Ministry Of High Education
Mansoura High Institute of Eng. &Tech.
Civil Engineering Department

Soil Laboratory Manual

Soil Mechanics And Foundations

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PREFACE

In Civil Engineering, materials on which structure built such as soil, rock, and etc. have the foremost importance to ensure the stability of the structure. Geotechnical Engineering is the specialty of Civil Engineering which deals with the property and behavior of soil and rock in engineering purposes. For getting assurance about the good stability and quality of the structure, different laboratory tests are needed to be performed. To obtain different properties of soil, laboratory tests are performed on collected disturbed and undisturbed soil samples, while field tests are performed on sub-soil at in-site condition following mainly ASTM standard methods.

This Lab manual mainly deals with the common and standard soil laboratory tests. Soil laboratory tests like- grain size analysis by sieve and hydrometer tests, specific gravity test, moisture content determination test, organic content determination test, Atterberg limits test, compaction test, relative density test and direct shear test may be performed on collected disturbed soil samples, whereas permeability test, unconfined compression test, consolidation test and Triaxial test may be performed on collected undisturbed soil samples according to ASTM (American Standards for Testing Materials) methods.

This manual can be used as a textbook in civil engineering undergraduate program as well as a reference in the geotechnical engineering practice. Each laboratory testing includes a brief introduction of the theoretical background, the applicable ASTM references, the types of soils and other materials needed, specimen preparation, the apparatus and tools needed, test procedure, and detailed data sheets. Each laboratory testing is explained using photo illustrations. Generic laboratory data sheets have been prepared for each exercise. These data sheets are intended for use by students, researchers, or practicing engineers.

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GENERAL DIRECTIONS FOR LABORATORY USERS

Do’s

1. Have observation notebooks, lab manuals and other necessary things with yourself during the class.
2. Use tools for mixing concrete and water
3. Check the instruments for proper working conditions while taking and returning the same.
4. Clean your laboratory workspace thoroughly at the end of the laboratory session.
5. Maintain silence and clean environment in the lab

Don’t

1. Do not operate the machines if no the permission from lab technicians
2. Do not put hands on equipment or never touch by your head while it is in function.
3. Do not fix or remove the test specimen while the main power source is switch on.
4. Do not spill the concrete and aggregates on the floor.

GENERAL APPLICATIONS OF SOIL TESTING

The evaluation of soil properties from reliable test procedures has led students to detail understanding of the nature and probable behavior of soils as engineering materials. Some of the resulting benefits in the realm of civil engineering construction have been:

1. Reduction of uncertainties in the analysis of foundations and earthworks.
2. Economies in design due to the use of lower factors of safety
3. Exploitation of difficult sites
4. Erection of structures, and below ground construction, which would not have been feasible without this knowledge
5. Increased economy in the use of soils as construction materials, example in earth dams and embankments.

A laboratory entrusted with soil testing should be capable of carrying the required tests in accordance with recognized standards, in a competent, safe and efficient manner. So, some of the requirements are:

1. All procedures are documented, and any departures from written standards are reported
2. Test equipment is properly maintained, checked and stored
3. Samples are suitably handled, protected and stored
4. Competent, experienced and fully trained staff
5. The laboratory provides appropriate and safe working environment, and
6. An audit system ensures that these requirements are maintained.

Testing Techniques

First and foremost, good laboratory practice depends upon the development of correct techniques in performing tests, observing data and recording observations. Careful plotting of graphs where necessary, accuracy in calculations and correct reporting of results are other skills that a technician must acquire.

Setting up a balance

The principles to be followed in setting up a balance will vary with each type of balance, and manufacturer's instructions or recommendations should be followed.

1. Balances should be sited in areas away from walkways, doors and other sources of vibration such as machinery and lifts, and preferably not adjacent to external wall.
2. Balances should not be placed next to a heater, radiator or oven and must be protected from direct sunlight and from draughts. Balances of high accuracy are sensitive to temperature changes.
3. A sensitive balance should have an independent support.
4. Sufficient space should be provided for an operator to recording data as well as for weights and samples.
5. Wherever the balance is situated, it should stand on a firm and solid level surface.
6. The balance should be protected from dust when not in use.

Weighing procedures

Before weighing a dried soil sample from oven, the sample should be allowed to cool in a desiccator.

Electronic balances

Electronic balances should leave switch on all the time, if that complies with the manufacturer's instructions.

1. Check that the pan is clean, and the zero reading when unloaded.
2. Set the tare adjustment to zero with the empty container on the pan, if this facility is used.
3. Place the item to be weighed on the pan gently, near to the center to avoid eccentric loading.
4. Read the indicated mass and write it down immediately, in the appropriate space on the test sheet, while in front of the balance.
5. Always check back to the indicated mass, and confirm that the correct value has been written down.
6. Remove the sample from the pan, and clean the pan.

Manually operated balances

Good practice in the use of in the older types of balance, which have two pans and need loose weighs, is summarized as follows:

1. Check that the pans are clean, and zero reading when unloaded.
2. Set the tare adjustment to zero with the empty container on the pan.
3. Place the item to be weighed on center of the pan and add loose weights.
4. When a balance that incorporates a test position to take the weight of the pans off the knife-edges is being used.
5. When the balance has steadied, read the indicated mass, and add to this the total weight value of any loose weights.
6. Write down this mass immediately in the appropriate space on the test sheet while in front of the balance.
7. Always check the indicated mass and loose weights, and confirm that the correct value written down.
8. Remove any loose weights and in doing so recheck the total. Replace them in the box.
9. Remove sample from pan, and clean the pan.
10. Switch off the indicator lamp if appropriate.

General care

1. Before use, check that the balance is level and firm.
2. Always keep a balance clean and dust-free. Keep a small soft brush easy for available. If the balance has a cover, replace it after use.
3. Use the tweezers for handling small loose weights.
4. Loose weights must be replaced in the weighs box.
1. 5. Never use a highly sensitive balance for weighing out corrosive liquid

1. WATER CONTENT DETERMINATION

Theory

The moisture content of soil (also referred to as water content) is an indication of the amount of water present in soil. By definition, moisture content is the ratio of the mass of water to the mass of solids in the sample expressed as a percentage. In equation form,

$$w = \frac{M_w}{M_s} \times 100$$

Where,

w = moisture content of soil, in %.
M_w = mass of water in soil sample.
M_s = mass of solids in soil sample.

The water content of soil in the field is usually between 3% and 70% but value greater than 100% are sometimes found in soft soil below the ground water table, which simply means that more than 50% of the total mass is that of water**.** The water content is one of the most significant index properties used in establishing a correlation between soil behavior and its properties. Moreover, it is used in expressing the phase relationships of air, water, and solids in a given volume of material. In fine-grained (cohesive) soils, the consistency of a given soil type depends on its water content**.**

Apparatus

Drying oven, Balance, Container (tin or aluminum moisture can with lid), desiccator and container-handling apparatus: gloves or tongs, Miscellaneous: knives, scoops, quartering cloth, & sample splitters.

Samples and Test Specimen

- Keep the samples that are stored prior to testing in no corrodible airtight container at a temperature between approximately 30 and 300 and in an area that prevents direct contact with sunlight.
- The water content determination should be done as soon as possible after sampling.
- It is recommended to determine two or three separate moisture contents and to average them. However, if only a very small quantity of soil is available, it is better to use it all for one measurement.

- For water content being determined in conjunction with another Lab. Practices, the specimen mass specified in that practice should be used if one is provided. If no minimum specimen mass is provided in that practice then the values given below should apply.

Table 1:1: Minimum mass of moist test specimen

Maximum particle size (100% passing)	Minimum mass of moist test Specimen (W reported to ±0.1%)	Minimum mass of moist test Specimen (W reported to ±1%)
2mm or less	20g	20g
4.75mm	100g	20g
9.5mm	500g	50g
19.0mm	2.5kg	250g
37.5mm	10kg	1kg
75.0mm	50kg	5kg

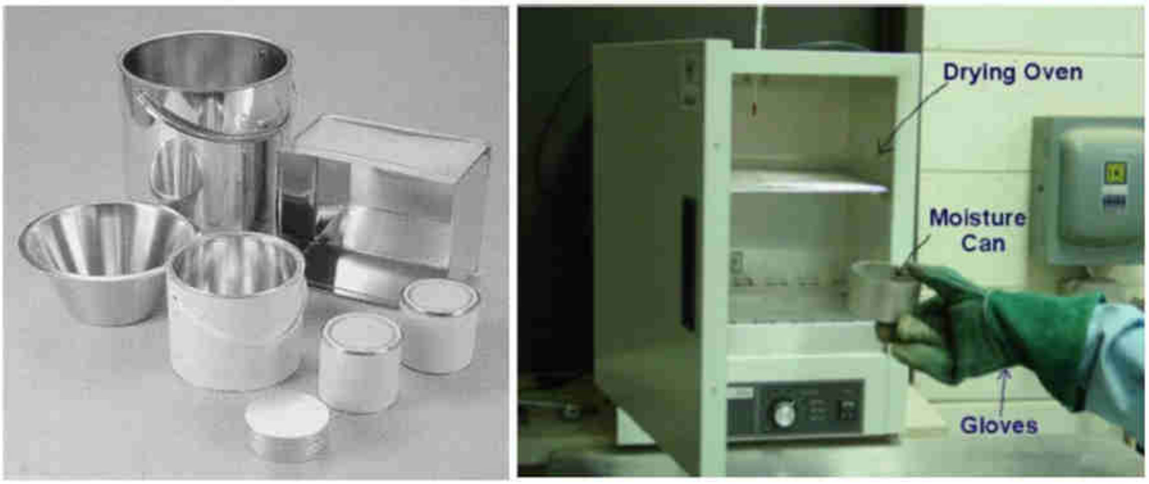


Figure 1:1. Moisture Content tin & sample container.

1. When the test specimen is a portion of a large amount of material, the specimen must be selected to be representative of the water condition of the entire amount of the material. The manner in which the test specimen is selected depends on the purpose and the application of the test, types of material being tested, the water condition, and the type of sample (from another test, bag and block).

Procedure

1. Record all identifying information for the specimen, such as boring number, sample number or other pertinent data, on the data sheet.
2. Record the number and tare weight of clean and dry specimen container (and its lid, if used).
3. Place the moist test specimen in the container and, if used, set the lid securely in position. Immediately determine the mass of the container and wet soil using a balance selected on the basis of the specimen mass.
4. Remove the lid (if used) and place the container with moist material in the drying oven, which is maintained at drying temperature of $105 \pm 5\ ^{0}$c. The time required to obtain constant mass will vary depending on the type of material, size of specimens, oven type and capacity, and other factors. In most cases, drying a test specimen overnight (about 12-16h) is sufficient.

Note-Since some dry materials absorb moisture from moist specimens, dried specimens should be removed before placing moist specimens in the same oven.

5. After the material has dried to constant mass, remove the container from the oven and replace the lids if used. Allow the material and container to cool to room temperature or until the container can be handled comfortably with bare hands. If the specimen cannot be weighted immediately after cooling, it should be placed in a desiccator; if the sample is left in the open air for considerable length of time it will absorb moisture.
6. After the specimen has cooled, determine its dry weight and record it on the data sheet.

$$w = \frac{M_{cws} - M_{cs}}{M_{cs} - M_c} \times 100$$

Where: w = water content, %

M_{cws}= mass of container and wet specimen, g

M_{cs} = mass of container and oven dried specimen, g

M_c = mass of container, g

M_w = mass of water (M_w=M_{cws}-M_{cs}), g

M_s = mass of particles (M_s=M_{cs}-M_c), g

Review Questions

1. Why is it not recommended to leave an oven-dried sample in the open air for a long time before measuring its dry weight?
2. Why do we use a fixed range of temperature to dry soils?
3. What is the function of the container lid when to determine the water content of soil?
4. Excluding oven drying are the other methods to determine the water content of soil?

Table 1.2: Moisture Content in Soils.

Mansoura High Institute of Eng. &Tech.				
Civil Engineering Department				
Soil Testing Laboratory		**Moisture Content determination**		
Project	Location	Depth		
Client	Lab. no.	Date		
Responsible Technician	Checked by	Approved by		
Test Method / Reference Codes				
		Trial #1	Trial #2	Trial #3
Specimen reference				
Container				
Mass of wet soil +Container	m2 (g)			
Mass of dry soil + Container	m3 (g)			
Mass of container	m1 (g)			
Mass of moisture	(m2 - m3) (g)			
Mass of dry soil	(m3 - m1) (g)			
Moisture content, w	{ (m2 - m3/(m3 m1)}*100%			
Average, w (%)				

2. ORGANIC MATTER DETERMINATION

This test is performed to determine the organic content of soils. The organic content is the ratio, expressed as a percentage of the mass of organic matter in a given mass of soil to the mass of the dry soil solids.

Standard Reference: ASTM D 2974 - Standard Test Methods for Moisture, Ash, and Organic Matter of Peat and Organic Soils

Significance

Organic matter influences many of the physical, chemical and biological properties of soils. Some of the properties influenced by organic matter include soil structure, soil compressibility and shear strength. In addition, it also affects the water holding capacity, nutrient contributions, biological activity, and water and air infiltration rates.

Equipment

Muffle furnace, Balance, Porcelain dish, Spatula, Tongs.

Figure 2:1 – oven

Test Procedure

1. Determine and record the mass of an empty, clean, and dry porcelain dish (MP).
2. Place a part of or the entire oven-dried test specimen from the moisture content experiment (Expt.1) in the porcelain dish and determine and record the mass of the dish and soil specimen (MPDS).
3. Place the dish in a muffle furnace. Gradually increase the temperature in the furnace to 440oC. Leave the specimen in the furnace overnight.
4. Remove carefully the porcelain dish using the tongs (the dish is very hot), and allow it to cool to room temperature. Determine and record the mass of the dish containing the ash (burned soil) (MPA).
5. Empty the dish and clean it.

Data Analysis

1. Determine the mass of the dry soil. $M_D = M_{PDS} - M_P$
2. Determine the mass of the ash (burned) soil. $M_A = M_{PA} - M_P$
3. Determine the mass of organic matter. $M_O = M_D - M_A$
4. Determine the organic matter (content). $OM = \frac{M_O}{M_D} \times 100$

Table 2:1: Organic Content in soils

Mansoura High Institute of Eng. &Tech.				
Civil Engineering Department				
Soil Testing Laboratory		Organic content determination		
Project	Location	Depth		
Client	Lab. no.	Date		
Responsible Technician	Tested by	Approved by		
Test Method				
Specimen reference		Trial #1	Trial #2	Trial #3
Mass of empty, clean porcelain dish	M_p (g)			
Mass of dish and dry soil	M_{PDS} (g)			
Mass of the dish and ash (burned soil)	M_{PA} (g)			
Mass of the empty dry soil	M_D (g)			
Mass of the ash (burned soil)	M_A (g)			
Mass of organic matter	M_o (g)			
Organic matter	*OM (%)*			
Average				

3. SPECIFIC GRAVITY OF SOIL

The specific gravity of a given material is defined as the ratio of the mass of a given volume of a material to the mass of an equal volume of distilled water. In effect, it tells us how much the material is heavier than (or lighter) than water. In soil mechanics, the specific gravity of soil is an important parameter for calculation of the weight-volume relationship. The particular specific gravity of a soil actually denotes the specific gravity of the solid matter of the soil and refers, therefore, to the ratio of the mass of solid matter of a given soil sample to the mass of an equal volume (i.e. equal to the volume of the solid matter) of water. Alternatively, specific gravity of soil may be defined as the ratio of the unit mass of solids (mass of solids divided by volume of solids) in the soil to the unit mass of water. In equation form,

$$G_S = \frac{M_S}{V_S \, \rho_w}$$

Where, G_s =specific gravity of soil

M_S =mass of soil solid (g)

$V_{s.}$ = volume of solid (cm3)

ρ_w =unit mass of water (1g/cm3)

The specific gravity of most natural soil falls in the general range of 2.5 - 2.85. the smaller the values are for coarse-grained soil. But organic soil or soil containing porous particles such as diatomaceous earth show low specific gravity values such as 2.3 or less. On the other hand soils containing heavy substances such as iron may have values above 3. The following table gives some typical specific gravity values of soil and these values are used as a guide in evaluating the accuracy of the results. But, they are by no means a substitute for performing the specific gravity test and classification of soil type.

Table 3:1 – Typical Specific Gravity of Soils

Type of soil	Specific gravity of soil
Sand	2.65 - 2.67
Silty sand	2.67 - 2.70
Inorganic clay	2.70 - 2.80
Soil with mica or Iron	2.75 - 3.00
Organic soil	less than 2 but variable

Knowledge of the specific gravity is essential in relation to other soil tests. It is used when to calculate porosity and void ratio and is particularly important when compaction and consolidation properties are being investigated.

There are generally four methods: Density bottle method, Pycnometer method, Measuring flask method, and Gas jar Method. In all the various methods employed, the sequences of observation remain the same. Here, Pycnometer method is treated. This method covers determination of specific gravity of soil that passes the 4.75mm sieve. When the specific gravity is to be used in calculations in connection with the hydrometer test, the specific gravity should be made on that portion of the sample passes the 2.00mm sieve

Apparatus

Pycnometer, Vacuum pump (optional), or hot plate, Balance(0.01gm accuracy), Drying oven, Desiccator, Spatula, Thermometer, Filter paper, & Wash bottle with distilled water.

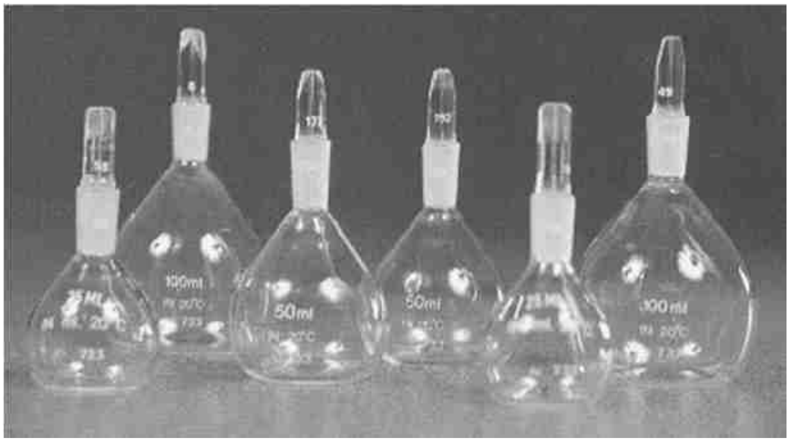


Figure 3:1 - Pycnometer

Calibration of Pycnometer

One parameter that is required in order to compute the specific gravity of soil is the mass of the Pycnometer when filled with water, M_{pw}. The value of M_{pw} is not constant; it varies slightly as a function of water temperature (for the same volume of water). Furthermore, M_{pw} must be known at a temperature equals the temperature of the same Pycnometer when filled later with a mixture of water and soil sample. The value of M_{pw} at any desired temperature can be obtained by proper calibration of the Pycnometer.

The following procedure may be used to calculate the device:

1. The Pycnometer must be cleaned and dried, and its mass (M_P) determined and recorded.
2. The Pycnometer is then filled with distilled water that is approximately at room temperature, and the mass of the Pycnometer plus water, Mpw, is accurately determined and recorded.
3. The water temperature Ti must be determined and recorded to the nearest 0.50c by inserting a thermometer in the water.
4. The value of Mpw can then be computed for any other water temperature Tx, from the equation;

$$M_{pw}(\text{at } T_x) = [[\text{density of water @ } T_x/\text{density of water @ } T_i]\,[M_{pw}@T_i - M_p]] + M_p$$

Where, M_{pw} = mass of Pycnometer and water, g

M_p = mass of Pycnometer, g

T_i = observed temperature of water, ^{o}c

T_X = any other desired temperature, ^{o}c

Preparation of sample

The test shall be representative of the total sample. For minimum mass in oven-dried state ASTM recommend the following:

Table 3:2 – ASTM recommended minimum mass in oven dried state

Max. Particle size, mm	Min. Mass of specimen
2	20g
4.75	100g

Procedure

1. Dry the specimen to a constant mass in an oven maintained at 105 ± 5^{o}c and cools it in a desiccator.
2. Determine and record the mass of a clean, dry, calibrated Pycnometer, M_p.

3. Place the specimen in the Pycnometer. Determine the mass of specimen and the Pycnometer, M_{ps}.
4. Fill the Pycnometer with de-aired distilled water to a level slightly above that required to cover the soil, and soak it for at least 12h. Adding distilled water to just cover the soil makes it easier to control boil-over during removal of entrapped air.
5. Remove the entrapped air by heating the Pycnometer with the contents on the hot plate for at least 10min or by subjecting the contents to a vacuum for at least 30min by connecting the Pycnometer to vacuum pump or an aspirator.
6. Fill the Pycnometer with de-aired distilled water completely up to the mark. Dry it with filter paper from the outside. Take the mass, M_{pws}. Insert the thermometer into the water, and determine and record its temperature, TX, to the nearest 0.5^{o}c.
7. Fill in the data sheet and calculate the specific gravity at 20^{o}c(which is the usual practice)

Calculation

Calculate the specific gravity to the nearest 0.01 using the equation

$$G_S = K\left[\frac{M_S}{M_S + M_{pw}(at\ T_X) - M_{pws}}\right]$$

Where: G_s = specific gravity of soil at 20^{o}c.

K = conversion factor (See Appendix B)

= specific gravity of water at T x/specific gravity of water at 20oc.

Ms =mass of sample of oven dried soil (i.e. M_{ps}-M_p),g

M_{pw} (at T_x)=mass of Pycnometer filled with water at temperature T_x ,g

T_x = temperature of contents of Pycnometer when M_{pws} was taken, ^{o}c.

M_{pws}=mass of Pycnometer plus water and soil (at Tx),g.

Note - When soil samples contains particles larger than the 4.75mm, ASTM C127 should be used for the material retained on 4.75mm sieve and this test method is used for the material passing 4.75mm. Then average value of the specific gravity of the soil will be:

$$G_{avg} = \frac{1}{\frac{P_r}{100G_r} + \frac{P_p}{100G_P}}$$

Where: G_{avg} = average specific gravity.

P_r = percentage of soil particles retained on 4.75mm sieve.

P_p = percentage of soil particles passing on 4.75mm sieve.

G_r = specific gravity of soil particles retained on 4.75mm sieve.

G_p = specific gravity of soil particles passing on 4.75mm sieve.

Review Questions

1. Why do we use vacuum or hot plate while determining the specific gravity of a soil?
2. What are the effect of water temperature and the presence of air in soil-water mixture on the determination of the specific gravity of a soil?
3. How do we identify soils depending on the obtained specific gravity?

Table 3:3: Specific Gravity of Soil

Mansoura High Institute of Eng. &Tech.			
Civil Engineering Department			
Soil Testing Laboratory		**Specific Gravity determination**	
Project	Location	Depth	
Client	Lab. no.	Date	
Responsible Technician	Checked by	Approved by	
Test Method / Reference Codes			
[A] Calibration of Pycnometer			
1. Mass of dry, clean Pycnometer, M_p			
2. Mass of Pycnometer + water, M_{pw}			
3. Observed temperature of water, T_i			
[B] Specific Gravity Determination			
Specimen reference	Trial #1	Trial #2	Trial #3
Mass of dry, clean Calibrated Pycnometer, M_p			
Mass of specimen + Pycnometer, M_{ps}, in g			
Mass of Pycnometer + soil + water, M_{psw}, in g			
Temperature of contents of Pycnometer when Mpsw was taken, T_x, in ^{o}c			
Mass of Pycnometer + water at temperature T_x			
K for T_x			
Specific gravity			
Average Specific gravity at 20^{o}c, G_s			

4. RELATIVE DENSITY DETERMINATION

The relative density of a soil is the ratio, expressed as a percentage, of the difference between the maximum index void ratio and the field void ratio of cohesion less, free-draining soil; to the difference between its maximum and minimum index void ratios. This lab is performed to determine the relative density of cohesion less, free-draining soils using a vibrating table.

Standard References

- ASTM D 4254 - Standard Test Methods for Minimum Index Density and Unit Weight of Soils and Calculation of Relative Density.
- ASTM D 4253 - Standard Test Methods for Maximum Index Density and Unit Weight of Soils Using a Vibratory Table.

Significance

Relative density and percent compaction are commonly used for evaluating the state of compactness of a given soil mass. The engineering properties, such as shear strength, compressibility, and permeability, of a given soil depend on the level of compaction.

Equipment

Vibrating Table, mold Assembly consisting of standard mold, guide sleeves, surcharge base-plate, surcharge weights, surcharge base-plate handle, and dial-indicator gage, balance, scoop and straightedge.

Figure 4:1: Relative density of soil determination apparatus

Test Procedure

1. Fill the mold with the soil (approximately 0.5 inch to 1 inch above the top of the mold) as loosely as possible by pouring the soil using a scoop or pouring device (funnel). Spiraling motion should be just sufficient to minimize particle segregation.
2. Trim off the excess soil level with the top by carefully trimming the soil surface with a straightedge.
3. Determine and record the mass of the mold and soil. Then empty the mold (M_1).
4. Again fill the mold with soil (do not use the same soil used in step 1) and level the surface of the soil by using a scoop or pouring device (funnel) in order to minimize the soil segregation. The sides of the mold may be struck a few times using a metal bar or rubber hammer to settle the soil so that the surcharge base-plate can be easily placed into position and there is no surge of air from the mold when vibration is initiated.
5. Place the surcharge base plate on the surface of the soil and twist it slightly several times so that it is placed firmly and uniformly in contact with the surface of the soil. Remove the surcharge base-plate handle.
6. Attach the mold to the vibrating table.
7. Determine the initial dial reading by inserting the dial indicator gauge holder in each of the guide brackets with the dial gage stem in contact with the rim of the mold (at its center) on the both sides of the guide brackets. Obtain six sets of dial indicator readings, three on each side of each guide bracket. The average of these twelve readings is the initial dial gage reading, R_i. Record R_i to the nearest 0.001 in. (0.025mm).
8. Firmly attach the guide sleeve to the mold and lower the appropriate surcharge weight onto the surcharge base-plate.
9. Vibrate the mold assembly and soil specimen for 8 min.
10. Determine and record the dial indicator gage readings as in step (7). The average of these readings is the final dial gage reading, Rf.
11. Remove the surcharge base-plate from the mold and detach the mold from the vibrating table.
12. Determine and record the mass of the mold and soil (M2)
13. Empty the mold and determine the weight of the mold.
14. Determine and record the dimensions of the mold (i.e., diameter and height) in order to calculate the calibrated volume of the mold, Vc. and the thickness of the surcharge base-plate, T_p.

Analysis

1. Calculate the minimum index density (ρ_{dmin}) as follows:

$$\rho_{d\ min} = {}^{M_{s1}}/_{V_s}$$

Where:

M_{s1}= mass of tested-dry soil = Mass of mold with soil placed loose - mass of mold

V_C= Calibrated volume of the mold

2. Calculate the maximum index density (p_{dmax}) as follows:

$$\rho_{d\ max} = {}^{M_{s2}}/_{V}$$

Where:

M_{s2} = mass of tested-dry soil = Mass of mold with soil after vibration - Mass of mold

V = Volume of tested-dry soil = $V_C - (A_c \times H)$

Where: Ac = the calibrated cross sectional area of the mold

$$H = |Rf - Ri| + Tp$$

3. Calculate the maximum and the minimum-index void ratios as follows (use Gs value determined from specific gravity test result; ρ_w=1g/cm3) :

$$e_{min} = \frac{\rho_w G_S}{\rho_{d\ min}} - 1$$

$$e_{max} = \frac{\rho_w G_S}{\rho_{d\ max}} - 1$$

4. Calculate the relative density as follows :

$$D_d = \frac{e_{max} - G_S}{\rho_{d\ max}} - 1$$

5. Calculate the ratio of the natural state of the soil based on P_d, P_s and $P_s = G_S \times \rho_W$.

Table 4:1: Relative Density of Soils data sheets

Mansoura High Institute of Eng. &Tech.	
Civil Engineering Department	
Relative Density of Soils	
Date Tested	
Tested By	
Project Name	
Sample Number	
Sample Description	
Mass of empty mold	
Diameter of empty mold	
Height of empty mold	
Mass of mold and soil (M_1)	
Average initial dial gauge reading (R_i)	
Average final dial gauge reading (R_f)	
Thickness of surcharge base plate (T_P)	
Mass of mold and soil (M_2)	
Calculations	

5. ATTERBERG LIMITS

Liquid and Plastic Limits

A fine-grained soil can exist in solid, semisolid, plastic, viscous or fluid state depending on its water content. Atterberg proposed four states of soil and corresponding three boundaries as follows:

Solid state (Brittle)	Semi -solid state (Non-plastic)	Plastic state	Viscous- fluid state

Shrinkage limit SL — Plastic limit PL — Liquid limit LL

Definite reproducible values of these limits have to be obtained for engineering purposes.

The liquid and plastic limits are widely used for engineering classification of fine-grained soil or fine portion of coarse-grained soil. The liquid limit, plastic limit, and plastic index of soils are used, either individual or together with other soil properties, in developing correlation such as compressibility permeability, shrink-swell and shear strength. The dividing line between liquid and plastic states is the liquid limit, the dividing line between plastic and semi-solid states is the plastic limit, and the dividing line between semi solid and solid states is shrinkage limit. If a soil in a liquid state is gradually dried out, it will pass through the liquid limit, plastic state, plastic limit, semi-solid state, and shrinkage limit and reach solid state.

The three limits and index just defined are useful numbers in classifying soils and are used to correlate with engineering behavior such as compressibility, permeability, compatibility, shrink-swell and shear strength.

5.1. Liquid Limit

[A] Liquid Limit - Casagrande Method (ASTM D 4318)

Liquid limit is the dividing line between the liquid and plastic states. It is quantified for the given soil as specific water content; from a physical standpoint, it is the water content at which the shear strength of the soil becomes so small that the soil “flows” to close standard groove cut in a sample of soil when it is jarred in a standard manner. The liquid limit is identified in the laboratory as that water content at which the groove cut into the soil pat in standard liquid limit device requires 25 blows (drops) from a height of 1cm to close along a distance of 13mm(Casagrande method).

In addition to being useful in identifying and classifying soils, the liquid limit can also be used to compute an approximate value of the compression index C_c for normally consolidated clays by equation

$$C_c = 0.009(LL - 10)$$

Where LL (liquid limit) is expressed in percent. The compression index is used in determining expected consolidation settlement of load on clay. The liquid limit is determined in the laboratory either by Casagrande method or by Cone penetration method.

Apparatus

Liquid Limit Apparatus (Casagrande7 Apparatus), Grooving tools (of two type: Casagrande tool and ASTM tool), Sieve (425µm), Spatula, Equipment for water content determination.

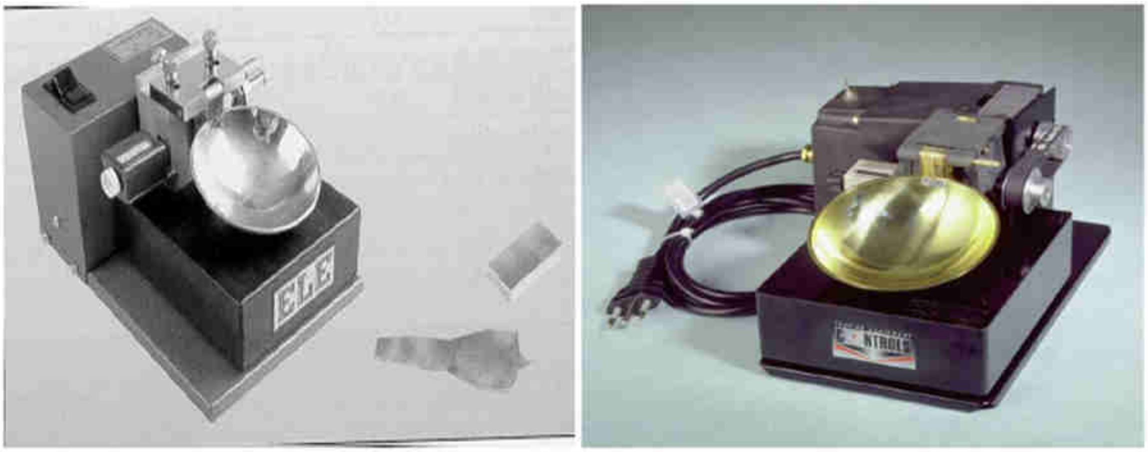


Figure 5:1 - Liquid limit Device with accessories (Manual and Electronic)

Preparation of Test Sample

1. Expose the soil to the air until it is dried.
2. Pulverize the air-dried sample and take a representative of it.
3. Pass the sample on sieve No.40 (425µm Sieve) and take 250g of soil passing this sieve. This much of soil is sufficient for both liquid and plastic limits.
4. Mix thoroughly with distilled water to form a uniform paste and place the mixed soil in a storage dish, cover it to prevent loss of moisture, allow standing for at least 16h.

Adjustment of Mechanical Device

1. Adjust the liquid limit apparatus with the aid of height gauge to obtain the height of the drop of the cup so that the point of the cup that comes in contact with the base rises to a height of 10±0.2mm.
2. Check if all parts of the device are in good working order.
3. Turn the handle and practice to obtain a speed of giving the blows at 2blows per second.

Procedure

[A] Multipoint Liquid Limit Method

1. Place a portion of the prepared soil in the cup of the liquid limit device at the point where the cup rests on the base, squeeze it down, and spread it into the cup to a depth of about 10mm at its deepest point, tapering to form approximately horizontal surface. Take care to eliminate air bubbles from the soil pat but form the pat with as few strokes as possible. Keep the unused soil in the storage dish. Cover the storage dish with a wet towel (or use other means) to retain the moisture in the sample.
2. Form a groove in the soil pat by drawing the tool, beveled edge forward, through the soil on a line joining the highest point to the lowest point on the rim of the cup. When cutting the groove, hold the grooving tool against the surface of the cup and draw in an arc, maintaining the tool perpendicular to the surface of the cup throughout its movement. In soils where a groove cannot be made in one stroke without tearing the soil, cut the groove with several strokes of the grooving tool. Alternatively, cut the groove to slightly less than required dimensions with a spatula and use the grooving tool to bring the groove to final dimensions. Exercise extreme care to prevent sliding the soil pat relative to the surface of the cup.
3. Verify that no crumbs of soil are present on the base or the underside of the cup. Lift and drop the cup by turning the crank at a rate of 2 drops per second until the two halves of the soil pat come in contact at the bottom of the groove along a distance of 13mm. Use of a scale is recommended to verify that the groove has closed 13mm.
4. Verify that an air bubble has not caused premature closing of the groove by observing that both sides of the groove have flowed together with approximately the same shape. If a bubble has caused premature closing of the groove, reform the soil in the cup, adding a small amount of soil to make up for that lost in the grooving operation and repeat (1) to (3). If the soil slides on the surface of the cup, repeat (1) through (3) at higher water content. If, after several trails at successively higher water content, the soil pat continues

to slide in the cup or if the number of blows required to close the groove is always less than 25, record that the liquid limit could not be determined, and report the soil as non-plastic without performing the plastic limit test.

5. Record the number of blows N required to close the groove. Remove a slice of soil approximately the width of the spatula, extending from edge to edge of the soil cake at right angle to the groove and including that portion of the groove in which the soil flowed together, place in a weighed container, and cover.
6. Return the soil remaining in the cup to the storage dish. Wash and dry the cup and grooving tool and reattach the cup to the carriage in preparation for the next trial.
7. Remix the entire soil specimen in the storage dish adding distilled water (additions of water shall be made in increments of 1 to 3 % by mass of the specimen) to increase the water content of the soil and decrease the number of blows required to close the groove. Repeat (1) through (6) for at least two additional trials producing successively lower numbers of blows to close the groove. One of the trials shall be for a closure requiring 25 to 35 blows, one for closure between 20 and 30 blows, and one trial for a closure requiring 15 to 25 blows.

   Note - The test shall always proceed from the dryer to the wetter condition of the soil. In no case shall dried soil be added to the seasoned soil being tested.
8. Determine the water content of the soil specimen from each trial. Initial weighing should be performed immediately after completion of the test.

[B] One-Point Liquid Limit Method

1. Proceed as described in (1) through (5) for Multipoint Liquid Limit Method except that the number of blows required to close the groove shall be 20 to 30.If less than 20 or more than 30 blows are acquired, adjust the water content of the soil and repeat the procedure.
2. Immediately after removing a water content specimen as described by in (5) above, reform the soil in the cup, adding a small amount of soil to make up for that lost in grooving and water content sampling orientations. Repeat (2) through (5) above, and if the second closing of the groove acquires the same number of drops or no more than two drops difference, secure another water content specimen. Otherwise remix the entire specimen and repeat.

   Note Excessive drying or inadequate mixing will cause the number of blows to vary.
3. Determine the water content of the specimens in accordance with (8).

Computation

For Multipoint Liquid Limit Method

1. Plot the relationship between the water content, W, and the corresponding number of drops, N, of the cup on a semi-logarithmic graph with the water content as ordinate on the arithmetic scale, and the number of drops as abscissas on the logarithmic scale.
2. Draw the best straight line through the plotted points.
3. On the plot (known as flow curve), take the water content corresponding to the intersection of the line with the 25-drop abscissa as a liquid limit of the soil.

   Note: Calculator or computer can also be used for logarithmic regression so as to define the equation of the best straight line.

For one point Method

$$LL = W({}^{N}/_{25})^{0.121}$$

Where: N = the number of drops

w = the water content

The liquid limit is the average of the two trail liquid limit values. If the difference between the two trail liquid limit values is greater than one percent point, repeat the test.

Cone Penetrometer Method

The test is based on the relationship between water content and the penetration of a cone into the soil sample under controlled conditioned. It has several advantages over the Casagrande method:

1. It is easier to perform.
2. The method is applied to a wide range of soil.
3. The results are reliable, and don’t depend upon the judgment of the operator.

Apparatus

Cone Penetrometer, which has a cone of 35mm long with a smooth surface at an angle of 30°, Test Gauge, Test cup (55mm diameter by 40mm deep), Equipment for water content determination.

Preparation of the specimen

Prepare the soil in similar way as Casagrande method.

Procedure

1. Fill a portion of the sample soil in the cup, taking care so as not to entrap air. Remove the excess soil and level up the surface of the soil.
2. Adjust the cone Penetrometer such that the cone point just touches the top surface of the soil in the container, and set the scale to zero.
3. Release the vertical rod so as to penetrate the soil paste with a standard weight. Allow to penetrate for 30 seconds.
4. Record the penetration. It should be between 20 to 30mm, as this method is applicable only when the penetration is within this range. If the penetration is within this range, compute the liquid limit as described in computation section. If the penetration is out of this range, take the soil in the cup out and adjust the water content, & under take another trail.
5. Take a representative sample for water content determination.

Computation

$$\mathrm{LL} = \mathrm{W_y} + 0.01\left[(25 - \mathrm{y})\left(\mathrm{W_y} + 15\right)\right]$$

Where, LL = liquid limit

y = the penetration when the water content is $\mathrm{W_y}$

5.2. Plastic limit

[B] Plastic Limit (Test method - ASTM D 4318)

The plastic limit is the dividing line between the plastic and semisolid state. It is quantified for a given soil as specific water content, and from a physical stand point it is the water content at which the soil will begin to crumble when rolled into small threads. It is identified in laboratory as the water content at which the soil can be rolled in treads 3.2mm in diameter without the treads breaking into pieces. The plasticity index is the difference between the liquid and plastic limits.

Apparatus

Glass plate-at least 30cm square by 1cm thick for mixing soil and rolling plastic limit treads, Short metal rod of 3mm diameter, Balance(with accuracy to 0.01), & Equipment for water content determination.

Preparation of Test Specimen

Select a 20g portion soil from the material prepared for the liquid limit test. If it is too wet, reduce the water content of the soil to a consistency at which it can be rolled without sticking to the hands by spreading and mixing continuously on the glass plate or in a storage dish.

Procedure

1. From the 20g mass, select a portion of 1.5 to 2.0g. Form the test specimen into an ellipsoidal mass. Roll this mass between the palm or fingers and glass plate with just sufficient pressure to roll the mass into a tread of uniform diameter throughout its length. The tread shall be further deformed on each stroke so that its diameter reaches 3.2mm, taking no more than 2min.

   Note

   - A normal rate of rolling for most soils should be 80-90 strokes per minute, counting a stroke as one complete motion of the hand forward and back to the starting point.
   - A 3.2mm diameter rod or tube is useful for frequent comparison with the soil tread to ascertain when the tread has reached the proper diameter.

2. When the diameter of the tread becomes 3.2mm, break the tread into several pieces. Squeeze the piece together, knead between the thumb and first finger of each hand, reform into an ellipsoidal mass, and roll. Continue this alternate rolling to a tread 3.2mm in diameter, gathering together, kneading and rerolling, until the tread crumbles under the pressure required for rolling and the soil can no longer be rolled into 3.2mm diameter tread. It has no significance if the tread breaks into treads of shorter length. Roll each of these shorter treads to 3.2mm in diameter. The only requirement for continuing the test is that they can be reformed into an ellipsoidal mass and rolled out again. The operator shall at no time attempt to produce failure at exactly 3.2mm diameter by allowing the tread to reach 3.2mm then reducing the rate of rolling or the hand pressure, or both, while continuing the rolling without further deformation until the tread falls apart. If the crumbling occurs when the tread has a diameter greater than

3.2mm, this shall be considered a satisfactory end point, provided the soil has been previously rolled into a tread 3.2mm in diameter.

3. Gather the portion of the crumbled thread together and place in a weighed container. Immediately cover the container.
4. Select another 1.5 to 2.0g portion of soil from the original 20g Specimen and repeat the operations described in (1) through (3) until the container has at least 6g of soil.
5. Repeat (1) through (4) to make another container holding at least 6g of soil. Determine the water content of the soil contained in the container.

Calculation

1. Compute the average of the two water contents. If the difference between the two water contents is greater than two percentage points, repeat the test. The plastic limit [PL] is the average of the two water contents.
2. PI = LL - PL, where PI is the plastic index

   Note: Both LL and PL are whole numbers. If either the LL or PL could not be determined, or if the PL is greater than the LL, report the soil as non-plastic, NP.

Review Questions

1. Why is the result of the hydrometer analysis insufficient for characterizing fine-grained soil?
2. Is it possible for a soil to have a liquid limit and plastic index both equal to 30%? Why?
3. Should you add or remove water to obtain a lower blow count?
4. What is the purpose of calibration of the Atterberg device?
5. List and discuss for what type of soils we use Casagrande and ASTM grooving stools.
6. Before conducting Atterberg limit test, why we need to sieve the sample on sieve No. 40?
7. What are the advantages of adding distilled water to the soil to be tested?
8. How do we interpret the Atterberg limit test result in relation to soil expansiveness and uplift pressures?

5.3. Shrinkage Limit

Test method- ASTM D 427

Shrinkage limit is the smallest water content at which the soil is saturated. It is also defined as the maximum water content at which a reduction of water content will not cause a decrease in the volume of the soil mass. Shrinkage ratio and linear shrinkage are soil parameters which are often determined in conjunction with shrinkage limit. Shrinkage ratio indicates how much volume change may occur as change in water content above the shrinkage limit takes place, and linear shrinkage gives an indication on the amount of axial strain that drying may cause to soil samples.

Large changes in soil volume are important considerations for soils that are to be used as fill material for highways and railroads or for soils that are to support structural foundations. Unequal settlements resulting from such volume changes can result in cracks in structures or unevenness in roadbeds. The shrinkage limit and shrinkage ratio are particularly useful in analyzing soils that undergo large volume changes with changes in water content (such as clays).

Equipment

Evaporating dish, Shrinkage dish, Glass cup, Glass plate, Shallow pan, Spatula, Straightedge, Graduate(glass), Mercury, Petroleum jelly.

Preparation of Sample

Air-dry the sample first and then pulverize them. Pass the pulverized sample through a 425µm sieve and take about 30g of the portion of the sample that passes through the sieve.

Procedure

1. Place the soil in the evaporating dish and thoroughly mix with distilled water. The amount of water added should produce a soil of the consistency somewhat above liquid limit based on visual inspection.
2. Coat the inside of the shrinkage dish with a thin layer of petroleum jelly or similar lubricant to prevent the adhesion of the soil to the dish. Determine and record the mass in grams of the empty dish, MT.
3. Place the shrinkage dish in the shallow pan in order to catch any mercury overflow. Fill the shrinkage dish to overflowing with mercury. Remove the excess mercury by pressing the glass plate firmly over the top of the shrinkage dish. Observe that there is no air trapped between the plate and mercury, and if there is, refill the dish and repeat the process. Determine the volume of mercury held in the dish either by means of the glass graduate or by dividing the measured mass of the mercury by its mass

density (13.53g/cc).Record this volume in cubic centimeter of the wet soil pat, V.

4. Place an amount of the wetted soil equal to about one-third the volume of the dish in the center of the dish, and tap the dish on a firm surface, causing he soil to flow the outer edges, continue tapping the dish until all air bubbles are eliminated from the soil. Repeat this step for two more layers. The final layer shall fill the dish completely, with some excess soil allowed to stand above the rim of the dish. Strike off the excess soil with straightedge and remove all soil adhering to the outside of the dish. Determine and record the mass in grams of the dish and wet soil.

5. Allow the soil pat to dry in air until the color of the soil turns from dark to light. Oven-dry the soil pat to constant mass at 105 + 50c. If the soil pat is cracked or has broken in pieces, return to (1) and prepare another soil pat using lower water content. Determine and record the mass in grams of the dish and dry soil, MD.

6. Determine the volume of the dry soil pat by removing the pat from the shrinkage dish and immersing it in the glass cup full of mercury in the following manner.

   6.1. Place the glass cup in the shallow pan in order to catch any mercury overflow. Fill the glass cup to overflowing with mercury. Remove the excess mercury by pressing the glass plate with the three prongs firmly over the top of the cup. Observe that there is no air trapped between the plate and mercury, and if there is, refill the dish and repeat the process. Carefully wipe off any mercury that may be adhering to the outside of the cup.

   6.2. Place the evaporating dish in the shallow pan in order to catch any mercury overflow. Place the cup filled with mercury in the evaporating dish and rest the soil pat on the surface of the mercury (it will float). Using the glass plate with the three prongs, gently plat the pat under the mercury and press the plate firmly over the top of the cup to expel any excess mercury. Observe that no air is trapped between the plate and mercury, and if there is, repeat the process starting from (6.1). Measure the volume of the mercury displaced into the evaporating dish either by means of the glass graduate or by dividing the measured mass of mercury by the mass density of mercury. Record the volume in cubic centimeters of the dry soil pat, Vo.

7. Transfer the mercury back into its original container, by working above a large tray, without spilling.

Calculate the following equations

1. Water content, w, of the wet specimen
   Where M is initial wet soil mass in ‘g’ and M_o is dry soil mass in ‘g’
2. Shrinkage Limit, SL
   Where V is the volume (in cm^3) of wet soil pat, V_o is volume (in cm^3) of oven dried soil, and ρw is density of water.
3. Shrinkage ratio, R
4. Linear shrinkage ratio, L_s

Review Questions

1. Why do we use mercury in shrinkage limit test?
2. Why do we coat the shrinkage dish with petroleum jelly?
3. How do shrinkage limit relate to building crack and settlements?

Table 5:1 – Liquid Limit and Plastic Limit data sheet

Mansoura High Institute of Eng. &Tech.

Civil Engineering Department

Soil Testing Laboratory	**Liquid Limit**	
Project	Location	Depth
Client	Lab. no.	Date
Responsible Technician	Tested by	Approved by
Test Method	**ASTM, BS 1377**	

Specimen reference	Legends and Units	Trial #1	Trial #2	Trial #3
Number of drops				
Can No.				
Mass of can + Moist Soil,	$M_{cms\ (g)}$			
Mass of can + dry soil,	$M_{cds\ (g)}$			
Mass of can,	$M_{c(g)}$			
Mass of water	$M_{w(g)}$			
Mass of dry soil,	$M_{ds(g)}$			
Moisture content,	w (%)			

From the flow curve or from equations, LL = ………..%

Plastic limit

Specimen reference	Legends and Units	Trial #1	Trial #2	Trial #3
Can no.				
Mass of can + Moist Soil	$M_{cms\ (g)}$			
Mass of can + dry soil,	$M_{cds\ (g)}$			
Mass of can,	$M_{c(g)}$			
Mass of water,	$M_{w(g)}$			
Mass of dry soil,	$M_{ds(g)}$			
Water content,	W (%)			
Plastic limit	PL (%)			
Average PL (%)				

Table 5:2 – Shrinkage Limit determination data sheets

Mansoura High Institute of Eng. &Tech.				
Civil Engineering Department				
Soil Testing Laboratory		**Shrinkage Limit**		
Project		Location	Depth	
Client		Lab. no.	Date	
Responsible Technician		Tested by	Approved by	
Test Method		**ASTM, BS 1377**		
Specimen reference		Trial #1	Trial #2	Trial #3
Mass of dish coated with petroleum jelly,	$M_{t(g)}$			
Volume of wet soil pat,	V (cc)			
Mass o dish coated with petroleum jelly + wet,	M_w (g)			
Mass of dish coated with petroleum jelly + oven dried soil,	M_d (g)			
Mass of wet soil pat,	M (g)			
Mass of oven dried soil pat,	M_o (g)			
Mass of water in wet soil pat,	M_w (g)			
Water content of soil when placed in dish,	w			
Volume of oven-dried soil pat,	V_o (cc)			
Shrinkage limit,	SL			
Shrinkage ratio,	R			
Linear shrinkage,	Ls			
Average				

6. GRAIN SIZE ANALYSIS

A soil consists of particles of various shapes, sizes and quantity. Grain-size (particle size) analysis is a method of separation of soils in to different fractions based on particle size. It expresses quantitatively the proportions, by mass, of varies sizes of particles present in a soil. It is shown graphically on a particle size distribution curve. Test Method- **ASTM D 422**.

The grain-size distribution of coarse-grained soils (size > 75µm) is determined directly by a sieve analysis, while that of fine-grained soils (size < 75µm) is determined indirectly by hydrometer analysis. The grain-size distribution of mixed soils is determined by combined sieve and hydrometer analysis.

In geotechnical engineering grain-size analysis is useful for various practical applications:

- It is used in engineering soil classification system.
- It is used in part of specification of soil for airfield, road, earth dams, and other soil embankment construction.
- It is used in part of specifications for drainage filter.
- Frost susceptibility of soils, drainage characteristics of the ground and the most suitable grouting process depending mainly on the grading characteristics of soils.

[A] Sieve Analysis

Introduction- The sieve analysis determine the grain size distribution curve of soil samples by passing them through a stack of sieves of decreasing mush opening sizes and by measuring the weight retained on each sieve. The sieve analysis is generally applied to the soil fraction larger than 75µm. The coarse grained soil (particles greater than 75µm) can be further sub divided in-to gravel fraction (size greater than 4.75mm) and sand fraction (75µm < size < 4.75mm).

Sieving can be performed in either wet or dry condition. Dry sieve analysis is suitable for cohesion less soils, with little or no fines, and wet sieve analysis is for soil containing a substantial of fine particles.

Equipment

Series of standard Sieves (for gravel fraction 4.75-75mm aperture size, and for sand fraction 0.075-2mm aperture size), Lid (cover), Pan (receiver), Sieve shaker, Balance sensitive to 0.1g, Soft wire brush, Sample splitter, Mortar, and rubber-covered pestle for breaking up aggregates of soil particles, & Oven.

Figure 6:1 - Sieves stacked on sieve shaker

Preparation of sample Soil

1. Dry the sample soil in air.
2. Thoroughly break up the aggregates or lumps with fingers or with mortar and pestle.
3. Obtain representative sample soil by dividing using sample splitter or riffle.
4. Take optimum sample (i.e. neither small which is not representative nor large which overloads the sieve).

Table 6:1 - Guidelines for selecting the minimum sample weight

Maximum particle size	Minimum weight of sample, g
7.5cm	6000
5cm	4000
2.5cm	2000
1cm	1000
Finer than 4.75mm	200
Finer than 2mm	100

Procedure

There are two different procedures for dry and wet sieving

Dry Sieving

1. Oven dry the sample, allow it to cool, and measure its weight.
2. Sieve it through a 4.75mm sieve. Take the soil fraction retained on 4.75mm sieve for the coarse sieve analysis (Part I) and that passing through the sieve for the fine sieve analysis (Part II).

Part I (Coarse Sieve analysis)

3. Select a stack of sieves suitable to the soil being tested (4.75-75mm). The choice of sieves usually depends on experience, judgment, and the intended applications of grained size analysis. A stack of six or seven sieves is generally sufficient for most soils and applications.
4. Arrange the stack of sieves so that the largest mesh opening is at top and the smallest is at the bottom. Attach a pan at the bottom of the sieve stack. Pour the sample on the top sieve and add a cover plate (lid) to avoid dust and loss of particles while sieving.
5. Place the stack of sieves in mechanical shaker, and shake for about 10minute or until additional shaking doesn’t produce appreciable changes in the amounts of material retained in each sieve.
6. Remove the stack of sieves from the shaker. Beginning with the top sieve, transfer its contents to a piece of paper or a large recipient. Carefully empty the sieve without losing any material, and use a brush to remove grains stuck in its mesh opening. Measure the mass of soil retained in each sieve and notes the corresponding sieve mesh opening and number.
7. Repeat step 6 for each sieve. As a preliminary check, the mass retained on all sieves and the bottom pan is added, and their sum is compared to the initial sample weight. Both weights should be within about 1%. If the difference is greater than 1%, too much material was lost, and weighting and/or sieving should be repeated.
8. Determine the percentage retained, cumulative percentage retained, and the percentage finer, based on the total mass taken in step (1). Draw the particle size distribution curve.

Part II Fine Sieve Analysis

9. Take the portion of soil passing 4.75mm sieve. Weigh it.
10. Select the appropriate sieve size (0.075mm-2mm), and repeat the steps from (4) to (8)

Wet Sieve Analysis

1. Take a representative sample and weigh it.
2. Put the dried sample in a tray and soak it with water. If deflocculating is required, sodium hexametaphosphate, at the rate of 2g per liter of water, is added. Soaking may take 2 to 24hr, depending on the soil.
3. Transfer the slurry into a 4.75mm sieve and wash it with a jet of water. The material retained on the sieve is the gravel fraction. Dry it in an oven, and follow steps (3) to (8) above.
4. Transfer the material passing through 4.75mm to a 75µm sieve, and wash it with a jet of water. Collect the material retained on the sieve and dry it in an oven, and follow step (10).

Computation

- See the data sheet of sieve analysis for computation of percentage finer.
- Grain size distribution curve: It is obtained by plotting grain size as abscissa on logarithmic scale versus percentage fines as ordinate on arithmetic scale.
- D10, D30 and D60 are the grain size corresponding to 10%, 30%, and 60 % by weight finer. It can be obtained by using semi-logarithmic interpolation between the data points of the grain size distribution curve. For instance, when pi $<10<$ p_i+1, then

$$D_{10} = d_i\left(\frac{d_{i+1}}{d_i}\right)^{(10-p_i)(p_{i+1}-p_i)}$$

  Where *di* and *di+1* are the sieve opening corresponding to P_i and P_i+1. D30 and D60 are calculated similarly to D10.

- Coefficient of uniformity (C_u) and curvature (C_c)

$$C_u = \frac{D_{50}}{D_{10}} \qquad C_c = \frac{(D_{50})^2}{D_{60} \times D_{10}}$$

[B]Hydrometer Analysis

Basically the behaviors of fine-grained soils are influenced by the shape, arrangement of particles and geological history. However, there are some cases in which the grain size distribution of these soils is required, for example, in the design of filters for drainage system and rise of water in the capillary opening. The behavior of expansive soils is also a function of the proportion of clay fraction in the soil. Hydrometer analysis is a method used to determine the grain size distribution of fine grained soil having particles sizes smaller than 75µm using Hydrometer. It is based on the Stake's law, which says that the larger the grain-size, the greater it setting velocity in a fluid.

Equipment

- Soil Hydrometer: There are two types of hydrometer. One is graduated in specific gravity of fluids and is calibrated to read 1.000 g/cm3 in pure water at 20 ^{0}C (ASTM 151H). The other is graduated in grams of soil and is calibrated at 0g/l in pure water at 20 0C (ASTM 152H).
- Two sedimentation cylinders of glass, marked for a volume of 1000ml.
- Mechanical stirrer; Thermometer, ranging from 0 to 50 ^{0}C, accurate to 0.5 0C; stopwatch; Balance accurate to 0.01g; Oven; Desiccator; Evaporating Dish; Wash bottle; Glass rod about 12mm in diameter and about 400mm long; Water bath; Sieve 75µm; Scale; 500ml of hydrogen peroxide, 500ml of a stock solution of sodium hexametaphosphate with a concentration of 40g per liter of distilled or demineralized water. This solution should be prepared frequently and should be less than a month old: 3l of distilled or demineralized water.

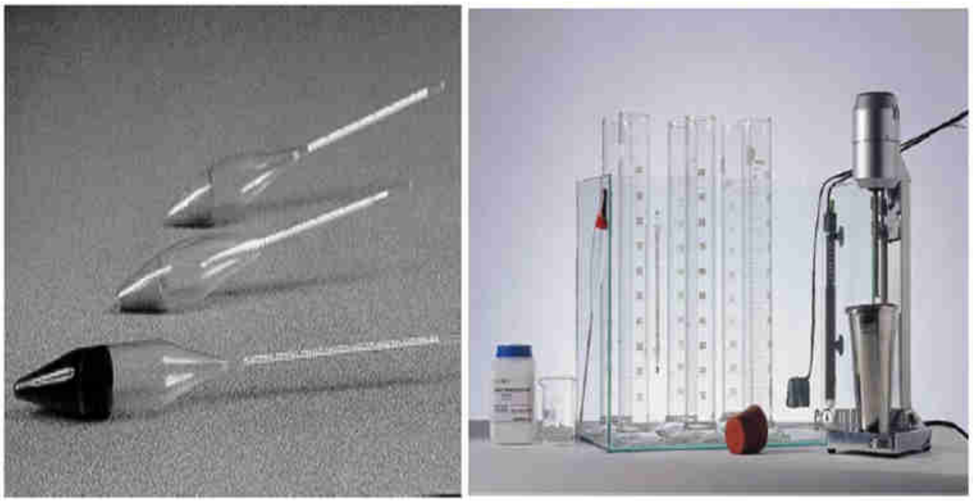


Figure 6:2 – Hydrometer analysis apparatus

Preparation and pretreatment of Sample

1. The test specimen is obtained from the fraction of sample soil that smaller than 75µm. The approximate weight of the dry specimen may be selected as shown in the table below.

Table 6:2 - Approximate Quantity of Material for Sedimentation Analysis

Soil type	Dry weight (g)
Fat clay	30.0
Lean clay and silty soil	50.0

2. Organic soils must be treated with chemicals to remove organic matter. The organic matter is removed from soils by oxidation and accomplished by mixing the soil sample with a solution of 30% hydrogen peroxide.
3. Very fine soil grains will normally tend to flocculate in suspension (i.e., will adhere to each other and settle together). A dispersing agent is added to all samples to prevent grains from flocculating.

Hydrometer and Cylinder calibration

Prior to the hydrometer test, the hydrometer and the sedimentation cylinder are calibrated as follows

1. Determination of the cross-sectional area (A) of the cylinder. It can be determined by measuring its internal diameter or noting the difference in volume between two graduations and then dividing the distance between them. The distance has to measure with accurate scale.
2. Determination the volume of the hydrometer bulb (V_b).

   - Take about 800ml of water in one measuring cylinder. Place the cylinder on a table and observe the initial reading.
   - Immerse the hydrometer in the cylinder. Take the reading after the immersion.
   - Determine the volume of the hydrometer bulb, which is equal to the difference between the final and initial readings. Alternately, weigh the

hydrometer to the nearest 0.1g. The volume of the hydrometer in ml is approximately equal to its mass in grams.

3. Determination the effective depth (L).

- Measure the distance between the hydrometer neck and the bottom of the bulb. Record it as the height of the bulb (L2).
- Measure the distance (L1) between the neck to each of the marks on the hydrometer(R).
- Determine the effective depth (L), corresponding to each of the mark (R), as $L = L1 + \frac{1}{2}(L2 - (Vb/A))$

  Note -The factor Vb/A should not be considered when the hydrometer is not taken out.

- Draw a calibration curve between L and R. The curve may be used for finding the effective depth L corresponding to reading R.

Correction of Hydrometer Reading

Three corrections are applied to the hydrometer reading R: Cm, the meniscus correction; Ct, the temperature correction; and Cd, the dispersing agent correction. Cm applies to the calculation of grain size where as for the computation of percent by weight finer all shall be applied.

1. Meniscus correction: Hydrometers are calibrated to read correctly at the surface of transparent liquid, but soil suspensions are not transparent, making such readings impossible. Therefore, the hydrometer is read systematically at the upper rim of the meniscus and later makes correction.
   - Insert the hydrometer in the measuring cylinder containing about 700ml of water.
   - Take the readings of the hydrometer at the top and the bottom of the meniscus.
   - Determine the meniscus correction, which is equal to the difference between the two readings. It is positive and is constant for a hydrometer.

2. Temperature correction: Temperature influences the solution density and hydrometer volume (caused by thermal contraction or expansion) and consequently the density reading. Therefore, if the temperature of the suspension is different from the temperature at which the hydrometer calibrated (it is usually at 200c), a temperature correction Ct is required for the hydrometer reading.

   - ➢ Record the number of the hydrometer and 1000cc cylinder you are going to use for hydrometer analysis.
   - ➢ Take cool water in the cylinder (at about 140c) and note the temperature and the corresponding hydrometer reading at interval of 20 up room temperature.
   - ➢ Continue step 2 at higher temperatures up to 330 by adding warm water to the cylinder.
   - ➢ Plot a graph between temperature (X-axis) and hydrometer reading (Y-axis).

   Alternately you can conduct the test in a water bath, which is maintained at a temperature at which the hydrometer is calibrated, without introducing temperature correction.

3. Dispersion agent correction: Addition of the dispersing agent to the soil specimen cause and increase in the specific gravity of the suspension. Therefore, the dispersion agent correction is always negative. The dispersing agent correction can be determine by noting the hydrometer reading in clear water and again in the same water after adding the dispersion agent. The given difference is the dispersion correction. Thus, the corrected reading can be obtained from the observed reading R as under

- R"= R + Cm + Ct - Cd - for computation of percent by weight finer
- R' = R + Cm - for computation of grain size

Test Procedure

1. Take the required mass from dried soil passing 75µm sieve. And determine the specific gravity of solids using the remaining soil sample.
2. Place the sample in the 250-ml beaker and cover with 125-ml of sodium hexametaphosphate solution at 5%.
3. Stir until the solution is thoroughly wetted. Allow to soak at least 16h.
4. Transfer the material into the dispersing apparatus, taking care that no particle is left into the beaker by cleaning it with distilled water.
5. Add distilled water, if necessary, so that the cup is more than half full.
6. Stir for a period of 1min.
7. Immediately after dispersion, transfer the soil-water slurry to the glass sedimentation cylinder.
8. Add distilled water until the total volume is 1000ml. Shake the solution to complete the agitation of the slurry. About one minute before starting the test, take the cylinder in one end and, using the palm of the other hand or a suitable rubber cup as a stopper, shake the suspension vigorously for a few second to mix the sediment at the bottom of the cylinder into a uniform suspension. Repeat this agitation several times by turning the cylinder upside down.
9. Set the cylinder in a convenient location and take hydrometer reading at the following interval of time (measured from the beginning of sedimentation) : 1min, 2, 5, 15, 30, 60, 120, …1440. Reading taken up to 2min. can be performed without taking off the hydrometer from the cylinder. For the remaining readings slowly insert the hydrometer about 20-25 seconds before the reading is due. As soon as the reading is taken, carefully remove the hydrometer and place it in a cylinder with distilled water.
10. After each reading take the temperature of the suspension by inserting the thermometer into the suspension. If the hydrometer test is conducting at constant temperature at which the hydrometer is calibrated (in constant temperature bath), this step is not required.

Computation and Plotting

1. For computation of diameter of grains

$$D = K\sqrt{\frac{L}{T}}$$

Where

D = Grain-size, in mm

K = (See Appendix)

H = Viscosity of the water at temperature T in g/cm.sec

G_s = the specific gravity of the soil particles

ρ_w = The unit mass of water at temperature T in g/cm3

L = Effective depth corresponding to R' in cm

T= the time after the beginning of sedimentation, in min

2. The percentage p by weight of particles with diameter smaller than D is

For ASTM 152H: $P = a\frac{R''}{M_o} \times 100$

For ASTM 151H: $P = b\frac{R''-1}{M_o} \times 100$

Where

$a = 0.6226\frac{G_S}{G_S-1}$ $\quad b = V\frac{G_S}{G_S-1}$

M_o= Oven-dried weight of soil per liter of suspension

R" = Corrected hydrometer reading

Gs = Specific gravity of the soil particles and

V =Volume of suspension usually it is 1000cc.

3. Plot percentage finer versus grain size on semi-logarithmic paper.

Review Questions

1. What is the purpose of grain size analysis?
2. Under what conditions should you use wet sieving instead of dry sieving?
3. On what bases do you select the number and opening of sieve for the sieve analysis of a given soil?
4. A mass of volcanic ashes with highly crushable grains is brought to the laboratory. What precaution do you take to determine its grain size distribution?
5. On what range of particle size does the sieve analysis apply?
6. Is it possible to carry out a sieve analysis on a sample of clay?
7. How can you quickly verify the result of dry sieving?
8. Mention the advantages of Grain size distribution curve.
9. Why do you correct the distance of fall of particles during hydrometer? In what unit is this quantity expressed?
10. Does the hydrometer go up or down during sedimentation of soil particles?
11. What is the purpose of dispersing agent? Does it use require a correction?
12. Why should you remove the hydrometer from the sedimentation cylinder after each reading?
13. What physical quantity does the hydrometer measure? At what location does it measure it?
14. Why must you slowly insert and remove the hydrometer in the sedimentation cylinder?
15. Why do you measure the water temperature during the hydrometer analysis?
16. For what reason do you agitate the suspension at the beginning of the hydrometer test?

[C] Combined Grain size analysis

A combined grain size analysis is required when neither the fraction of soil particles smaller than 75µm nor that with particles larger than 75µm can be neglected.

Equipment

The equipment for the combined analysis is identical to that used for sieve and hydrometer analysis.

Preparation of sample

The total amount of sample should be sufficient to yield the required amounts of material for both sieve and hydrometer analysis. Sample of soils having fines with little or no plasticity are oven dried, weighed, and then separated on 75µm sieve. Samples of soils having plastic fines are soaked in water as explained for wet sieving, and then washed over 75µm sieve.

Procedure

1. Perform a sieve analysis on a representative portion of sample, and measure the weight passing through the 75µm sieve.
2. Perform hydrometer analysis on a sample passing through a 75µm sieve.

Computation

For the combined sieve and hydrometer analysis since the particles passing 75µm sieve are an X fraction of total amount of particle size-analysis, percentage obtained from hydrometer analysis must be multiplied for X.

Table 6:3 – Grain size Analysis data sheet

Mansoura High Institute of Eng. &Tech.				
Civil Engineering Department				
Soil Testing Laboratory		**Grain size / Sieve Analysis**		
Project	Location		Depth (m)	
Client	Lab. no.		Date	
Responsible Technician	Tested by		Approved by	
Test Method		ASTM ….. , BS ……		
1.Sieve Analysis				
Maximum Particle size: …………				
Sample mass, M0 : …………				
Sieve Size (opening)	Mass retained (g)	Percentage retained	Cumulative percentage retained	Percentage finer
Total mass =……… g				
From plot		D10 = ……. mm Cu = ………		
		D30 = ……..mm Cc = ………		
		D60 ……. mm		
[A] Specimen and Equipment Data				
Percentage of soil passing 75µm sieve				
Specific gravity of the soil, G_s				
Mass in suspension, M_o				
Dispersing agent correction, C_d				
Meniscus correction, C_m				
Temperature correction, C_t				
Area of sedimentation cylinder, A				
Hydrometer bulb volume, V_b				
Hydrometer bulb height, L_2				
Hydrometer No.				

[B] Hydrometer Reading					
Time (min)	Hydro. Reading	Temp. (0c)	Corrected Hydrometer reading,	Effective depth, L (m)	Grain size, D (mm)
R			R’	R’’	
1					
2					
5					
15					
30					
60					
120					
240					
480					
960					
1440					

Plot - Grain size distribution curve

7. SOIL COMPACTION TESTS

A. Laboratory Compaction Tests

In soil mechanics, compaction means to press soil particles tightly together by expelling air from void spaces between the particles. Compaction increase soil unit weight, thereby producing three important effects:

(1) An increase in shear strength,

(2) A decrease in future settlement, and

(3) Decease in permeability. These three changes in soil characteristics are beneficial for some types of earth construction, such as highway, airfield, and earth dams; as a general rule, the greater the compaction, the greater the benefit will be. Compaction is actually a rather cheap and effective way to improve the properties of soil.

The amount of compaction is quantified in terms of the dry unit weight of the soil. Usually, dry soils can be compacted best (and thus a greater unit weight achieved) if for each soil, a certain amount of water is added. In effect, water acts as a lubricant, allowing soil particles to be packed together better. However, if too much water is added, a lower unit weight is result. Thus, for a given compactive effort, there is a particular moisture content at which dry unit weight is greatest and compaction is best. This moisture content is known as the *optimum moisture content,* and the associated dry unit weight is called the **maximum dry unit weight.**

The usual procedure in construction project is to perform laboratory compaction test on representative samples from the construction site to determine the optimum moisture content and maximum dry unit weight. The maximum dry unit weight is used by designers in specifying design shear strength, resistance to future settlement, and permeability characteristics. The soil is then compacted by field compaction methods to achieve the laboratory maximum dry unit weight (or percentage of it). In place unit weight is tests are used to determine if and when the laboratory maximum dry unit weight (or an acceptable percentage thereof) has been achieved.

A common compaction test is known as the **standard proctor test**. The exact procedure for conducting a standard proctor test is described later in this practice, but the basic premise of the test is that a soil sample is compacted in a 4- or 6-in (101.6-or 152.5-mm) diameter mold by dropping a 24.4-N hammer onto the sample from a height of 305mm, producing a compactive effort of 600 KN-m/m3. An alternative test, known as the **modified proctor test***,* uses a 44.5-N hammer that is dropped 457mm. The later produces greater compaction and, hence, greater soil unit weight (since the hammer is heavier, drops farther, and therefore exerts greater compaction effort on soil sample). Therefore, the modified proctor test may be used when greater soil unit weight is required.

[A] Standard Proctor Test (Test method- ASTM D 698)

Three alternative procedures are provided for carrying out a standard proctor test

Table 7:1 – Alternative procedures for standard compaction test

	Procedure A	Procedure B	Procedure C
Mold	4-in	4-in	6-in
Material	Passing 4.75 mm Sieve	Passing 9.5 mm sieve	Passing 19.0 mm sieve
Layer	Three	Three	Three
Blow per layer	25	25	56

Note

- **Procedure A** is used if 20% or less by weight of material is retained on the 4.75mm sieve.
- **Procedure B** is used if more than 20% by weight of material is retained on the 4.75mm sieve and 20% or less by weight of material is retained on 9.5mm sieve.
- **Procedure C** is used if more than 20% by weight of material is retained on 9.5mm sieve and less 30% by weight of the material is retained on 19.0mm sieve.

Equipment

Compaction equipment, Mold (4in or 6in), Sample extruder, Balance (one with 20kg capacity and accuracy to 1g, one with 1kg capacity and accuracy 0.01g), Straightedge, Oven, Sieves, etc.

Figure 7:1 - Manual Compactor and compaction mold

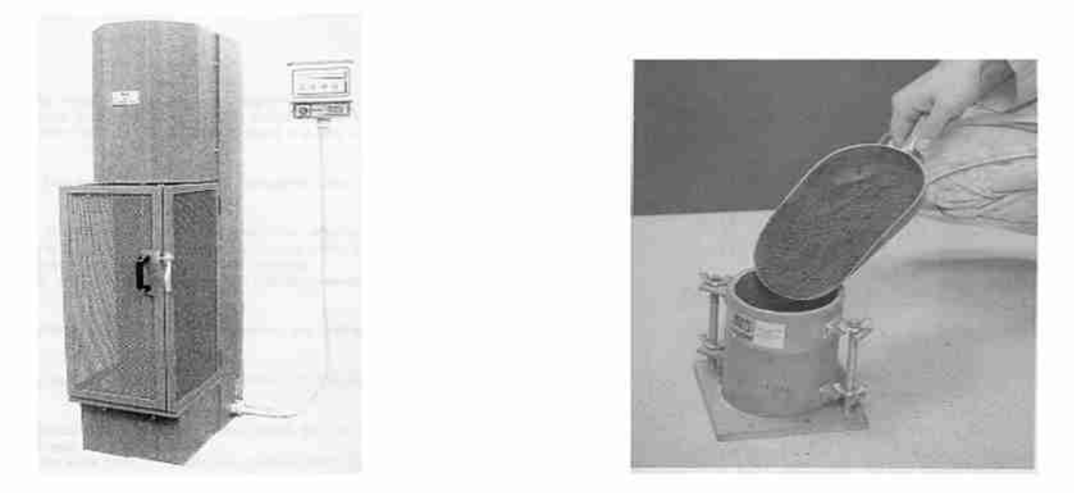


Figure 7:2 - Automatic Compactor with safety cage and compaction mold

Preparation of Equipment

i. Clean and dry the mold& extension collar. Measure the internal diameter 'D' and height 'H' of the mold body. The mold volume 'V' is

$$V= (\pi D^2 H)/4$$

ii. Select the proper compaction mold in accordance with a proper (A, B, or C) being used. Determine and record the mass of the mold body and base plate without extension collar to the nearest gram.

iii. Check that rammer assembly is in good working conditions and parts are not loose or worn. Make any necessary adjustment or repairs.

Preparation of Soil sample

1. ASTM recommends using a fresh soil sample for each test points, which requires about 16kg of soil for procedure A, and B, and 29kg for procedure C for five test points. Therefore, the field sample should have a moist mass at least 23kg and 45kg respectively.
2. After selecting a representative portion of quantity adequate for the test, prepare the specimen in accordance with either i or ii, the first is preferred.
    i. Moist preparation method - Without previously drying the sample, pass it through a 4.75mm, 9.5mm, or 19.0mm sieve.
    ii. ii. Dry preparation method - If the sample is too damp to be friable, reduce the water content by air-drying or by the use of a drying apparatus such that the temperature of the sample doesn't exceed 60oc until the material is friable. Thoroughly break up the aggregations in such a manner as to avoid breaking individual particles. Pass the material through the appropriate sieve.
3. Determine the percentage of the material retained on the 4.75mm, 9.5mm and 19.0mm sieves as appropriate for choosing procedure A, B or C.
4. Prepare at least four (preferably five) specimens [each 2.3kg for procedure A&B, 5.9Kg for procedure C] having water contents such that they bracket the estimated optimum water content. A specimen having a water content close to optimum should be prepared first by trail addition of water and mixing (Typically, soil at optimum moisture content can be squeezed onto lump that sticks together when hand pressure is released, but will break cleanly into two sections when "bent". At water content dry of optimum, soils tend to crumble; wet of optimum, soils tend to stick together in a sticky cohesive mass. Optimum water content is typically slightly less than the plastic limit). Select water content for the rest of the specimens to provide at least two specimens wet and two dry of optimum, and water contents varying by about 2%. Some soil with very high optimum moisture content or relatively flat compaction curve may require larger water content increments to obtain a well-defined maximum dry unit weight. Water content increments should not exceed 4%.

5. Thoroughly mix each specimen to ensure even distribution moisture throughout and then place on a separate covered container and allow standing prior to compaction in accordance with table below. For the purpose of selecting a standing time, it is not required to perform the actual classification procedure described in ASTM D2487 [Refer to Soil properties Testing, Measurement, and Evaluation by ChengLiu & Jack B.Evett], except in the case of referee testing, if previous data exist which provide a basis for classifying the sample.

Table 7:2 - Required Standing Times of Moisturized Specimens

Classification	Min. Standing time, hrs.
GW,GP,SW,SP	No requirement
GM,SM	3
All other soils	16

Test Procedure

1. Apply a thin layer of grease on the inner side of the mold.
2. Assemble and secure the mold on the base of the compactor.
3. Divide the each specimen into three equal parts.
4. Place the loose soil into the mold and spread into a layer of uniform thickness and lightly press in with fingers.
5. Compact the first layer with 25 blows for the 4in mold using the automatic compactor by pushing the appropriate button.
6. After compacting the first layer, scrap the top of surface of the layer to have bond between the next layer. Place the next portions of the specimen, press and compact it as described in steps 4 and 5.
7. Following compaction of the last layer, remove the collar and base plate from the mold. Carefully trim the compacted specimen even with the top of the mold by means of the straightedge scraped across the top of the mold to form a plane surface even with the top of the mold. Initial trimming of the specimen above the top of the mold with a knife may prevent the soil from tearing below the top of the mold. Fill any holes in the top surface with

unused or trimmed soil from the specimen, press in with fingers, and again scrap the straightedge across the top of the mold.

8. Determine and record the mass of the specimen and mold to nearest gram.
9. Remove the material from the mold (sample extruder may be used for this purpose). Obtain a specimen for water content by using either the whole specimen (preferred) or a representative portion.

   Note- The total amount of soil used should be such that the third compacted layer slightly extends into the collar, but doesn't exceed 6mm above the top of the mold. If the third layer does extend above the top of the mold by more than 6mm, the specimen should be discarded. The specimen should be discarded when the last blow of the hammer for the third layer results in the bottom of the rammer extending below the top of the compaction mold.
10. Compact the remaining four or above specimen in similar way as described in steps 1 through 9.
11. Following compaction of the last specimen, compare the wet unit weight to ensure that a desired pattern of obtaining data on each side of the optimum water content will be attained for dry unit weight compaction curve. If the desired pattern is not obtained, additional compacted specimens will be required. Generally, on water content value wet of the water content defining the maximum wet unit weight is sufficient to ensure data on wet side of optimum water content for the maximum dry unit weight.

Computation

The moisture-unit weight relationship for the soil sample being tested can be analyzed by plotting a graph with moisture contents along the abscissa and corresponding dry unit weight along the ordinate. The moisture content and dry unit weight corresponding to the peak of the plotted curve are termed "optimum moisture content" and "maximum dry unit weight," respectively.

- The wet unit weight and dry unit weight can be determined by the equation

$\gamma wet = (M_{sm} - M_m) / V_m$ $\gamma_{dry} = \gamma_{wet} / (1+w)$

Where

M_{sm}= mass of compacted soil plus mold

M_m = mass of mold

V_m = volume of mold

W = water content, expressed here as decimal (to the nearest 0.001)

- The dry unit weight can also be determined using the equation

$\gamma_{dry} = \gamma_w [G_s / (1+G_sW/S_r)]$

Where

γ_w= unit weight of water S_r = degree of saturation

W = water content of the specimen G_s = specific gravity

When Sr, γ_w, and Gs are given the equation defines the saturation line. The 100% saturation line defines the upper limit of compaction curve. No data point can be beyond this line. The 100% saturation line is commonly plotted next to compaction curves while reporting the result of compaction test.

[B] Modified Proctor Test

Follow the same procedure as the standard compaction test, but use the heavier rammer (44.5 KN instead of 24.4 KN) with larger height of drop (457 mm instead of 305 mm). Also compact the soil in 5layers (instead of 3) by applying 56 blows per layer (instead of 25).

Review Question

1. Why do we compact soil in civil engineering?
2. How do you select the water content for the five samples in compaction test?
3. Why is important for the final level of compacted soil to be just above the mold body?
4. What is 100% saturation line? How is it related to compaction curve?
5. What is the influence of compactive effort on compaction curve?

Field Control of Compaction

Field control of compaction involves measuring of insitu-density and comparing it with the laboratory maximum dry unit weight value for the soil, to ascertain if the specifications have been met. There are different methods of determining field density: Core cutter, Sand replacement, Rubber balloon, Nuclear method, etc. Here only two are presented, and you are expected to practice the first one only, the second is left as reading assignment because we have no equipment.

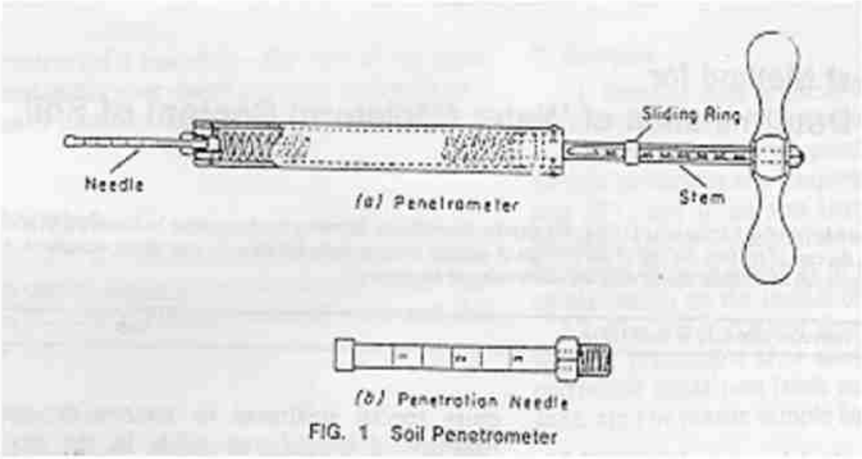
I. Moisture Content Penetration Resistance Relation of Fine-grained soils - Test Method- ASTM D 1558

This test method is used with method (Procedure) A and B of Standard Proctor Test to develop relationships between moisture content, density, and penetration resistance. These relationships are used with a previously prepared family of moisture-penetration curves as a rapid field test to determine the approximate amount of moisture in the soil. When a penetration-resistance measurement of material in place is compared at given moisture content with penetration-density curves prepared at a specified compact effort, an approximate check of compaction (density) may be obtained.

Note-Penetration resistance determinations are not reliable for very dry molded soil specimens or very granular soils.

Apparatus

Moisture-density apparatus, Soil (Proctor) Penetrometer (consists of a special spring dynamometer with pressure indicating scale on the stem of the handle. The pressure scale shall be graduated to 90-lb in 2-lb divisions with a line encircling the stem at each 10-lb interval, or graduated to 40 kg in 1kg divisions with a line encircling the stem at 5kg interval.), Set of Penetrometer Needles.



(a) Penetrometer

(b) Penetration Needle

FIG. 1 Soil Penetrometer

Figure 7:3 - Soil Penetrometer

Sample soil preparation

Prepare the sample soil in accordance with either Procedure A or B. After preparation the fraction passing the 4.75mm sieve shall have at least 20% passing the 75µm sieve.

Procedure

1. Compact the soil in the moisture density mold in accordance with the procedure described in procedure A or B.
2. Place the mold containing the soil specimen on a smooth space between the feet of the operator. The operator shall hold the Penetrometer in a vertical position and shall control the rate of penetration by steadying the arms against the front of the legs at the same times applying pressure to the Penetrometer handle. Penetrate the soil sample at the rate of 13mm/s for a distance of not less than 76mm. Take the reading.
3. Place the penetration needle away from the edge of the mold (approximately four times the needle diameter), near the center, and place the individual penetrations so as not to interfere with one another. Penetrate the soil specimen not less than three times and use the average of the readings.
4. Determine the penetration resistance on each molded soil specimen as described in steps1-3.

Calculation and Plotting

1. Divide the average Penetrometer reading by the end area of the penetration needle and record the resulting value as the penetration resistance of the soil expressed in Kilopascals. Calculate the moisture content of the soil.
2. Plot the penetration-resistance values and the corresponding moisture contents on the same graph sheet with the corresponding moisture-density relations data. Plot the moisture-penetration resistance data immediately above the moisture-density data, using the same moisture content scale for both sets of data. The moisture-penetration resistance curve shall be established by not less than three determinations.

II. Sand Replacement Method (Test Method - ASTM D 1556)

Apparatus

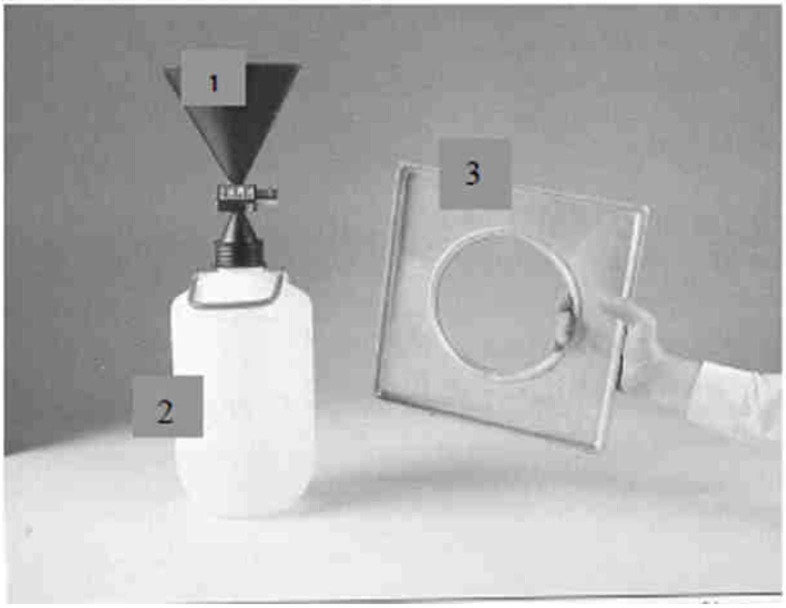
- Sand cone fitted with valve. The metal funnel is screwed on plastic jar, Base plate
- Sand: a clean, dry, a free flowing, unfermented sand having maximum particle size smaller than 2mm and less than 3% by weight passing 250μm, the uniformity coefficient (Cu=D60/ D10) must be less than 2.0(its uniformity helps to keep a constant density which is a requirement when volumes are to be determined from weight measurement). About 1kg of sand is required for each field measurement.
- Balances: one a 10kg capacity and accuracy to 1.0g and one with a 500g capacity and accuracy to 0.1g.
- Digging tools (chisels, hammers, picks, and large spoons)
- Airtight plastic bag or container to collect soils samples, Drying equipment, etc.

Calibration of Mechanical Device

Two calibration procedures are required for this test, one to determine the density and unit weight of the sand used in the test and the other to determine the mass of sand required to fill the sand cone (the funnel).

[A] Determination of Bulk Density and Unit Weight of Sand

1. Select a container or mold of known volume (or can be calculated). Take the mass. Fill the assembled sand cone apparatus with sand. Invert and support the apparatus over the calibrated container so that the sand falls approximately the same distance and location as in a field test, and fully open the valve.
2. Fill the container until it just overflow and close the valve. Using a minimum number of strokes and taking care not to jar or density the sand, carefully strike of excess sand to a smooth, level surface.
3. Clean any sand from outside the calibrated container. Determine the mass of container and sand. Determine the net mass of the sand by substituting the mass of the empty container.
4. Perform at least three bulk density determinations and calculate the average. The maximum variation between any one determination and average will not exceed 1%.



1-Sand Cone 2-Plastic jar 3-Base plate

Figure 7:4 - Sand Cone Apparatus.

[B] Determination of Mass of Sand Required to Fill Sand Cone and Base Plate

1. Fill the jar with sand completely, and measure its weight
2. Place the base plate on a clean, level, plane surface. The groove along the circular hole of the base plate should be faced up. Turn the sand cone upside down with the valve closed, and position the metal funnel on the base plate.
3. Open the valve fully and keep until the sand stops running, making sure the apparatus, base plate or plane surface are not jarred or vibrated before the valve is closed.
4. Close the valve sharply, determine the mass of the apparatus(jar)with remaining sand, and calculate the loss of sand. This loss represents the mass of sand required to fill the funnel and base plate.
5. Repeat the procedure in (1)-(4) at least three times. The mass of sand used in the calculation shall be the average of three determinations. The maximum variation between any determination and the average shall not exceed 1%.

Procedure

1. Inspect the cone apparatus damage free rotation of the valve, and properly matched base plate. Fill the cone container conditioned sand for which the bulk density has been determined, and determine the total mass.
2. Select a location/elevation that is representative of the area to be tested and level off the ground surface (the base plate may be used for this purpose).
3. Seat the base plate on the plane surface, making sure there is contact with the ground surface around the edge of the flanged center hole. Mark the outline of the base plate to check for movement during the test, and if needed, secure the plate against movement using nails pushed into the soil adjacent to the edge of the plate, or by other means, without disturbing the soil to be tested.
4. By using screwdriver, mark the base plate opening on the ground. Remove the base plate, and dig a hole with an opening size slightly larger than the base plate opening. The volume of the excavated hole should be smaller than 3830cm3 the full capacities of the sand cone jar. The sides of the hole should slop slightly in wards, and the bottom should be reasonably flat or concave. The hole should be kept as free as possible of pocket, overhangs, and sharp obtrusions since this affect the accuracy of the test. As a guide ASTM suggest the following volumes for the holes:

Table 7:3 - Minimum test hole volume suggested by ASTM

Maximum grain size, mm	Minimum test hole volume, cm3
4.75	700
12.7	1400
25.0	2100
50.0	2800

5. Carefully place all excavated soil, any soil loosened during digging in a moisture tight container that is marked to identify the test number. Take care to avoid losing any materials.
6. Center the base plate above the hole. The base plate opening should be facing up. If necessary, brush soils off the base plate. Turn the sand cone

upside down with the valve closed and positions the metal funnel on the groove of the base plate. Open the valve to let sand fill the hole, funnel and base plate. Take care to avoid jarring or vibrating the apparatus while the sand is running. When the sand stop flowing, close the valve.

7. Determine the mass of partially empty jar and calculate the mass of the sand used.
8. Salvage as much sand from the hole as possible.
9. Determine the mass of the moist materials that was removed from the test hole, and take a representative sample for water content determination.
10. Put the result in your data sheet and calculate.

Computation

The volume, V, of the sampling hole is as follows:

$$V = (W_f - W_e - W_s) / \rho_{sand}$$

Where

W_f=weight of the jar completely filled with sand

W_e=weight of partially empty jar

W_s=sand required to fill the cone and the base plate

ρ_{sand}= density of sand

$\rho = M / V$ Where M= the weight of the sample collected

$\rho_d = \rho / (1+w)$ Where w = the water content

Review Question

1. Why is it important not to lose any soil from the excavated hole during the sand cone method?
2. Why do we use particular sand for the sand cone method? Why not use any sand?
3. Do we recommend compaction for all types of soils?
4. How do we differentiate compaction and consolidation?
5. How do we relate compaction stages with subgrade constructions?

Table 7:4 - Soil Compaction Test data sheet

Mansoura High Institute of Eng. &Tech.					
Civil Engineering Department					
Soil Testing Laboratory			**Soil Compaction Test**		
Project	Location			Depth	
Client	Lab. no.			Date	
Responsible Technician	Tested by			Approved by	
Test Method	ASTM ……			BS ……	
Water content - Sample no.	**1**	**2**	**3**	**4**	**5**
Moisture can number - Lid number					
M_C = Mass of empty, clean can + lid (grams)					
M_{CMS} = Mass of can, lid, and moist soil (grams)					
M_{CDS} = Mass of can, lid, and dry soil (grams)					
M_S = Mass of soil solids (grams)					
M_W = Mass of pore water (grams)					
w = Water content, w%					
Density Determination:					
Compacted Soil - Sample no.	**1**	**2**	**3**	**4**	**5**
w = Assumed water content, w%					
Actual average water content, w%					
Mass of compacted soil and mold (grams)					
Mass of mold (grams)					
Wet mass of soil in mold (grams)					
3 Wet density, ρ , (g/cm)					
3 Dry density, ρ_d , (g/cm)					

8. PERMEABILITY

Permeability refers to the propensity of a material to allow fluid to move through its pores or interstices. In the context of soil, permeability generally relates to the propensity of a soil to allow water to move through its void spaces. According to Darcy's law, the flow rate of water through a soil of cross-sectional area A is directly proportional to the imposed gradient (slope) I, or

$$q/A \sim i$$

If a constant of proportionality K is introduced, we obtain the equation

$$q = KiA$$

The constant K is known as the coefficient of permeability, or just permeability. Obviously, it indicates the ease with which water will flow through a given soil. The greater the value of permeability, the greater the flow will be for a given area and gradient.

Permeability is an important soil parameter for any project where flow of water through soil is a matter of concern- for example, seepage through or under a dam, losses from irrigation ditches, estimate of pump age capacity for unwatering cofferdams and excavation below the water table. Determination of rate of settlement of a saturated compressible soil layer is also possible provided we know the permeability coefficient of that soil under the same in situ conditions. Spacing and depth of under-drains for lowering the water table under a road or runway in order to improve subgrade stability or draining water logged agricultural land is another type of problem in which Permeability of soil is paramount importance.

Permeability of soil depends on the viscosity of its water (which is a function of temperature), size and shape of particles, degree of saturation, and void ratio. Permeability is directly proportional to void ratio. Each value of permeability for a soil, therefore, should be associated with a particular void ratio. Normally, when a permeability value is needed, it is for the permeability of the soil in situ. Permeability is often, however, determined by laboratory tests; and to be representative of the soil's in situ permeability, tests should be performed on undisturbed samples. In the case of granular soils, however, it is extremely difficult to obtain undisturbed samples. Thus, the recommended procedure is to perform permeability test on three soil specimens of the same sample, with each specimen having a different void ratio. a relation between void ratio and permeability on a logarithmic scale verses void ratio on arithmetic scale. Then, whenever the value of the permeability of the soil in situ is needed, a sample can be taken at the project site, its void ratio determined, and associated permeability obtained from the graphical relationship.

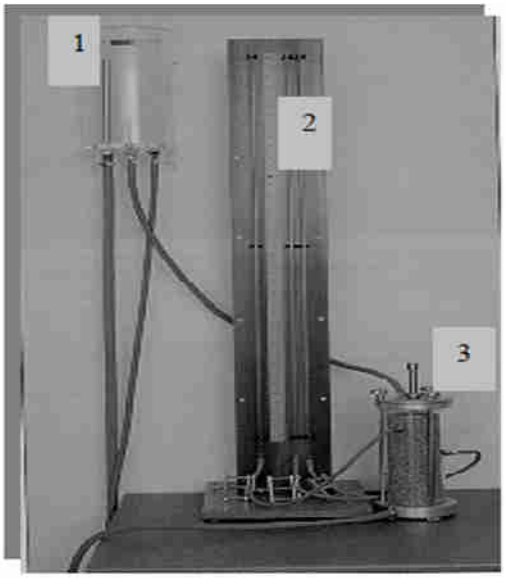
The coefficient of permeability of a soil sample in laboratory can be determined by (1) Constant-head permeability test or (2) Variable-head permeability test. The instruments used are known as permeameters. The former test is suitable for coarse-grain soils and the latter for fine-grained soils.

[A] Constant Permeability (Test Method- BS 1377 Part 5, 1990)

The test procedure described in this portion covers the determination of the coefficient of permeability using a constant-head permeameter in which the flow of water through the sample is laminar.

Equipment

Permeameter, Flexible transparent hoses and screw clamps necessary to connect piezometers and water supply, Timing device, Graduated cylinder (100ml), Internal caliper, Thermometer, etc.



1-Constant over head tank.

2- Manometer gland and its stand.

3-permeameter cell with sample.

Figure 8:1 – Permeameter

Selection and Preparation of Sample

1. Obtain a representative sample from the original soil sample and if required carry out a sieve analysis on a representative portion of the sample. Remove any particles that are larger than one-twelfth of the diameter of the permeability cell. The resulting sample should not be dried. The volume of the sample after removing the oversize material should be about twice that required to fill the permeability cell.

2. Take two or more representative sample from the prepared material for the determination of moisture content. Weigh the remainder of the prepared sample to 1g.

3. If a number of tests are to be performed at different densities to establish a relationship between permeability and void ratio, prepare several samples (one for each determination).

Preparation and Assembly

1) Initial preparation of apparatus

- Measure the internal diameter of the permeameter cell at several places and record the average diameter to the nearest 1mm(D).

- Measure the distance between each manometer gland and the next along the same vertical line, to the nearest 1mm.

- Ensure that the permeameter cell, gauze or porous discs, perforated plats, glands and joints are clean and free from blockage.

- Assemble the base plate, with perforated base, to the permeameter cell body.

- Place the graded filter material in bottom of the cell to a depth of about 50mm. Level the surface and place a wire gauze or porous disk on top.

2) Placing the test specimen

Place the soil to be tested into the permeameter in such a way as to give a homogeneous deposit at the required density or void ratio. The final height diameter ratio of the test sample should be not less than 2:1

- Place the soil in the permeameter in at least four layers, each of which is a thickness about equal to half the diameter. Place the first layer on the wire gauze or porous disc, and place subsequent layer on the previously leveled soil layer.
- Avoid segregation of soil particles when placing. Tamp each layer with a controlled number of standard blows with the tamping rod, ensuring that the blows are evenly distributed. Level the surface of each layer, and lightly scarify it, before adding the next.

3) Assembly of apparatus

After placing the test sample assemble the permeameter cell as follows

- Place the upper wire gauze or porous disc on top of the prepared sample. Avoid any disturbance of the sample if it is a low density.
- Place the graded filter material on top of the disc to a depth of at least 50mm.
- Release the piston on the top plate and withdraw it to its fullest extent.
- Fit the top plate to the permeameter cell and tighten it down into position.
- Lower the piston carefully and bed perforated plate on the filter material. Hold the piston down firmly and tighten the collar.

4) Measurements

- Determine the mean height of the test sample, by measuring to 1mm, the distance between the upper and the lower wire gauze or porous discs at three or more location around the perimeter.
- Weigh the mass of the remaining sample. The mass of sample in the permeameter cell is determined by subtracting this mass from mass of the original sample.

Test Procedure

1. Connect the inflow to the constant level overhead tank with a suitable connection.

2. Connect the overhead tank to a continuous water tap and connect the drainpipe of the overhead tank by a rubber tube and level the other end in a sink.
3. Open the air vent of the top cap of the permeameter and allow water to flow.
4. Close the air valve when all air has been expelled from the cap.
5. Allow sufficient time for water to flow and saturate the soil sample and eliminate the entrapped air in the soil pores.
6. When a constant flow has been established measure the discharge in a given time. Alternatively record the time required to fill the cylinder up to a given volume.
7. Record the level of water in the manometer tube. If the three (or more) levels indicate significant non-uniformity of the hydraulic gradient, remove and replace the sample.

   Note -Laminar flow is indicated when the relationship between the rate of flow and hydraulic gradient is linear. Deviation from the straight line at high gradient indicates turbulent flow.
8. Record the temperature of the water in the discharge reservoir.
9. Repeat (6) through (8) at least three more times, or until consistent reading are obtained.
10. If a relationship between coefficient of permeability and void ratio over a range of void ratio is required, repeat the whole test from (6) onwards using different portion of the same soil, but placed and compacted to different densities.

Calculation and Plotting

1) Calculate the rate of flow, q_1, q_2, etc. (in ml/s), during the period of each observation of flow from the equation.

   $$q_1=Q_1/t$$

   where

   Q1, Q2,(in ml) etc. is the volume of water collected from the outlet reservoir during each time period t(in s)

   Calculate the average rate of flow, q, for the set of reading at one hydraulic gradient.

2) Calculate the hydraulic gradient, i, between the uppermost and lower manometer gland points from the equation

   $$i= h/y$$

   Where

   h is the difference between the two manometer level (in mm)

   y is the difference between the corresponding gland points (in mm)

   Note- The intermediate manometer point is (or points are) used to provide a check on the uniformity of the hydraulic gradient between the outer points.

3) Calculate the coefficient of permeability, k (in m/s), for one set of reading from the equation

   $$k= R_t\,[q/(iA)]$$

   Where

   A = area of cross-section of the sample (in mm^2)

   Rt = is the temperature correction factor for the viscosity of water= η_T/η_{20^0c}

   Where η_T =Viscosity of water at temperature T.

   η_{20^0c} = Viscosity of water at 20^0c.

4) Calculate the bulk density and dry density of the test sample.

   ɣ= (mass of the sample in the permeability cell)/its volume

   The volume V= πD2L/4

$$\gamma_d = \gamma / (1+w)$$

Where D= sample diameter (in mm)

L = overall length of the sample

w = water content of the soil sample.

5) If the coefficient of permeability is determined at several densities, plot the calculated values of k as ordinates, to a logarithmic scale, against density or void ratio, e, as abscissa, to a linear scale. The void ratio, e, can be calculated as follows

$$e = (G\gamma_w/\gamma_d) - 1$$

[B] Falling Head Permeability Test

The falling-head method, covered in this part, may be used to determine the permeability of both fine-grained soils (such as silts and clays) and coarse-grained soils or granular soils.

Equipment

Permeameter, Ring stand with test tube clamp, Burette (100ml), Stopwatch, Thermometer, etc.

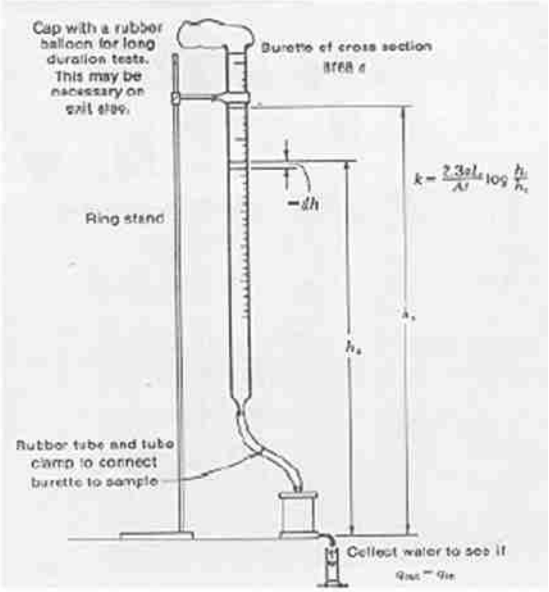


Figure 8:2 – Falling head permeability equipment

Preparation of Equipment

- Weigh the permeameter with baseplate and gasket attached.

- Measure the inside diameter of the permeameter, and calculate the area 'A'.
- Determine the area 'a ' of the standpipe (Burette) by measuring the volume of water contained in the standpipe section of given height.

Selection, Preparation and Placing of Specimen

Select, prepare and place the specimen as described in part [A]. Calculate the dry density of specimen by finding the mass of the permeameter and the permeameter plus compacted soil and taking the sample for water content determination. Also, measure specimen's length 'L'.

Test Procedure

1. Place the permeameter in a sink in which water is about 2in above the cover. Be sure the out let pipe is open so that water can back up through the specimen. This procedure will saturate the sample with a minimum amount of entrapped air. When water in the plastic inlet tube on the top of the mold reaches equilibrium with water in the sink (allowing for capillary rise in the tube), the specimen may be assumed to be saturated. (A soaking period of 24h might provide better result.)

2. With the water level stabilized in the inlet tube of the permeability mold, take a hose clamp and clamp the exit tube. Remove the permeability from the sink and attach it to the rubber tube at the base of the burette, which has been fastened to a ring stand. Fill the burette with water from a supply, which should be temperature-stabilized (and de-aired if desired).

3. Open the inlet tube from the burette. Fill the burette to a convenient height, and measure the hydraulic head across the sample to obtain h0. Remember that the exit tube is still clamped shut.

4. Open the exit tube and simultaneously start timing the test. Allow water to flow through the sample until the burette is almost empty. Simultaneously record the elapsed time and clamp only the exit tube. Measure the hydraulic head across the sample at this time’t’ to obtain h1. Take the temperature each time.

5. Refill the burette and repeat two additional times. Take the temperature each time.

Note - To check on whether the sample is saturated, one may collect the water coming out the exit tube and compare this volume with that entering the sample. Obviously, if $q_{out} < q_{in}$ the specimen was not saturated.

Calculation

1. Unit Weight Determination : Values of the unit weight of the air-dried soil specimen, water content of the air-dried soil, dry unit weight of the soil specimen, and void ratio can be computed in the same manner as related in part [A].
2. Permeability Test : The coefficient of permeability can be computed using the equation

$K = R_t (2.3aL)/ (At)* \log (h_0/h_l)$

Where

k = Coefficient of permeability, cm/s

a = cross-sectional area of standpipe, cm^2

L = length of the specimen, cm

A = cross-sectional area of soil specimen, cm^2

h_0 = hydraulic head at beginning of test, cm

h_l = hydraulic head at end of test, cm

t= total time for water in burette to drop from h0 to h1, s

R_t = is the temperature correction factor for the viscosity of water,

$R_t = \eta_T/\eta_{20^0c}$

Where η_T =Viscosity of water at temperature T.

η_{20^0c} = Viscosity of water at 20^0c.

Table 8:1: Constant Head Permeability test

<table>
<tr><td colspan="6">Mansoura High Institute of Eng. &Tech.</td></tr>
<tr><td colspan="6">Civil Engineering Department</td></tr>
<tr><td colspan="3">Soil Testing Laboratory</td><td colspan="3">Constant head permeability test</td></tr>
<tr><td colspan="2">Project</td><td colspan="2">Location</td><td colspan="2">Depth</td></tr>
<tr><td colspan="2">Client</td><td colspan="2">Lab. no.</td><td colspan="2">Date</td></tr>
<tr><td colspan="2">Responsible Technician</td><td colspan="2">Checked by</td><td colspan="2">Approved by</td></tr>
<tr><td colspan="6">Test Method</td></tr>
<tr><td colspan="6">Specimen Mass, Height, Diameter respectively</td></tr>
<tr><td colspan="6">Bulk density, γ</td></tr>
<tr><td colspan="6">Water Content, w</td></tr>
<tr><td colspan="6">Dry density, γ_{dry}</td></tr>
<tr><td colspan="6">Specific gravity of soil, Gs</td></tr>
<tr><td colspan="6">Initial void ratio, e</td></tr>
</table>

Trial	1	2	3
Piezometer tap distance, Y			
Piezometer level distance, Δh (mm)			
Duration of sampling, t (s)			
Volume of water collected, V			
Water temperature, T (0c)			
Hydraulic gradient, $i=\Delta h/y$			
Rate of flow, $q=Q/t$			
Rt at T			
Permeability at temperature of 200c			
Average Permeability, K, at 200c , m/s			

Table 8:2: Falling Head permeability test

Mansoura High Institute of Eng. &Tech.		
Civil Engineering Department		
Soil Testing Laboratory	**Falling Head Permeability**	
Project	Location	Depth
Client	Lab. no.	Date
Responsible Technician - - -	Checked by	Approved by
Test Method		
Specimen Mass		
Specimen Height, L		
Specimen diameter, D		
Bulk density, ɣ		
Water Content, w		
Dry density, γ_{dry}		
Specific gravity of soil, Gs		
Initial void ratio, e		

Cross-sectional area of stand pipe, a ________cm^2

Length of soil specimen in permeameter, L ______cm

Cross-sectional area of soil specimen, A______cm^2

Trial	1	2	3
Head, h_o(cm)			
Head,h_1 (cm)			
Time, t (s)			
Temperature, T (^{o}c)			
Permeability at T_{oc}, K_T			
R_t for T			
Permeability at 20^{o}C, K20			
Average K_{20} (cm/s)			

Review Question

1. What is the purpose of the constant head permeability test?
2. Is the permeability coefficient of sands influenced by their void ratio? What is the trend?
3. Why do you use de-aired water instead of tap water for the permeability test? Does it increase or decrease with the air content of the test water?
4. Does the permeability coefficient increase or decrease with the water temperature? Why?

9. ONE DIMENSIONAL CONSOLIDATION TEST

Consolidation is the process of time-dependent settlement of saturated clay soil when subjected to an increased loading. In this chapter, the procedure of a one-dimensional laboratory consolidation test will be described, and the methods of calculation to obtain the void ratio pressure curve (e vs.log p), the reconsolidation pressure (Pc), and the coefficient of consolidation (cv) will be outlined. Test method -**ASTM D 2435**.

When structures are built on saturated soil, the load is presumed to be carried initially by incompressible water with in the soil. Because of additional load on the soil, water will tend to extrude from the void in the soil, causing a reduction in void volume and settlement of a structure. The phenomenon of this compression due to very slow extrusion of water from the void in a fine-grained soil as a result of increased loading (such as the weight of a structure on the soil) is known as **consolidation**. Associated settlement is referred to as **consolidation settlement.**

In soils of high permeability (coarse-grained soils), consolidation requires a short time interval for completion, with the result that almost all of the settlement has occurred by the time of construction is complete. However, in soils of low permeability (fine-grained soils particularly clayey soils), the process requires a long time interval for completion, with the result that strain occurs very slowly.

The method presents in this practice cover a procedure for determining the rate and the magnitude of consolidation of soil when it is restrained laterally and loaded and drained axially (known as one-dimension consolidation test). The data from the consolidation test can be used to develop an estimate of both the rate and the amount of both differential and total settlement of a structure or a landfill. Estimates of this type are often of key importance in first selecting a foundation type and secondly in evaluating its adequacy.

Apparatus

Load device, Consolidometer, Porous stone, Specimen ring, Extensometer (dial gauge) of sensitivity 0.0025mm, specimen trimming equipment (wire saw, sharp-edged knife), Balance(sensitive to 0.01g), Drying oven, stop watch, moisture can, and etc.

Specimen Preparation

1. Trim the specimen from an undisturbed sample of soil, taken from either from a sample tube or as an excavated block sample, to the inside diameter of the Consolidometer forcing it directly into the ring during trimming. Trim it flush with the plane surface of the ring. For soft to medium soils, a wire saw should be used for trimming the top and the bottom of the

specimen to minimize smearing. A straightedge with a sharp cutting edge may be used for the final trim after the excess soil has first been removed with a wire saw. For stiff soil, a sharpened straightedge alone may be used for trimming the top and bottom. If desired, the specimen height may be made less than the ring height by partial extrusion and trimming, provided the minimum specimen thickness requirement is used. The minimum specimen height should be 13mm but should not less than 10 times the maximum particle diameter. The minimum specimen diameter-to-height ratio should be 2.5.

2. Specimen measurement

- Determine the initial wet mass of the specimen, M_O, in the consolidation ring by measuring the mass of the ring with the specimen and subtracting the tare mass of the ring.
- Determine the initial height H_o, of the specimen to the nearest 0.025mm.
- Compute the initial volume $V_{o,}$ of the specimen to the nearest 0.25cm^3 from diameter of the ring and initial specimen height.

3. Obtain two or three water content determination of the soil from the material trimmed adjacent to the test specimen if sufficient material is available.
4. When index properties are required store the remaining from the trimming taken from around the specimen.

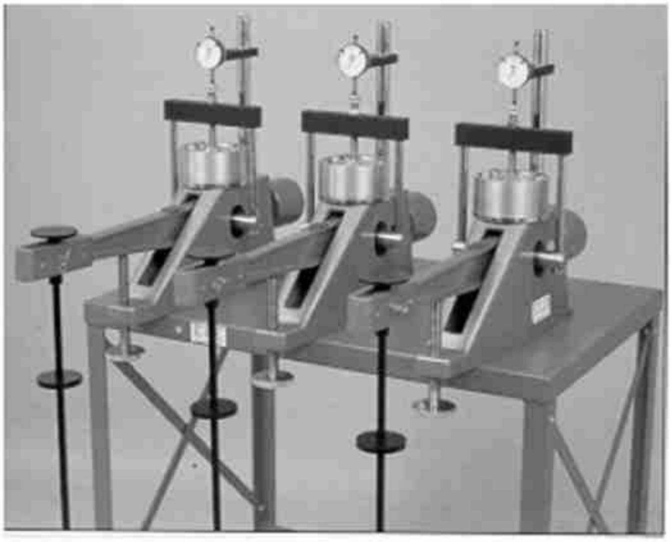


Figure 9:1 - Consolidation frame with Dial Gauge (with three gangs)

Soil index property determination

The determination of index properties is an important adjunct to but not a requirement of the consolidation test. When required all index tests such as: specific gravity, Atterberg limits, and particle size distribution may be performed on adjacent trimmings collected in specimen preparation.

Procedure

1. Porous plates. Before using the porous plate in a test they should be prepared as follows:

1.1. Clean the surfaces a natural bristle or nylon brush.

1.2. If the specimen is saturated, saturate the porous by boiling in distilled water for at least 20min, until the time of their contact with the specimen. If the specimen is very dry, highly expansive soil, place it on dry stone, but if it is partially saturated, place it on stones that have simply been damped.

2. Assembly of consolidation cell

2.1. Place the bottom porous plate, which is prepared as in step 1.

2.2. Place the specimen contained in its ring centrally on top of the porous plate.

2.3. Assemble the cell components so that the consolidation ring is laterally confined and in correct alignment.

2.4. Place the top porous plate and loading cap centrally on top of specimen.

3. Assembly in load frame

1) Place the consolidation cell in position on the bed of the loading apparatus.

2) Adjust the counter balanced loading beam so that when the load-transmitting members just make contact with the loading cap the beam is slightly above the horizontal position.

3) Add a small weight to the beam hanger, sufficient to maintain contact between the load-transmitting members while final adjustments are made. The resulting seating pressure should not exceed 5Kpa.

4) Within 5min after application of setting load, arrange the gauge to allow for measurement of a small amount of swelling of the specimen, while the greater part of the range of travel allows for compression. Record the initial reading of the gauge, di.

4. Loading sequence. Arrange of pressure selected from the following sequence has been found to be satisfactory. 6,12,25,50,100,200,400,etc Kpa

5. Record the gauge reading for the load increment stage, di.

6. Apply the required pressure to the specimen at a convenient moment by adding the appropriate weight to the beam hanger without jolting. Remove the weight used for the seating load.

7. Fill the consolidation cell with water (i.e inundate the specimen) after applying the pressure. If the specimen begins to swell, or if compression virtually ceases with short time, proceed to the next higher pressure to prevent swelling. Alternatively, if required, determine the swelling pressure.

8. Take readings of the compression gauge at suitable interval of time. The following approximate periods of elapsed time from zero are convenient.

   - 0.1,0.25,0.5,1,2,4,8,15,and 30min, 1,2,4,8,etc h if displacement versus log of time plot is required.

   - 0.09, 0.25, 0.49, 1, 4, 9, etc. min if displacement versus square root of time plot is required.

9. Plot the dial gauge readings against log of time, or square root of time, while the test is in progress.

10. Maintain the pressure until the plotted readings indicate that primary consolidation (see calculation and plotting part of this Lab Practice) has been completed. For soils that have slow primary consolidation, pressures should be applied for at least 24h. In extreme cases, or where secondary compression must be evaluated, they should be applied much longer.

11. Record the time and compression gauge reading at the termination of load increment stages. This reading becomes the initial reading for the next stage.

12. Increase the pressure to the next value in the selected sequence.

13. Repeat step 12 for further stages of the sequence of loading, making at least four stages in all (BS 1377). The maximum pressure to the specimen should be greater than the effective pressure, which will occur in situ due to the overburden and proposed construction.

14. Rebound (Unloading)

1) On completion of the recording of the compression gauge readings, in accordance with step10 under the maximum required pressure, unload the specimen as follows if the unloading curve is required. Otherwise proceed at step 15. The unloading portion of the log pressure versus void ratio curve is required in some methods of analysis for estimating the reconsolidation pressure (which is the largest effective stress undergone by the soil, see Calculation and Plotting section) for the soil.

2) The standard rebound or unloading, schedule should be selected by halving the pressure on the soil (i.e use the same increments of step 4, but in reverse order). However, if desired, each successive load can be only one fourth as large as the preceding load; that is, skip a decrement.

3) Record readings of the compression gauge at convenient intervals such as those indicated in step 8.

4) Plot the readings so that the completion of swell can be identified.

5) Record the final reading of the compression gauge.

6) Repeat 14.2-14.5, finishing with an applied pressure equal to the swelling pressure (if applicable) or to the initial applied pressure.

7) When the compression gauge indicates that equilibrium under the final pressure has been reached proceed to step 15.

15. Dismantling

1. To minimize swell during disassembly, rebound the specimen back to the seating load. Once height change has ceased (usually overnight), remove the load from the specimen and remove the consolidation cell from the apparatus and wipe any free water from the ring and specimen.

2. Determine the mass of the specimen in the ring and subtract the tare mass of the ring to obtain the final wet specimen mass.

2.1 Transfer the entire specimen on moisture can to oven maintained at 105°c to 110°c to get the final dry mass and water content.

Calculation and plotting

1. Specimen parameters

1.1 Initial wet density, ρ_o (in g/cm^3)

$$\rho_o = \frac{m_o}{v_o}$$

Where

m_o= the initial mass of the specimen in ring

v_o= the initial volume

1.2 Initial dry density, ρ_{do} (in g/ cm^3)

$$\rho_{do} = \frac{\rho_o}{1+w_o}$$

Where w_o = the initial water content (in decimal)

1.3 Initial void ratio, e_o

$$e_o = \frac{G\rho_w}{\rho_{do}} + 1$$

Where

G = the specific gravity of the soil

ρ_w = density of water (1g/cm^3)

1.4 Initial degree of saturation, So (this value can be used to indicate whether the test specimen is fully saturated initially)

$$S_O = \frac{GW_o}{e_o}$$

1.5 The water content and void ratio after the consolidation test are calculated similarly to the initial quantities by the sample height and weight of wet sample after the test.

2. Coefficient of consolidation, c_v

   It relates to how long it will take an amount of consolidation to take place. Two curve fitting methods are recognized for evaluating the coefficient of consolidation, namely logarithm-of-time curve-fitting method and the square root time curve-fitting method.

2.2 **Log time curve- fitting method**

2.2.1 From those increments of load where time-versus-deformation readings are obtained, plot deformation readings versus logarithm of time (in minute) for each increment of load or pressure as the test progresses and for any increments of rebound where time-versus-deformation data have been obtained.

2.2.2 Find the deformation representing 100% primary consolidation for each load increment. First, draw straight line through the points representing final readings that exhibit a straight line trend and flat slop. Then, draw a second straight line tangent to the steepest part of the curve. The intersection of these two lines represents the deformation corresponding to 100% primary consolidation. Compression that occurs subsequent to 100% primary consolidation is defined as secondary compression.

2.2.3 Find the deformation representing 0% primary consolidation by selecting deformation at any two times that have a ratio of 1:4. The deformation corresponding to the larger of the two times should be greater than one-fourth but less than one-half of the total change in deformation for the load increment. The deformation corresponding to 0% primary consolidation equal to the deformation corresponding to the smaller time interval less the difference in deformations for the two selected times.

2.2.4 The deformation corresponding to 50% primary consolidation (d50) for each load increment is equal to the average of the deformations corresponding to the 0 and 100% deformations. The time required for 50% consolidation under any load increment may be found graphically from the curve for that load increment by observing the time that corresponds to 50% of the primary consolidation of the curve.

2.2.5 Determine the sample height, H, at 50% consolidation

$$H = H_o - (d_{50} - d_i)$$

Where H_o = initial height of specimen at the beginning of test

d_{50} = deformation reading @50% consolidation

d_i = deformation reading @ the beginning of the test

2.2.6 Calculate the coefficient of consolidation, cv (in m^2/year), for each load increment from the equation

$$C_v = 0.05\frac{H^2}{t_{50}}$$

Where C_v= coefficient of consolidation, in m^2/year

H= sample height for doubly drained sample @50%

Consolidation for singly drained H equals twice the sample height

$H=2[H_0-(d_{50}- d_i)]$, in m

t_{50}=time for 50% consolidation, in year

2.2.7 Repeat 2.1.1 - 2.1.6 for each of the applied load.

2.3 Square root time curve -fitting method

2.3.1 From those increments of load where time-versus-deformation readings are obtained, plot deformation readings versus the square of time in minute for each increment of load.

2.3.2 Draw a straight line of best fit to the early portion of the curve (usually within the first 50% of compression) and extend it to intersect the ordinate of zero time. The corresponding deformation ordinate do represents 0% primary consolidation.

2.3.3 Draw second straight line through do point which at all points has abscissa 1.15 times as great as those on the first straight line. The intersection of this line with the deformation -square root time curve gives 90% primary consolidation.

2.3.4 The deformation at 100% primary consolidation is 1/9 more than the difference in deformation between 0 and 90% consolidation. Similarly, the deformation at 50% consolidation is 5/9 of the difference between that at 0 and 90%.

2.3.5 Determine the sample height ,H, at 90% consolidation

$$H = H_o - (d_{90} - d_i)$$

Where

H_o = initial height of specimen at the beginning of test

d_{90} = deformation reading @90% consolidation

d_i = deformation reading @ the beginning of the

2.3.6 Calculate the coefficient of consolidation, cv, in m2/year from the time of 90% consolidation by the equation

$$C_v = 0.21\frac{H^2}{t_{90}}$$

Where

c_v= coefficient of consolidation, in m2/year

H= sample height for doubly drained sample @90% Consolidation, in m

t_{90}=time for 90% consolidation, in year

2.3.7 Repeat 2.2.1-2.2.6 for each of the applied load

2.4 Coefficient of secondary compression

The coefficient of secondary compression, if requires, is derived from log of time curve as follows

2.4.1 Extend the linear portion of the secondary compression portion of the curve, obtain as described in 2.1.2, so that it covers one complete cycle of log time. It may be necessary to prolong the duration of the load increment to establish a linear relationship.

2.4.2 Read off the compression dial gauge readings at the beginning and end of the cycle, e.g. at 1000min and 10000min, and calculate the difference , δH_s (in mm), between them.

2.4.3 Calculate the coefficient of secondary compression, c_{sec}, from the equation

$$C_{sec} = \frac{\delta H_s}{H_o}$$

Where H_o = the initial height of the specimen.

2.4.4 Repeat 2.3.1-2.3.3 for each of the applied loading stage.

3. Compression and swelling indices, Coefficient of compressibility, m_v, and Preconsolidation pressure

3.1 First prepare plot of void ratio versus log of pressure curve following steps

3.1.1 Compute void ratio corresponding to 100% primary consolidation for each load.

$$e = e_o - \Delta e$$

$$\Delta e = G\rho_w A \frac{d_{100} - d_i}{M_s}$$

But

Where d_{100}= dial gauge reading @ 100% pre consolidation

d_i= dial reading at the beginning of the test

G = specific gravity of the soil

ρ_w = density of water

A =c/s area of specimen

M_s = mass of entire dry specimen at end of test

3.1.2 Plot values of void ratio (computed in3.1.1) as ordinate against the corresponding applied pressure on logarithmic scale as abscissa

3.1.3 Indicate the position of e_o on the plot.

3.2 Compression index (C_c) and Swelling index (C_s)

First plot the field consolidation line [Refer to Soil and Foundations, by Liu and Evett, how to prepare this.] From this plot:

C_c = the slop of the virgin consolidation line (VCL) or Field consolidation line

$$C_c = \frac{e_B - e_c}{\log({}^{P_c}/_{P_B})}$$

Where B and C are two points on the VCL

Cs = the slope of a swelling curve (Rebound line)

$$C_s = \frac{e_D - e_c}{\log({}^{P_c}/_{P_D})}$$

Where C and D are two points on a swelling line.

3.3 **Coefficient of compressibility** *,mv*

Within the small stress interval from p_1 to p_2 , the e-log p curve is characterized by the coefficient of compressibility as:

$$m_v = (\frac{e_1 - e_2}{1 + e_1})\frac{1}{P_2 - P_1}$$

Where e_1 and e_2 are the void ratio at p_1 and p_2 respectively.

Note: mv varies with the stress level and loading direction (i.e., loading or unloading). m_v is generally used to calculate the vertical settlement s of a layer of initial thickness ho subjected to the increased Δp in pressure

$$S = m_v h_o \Delta p$$

(This equation applied provided that the soils in the laboratory and field undergo a similar stress load, stress increment, and loading direction).

3.4 Determination of Preconsolidation pressure (Casagrande Method)

3.4.1 Choose the point P1 of minimum curvature on the consolidation curve(e-log p curve)

3.4.2 Draw horizontal line through P1

3.4.3 Draw tangent line to the curve at P1

3.4.4 Divide the angle formed by lines drawn at 3.4.2 and 3.4.3 by a line l.

3.4.5 The intersection between the line formed by 3.4.4 and the extension of VCL give the point of preconsolidation pressure.

4. Prepare a graph of pressure along the abscissa on a logarithmic scale versus coefficient of consolidation along the ordinate on arithmetic scale to see the variation of coefficient of consolidation with pressure.

Table 9:1: Consolidation of Soils

<table>
<tr><th colspan="3">Mansoura High Institute of Eng. &Tech.</th></tr>
<tr><th colspan="3">Civil Engineering Department</th></tr>
<tr><th colspan="2">Soil Testing Laboratory</th><th>Consolidation of Soils</th></tr>
<tr><td>Project</td><td>Location</td><td>Depth</td></tr>
<tr><td>Client</td><td>Lab. no.</td><td>Date</td></tr>
<tr><td>Responsible Technician</td><td>Checked by</td><td>Approved by</td></tr>
<tr><td colspan="3">Test Method</td></tr>
</table>

[A] Specimen Data

At Beginning of Test

(1) Type of specimen (check one) ……. Undisturbed ……… Remolded

(2) Area of Specimen, A ………..

(3) Initial height of specimen, H_0 …………

(4) Initial volume of specimen [i.e., (2) x (3)]………….

(5) Mass of specimen ring ……….. g

(6) Mass of specimen ring + specimen ……….. g

(7) Initial wet mass of specimen [i.e., (6)-(5)] ……….. g

(8) Initial wet unit weight, ρ_0

(9) Initial moisture content

a. Can No. ……..

b. Mass of wet soil + can ………….. g

c. Mass of dry soil + can ………….. g

d. Mass of can ……… g

e. Mass of water [i.e., b-c] ...……… g

f. Mass of dry soil [i.e., c-d] ………. g

g. Initial moisture content ………… %

(10) Initial dry unit weight, ρ_{d0} ………..

(11) Specific gravity of soil …………...

(12) Initial void ratio [i.e., $e_0 = (G\rho_w/\rho_{d0})-1$] ……..

(13) Initial degree of saturation [i.e., $s_0 = Gw_0/e_0$] …….. %

At End of Test

(14) Can No. ………

(15) Mass of can + wet specimen removed from Consolidometer ……… g

(16) Mass of can + oven-dried specimen ………. g

(17) Final mass of water in the specimen [i.e., (15)-(16)]…….. g

(18) Final dry mass of specimen [i.e., (16)-(14)]……… g

(19) Final Moisture content …………. %

(20) Final degree of saturation ………. %

[B] Time-verses-Deformation Data

(1) Pressure increment from ……… Kpa to ……… Kpa

Elapsed Time (min)	Deformation Dial Reading (mm)

[C] Void Ratio

(1) Initial void ratio, e_0= ………

(2) Height of solid in specimen [i.e. $H_s=M_s/AG\rho_w$] ……….

(3) Initial Deformation Dial Reading at Beginning of the test ………….

Pressure (Kpa)	Deformation Dial reading representing 100% primary consolidation	Change in Thickness of Specimen, ΔH	Change in Void Ratio [$\Delta e=\Delta H/Hs$]	Void Ratio [$e=e_0-\Delta e$]
(4)	(5)	(6)=(5)-(3)	(7)=(6)/(2)	(8)=(1)-(7)

[D] Coefficient of Consolidation

(1) Initial Height of specimen at the beginning of the test, H_0

Pressure P (Kpa)	Deformation dial reading at 50% consolidation	Thickness of specimen at 50% consolidation	Half-thickness of specimen at 50% consolidation.	Time for 50% consolidation (min)	Coefficient of consolidation, Cv (m^2/year)
(2)	(3)	(4)=(3)-(1)	(5)=(4)/2	(6)	(7)=0.2x(5)2 / (6)

Review Questions

1. Which soil properties to be measured during a consolidation test? To what kinds of soils is well suitable for the consolidation test? Why? Which are not well suited? Why?
2. What is the physical meaning of coefficient of consolidation?
3. What are normally consolidated and over consolidated clays? Give example of geologic conditions that would form each type. How do you know that a sample of clay is normally consolidated or over consolidated from the laboratory test?
4. In what range should a loading sequence in the consolidation test be selected?
5. How do you detect the secondary compression during the consolidation test?
6. Why do we measure the final height of the sample after consolidation test?
7. Define virgin consolidation line and swelling line.
8. Why do we have to keep the sample fully saturated during the consolidation test?
9. By using the log time method, calculate the coefficient of consolidation and secondary consolidation for the given data.

Assume H_o=2cm. Pressure increment= 9.6-19.2 Kpa

Elapsed Time	Dis. Dial gage, cm
0.00	0.0000
0.10	0.0170
0.25	0.0175
0.50	0.0180
1.00	0.0196
2.00	0.0213
4.00	0.0241
8.00	0.0271
15.00	0.0305
30.00	0.0335
60.00	0.0366
120.00	0.0386

240.00	0.0401
480.00	0.0406
1380.00	0.0411
1560.00	0.0411

10. Plot for the data in the following table void ratio-versus-effective stress curve, and determine the preconsolidation pressure and compression and swelling indices. Assume the initial void ratio to be 0.640 and the present effective overburden pressure 80Kpa.

Effective stress, Kpa Void ratio, e

Effective stress, KPa Void ratio, e

Effective stress, KPa	Void ratio, e
1.8	0.639
7.9	0.634
16.1	0.629
30.5	0.620
74.5	0.607
151.0	0.573
322.0	0.513
652.8	0.459
1258.2	0.394
2728.4	0.340
1196.3	0.346
316.6	0.365
78.4	0.382
33.8	0.396
17.2	0.408

10. APENDICES

AASTHO AND ASTM SOIL TEST DESIGNATION

Table 11:1: Some important AASHTO and ASTM soil test designations

Name of test	AASHTO test designation	ASTM test designation
Water content	T- 265	D-2216
Specific gravity	T-100	D-854
Sieve analysis	T-87, T-88	D-421
Hydrometer analysis	T-87, T-88	D-422
Liquid limit	T-89	D-4318
Plastic limit	T- 90	D-4318
Shrinkage limit	T- 92	D-427
Standard proctor compaction	T- 99	D-698
Modified	T- 180	D-1557
Field density by sand cone	T- 191	D-1556
Permeability of granular soil	T- 215	D-2434
Consolidation	T- 216	D-2435
Direct shear (granular soil)	T- 236	D-3080
Unconfined compression	T- 208	D-2166
Triaxial	T- 234	D-2850
AASHTO soil classification system	M-145	D-3282
Unified soil classification system	-	D-2487

SYMBOLS FOR SOIL AND WATER PROPERTIES

Table 11:2: Symbols for Soils and Water properties

Measured quantity	**Symbol**	**Unit of measurement**
Moisture content	w	%
Liquid limit	W_l	%
Plastic limit	W_p	%
Plastic index	L_p	%
Non-plastic	NP	
Relative consistency	C_r	
Liquidity index	I_l	
Shrinkage limit	W_s	%
Linear shrinkage	L_s	%
Shrinkage ratio	R	
Unit weight	γ	kN/m^2
Bulk (mass) density	ρ	Mg/m^3
Dry density	ρ_d	Mg/m^3
Saturated density	ρ_s	Mg/m^3
Submerged density	ρ’	Mg/m^3
Minimum dry density	ρ_{dmin}	Mg/m^3
Maximum dry density	ρ_{dmax}	Mg/m^3
Optimum moisture content	OMC	%
Density of soil particles	ρ_s	Mg/m^3
Density of liquid	ρ_l	g/ml or Mg/m^3
Degree of situation	S	%
Voids ratio	e	
Porosity	n	
Percentage air voids	V_a	%
Particle size	D	µm or mm
Percentage smaller than D	P	%
Effective size	D_{10}	Mm
‘60% finer than’ size	D_{60}	mm
Uniformity coefficient	`U	
Dynamic viscosity of water	η	MPas

Table 11:3: Density of Water & Correction Factor K for Various Temperatures (Specific Gravity)

Temperature, ^{o}C	Density of water(g/ml)	Correction Factor, K
16.0	0.99897	1.0007
16.5	0.99889	1.0007
17.0	0.99880	1.0006
17.5	0.99871	1.0005
18.0	0.99862	1.0004
18.5	0.99853	1.0003
19.0	0.99843	1.0002
19.5	0.99833	1.0001
20.0	0.99823	1.0000
20.5	0.99812	0.9999
21.0	0.99802	0.9998
21.5	0.99791	0.9997
22.0	0.99780	0.9996
22.5	0.99768	0.9995
23.0	0.99757	0.9993
23.5	0.99845	0.9992
24.0	0.99732	0.9991
24.5	0.99720	0.9990
25.0	0.99707	0.9988
25.5	0.99694	0.9987
26.0	0.99681	0.9986
26.5	0.99668	0.9984
27.0	0.99654	0.9983
27.5	0.99640	0.9982
28.0	0.99626	0.9980
28.5	0.99612	0.9979
29.0	0.99597	0.9977
29.5	0.99582	0.9976
30	0.99567	0.9974

Table 11:4: Factors a and b for Different Specific Gravity (for hydrometer analysis)

Gs	**2.95**	**2.90**	**2.85**	**2.80**	**2.75**	**2.70**	**2.65**	**2.60**	**2.55**	**2.50**	**2.45**
a	0.94	0.95	0.96	0.97	0.98	0.99	1.00	1.01	1.02	1.03	1.05
b	1509.80	1525.86	1541.92	1557.98	1574.04	1590.11	1606.17	1622.23	1638..29	1654.35	1686.48

Table 11:5: Value of K for Use in Equations for Computing Diameter of Particle in Hydrometer Analysis

Temp. (^oC)	**Specific Gravity of Soil Particles**								
	2.45	**2.50**	**2.55**	**2.60**	**2.65**	**2.70**	**2.75**	**2.80**	**2.85**
16	0.01510	0.01505	0.01481	0.01457	0.01435	0.01414	0.01394	0.01374	0.01356
17	0.0151	0.01486	0.01462	0.01439	0.01417	0.01396	0.01376	0.01356	0.01338
18	0.01492	0.01467	0.01443	0.01421	0.01399	0.01378	0.01359	0.01339	0.01312
19	0.01474	0.01449	0.01425	0.01403	0.01382	0.01361	0.01342	0.01323	0.01305
20	0.01756	0.01431	0.01408	0.01386	0.01365	0.01344	0.01325	0.01307	0.01289
21	0.01438	0.01414	0.01391	0.01369	0.01348	0.01328	0.01309	0.01291	0.01273
22	0.01421	0.01397	0.01374	0.01353	0.01332	0.01312	0.01294	0.01276	0.01258
23	0.01404	0.01381	0.01358	0.01337	0.01317	0.01297	0.01279	0.01261	0.01243
24	0.01388	0.01365	0.01342	0.01321	0.01301	0.01282	0.01264	0.01246	0.01229
25	0.01372	0.01349	0.01327	0.01306	0.01286	0.01267	0.01249	0.01232	0.01215
26	0.01357	0.01334	0.01312	0.01291	0.01272	0.01253	0.01235	0.01218	0.01201
27	0.01342	0.01319	0.01297	0.01277	0.01258	0.01239	0.01221	0.01204	0.01188
28	0.01327	0.01304	0.01283	0.01264	0.01244	0.01225	0.01208	0.01191	0.01175
29	0.01312	0.01290	0.01269	0.01249	0.01230	0.01212	0.01195	0.01178	0.01162
30	0.01298	0.01276	0.01256	0.01236	0.01217	0.01199	0.01182	0.01165	0.01149

Table 11:6: Viscosity Correction for $R_t = \eta / \eta 20$ (for permeability)

ºC	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
10	1.3012	1.2976	1.2940	1.2903	1.2867	1.2831	1.2795	1.2759	1.2722	1.2686
11	1.2650	1.2615	1.2580	1.2545	1.2510	1.2476	1.2441	1.2406	1.2371	1.2336
12	1.2301	1.2268	1.2234	1.2201	1.2168	1.2135	1.2101	1.2068	1.2035	1.2001
13	1.1968	1.1936	1.1905	1.1873	1.1841	1.1810	1.1777	1.1746	1.1714	1.1683
14	1.1651	1.1621	1.1590	1.1560	1.1529	1.1499	1.1469	1.1438	1.1408	1.1377
15	1.1347	1.1318	1.1289	1.1260	1.1231	1.1202	1.1172	1.1143	1.1114	1.1085
16	1.1056	1.1028	1.0999	1.0971	1.0943	1.0915	1.0887	1.0859	1.0803	1.0802
17	1.0774	1.0747	1.0720	1.0693	1.0667	1.0640	1.0613	1.0586	1.0560	1.0533
18	1.0507	1.0480	1.0454	1.0429	1.0403	1.0377	1.0351	1.0325	1.0300	1.0274
19	1.0248	1.0223	1.0198	1.0174	1.0149	1.0124	1.0099	1.0074	1.0050	1.0025
20	1.0000	0.9976	0.9952	0.9928	0.9904	0.9881	0.9857	0.9833	0.9809	0.9785
21	0.9761	0.9738	0.9715	0.9692	0.9669	0.9646	0.9623	0.9600	0.9577	0.9554
22	0.9531	0.9509	0.9487	0.9465	0.9443	0.9421	0.9399	0.9377	0.9355	0.9333
23	0.9311	0.9290	0.9268	0.9247	0.9225	0.9204	0.9183	0.9161	0.9140	0.9118
24	0.9097	0.9077	0.9056	0.9036	0.9015	0.8995	0.8975	0.8954	0.8934	0.8913
25	0.8893	0.8873	0.8853	0.8833	0.8813	0.8794	0.8774	0.8754	0.8734	0.8714
26	0.8694	0.8675	0.8656	0.8636	0.8617	0.8598	0.8579	0.8560	0.8540	0.8521
27	0.8502	0.8484	0.8465	0.8447	0.8428	0.8410	0.8392	0.8373	0.8355	0.8336
28	0.8318	0.8300	0.8282	0.8264	0.8246	0.8229	0.8211	0.8193	0.8175	0.8157
29	0.8139	0.8122	0.8105	0.8087	0.8070	0.8053	0.8036	0.8019	0.8001	0.7984
30	0.7967	0.7950	0.7934	0.7917	0.7901	0.7884	0.7867	0.7851	0.7834	0.7818
31	0.7801	0.7785	0.7769	0.7753	0.7737	0.7721	0.7705	0.7689	0.7673	0.7657
32	0.7641	0.7626	0.7610	0.7595	0.7579	0.7564	0.7548	0.7533	0.7517	0.7502
33	0.7486	0.7471	0.7456	0.7440	0.7425	0.7410	0.7395	0.7380	0.7364	0.7349
34	0.7334	0.7320	0.7305	0.7291	0.7276	0.7262	0.7247	0.7233	0.7218	0.7204
35	0.7189	0.7175	0.7161	0.7147	0.7133	0.7120	0.7106	0.7092	0.7078	0.7064

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