight of the sample and the container. If there is a less than 0.1 percent difference between the weights, the sample is dry.
- Note: Care must be taken to avoid losing any of the sample.

2.3.4 Moisture Calculations:

- Moisture content of soil/aggregate:

$$\mathbf{w}, \% = \frac{(\boldsymbol{W_{wet}} - \boldsymbol{W_{dry}})}{(\boldsymbol{W_{dry}})} \times \mathbf{100}$$

Where: $\mathbf{w}, \%$ = percent moisture
$\boldsymbol{W}$ = weight of soil sample

For example – See Part 5 (5.3)

2.3.5 Common Testing Errors

- Spillage or loss of sample – voids test results.
- Insufficient sample quantity (size) to yield accurate results.
- Overheating sample during drying process causing a loss of organic material or partial oxidation of another sample.

PART 3

In-Place Density and Moisture Content of Soil and Soil-Aggregate Mixture

3.1 MSMT 351 (AASHTO T 191) - Density of Soil In-Place by the Sand Cone Method

This test uses a sand-cone apparatus to determine the in-place density of soil or soil aggregate mixtures. Density is used to calculate the compaction levels of the constructed soil or soil aggregate layers. Percent density is the ratio of the in-place density to the maximum (target) density as determined in the laboratory according to standard testing procedures.

3.1.1 Summary of the procedure

Prior to testing soil or aggregate compaction, calibrations must be done to determine the volume of a sand-cone apparatus, sand density, and weight of sand in the large cone. To determine the in-place density using the sand-cone method, start by excavating a hole as deep as the thickness of the compacted lift. Remove all excavated material and weigh it. After weighing, set aside a representative sample to determine the moisture content. Then the volume of the hole is measured by first filling the hole with sand whose unit mass (weight) is known. The mass of the sand required to fill the hole is converted into volume using the density formula and the sand calibration results. The mass of the soil removed from the hole divided by the volume of the hole is the wet density of the soil.

3.1.2 Equipment

Before beginning any procedure, you must first assemble all the equipment you will need to perform the test. To determine in-place density using a sand- cone, you will need:

- **Density apparatus:** consisting of a 3.79 L (1 gal) jar and a detachable appliance consisting of a cylindrical valve with an orifice 12.7mm (½ in.) in diameter and a small funnel continuing to a standard G mason jar top on one end and a large funnel on the other end. The valve shall have stops to prevent rotating the valve past the completely open or completely closed positions.
- **Sand:** Should be a clean, non-cementitious sand with few or no particles passing the No. 200 sieve, and none retained on the No. 10 sieve. AASHTO T 191 requires that the bulk density of the sand be measured several times to ensure that the sand does not have a variation in bulk density greater than 1 percent.

- **Balances:** AASHTO M 231, Class G20 (over 5 Kg through 20 Kg principal sample mass, sensitivity of 5 g); and AASHTO M231 Class G2 (2 Kg or less, sensitivity of 0.1 g).
- **Drying equipment:** Suitable for drying moisture content samples, usually a hot plate or gas stove in the field.
- **Miscellaneous equipment:** Digging tools for test hole, which might include a small pick, chisels, spoons, scoops, etc.; suitable container for drying moisture sample (small pan), buckets or canvas bags to retain density sample, cache of density sand, thermometer for water temperature determination (if calibrating cone in field), brush for fines.

3.1.3 SOP for performing Sand Cone Test and filling up form OMT 031

Fill up test information on Form OMT 031 – project data, test location, type of material, layer, depth, and percent compaction required.

1. **Find the volume of the sand cone apparatus as follows:**
   a) Weigh the empty apparatus (lb.)
   b) Fill the apparatus with water to a level above the valve and close the valve (20 C° ± 2)
   c) Remove the water in the cone.
   d) Weigh the apparatus filled with water (lb.)
   e) Find the weight of the water in the apparatus by subtracting the weight of the empty apparatus from the weight of apparatus filled with water (lb.).
   f) Use the following formula to find the volume (V) of the apparatus:

$$Volume\ (ft^3) = \frac{Mass\ of\ Water\ (lb)}{62.4\ lb/ft^3\ (Density\ of\ Water)}$$

   g) Repeat the procedure minimum of three times or as many as necessary to obtain constant results.

2. **Determine density (calibrate) of the sand before each compaction determination test as follows:**

   Note: Use **Sand Cone Calibration Form** for all entries and calculations

   a) Weigh the empty apparatus (lb.) – **Line A**
   b) Place the apparatus on a firm level surface, close the valve and fill up the cone with dry sand that has been sieved through #10 sieve.

c) Open the valve and fill up the apparatus with dry sand, keeping the cone at least half full of sand. Do not shake tap or vibrate the apparatus while filling.
d) Close the valve when the apparatus is full and empty the excess sand remaining in the cone.
e) Weigh the full apparatus (lb.) – **Line B**
f) Find the weight of the sand by subtracting the weight of empty apparatus (**Line A**) from the weight of the full with sand apparatus (**Line B**) – record the result on **Line C**
g) Place the base plate on flat surface.
h) Seat the inverted apparatus on the base plate and open the valve of the apparatus sharply. Leave the valve open until the sand stops flowing and then sharply close the valve.
i) Weigh the apparatus with the remaining sand and record the result on **Line F**. Subtract it from the initial weight of the full apparatus (**Line B**) and record the result of the weight of the sand in apparatus' cone on **Line G**. This result will be used in OMT 031 form **Line 8.**
j) Repeat the calibration process steps a) through i) a minimum of **three times** and average the results. The maximum density variation between any one determination and average shall be no more than 1%. (For example - see **5.4**)
k) Find the density of the sand by dividing the weight of the sand by the volume of the apparatus. – **Line E**

$$D_{sand} = \frac{W_{weight\ of\ sand\ in\ apparatus}}{V_{volume\ of\ the\ apparatus}}$$

l) Record the sand density on **Line A**. This density value will be used on **Line 4** of OMT 031 form.

3. Obtaining a field sample for density and moisture determination test.

Note: Use form **OMT 031** for all Line # entries and calculations

a) Weigh the empty container that will be used for the compacted material sample. Record the weight (lb.) on **Line 2** of the form.
b) Place the base plate on a flat surface.
c) Dig up a concave hole within the limits of the base plate opening. Depth of the test hole shall be the full thickness of the compacted layer.
d) The excavated material from the test hole shall be placed in a container and kept in a manner to prevent loss of moisture before the field moisture determination test.
e) Weigh the container with the material from the test hole (lb.) and record it on **Line 1** of the form.

f) Find the weight of the excavated material from test hole by subtracting **Line 2** from **Line 1** on the form.

4. Moisture determination test of the field test sample

Note: Use form **OMT 031** for all Line # entries and calculations

a) Select a representative sample of material with a minimum mass of 500 grams.
b) Weigh a sample of the material from the test hole in grams and record the net weight on **Line 18** of the form.
c) Place the sample on a gas stove or hot plate using a low flame/heat setting. Mix the sample continuously to expedite the drying process and prevent the burning of particles. Always use a low flame or heat setting. Extreme/concentrated heat may cause over burning and loss of material.
d) When the sample looks dry, remove it from the stove, allow for it to cool, and weigh it. Afterwards, return the sample back to the heating element, continue drying for another two to three minutes, cool, and re-weigh. When a constant weight has been achieved (**less than 0.1 % difference between the weights**), the sample is dry. Record the net weight of the dry sample on **Line 19** of the form.

Note: Care must be taken to avoid losing any of the sample.

Calculate % difference in moisture using the following formula:

$$\%\ \boldsymbol{difference} = \frac{\boldsymbol{W}_{\boldsymbol{weight\ of\ wet\ material}} - \boldsymbol{W}_{\boldsymbol{weight\ of\ dry\ material}}}{\boldsymbol{W}_{\boldsymbol{weight\ of\ dry\ material}}} * \mathbf{100}$$

Calculate final % moisture using the following formula:

$$\boldsymbol{w}\ \%_{\boldsymbol{percent\ moisture}} = \frac{\boldsymbol{W}_{\boldsymbol{initial\ weight\ of\ wet\ material}} - \boldsymbol{W}_{\boldsymbol{final\ weight\ of\ dry\ material}}}{\boldsymbol{W}_{\boldsymbol{final\ weight\ of\ dry\ material}}} * \mathbf{100}$$

e) Calculate weight of the moisture in the sample by subtracting weight of the dry material from weight of the wet material (**Line 18 – Line 19**) and record it on **Line 20** of the form.
f) Record % moisture from the sample by dividing the weight of moisture by weight of dry material and multiply the result by 100 as shown on **Line 21.**

5. Find the mass of sand in the test hole.

Note: Use form **OMT 031** for all Line # entries and calculations

a) Weigh the apparatus filled with sand (lb.) and record it on **Line 5** of the form.
b) Invert and seat the apparatus on the base plate over the test hole. Open the valve and leave the sand flowing into the test hole. Close the valve sharply after the sand has finished flowing. Be sure not to vibrate or tap the apparatus during the test.
c) Weigh the apparatus with the remaining sand and record the weight (lb.) on **Line 6** of the form.
d) Subtract **Line 6 from Line 5** and record the result (lb.) on **Line 7.**
e) Find the weight of the sand in the test hole by subtracting the weight of the sand in the cone from the sand used for the test **(Line 7 – Line 8).** Record the result (lb.) on **Line 9** of the form.
f) Find the volume of the hole by dividing the weight of the sand in the hole by the density of the sand **(Line 9 / Line 4)** Record the result on **Line 10** of the form.
g) Find the in place wet density by dividing the weight of the material from test hole by its volume (Line 3/Line 10). Record the result on **Line 11** of the form.
h) Find the in place dry density using the formula (L11) ÷ (100 + L17) x 100 on **Line 12** and record the result.
i) Calculate percent compaction (relative compaction) by dividing the in place dry density by the lab provided or One-Point Proctor test maximum dry density **(Line 12/Line 17) x 100.**

3.1.4 Common testing errors

- Equipment not calibrated properly.
- The jar is vibrated while sand is flowing into the test hole.
- Moisture content not properly determined.

For example – See Part 5 (5.4)

PART 4

In-Place Density and Moisture Content of Soil and Soil-Aggregate Mixture Using Nuclear Density Gauge

MSMT 352 (AASHTO T 310)

4.1 Nuclear Density Gauge

The nuclear gauge is a portable instrument containing a radioactive source, electronics and rechargeable battery packs. The gauge uses radiation (a gamma source and a gamma detector) to obtain several different readings. These readings are then calculated to acquire a number for in-place or dry density for soils and soil-aggregate mixtures. Density readings for depths between 2 in. and 12 in. (depending upon the method used) can be determined.

4.1.1 Summary of Testing Procedure

Since a wet density reading, and a moisture reading are required to determine dry density, both values must be determined. A separate radioactive source is necessary for each technique. The nuclear gauge has a radioactive source at the tip of its probe or source rod and another source located in the body of the gauge. Some gauges may have both sources located in the probe. At the back of the gauge, at opposite ends from the probe are detector tubes (Geiger-Muller tubes). Once the test is underway, these detector tubes pick up or count the gamma rays that travel through the material to them and relay this count to the master controls inside the body of the gauge. A certain percentage of gamma rays emitted by the source is absorbed by the soil, a certain percentage is scattered in the material and a certain percentage will pass through the material. The detector counts the rays that pass through the material and this count is relayed to the master control, called a scaler, by means of electrical impulses. The number of rays counted depends on the density of the material. The higher the density of the material the lower the gamma ray count.

Note: If there is a reason to suspect that the nuclear gauge readings are incorrect, use sand cone test to accept or reject the nuclear gauge test results. Contact the company RSO.

4.1.2 Moisture Reading

The nuclear gauge uses a fast neutron source and a thermal neutron detector which determines the intensity of slow or moderated neutrons. Neutrons have an affinity for hydrogen. Hydrogen is an excellent material for slowing down neutrons. Moisture is determined by the relationship of nuclear count to mass of water per unit volume of soil. The more water that is present, the more hydrogen atoms that will be slowed down and reflected to the detector tubes to be counted. The moisture content is used in conjunction with the density measurement to determine dry density.

4.1.3 Common Testing Errors:

- Soil chemical composition such as excess of hydrogen molecules.
- Soil is not homogenous.
- Equipment not calibrated properly.
- Surface texture.
- Testing to close to a vertical wall or other mass (e.g., cars, construction equipment, body of water, a large pipe).
- Groups of observers gathered too close to the device during operation.
- Presence of asphaltic materials, recycled PCC, cement, lime, fly ash, etc. in soil materials.

4.1.4 Safety and licensing

This device which is used for density testing is like any other tool used on the job. It is there to make your job of taking accurate density readings easier and more efficient. It can be dangerous if used improperly. However, this device is different in that the danger it poses is invisible. Radiation poisoning is very serious. Therefore, taking proper safety precautions is so vital when dealing with this machine at any level. Safety rules are simple to follow and will cause you very little inconvenience. If you follow them correctly, the nuclear gauge will be one of the safest tools you use. There are two important facts to remember when working with nuclear gauges. One, the gauge is radioactive and, two, it is very expensive. It must always be handled carefully and treated with the utmost respect. It is important to take care of the nuclear gauge, but it is also important to take care of yourself while you are using it. You should not be afraid of radiation but should have a healthy respect for it. By realizing the dangers involved, you will know the importance of following safety regulations carefully.

Nuclear Gauge Radiation Safety Course is required annually.

U.S. D.O.T. HAZMAT Course is required every three years.

4.1.5 Gauge Cleaning

The nuclear gauge must always be kept clean. Dirt and dust from the field can build up and cause delicate mechanisms within the machine to malfunction. The device must be cleaned before and after use. When cleaning, put the source rod in the safe storage position. This safe position is obtained by making sure that the index rod is pulled up to the top position and that the trigger button is released. To clean the outside of the device, use mild soap and water on a damp cloth. Before use, wipe the bottom of the device with a long-handled brush or equivalent to remove any dust and moisture. Turn the bottom away from you when doing this. Do the same when you are finished taking your reading. Make sure to clean off the standard block.

4.1.6 SOP for performing direct transmission in-place density and moisture test using Nuclear Density Gauge (NDG)

All gauge operators must be certified and wear radiation dosimeter badge!

1. Turn the gauge on and allow it to warm up for 5 minutes (300 sec).

2. Take standard count of the gauge as follows**:**

> **Note:** Standard count of the gauge is required each day prior to usage, during the day, if required by state specifications, or whenever gauge readings are suspect. In order to check the standard count, the gauge must be turned on and warmed up prior to use according to the manufacturer's instructions.

a) Make sure the bottom of the gauge and the top of the standard block are clean. The standard block must be the one assigned to the gauge.
b) Ensure that the gauge is at least 10 ft away from any vertical object and 33 ft away from another nuclear source.
c) Site requirements for taking NDG standard test: on asphalt, concrete, or compacted soil at least 4" thick and with a density of at least 100 pcf.
d) Place the gauge on the standard block (provided in the NDG box) with the keyboard side of the gauge against the butt plate of the standard block.
e) Push "Standard" button and record previous standard counts on Form OMT 161.
f) Gauge asks, "Take new count?". Press "Yes".
g) Gauge asks," Is gauge on std block & source rod in safe position?". Ensure that it is and press" Yes".
h) Gauge starts 4 min (240 sec) standard count test.

i) After NDG completes the standard test, record the moisture and density counts and check to see if the test passed (%P, %P) for both density and moisture count.
j) If any of the counts (DS or MS) fails (%F), press “Yes” to accept the result and standardize the gauge again.
k) If the standard count fails a third time, call RSO.

3. Change Proctor value if needed as follows:

a) Press “Proctor/Marshal” button on the gauge and follow directions on the screen.
b) Gauge asks, “Want to change?”, press “Yes”
c) Gauge asks “1-MA, 2-PR, 3-VD" - press "2"
d) Gauge asks "1-use a stored value or 2-input a new one?" - press “2”
e) Input new proctor number including decimal point (i.e. 142.1)
f) Gauge asks, "do you want to store for later use?" Press yes or no
g) If you press yes to save, select which memory cell to save in and press corresponding number

4. Determine the test method

a) Backscatter if unable to drive pin for direct transmission.
b) Direct transmission is the most accurate test method.

5. Test site preparation

a) Prepare test site for test by smoothing out an area with the scrapper plate.
b) The maximum void space beneath the gauge shall not be more than 3 mm (1/8 in.). Use native fines or fine sand to fill these voids. This filled area should not equal more than 10% of the surface area beneath the gauge.

6. Direct transmission method

a) Select a location where the gauge will be at least 0.6 m (2 feet) away from any vertical projection (if closer, use trench offset).
b) Prepare the test site by removing all loose and disturbed material and additional material as necessary to expose the top of the material to be tested.
c) Plane an area of sufficient size to a smooth condition to obtain. maximum contact between the gauge and the material being tested.
d) Place scrapper plate on testing surface.

e) Using the supplied hammer, drive the drill rod 2" past the desired test depth (don't forget to place the extruder on plate first).
f) Use the extruder to remove the drill rod.
g) Place gauge at area marked and lower source rod into the ground to desired test depth.
h) Gently pull gauge towards keypad to have source rod contact sidewall.
i) Press "START" to take 1-minute test, step back from gauge but always remain in control of gauge.
j) Gauge will "Beep" when test is completed, return source rod to safe position.
k) Record results from the test on lines 1 to 18 on **OMT 161 form.**

7. Backscatter transmission method

a) Select location and prepare it as per section **5** a) and b).
b) Place gauge on test site and lower source rod 1 notch.
c) Press "START" to take 1-minute test, step back from gauge but always remain in control of gauge.
d) Gauge will "Beep" when test is completed.
e) Return source rod to safe position and after that record the result on OMT form 161b.

Note: Backscatter mode is mainly used for asphalt density readings. However, backscatter may be used if the soil/aggregate is too hard for rod to penetrate, or disturbance may alter the in-place density of the material.

Special considerations are required when reporting density measurements as determined by the nuclear gauge. It should be noted that the volume of soil or soil-aggregate represented in the measurements is indeterminate and will vary with the source - detector geometry of the equipment used and with the characteristics of the material tested. In general, and with all other conditions constant, the denser the material, the smaller the volume involved in the measurement. The density so determined is not necessarily the average density within the volume involved in the measurement. For the usual density conditions, the total count is largely determined by the upper 3 to 4 inches of soils and soil aggregates with more than 50 % of the reading heavily weighted on the first inch of material below the gauge.

4.2 Offsets (Corrections)

Follow the steps in Troxler 3440 manual in the following cases:

4.2.1 Trench Offset

Vertical structures scatter neutrons and gamma photons back to the gauge. This could result in inaccurate moisture and density readings. To take readings in a trench or within 0.6 m (2 ft.) of a large vertical structure, perform a trench offset.

4.2.2 Moisture Offset

Perform a moisture offset if the test material contains hydrogenous materials (other than water) or materials that absorb neutrons. Materials such as cement, gypsum, coal, mica, and lime all contain chemically bound hydrogen that will cause the gauge to display a moisture content that is higher than it actual. Material such as boron and cadmium are neutron absorbers and will cause the gauge to display a moisture count that is lower than actual.

4.2.3 Density Offset

Perform a density offset if the test material is outside the density range for average soil or if the material composition varies from average soil/asphalt.

PART 5

Examples

5.1 Density of Soil

T 180-C proctor test is performed on soil sample.

Weight of the soil and mold after compaction – 16.85 lb.

Weight of 4” mold – 12.10 lb.

Volume of 4” mold – 0.0333 ft^3

$\boldsymbol{W}_{soil}$ = 16.85 – 12.10 = 4.75 lb.

$$\boldsymbol{D}_{soil} = \frac{\boldsymbol{W}_{soil}}{\boldsymbol{V}_{volume}} = \frac{4.75\ lb}{0.0333\ ft^3} = 142.6\frac{lb}{ft^3}$$

Calculation example for adding moisture in a soil sample

1 ml of water = 1 gram

How many grams of water need to be added to a 6050 g soil sample to increase its moisture by 2%?

$$6050 * 0.02 = 121\ g$$

Therefore, 121 ml of water should be added to bring the moisture content of the sample up by 2%.

5.2 Family of Curves Example

The Family of Curves in Figure 5.1 one is created in a lab using AASHTO T-180-C method. A field sample is obtained and one-point field proctor (T 272) test is performed. The wet density and moisture contents are determined as 123.2pcf and 12.3% respectively.

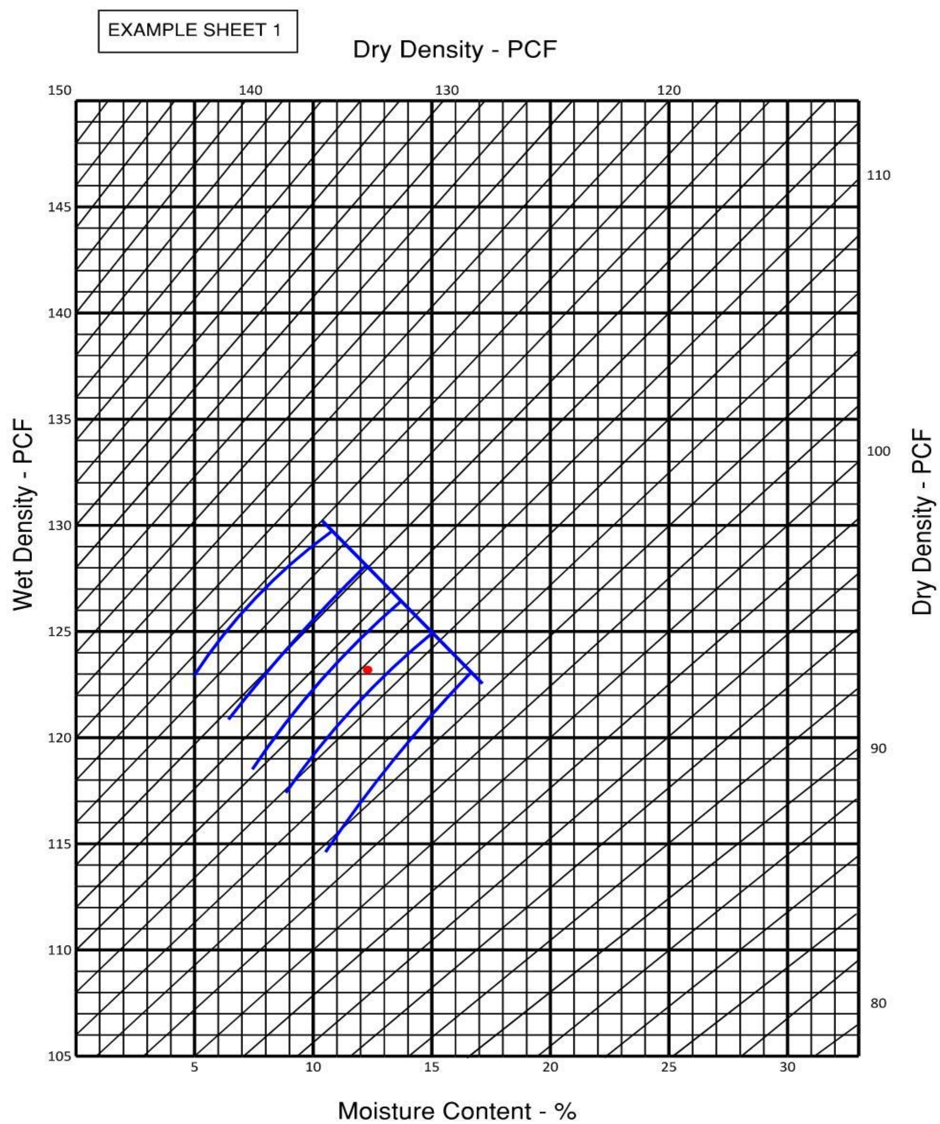

Figure 5.1

Step 1 – Plot the point moisture content vs. wet density) obtained from field one-point proctor test on the family of curves.

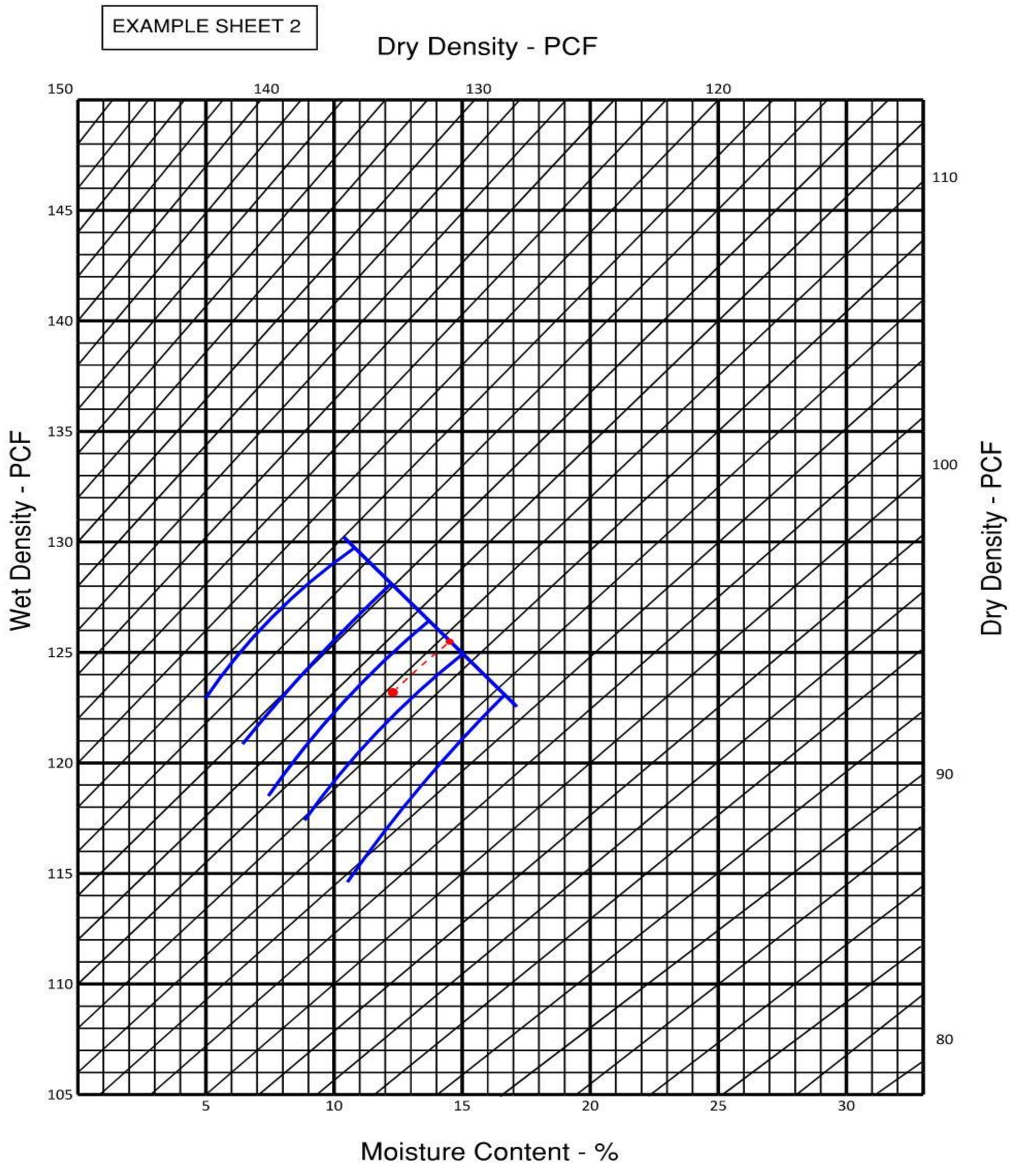

Figure 5.2

Step 2 – Observe the location of the mark if it falls within the family of curves. If the plotted mark is out of the family of curves, then the sample is either too wet or it is from a different soil than the one used for the family of curves.

Step 3 – If the 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.
If the one- point result falls between curves (as on Figure 5.2), draw a new curve parallel and in character with the nearest existing curve in the family of curves.

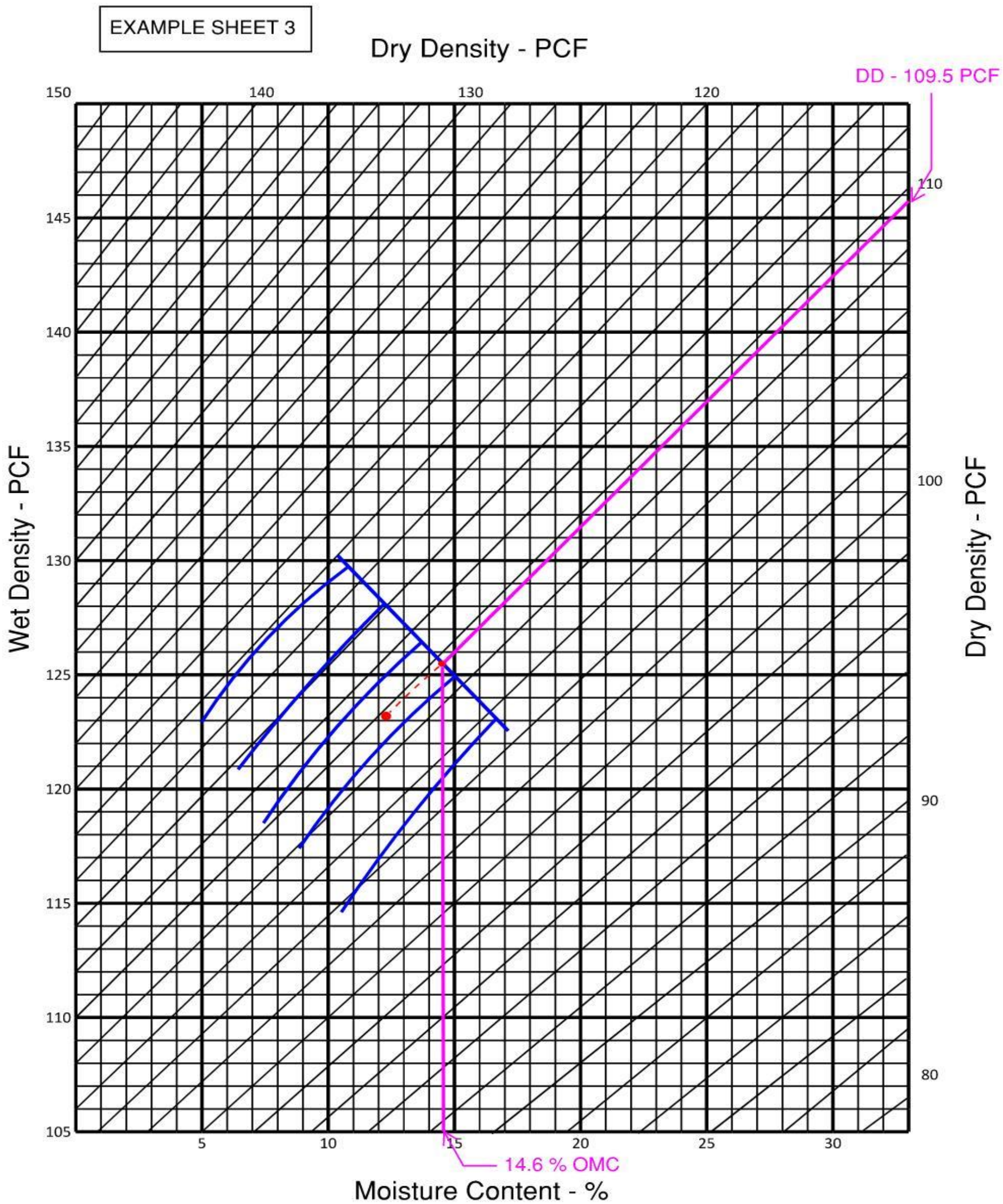

Figure 5.3

Step 4 – Determine the maximum dry density and optimum moisture content as defined by the new curve.

5.3 Moisture Determination Example

A sample for moisture determination has been obtained from a sand cone test hole. All the measured results are net weight:

$$\boldsymbol{W_{wet}} = \mathbf{530.0\ g}$$

$$\boldsymbol{W_{dry}} = \mathbf{512.5g}$$

$$\mathbf{w},\% = \frac{(\mathbf{530.0 - 512.5})}{(\mathbf{512.5})} \times \mathbf{100} = \mathbf{3.4}\ \%$$

Based on the initial drying result the sample need more drying. The data after the second moisture reduction process is as follows:

$$\boldsymbol{W_{wet}} = \mathbf{512.5\ g}$$

$$\boldsymbol{W_{dry}} = \mathbf{512.1\ g}$$

$$\mathbf{w},\% = \frac{(\mathbf{512.5 - 512.1})}{(\mathbf{512.1})} \times \mathbf{100} = \mathbf{0.08}\ \%$$

0.08 % < 0.1 % Therefore, the sample is dry, and no further moisture reduction is needed.

5.4 Sand Cone Calculations

1. Determining Bulk Density of Sand

Volume of Apparatus is 0.1340 cubic feet, weight of sand required to fill the apparatus is 13.1 lb.

Use the formula: $\boldsymbol{D_{bulk}} = \frac{W}{V} = \frac{13.1\ lb}{0.1340\ ft^3} = \mathbf{97.8}\ \boldsymbol{lb/ft^3}$

2. Calibration calculation example:

1st determination: $\boldsymbol{D_{bulk}} = \frac{W}{V} = \frac{13.1\ lb}{0.1340\ ft^3} = \mathbf{97.76}\ \boldsymbol{lb/ft^3}$

2nd determination: $\boldsymbol{D_{bulk}} = \frac{W}{V} = \frac{13.2\ lb}{0.1340\ ft^3} = \mathbf{98.51\ lb/ft^3}$

3rd determination: $\boldsymbol{D_{bulk}} = \frac{W}{V} = \frac{12.9\ lb}{0.1340\ ft^3} = \mathbf{96.27\ lb/ft^3}$

Average the results $\frac{97.76+98.51+96.27}{3} = \mathbf{97.51\ lb/ft^3}$

Use the result from the determinations that is furthest from the average result:

$$\frac{97.51 - 96.27}{96.27} * 100 = \mathbf{1.29}\ \%$$

The difference is larger than 1 % therefore the calibration procedure needs to be repeated.

3. Determining percent compaction:

Calculate relative compaction (% compaction) of subgrade soil given the following information:

Soil Proctor test: $\boldsymbol{D_{dry}} = \mathbf{120.9\ lb/ft^3}$

Sand Cone Calibration: $\boldsymbol{D_{dry\ sand}} = \mathbf{87.5\ lb/ft^3}$

$\boldsymbol{W_{sand\ in\ cone}} = \mathbf{3.12\ lb}$

Sand Cone Test Data: $\boldsymbol{W_{wet\ material\ from\ test\ hole}} = \mathbf{6.15\ lb}$

$\boldsymbol{W_{apparatus\ with\ sand\ before\ test}} = \mathbf{14.51\ lb}$

$\boldsymbol{W_{apparatus\ with\ sand\ after\ test}} = \mathbf{7.13\ lb}$

$\boldsymbol{w\%_{test\ hole\ material}} = \mathbf{12.3}\%$

a) Calculate volume of test hole

$$W_{apparatus\ with\ sand\ before\ test} - W_{apparatus\ with\ sand\ after\ test} - W_{sand\ in\ cone} =$$

$$14.51 - 7.13 - 3.12 = 4.26\ lb\ (dry\ sand\ in\ test\ hole)$$

$$\boldsymbol{V_{volume\ of\ test\ hole}} = \frac{W_{dry\ sand\ in\ test\ hole}}{D_{calibrated\ dry\ sand}} = \frac{4.26}{87.5} = \mathbf{0.0487\ ft^3}$$

b) Calculate wet density of in-place material

$$\boldsymbol{D_{wet}} = \frac{W_{wet\ material\ from\ test\ hole}}{V_{test\ hole}} = \frac{6.15}{0.0487} = \mathbf{126.3\ lb/ft^3}$$

c) Calculate dry density of in-place material

$$\boldsymbol{D_{dry}} = \frac{D_{wet}}{1+(\frac{w\%}{100})} = \frac{126.3}{1+0.123} = \mathbf{112.5\ lb/ft^3}$$

d) Find relative compaction of in-place material

$$\boldsymbol{RC}\% = \frac{112.5}{120.9} * 100 = \mathbf{92.9\ \%}$$