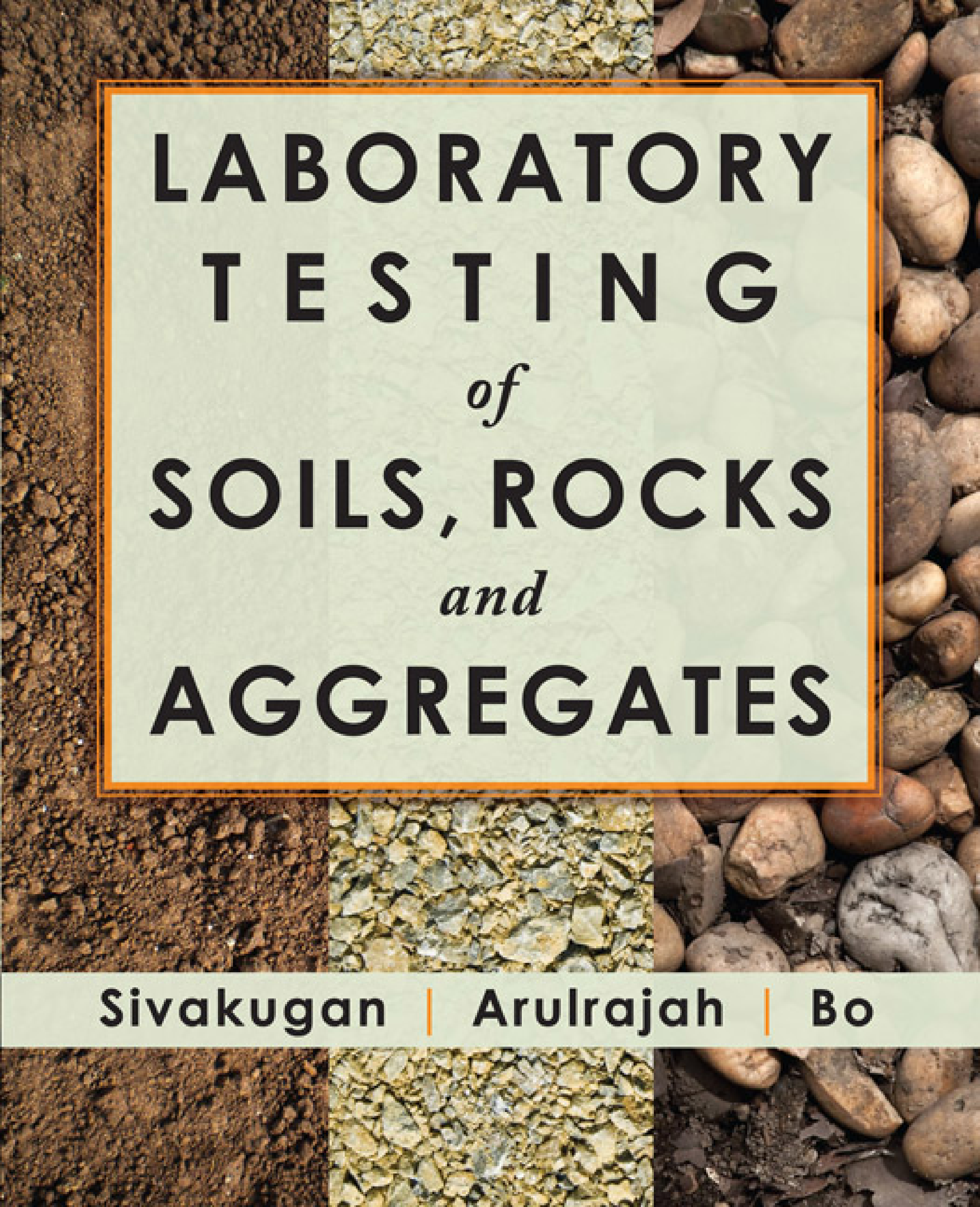

LABORATORY TESTING *of* SOILS, ROCKS *and* AGGREGATES

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Soil Testing

Part B

INTRODUCTION

Soil testing is an integral part of a site investigation program. The disturbed and intact soil samples collected at the site are taken to geotechnical laboratories where specific tests are performed. Some tests (e.g., consolidation or triaxial tests) require good quality intact samples whereas disturbed samples are adequate for the others (e.g., water content or Atterberg limits).

This section of the book covers most of the important soil tests that are carried out in geotechnical engineering laboratories. This includes visual classification and identification of soils, grain size distribution through sieve and hydrometer analyses, Atterberg limits, compaction, permeability, consolidation, strength, and others. Rock tests are covered in Part C and aggregates in Part D. Some of the tests that are covered in Part D, for example, aggregate testing, are also applicable to soils. The soil tests described in this section can be broadly categorized as:

I. Soil classification
    a. Visual identification and classification of coarse grained soils
    b. Visual identification and classification of fine grained soils
    c. Water content
    d. Specific gravity
    e. Sieve analysis
    f. Hydrometer analysis
    g. pH
    h. Organic content
    i. Liquid limit by Casagrande's percussion cup
    j. Liquid limit by fall cone
    k. Plastic limit
    l Linear shrinkage

II. Earthwork
    a. Compaction
    b. Maximum dry density of a cohesionless soil
    c. Minimum dry density of a cohesionless soil
    d. Field density measurement
    e. California Bearing Ratio

III. Permeability
  a. Permeability of a coarse grained soil—constant head
  b. Permeability of a fine grained soil—falling head
IV. Consolidation
  a. One-dimensional consolidation by incremental loading
V Strength
  a. Direct shear
  b. Consolidated, undrained triaxial
  c. Unconsolidated, undrained triaxial
  d. Unconfined, compressive strength

STANDARDS

The test procedures described here are based on the ASTM International standards (ASTM), the Australian standards (AS), and British standards (BS). The relevant standards are shown at the beginning of each test with an asterisk to signify the one that was followed more closely when it is not ASTM. For example, some of the aggregate tests are based on the British standards and most of the rock tests are based on the International Society of Rock Mechanics suggested procedures.

ASTM produces standards, in more than 75 volumes, for soils, rocks, aggregates, and other materials, including paint, textiles, rubber, and plastics. ASTM standards are published under several *sections*, one of which is "Section 4—Construction" which is subdivided into 13 volumes. All the standards relating to soils and rocks are covered in two volumes:

- *Volume 04.08 Soil and Rock (I): D420—D5876*
- *Volume 04.09 Soil and Rock (II): D5877—Latest*

The standards for aggregates are covered in *Volume 04.02 Concrete and Aggregates*. Geosynthetics are covered separately in *Volume 04.13 Geosynthetics*.

The Australian Standards cover material testing, designs, and construction. Some of the relevant standards are:

- AS 1289 Methods of testing soils for engineering purposes
- AS 1726 Geotechnical site investigations
- AS 2159 Piling—design and installation
- AS 2870 Residential slab and footing—construction
- AS 3798 Guidelines for earthworks on commercial and residential developments
- AS 4678 Earth-retaining structures
- AS 4969 Analysis of acid sulphate soils
- AS 5100.3 Bridge design—foundations and soil supporting structures

The British standards for soils tests are from BS1377:1990 which has been through a significant improvement from the previous version BS1377:1975 that was limited to a single document, little more than 100 pages. BS1377:1990 consists of nine parts. They are:

- Part 1: General requirements and sample preparation
- Part 2: Classification tests
- Part 3: Chemical and electrochemical tests
- Part 4: Compaction related tests
- Part 5: Compressibility, permeability and durability tests
- Part 6: Consolidation and permeability tests in hydraulic cells and with pore pressure measurement
- Shear strength tests (total stress)
- Shear strength tests (effective stress)
- In situ tests

The aggregates are covered separately in BS 812.

B1 Visual Identification and Classification of Coarse Grained Soils

Objective: To visually identify and classify a coarse grained soil

Standards: ASTM D2487 & D2488

Introduction

The person at the site classifying the samples is not the one who will do the designs and analysis in the office. Therefore, it is necessary to communicate the soil description as precisely as possible because the design office could be hundreds of kilometers away. A *soil classification system* becomes useful in this situation. It is a systematic method to group soils of similar behavior, and then to describe and classify them. The strict guidelines and the standard terms proposed within the system eliminate any ambiguity and make it a universal language among geotechnical engineers. There are several soil classification systems currently in use. The *Unified Soil Classification System* (USCS) (ASTM D2487) is the most popular one used in geotechnical engineering practice worldwide. The AASHTO classification system is quite popular for roadwork where soils are grouped according to their suitability as subgrade, embankment, sub-base, or base materials. There are also country-specific standards such as *Australian Standards* (AS), *British Standards* (BS), or *Indian Standards* (IS).

A good geotechnical engineer must be able to identify and classify soils in the field simply by the feel and appearance. This is easier with coarse grained soils where one can include qualitative information on *grain size* (e.g., fine, medium, or coarse), *grain shape*, *color*, *homogeneity*, *gradation*, *state of compaction* or *cementation*, *presence of fines*, and so forth. Based on relative proportions and this information, it is possible to assign the USCS symbol and a coherent description (ASTM D2488).

Soils can behave quite differently depending on their geotechnical characteristics. In coarse grained soils, where the grains are larger than 0.075 mm (75 μm), the engineering behavior is influenced mainly by the relative proportions of the different grain sizes present within the soil, density of their packing, and shapes of the grains. In fine grained soils, where the grains are smaller than 0.075 mm, the mineralogy of the soil grains and the water content have much greater influence than the grain sizes on the engineering behavior. The borderline between coarse and fine grained soils is 0.075 mm, which is the smallest grain size one can distinguish with the naked eye. Based on the grain sizes, soils can be grouped as clays, silts, sands, gravels, cobbles, and boulders as shown in Figure B1.1. It shows the borderline values as per the USCS, BS, and the AS. Within these major groups, soils can still behave quite differently, and we will look at some systematic methods of classifying them into distinct subgroups.

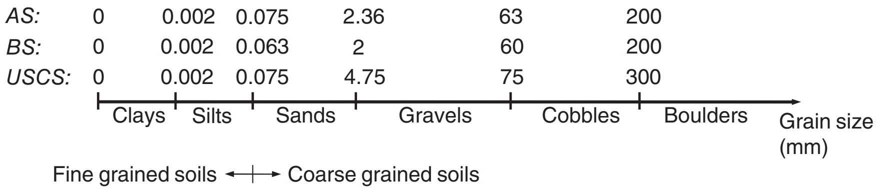


Figure B1.1 Major soil groups based on grain sizes

Procedure:

1. Select a representative sample.
2. Remove boulders and cobbles and estimate their percentage by weight.
3. Spread the remaining soil on a flat surface and check whether the coarse or fine grained soils are in majority. Remember, one can see the individual grains by the naked eye only in coarse grained soils. If the majority is coarse, classify the soil as a coarse grained soil (gravel or sand). If the majority is fine, classify the soil as a fine grained soil (silt or clay).
4. State whether the coarse grained soil is *clean* (i.e., contains less than 5% fines) or it has appreciable fines.
5. In clean coarse grained soil, state whether it is well graded or poorly graded. If there are appreciable fines, state whether the fines are silty or clayey. Use terms like *trace* (less than 5%), *few* (5 to 10%), *little* (15 to 25%), *some* (30 to 45%) and *mostly* (more than 50%) to describe the presence of grains of specific groups. Clays feel sticky and silts feel gritty when wet.
6. Note any of the following data wherever possible:
   - Grain size (at least qualitatively, as fine, medium, or coarse sand)
   - Grain angularity (e.g., angular, subangular, subrounded, or rounded) (see Figure B1.2)

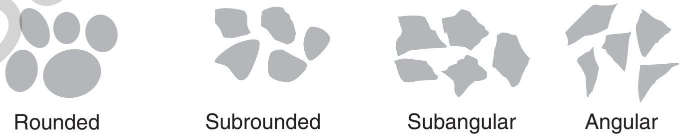
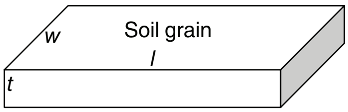


Figure B1.2 Grain angularity



Regular: $w/t < 3$ and $l/w < 3$
Flat: $w/t > 3$
Elongated: $l/w > 3$

Figure B1.3 Grain shape

  - Grain shape (e.g., regular, flat, elongated, or flat and elongated—based on three as the aspect ratio limit) (see Figure B1.3)
  - Moisture condition as dry, moist (damp), or wet (visible free water)
  - Color in conjunction with the moisture condition
  - Odor (only if organic or unusual)
  - Cementation between grains as weak, moderate, or strong
  - Reaction (formation of bubbles) to hydrogen chloride (HCl) to detect the presence of carbonates; describe as none, weak, or strong

7. USCS (or other) symbol and description of the soil based on the above data

ASTM suggests borderline symbols for soils with two possible identifications where the two symbols are separated by a solidus (e.g., GW/GP). The group name for such borderline soils should be the group name of the first symbol.
The borderline symbol applies to the following situations where some examples are also given:

- Soils containing approximately the same amount (45 to 55%) of coarse and fine grained soils: GM/ML or ML/GM.
- Coarse grained soils containing approximately the same amount of sands and gravels: GC/SC, GP/SP.
- Coarse grain soil that can be classified as well or poorly graded: GW/GP, SW/SP.

Here, G = gravel, S = sand, M = silt, C = clay, W = well graded, and P = poorly graded. Every effort must be made to avoid a borderline symbol; it should be used only if absolutely necessary.

Cost: US$10

B2 Visual Identification and Classification of Fine Grained Soils

Objective: To visually identify and classify a fine grained soil

Standards: ASTM D2487 & D2488

Introduction

Fine grained soils consist of silts and clays. The grains are smaller than 0.075 mm and are not visible to the naked eye. The grain size distribution of a fine grained soil is of little value. The purpose of this exercise is to identify the fines as one of the two broader groups, namely, silts and clays, and to further classify them on the basis of the plasticity that they display. The fines are identified on the basis of *dry strength*, *dilatancy*, *toughness*, and *plasticity*.

Dry strength: How easy is it to crush a dry lump by squeezing between the fingers? Describe dry strength as none, low, medium, high, or very high. Silts have low dry strength and clays have high dry strength.

Dilatancy: If a moist pat of fines is placed on the palm and shaken, how quick does the water appear on the surface and disappear upon squeezing? Use terms such as none, slow, or rapid. Silts show rapid dilatancy and clays show none to slow dilatancy.

Toughness: Plastic limit is the lowest water content at which the fines can be rolled into a 3 mm diameter thread. Toughness is a measure of the strength near the plastic limit. By kneading the moist pat of fines at a water content close to the plastic limit, it is possible to describe toughness as low, medium, or high. High plastic clays will have high toughness, and silts will have low toughness.

Plasticity: On the basis of the observation made while testing for toughness, describe plasticity as nonplastic, low, medium, or high. Silts are generally nonplastic and clays can have high plasticity.

An approximate guide to assign the Unified Soil Classification System (USCS) symbols based on these four is given in Figure B2.1.

Procedure:

1. Select a representative sample.
2. Use only the fraction passing a No. 40 (0.425 mm) sieve.
3. Test separately for dry strength, dilatancy, toughness, and plasticity. Use Figure B2.1 as the basis for deciding whether the fines are clay or silts and to assign a symbol. In addition, a moist pat of clay feels sticky and silt feels gritty.

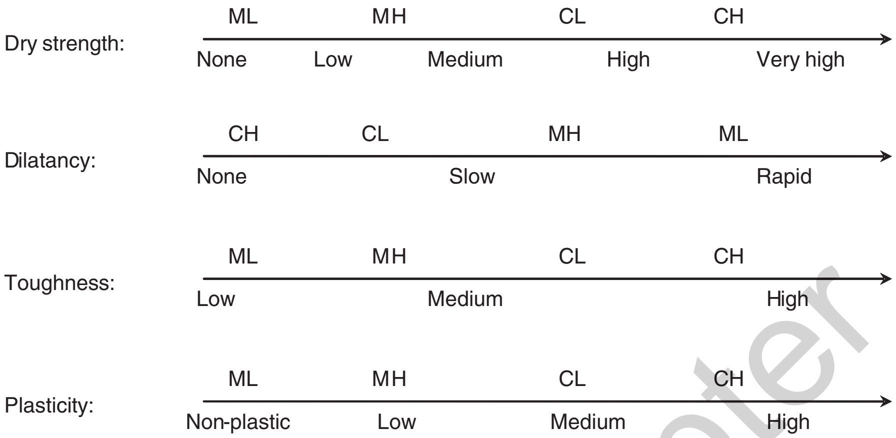


Figure B2.1 Visual classification of fine grained soils

4. Note any of the following data wherever possible:
   - Moisture condition as dry, moist (damp), or wet (with visible water)
   - Consistency (if moist or wet) as very soft, soft, firm, hard, or very hard
   - Color in conjunction with the moisture condition
   - Odor, especially for organic soils
   - Cementation between grains as weak, moderate, or strong
   - Reaction (formation of bubbles) to HCl for detecting the presence of carbonates; describe as none, weak, or strong.
5. USCS (or other) symbol and description of the soil, based on this data

While visually identifying and describing soils, sometimes it is quite likely that a soil can be assigned to one of the two groups. ASTM suggests borderline symbols for soils with two possible identifications, where the two symbols are separated by a solidus (e.g., CL/CH, GW/GP). *The group name for such borderline soils should be the group name of the first symbol*, with the following exceptions, where the group names are as follows:

CL/CH	lean to fat clay
ML/CL	silty clay
CL/ML	clayey silt

The borderline symbol applies to the following situations where some examples are also given.

- Soils containing approximately the same amount (45 to 55%) of coarse and fine grained soils: GM/ML or ML/GM; GP/SP; SC/GC, etc. ASTM D2488 notes that it is practically impossible to have GW/SW.

- A coarse grained soil that can be either well graded or poorly graded: GW/GP or SW/SP
- Fines that can be classified as clay or silt: CL/ML, CH/MH, SC/SM
- Fine grained soil that can be classified as having low or high compressibility: CL/CH, MH/ML

Here, G = gravel, S = sand, M = silt, C = clay, L = low plasticity, and H = high plasticity. Every effort must be made to avoid a borderline symbol; it should be used only if necessary.

Cost: US$10

B3 Water Content

Objective: To determine the water (moisture) content of a soil or aggregate sample by *oven drying*

Standards: ASTM D2216
AS 1289.2.1.1
BS 1377-2

Introduction

Water content determination is fairly straightforward and becomes a part of most laboratory tests. The most common method involves heating the sample in the drying oven for 24 hours. There are other methods using a microwave oven (ASTM D4643, AS 1289.2.1.4), infrared lights, and hot plate, which are not discussed here. Water content can vary from 0% for a dry soil to more than 1000% for slurries, organic, and soft soils. Water content measurements should be carried out on samples from the site at the earliest possible time before any moisture losses, corrosion of the sampling tube, and oxidation of the samples occur. In marine sediments containing significant salt content, special care is required to remove the salt or account for its presence in determining the water content.

Procedure:

1. Determine the mass m_1 of a clean and dry container. Metal cans made of aluminum, tin foil, porcelain, or watch glass can be used for this purpose.
2. Place the representative specimen in small pieces in the container and determine the mass m_2.
3. Place the specimen and the container in an oven at 105 to 110°C and dry to constant mass m_3. The specimen is deemed to have reached a constant mass if the mass loss between two successive measurements is less than 0.1% of the initial wet mass. This can take 12 to 18 hours, and, for convenience, the samples are often left in the oven for 24 hours. A pair of tongs and/or heavy gloves can be used for removing the specimen containers from the oven (The old asbestos gloves are not welcomed in laboratories anymore!). The specimen can be allowed to cool in a desiccator for 30 minutes before determining the mass.

Notes:

1. Organic soils that can decompose and soils containing gypsum that can dehydrate should be heated at lower temperatures and for a longer period if necessary. It is common practice to maintain the oven at 60°C for organic soils.

2. If there is a delay in transferring the container with the moist sample to the oven, it can collect moisture from the air. To avoid this, use containers with lids and remove the lids (and place at the bottom of the container) when placing inside the oven.

Depending on whether the water content will be recorded to the nearest 0.1 or 1%, the minimum wet mass recommended for the water content test is given in Table B3.1.

Datasheet:

A simple datasheet for this test, prepared in Excel, is shown in Table B3.2. The water content should be reported to the nearest 0.1% for water content less than 50%, 0.5% for water content between 50 and 100%, and 1% for water content greater than 100%. The other data recorded may include:

- Sample source
- Standard followed and deviations, if any
- Any material excluded from the test
- Whether the test specimen mass was less than what is given in Table B3.1
- Drying method and temperature

Table B3.1 Minimum wet mass for water content measurements

Largest grain size, mm (sieve no.)	To the nearest 0.1%	To the nearest 1%
< 2.0 (No. 10)	20 g	20 g
4.75 (No. 4)	100 g	20 g
9.5	500 g	50 g
19.0	2.5 kg	250 g
37.5	10 kg	1 kg
75.0	50 kg	5 kg

Table B3.2 Water content measurements

Sample no.	Tin no.	m_1 (g)	m_2 (g)	m_3 (g)	w (%)	Comments
JC001	12	49.25	74.21	68.23	31.5	24 hrs in oven
JC002	18	51.04	81.27	73.56	34.2	24 hrs in oven
BP018	A3	60.34	189.2	173.6	13.8	Clayey sand; 28 hours in oven

m_1 = Mass of container

m_2 = Mass of container + specimen

m_3 = Mass of container + dry specimen

Analysis:

The *water content of the soil specimen* is defined as:

$$w(\%) = \frac{m_2 - m_3}{m_3 - m_1} \times 100 \tag{B3.1}$$

Cost: US$5–US$10

B4 Specific Gravity of Soil Grains

Objective: To determine the specific gravity (particle density) of the soil grains

Standards: ASTM D854
AS 1289.3.5.1
BS1377-2

Introduction

Specific gravity of a substance is simply how many times heavier it is than water. Here, water is considered the reference material that has the density of 1.00 g/cm^3 at 4°C and reduces slightly with an increase in temperature, dropping to 0.99821 g/cm^3 at 20°C, which is commonly used as the reference temperature for laboratory tests. Specific gravity, a dimensionless number, denoted by G_s, is defined as:

$$G_s = \frac{\text{Density of soil grain}}{\text{Density of water}} \tag{B4.1}$$

Specific gravity is required in the phase relation calculations and, hence, in most laboratory tests. It lies in the range of 2.6 to 2.8 for most inorganic soils. Organic soils, fly ash, and porous particles such as diatomaceous earth may have specific gravity less than 2.0. On the other hand, mine tailing rich in minerals such as iron can have specific gravity as high as 4.0. In unit of g/cm^3, the absolute value of the *soil particle density* has the same magnitude as the specific gravity.

Pycnometer is a glass bottle of controlled volume in the form of a stoppered volumetric flask, density bottle, or iodine flask that can be filled to a specific volume (e.g., 250 or 500 ml). It is used to determine the specific gravity of a wet or dry sample. In cohesive soils, a small sample with an equivalent dry mass of 30 to 50 g is recommended. In coarse grained soils, a larger sample with an equivalent dry mass of about 200 g and larger pycnometers are suggested. In the case of a wet sample, the water content w can be determined separately, and the dry mass m_s can be determined from the wet mass m_t as $m_t/(1 + w)$, where w is expressed in decimal and not percentage. A better way to determine the dry mass is by drying out the sample slurry at the end of the test, ensuring no grains are lost.

Procedure:

The steps involved in a specific gravity measurement are illustrated in Figure B4.1. The procedures include:

1. Wash the density bottle with water, rinse using acetone or alcohol, and dry the bottle by blowing air. Determine the mass of the bottle with stopper, m_1. This measurement

is not required for the computations. It is used only in calibrating the pycnometer to ensure that:

$$m_3 = m_1 + \rho_w V \tag{B4.2}$$

where V = control volume of the pycnometer (or density bottle), m_3 = mass of the pycnometer (or density bottle) filled with water, and ρ_w = density of water. Lambe (1951) and Germaine and Germaine (2009) recommend developing a calibration curve where the mass of the pycnometer m_3 with water is plotted against the temperature, and m_3 for the appropriate temperature is read from this plot.

2. Transfer the test sample into the pycnometer carefully rinsing all remaining soil particles in it using a wash bottle. Fill with more water—up to about half of the volume. Shake the bottle with stopper and agitate the water to form slurry.
3. De-air the slurry by applying vacuum, heat (boiling), or a combination of both. Agitate the bottle during this process.
4. Fill the remaining volume of the pycnometer with de-aired water and determine the mass m_2.
5. Empty the pycnometer into an evaporating dish, ensuring that all the particles are transferred. Use wash bottle with squirt to wash all the grains into the evaporating dish, leaving the pycnometer clean. A few missing grains can affect the second decimal of the specific gravity value.
6. Place the evaporating dish in an oven at 105 to 110°C for 24 hours and dry to constant mass. From this the mass of the dry soil m_s can be determined.
7. Fill the pycnometer with water and determine the mass m_3. Alternately read off m_3 from the calibration curve (see Step 1).

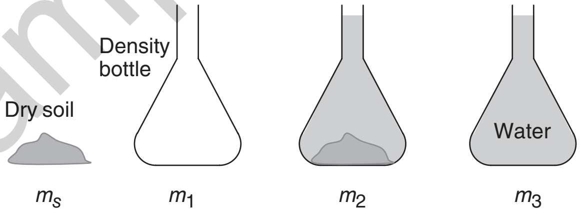


Figure B4.1 Specific gravity test

Datasheet:

A simple datasheet for this test, prepared in Excel, is shown in Table B4.1. The other data that may be included are:

- Identification of the soil (i.e., borehole, depth, and sample numbers)
- Visual description of the soil

- Percent passing 4.75 mm sieve
- Test temperatures to the nearest 0.1°C
- The average value of the readings
- Standard followed and deviations, if any
- Average specific gravity at 20°C to the nearest 0.01
- Comparison with typical values

Table B4.1 Specific gravity measurements

Sample description:	Dark brown sandy clay with high plasticity (CH)		
Sample location:	Kirwan Hospital		
Sample no.:	TP9-3		
Date:	12-March-2005		
Tested by:	Warren O'Donnell		
Notes:			
Test no.	1	2	3
Pycnometer no.	5	5	5
Mass of bottle + water, m_3 (g)	672.26	672.26	672.26
Mass of bottle + soil + water, m_2 (g)	707.88	705.98	706.32
Evaporating dish number	A	B	C
Mass of evaporating dish (g)	445.32	449.24	452.67
Mass of evaporating dish and dry soil (g)	501.34	502.35	506.21
Mass of dry soil, m_s (g)	56.02	53.11	53.54
Test temperature (°C)	25	25	25
Density of water (g/cm^3)	0.99705	0.99705	0.99705
Specific gravity @ above temperature	2.75	2.74	2.75
Specific gravity @ 20°C	2.74	2.74	2.75

Analysis:

The specific gravity of the soil grains is defined as:

$$G_s = \frac{m_s}{m_s + m_3 - m_2} \tag{B4.3}$$

where m_s = mass of the dry soil (Step 6), m_2 = mass of pycnometer, soil and water (Step 4), and m_3 = mass of pycnometer filled with only water (Step 7). The above value of G_s should be corrected to 20°C by multiplying by $\rho_w/\rho_{w,20}$ where ρ_w and $\rho_{w,20}$ are the densities of the water at laboratory temperature and 20°C respectively. The densities of water at different temperatures are given in Table B4.2. The computed values of G_s should be within 0.03. The average of the values lying within 0.03 should be presented to two decimals as G_s. In soils containing water

Table B4.2 Density of water at different temperatures

Temperature, °C	15.0	16.0	17.0	18.0	19.0	20.0	21.0	22.0
Density, g/cm^3	0.99910	0.99895	0.99878	0.99860	0.99841	0.99821	0.99799	0.99777
Temperature, °C	23.0	24.0	25.0	26.0	27.0	28.0	29.0	30.0
Density, g/cm^3	0.99754	0.99730	0.99705	0.99679	0.99652	0.99624	0.99595	0.99565

soluble salts, other liquids such as kerosene may be used instead of water, and Equation B4.3 should be modified as:

$$G_s = \frac{m_s}{m_s + m_3 - m_2} \times \frac{\rho_l}{\rho_w} \quad \text{(B4.4)}$$

where ρ_l is the density of the liquid. Some typical specific gravity values are given in Table B4.3.

Table B4.3 Typical values of specific gravity (after Day 2001, Bowles 1986, Lambe and Whitman 1979)

Soil type	G_s
Peat	1.0 or less
Organic clays	Varies; 2.0 or less
Serpentine	2.2–2.7
Attapulgite	2.30
Gypsum	2.3–2.4
Halloysite (2 H_2O)	2.55
K-feldspar	2.54–2.57
Na-Ca-feldspar	2.62–2.76
Kaolinite	2.61–2.66
Quartz sand	2.65
Silty sand	2.67–2.70
Inorganic clays	2.70–2.80
Calcite	2.70–2.72
Chlorite	2.6–2.9
Illite	2.60–2.86
Montmorillonite	2.4–2.8
Pyrophyllite	2.84
Dolomite	2.85
Soils with mica or iron	2.75–3.00
Muscovite	2.7–3.1
Biotite	2.8–3.2
Hematite	5.20–5.30
Galena	7.4–7.6

Cost: US$70–US$80