Laboratory 4
Moisture-Density Analysis
Unit Weight Determinations

INTRODUCTION

In many geotechnical applications, foundation soil improvement is necessary to improve the engineering properties and performance of the soil. During the construction of earthen dams and embankments, the is no other alternative than compacting remolded soils that have been obtained from adjacent areas and transported to the construction site. Generally speaking, the compaction process presses soil particles tightly together by expelling air from the void spaces between soil particles. Compaction is normally done deliberately, often with heavy compaction rollers, and proceeds rapidly during construction. Compaction is actually a rather inexpensive and effective way to improve the engineering properties of a soil.

Compaction increases the soil unit weight and produces three important effects: (1) an increase in shear strength, (2) a reduction in permeability, and (3) a reduction in compressibility of the soil. These three changes in soil characteristics are beneficial for some types of earth construction, such as highways, airfields, and earth dams. As a general rule, the greater the compaction, the greater the benefits will be. The amount of compaction is quantified in terms of the dry unit weight of the soil. Usually, soils can be best compacted if a certain amount of water is present during compaction. It is commonly believed that the water acts as a softening and lubricating agent, allowing soil particles to slide over one another more easily. In contrast, the true effect of soil moisture is to provide internal capillary tension forces that effectively provide attractive forces between soil grains, thus enabling a denser configuration of soil particles and providing higher degrees of dry unit weight. However, there is a point at which most of the voids are filled with water and, because of the relative incompressibility of water, the soil does not show a continued increase in dry density when compacted. As still more water is added, the dry density of the compacted soil begins to be reduced. Thus, for a given compactive effort, there is a particular “just right” moisture content at which dry unit weight is maximized. This moisture content is known as the ***optimum moisture content***, and the associated dry unit weight is called the ***maximum dry unit weight***. If the compactive effort is increased, the maximum dry unit weight will increase and the associated optimum moisture content will decrease.

In 1933, R.R. Proctor developed a standardized test procedure that was used in connection with the construction of earth dams in California. The Proctor test was developed to correlate with existing compaction equipment which, by today’s standards, was small and produced low field compacted unit weights. As construction equipment grew in size and capability, field densities eventually exceeded those produced in the lab and consequently, a new laboratory test was devised that put more energy into the compaction process. Thus, the original procedures became known as the Standard Proctor test (ASTM Designation D-698) and the newer test became the Modified Proctor test (ASTM Designation D-1557)

The optimum moisture content and maximum dry unit weight, developed through standard or modified Proctor tests, are provided to the field engineer or construction technologist so that he or she can perform field density tests for specification compliance and advise the earthwork construction supervisor on how to adjust the field moisture content and/or compactive effort to achieve the required in place density. The required in-place engineering properties of compacted soils (shear stability, permeability, compressibility) may vary as a function of a variety of factors, such as location, depth, state of stress under loading, etc. As such, the construction specifications for these soils may also vary to reflect these changing needs. Typically, end-result construction specifications are utilized that may state, for example: "The field density to be obtained shall be at least 95% of the laboratory maximum density achieved in accordance with ASTM D-698." For specifications of this type, the required percentage of laboratory maximum density and the specified test procedure may be varied to appropriately match performance requirements.

In many earthwork activities, the soil type used for construction may vary due to the particular needs of the completed project or as the borrow pit or excavation site extends through different soil layers. Information on the optimum moisture content and maximum dry unit weight for these differing soils must be available to the field personnel so that proper adjustments to construction procedures can be made, such as modifying the wetting or drying procedures used for the soils and/or selecting appropriate compaction equipment. Best results are obtained during compaction when the moisture content of the soils is controlled to be very near the optimum moisture content. For cohesive soils, this optimum moisture content is often near the plastic limit for the soil.

Laboratory Proctor Tests

Proctor compaction tests are conducted using equipment and procedures as outlined in Table 1. The soil is brought to a desired moisture content and compacted in layers in the selected mold. After compaction, the moist unit weight and moisture content are determined and the dry unit weight calculated. These procedures are repeated at a sufficient number of moisture contents to establish a relationship between dry unit weight and moisture content at compaction. This data, when plotted, represents a curvilinear relationship known as the compaction curve or moisture-density curve. The values of maximum laboratory dry unit weight ($\gamma_{d\text{-}max}$) optimum moisture content and are determined from the compaction curve as shown in Figure 1.

Table 1: Comparison of Standard and Modified Proctor Tests

Component or Procedure	Standard Proctor Test	Modified Proctor Test
Diameter of mold, inch	4 (1)	4 (1)
Volume of mold, ft^3	1/30 (1)	1/30 (1)
Weight of rammer, lb	5.5	10
Height of Drop, inch	12	18
No. of compaction layers	3	5
No. of Blows per layer	25	25
Energy of compaction ft-lb/ft^3	12,375	56,250

(1) An alternate mold of 6 inch diameter and 1/13.33 ft^3 volume may be used.

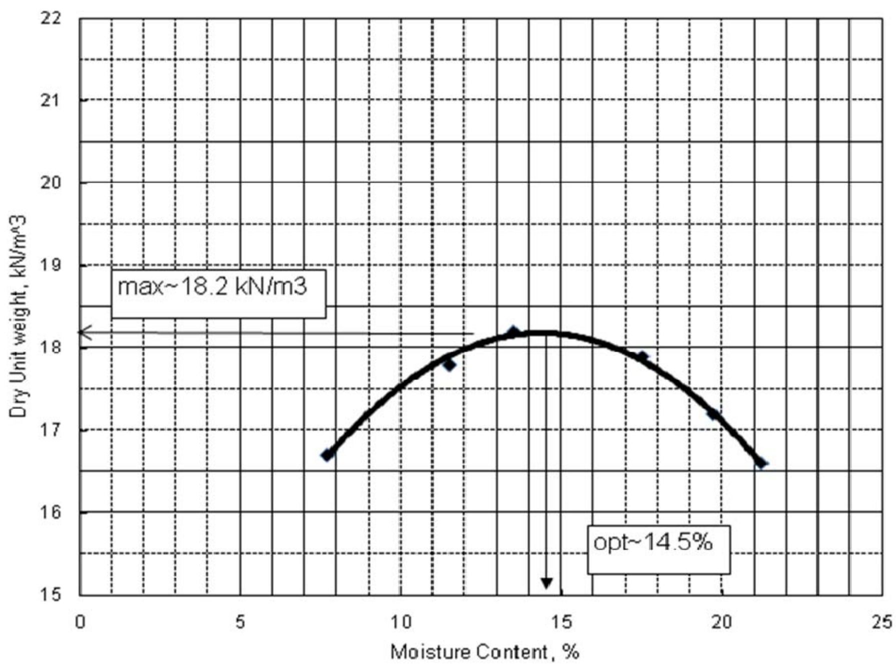


Figure 1: Example Moisture-Density Curve

Zero Air Voids Line

If the specific gravity of soil solids is known, the dry unit weight of soil can be determined for any assumed degree of saturation using the equation:

$$\gamma_d = G_s \gamma_w / (1 + w G_s / S)$$

A curve depicting the point of 100% saturation (S=1), also called the zero air voids line, is usually drawn on the moisture-density plot. The dry unit weight for the zero-voids condition can be computed as:

$$\gamma_{zav} = \gamma_w / (1/Gs + w)$$

A family of parallel curves representing lesser degrees of saturation (say 95, 90, 85%) may also be included on the moisture-density plot. Similarly, a family of zero air voids lines, each computed with a different specific gravity of soil solids, may be included. Normally the moisture-density curve will not approach the zero air voids line as most compacted soils will have a final degree of saturation between 80 - 95%. Furthermore, the right hand side of the moisture-density curve, sometimes referred to as the wet side of optimum, will be roughly parallel to the zero air voids line. If the moisture-density curve obtained from the Proctor tests intersects the zero air voids line, incorrect test data and/or an incorrect specific gravity value should be suspected.

Comparative Compaction Tests

The amount of energy put into the compaction process affects the values of optimum moisture content and maximum dry unit weight. As the compaction effort is increased for a given soil, a higher maximum dry unit weight and a lower optimum moisture content result. While the relative change in maximum dry unit weight and optimum moisture content are dependent on the soil type, the general trend of increased compactive effort will shift the plotted moisture-density curve up and to the left as shown in Figure 2. A line which connects the optimum moisture content-maximum dry density points on each curve is called the ***line of optimums***. The line of optimums can be used to estimate optimum density values for intermediate compactive efforts.

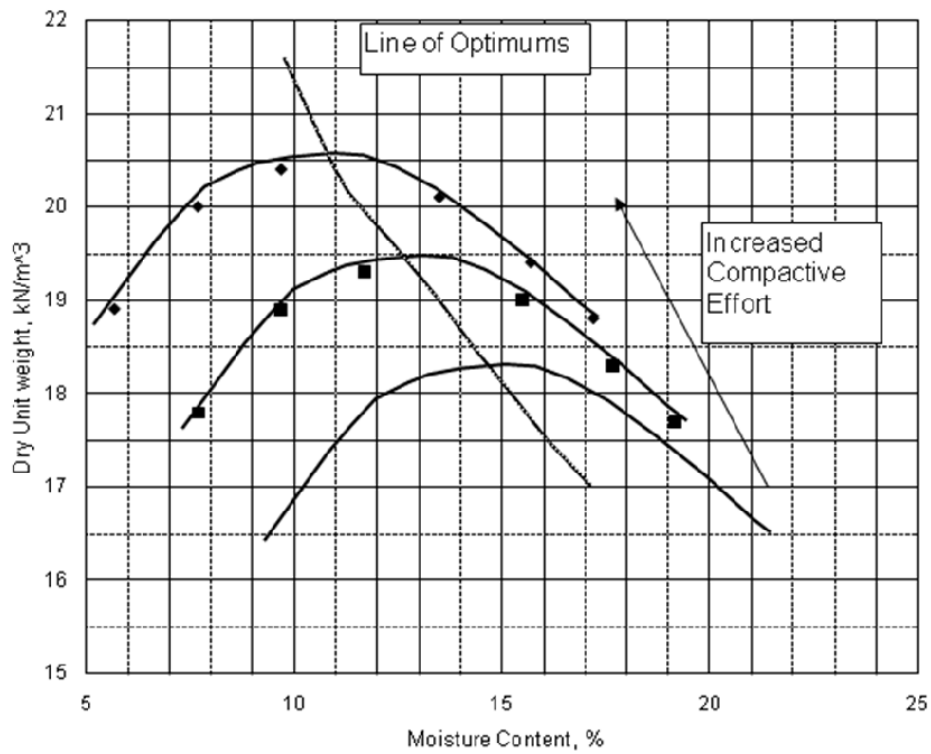


Figure 2: Example Compaction Curves

Unit Weight Determinations

The unit weight of a compacted soil mass must be determined by indirect and/or direct measures to ensure compliance to governing specifications. The nuclear density gauge is the predominant equipment type used for indirect measurement of in situ weight unit weight, moisture content, and dry unit weight. The gauge can measure soil density through direct transmission and backscatter modes and can typically provide readings to a depth of 12 inches below the surface.

Direct measurements of in situ density and moisture content are made via small- or large-scale excavations. In this process, the compacted soil is carefully excavated, with the wet and oven dried weights determined. The volume of the excavation is determined by filling the hole with water, oil or sand. Care must be exercised to ensure that the filling material completely fills the excavation and does not penetrate into the unexcavated soil. In some applications, an impermeable membrane is used to line excavation prior to filling.

The sand cone is a common apparatus used for determining in situ soil density for small excavations. The sand cone consists of a storage vessel topped with a metal cone, as illustrated in Figure 3. The storage vessel is typically filled with dry Ottawa sand, which is a uniformly sized and free-flowing.

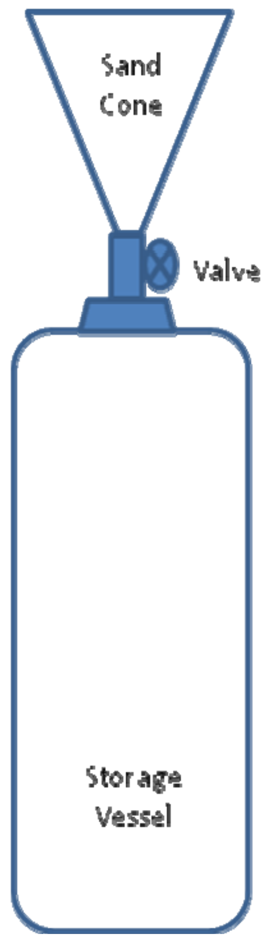
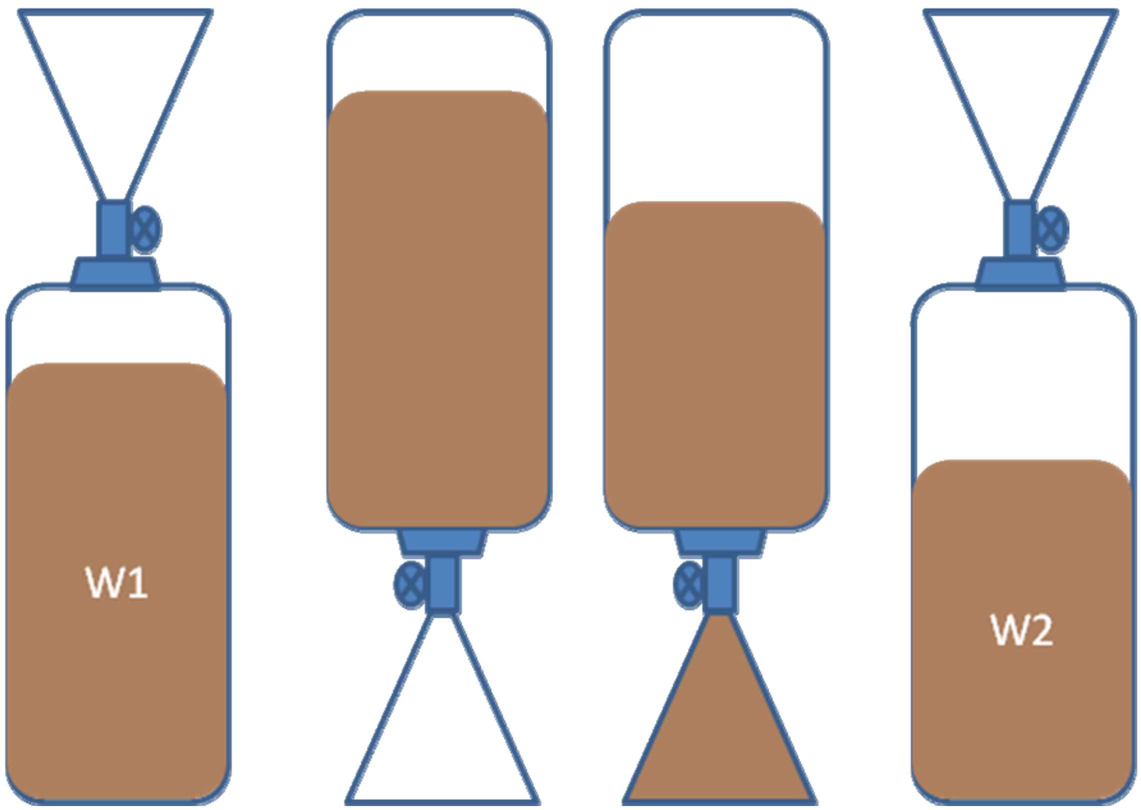


Figure 3: Sand Cone Apparatus

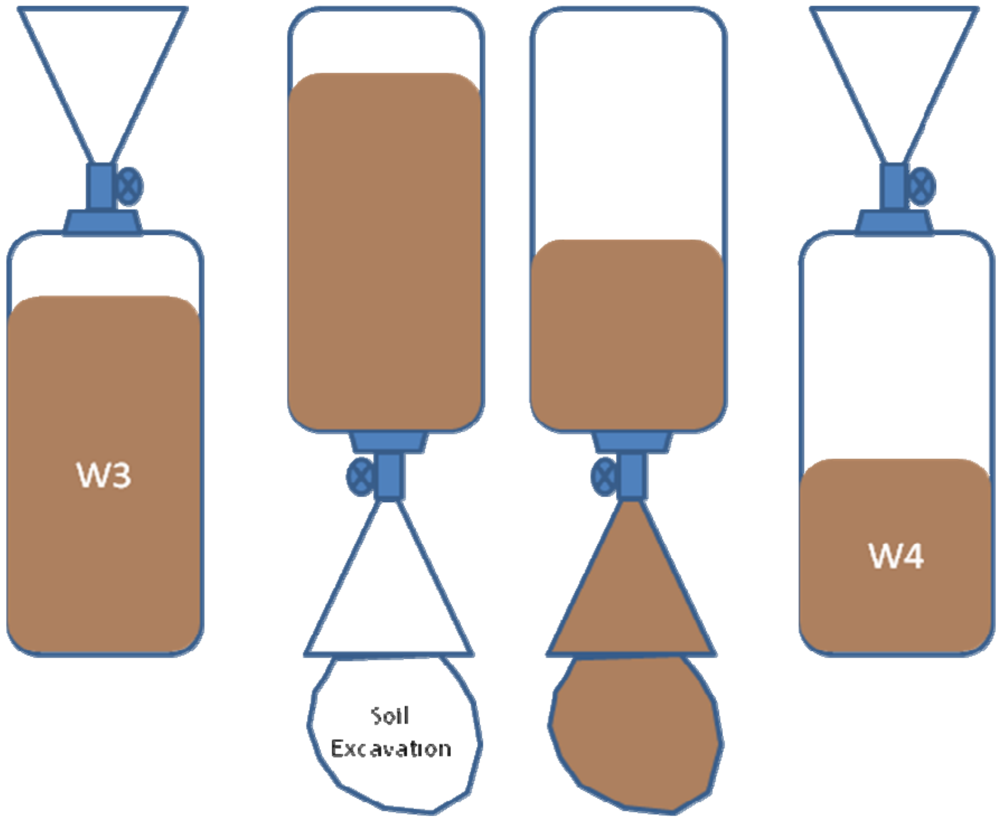
The sand cone is first calibrated to determine the weight of sand required to fill the metal cone as shown in Figure 4. This is simply done by first weighing the filled vessel and cone (4a). The apparatus is then inverted onto a level surface with the valve closed (4b). The valve is then opened to allow sand to flow from the vessel into the cone (4c). After complete filling of the cone, the valve is closed and the reduced weight of the apparatus determined (4d). The weight of sand required to fill the cone (Wc = W1-W2) is then recorded for use in subsequent measurements.



(a) (b) (c) (d)

Figure 4: Calibration of the Sand Cone

For direct measurements of in situ soil density, the steps to calibrate the sand cone are repeated, only this time the apparatus is inverted and positioned over the soil excavation, as shown in Figure 5b. When the valve is opened, sand will fill both the soil excavation and the sand cone (5c). After completion of the test, the weight of sand required to fill the excavation and cone (Wec = W3 - W4) is determined. Using the sand cone calibration data, the weight of sand required to fill only the soil excavation (We = Wec - Wc) is easily determined.



(a) (b) (c) (d)

Figure 5: Measurement of in situ Soil Density

The volume of the soil excavation (Ve) is then determined based on the weight of sand filling the excavation (We) and the reference loose unit weight of the Ottawa sand, γ_s:

$$Ve = We / \gamma_s$$

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Laboratory Session No. 4- Moisture-Density Relations and Unit Weight

PURPOSE: To study the moisture-density variations for a soil with variable compactive effort and to determine the maximum dry density and optimum moisture content values.

ASTM REF: D 698, D 1883

EQUIPMENT: Mold assembly, standard compaction hammer, sample extruder, balance, drying oven, straight-edge, mixing tools, sand cone apparatus, uncompacted voids apparatus, 3/8 inch sieve.

Moisture-Density Relations (Data Sheet 1):

1. Obtain a 4 lb sample of dry soil from the sample pan. Remove any large particles which would not pass through a 3/8 inch sieve. Mix thoroughly to break up any lumps and to ensure a homogeneous mix.

2. Record the mass of the compaction mold to the nearest 0.0001 lb. Clamp the mold and collar to the base.

3. Add the required amount of water and thoroughly mix. Compact the specimen in three layers, with each layer approximately equal in thickness. Prior to compaction, place the loose soil in the mold and spread to a uniform thickness. Lightly tamp the soil prior to compaction until it is not loose or fluffy. Compact each layer with 10 blows. Following compaction of the last layer, remove the collar and base plate and carefully trim the specimen. Record the mass of the mold and compacted specimen to the nearest 0.0001 lb.

4. Remove the soil from the mold with the sample extruder and section the specimen into thirds both vertically and horizontally. Place the central section into a tared moisture tin and record the wet mass and moisture tin to the nearest 0.0001 lb. Dry for 24 hours in an oven set to 220 ^{o}F. Record the oven dried mass of the specimen and moisture tin to the nearest 0.0001 lb.

5. Remix to soil remaining from the extruded sample with soils remaining in the mixing pan to obtain a homogeneous mixture. Repeat steps 1 - 4 using a compactive effort of 25 blows per layer. Prior to extruding and sectioning of the compacted specimen, conduct a unit weight test of the compacted soil.

6. Repeat steps 1 - 5 until a total of four compacted specimens, each with a moisture variation of approximately 2%, have been obtained at each compactive effort.

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Laboratory Session No. 4- Moisture-Density Relations and Unit Weight

Unit Weight Relations (Data Sheet 2):

1. Record the mass of the filled sand cone apparatus to the nearest 0.0001 lb. Place on a flat surface and open the valve fully. Keep the valve open until the Ottawa sand stops flowing, making sure the apparatus is not jarred or vibrated before the valve is closed. Close the valve sharply and record the mass of the sand cone apparatus to the nearest 0.0001 lb. Repeat this procedure two more times.

2. Record the mass of the empty brass cylinder to the nearest 0.0001 lb. Position the cylinder in the uncompacted voids apparatus. Obtain a 0.4 lb sample of Ottawa sand and place the sand sample in the jar, keeping the jar opening covered with a finger. Remove the finger and allow all of the sand to flow into the brass cylinder. Carefully strike off excess sand from the cylinder and obtain the mass of the filled cylinder to the nearest 0.0001 lb. Repeat this process three times.

3. Record the mass of the filled sand cone apparatus and a moisture tin to the nearest 0.0001 lb. Place the trimmed compaction specimen on a flat surface and carefully remove a small amount of soil from the central region of the top portion of the soil using a small spoon. Place this soil in the tared moisture tin and record the mass of moist mass and tin to the nearest 0.0001 lb. Position the sand cone over the excavation hole and open the valve fully until the sand stops flowing, making sure the apparatus is not jarred or vibrated before the valve is closed. Close the valve sharply and record the mass of the apparatus with remaining sand to the nearest 0.0001 lb.

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Laboratory Session No. 4- Moisture-Density Relations and Unit Weight

Calculations:

1. Using the values recorded in Data Sheet 1, calculate the wet unit weight, moisture content, and dry unit weight for each compacted specimen.

2. Calculate the zero-air-void dry unit weight using the water contents used during lab.

3. Prepare a plot of dry unit weight versus compacted moisture content for each specimen. Draw compaction curves by hand as smooth curves through the dry unit weight data at each compactive effort. Plot the zero-air-voids curve. Based on the compaction curves, estimate the maximum dry unit weight and optimum moisture content for each compactive effort.

4. Comment on the differences in the compaction curves for each compactive effort. Are the trends displayed similar to those discussed in class?

5. Using the values recorded in Data Sheet 2, calculate the average weight Ottawa sand required to fill the sand cone and the average dry unit weight of uncompacted Ottawa sand. Compute the volume of the soil excavation and the wet and dry unit weights for the compaction specimen. Comment on how these unit weights compare to those obtained in calculation step 1 above.

DATA SHEET 1

	Trial 1	Trial 2	Trial 3	Trial 4
Volume of Mold, ft^3	1/30	1/30	1/30	1/30
Weight of Mold, lb				
Weight of Dry Soil, lb				
Target Water Content, %				
Weight of Added Water, lb				
10 Blows Per Layer Compactive Effort				
Weight of Mold + Wet Soil, lb				
Moisture Tin No.				
Weight of Moisture Tin, lb				
Weight of Tin +Wet Soil, lb				
25 Blows Per Layer Compactive Effort				
Weight of Mold + Wet Soil, lb				
Moisture Tin No.				
Weight of Moisture Tin, lb				
Weight of Tin +Wet Soil, lb				
Calculations - 10 Blows Per Layer				
Weight of Tin + O.D. Soil, lb				
Wet Unit Weight, lb/ft^3				
Moisture Content, %				
Dry Unit Weight, lb/ft^3				
Calculations - 25 Blows Per Layer				
Weight of Tin + O.D. Soil, lb				
Wet Unit Weight, lb/ft^3				
Moisture Content, %				
Dry Unit Weight, lb/ft^3				
Zero Voids Unit Weight Calculations (Gs = 2.72)				
Moisture Content, %				
Zero Air Voids Unit Weight, lb/ft^3				

DATA SHEET 2

Sand Cone Apparatus Calibration		Trial 1	Trial 2	Trial 3
Initial weight of Sand Cone Apparatus, lb				
Final Weight of Sand Cone Appartatus, lb				
Uncompacted Voids Calibration		Trial 1	Trial 2	Trial 3
Cylinder Volume, ft^3		0.00353		
Weight of Empty Cylinder, lb				
Weight of Filled Cylinder, lb				
25 Blows Per Layer Compactive Effort				
Trial Number	1	2	3	4
Weight of Moisture Tin, lb				
Weight of Tin+Wet Soil, lb				
Initial Weight of Sand Cone Apparatus, lb				
Final Weight of Sand Cone Apparatus, lb				
Calculations - Sand Cone Apparatus Calibration				
Trial Number	1	2	3	Average
Weight of Sand to Fill Cone, lb				
Calculations - Uncompacted Voids Calibration				
Trial Number	1	2	3	Average
Weight of Sand to Fill Cylinder, lb				
Dry Unit Weight of Uncompacted Ottawa Sand, lb/ft^3				
Unit Weight Calculations - 25 Blows Unit Weight				
Trial Number	1	2	3	4
Weight of Soil From Excavation, lb				
Weight of Sand to Fill Excavation, lb				
Vol. of Sand to Fill Excavation, ft^3				
Wet Unit Weight of Soil, lb/ft^3				