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

Sivakugan | Arulrajah | Bo

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To the laboratory technicians and technical officers, the unsung heroes

Contents

Preface

The first soil testing book was written by Professor T.W. Lambe of MIT in 1951. The book covered 13 different soil tests in relatively good detail. This was widely used as a reference book for laboratory testing of soils for several decades. This 165-page classic is currently out of print. Since then, there have been a few soil testing books written by Bowles (1986), Das (2008), Day (2001), Germaine and Germaine (2009), Head (1992b, 1992c, 2006), and Liu and Evett (2009). The three-part manual by K.H. Head discusses the laboratory tests in great length, getting into the nitty-gritty details of each test and is quite valuable in troubleshooting. The second and third volumes closely follow the laboratory equipment manufactured by ELE International, one of the world's largest suppliers of soil testing equipment. For triaxial testing, *The Measurement of Soil Properties in the Triaxial Test* by A.W. Bishop and D.J. Henkel (1962) is probably the most popular book.

Lately, with the advancements in geotechnical and geo-environmental engineering, there have been substantial developments on the soil testing front. With the availability of new technology and our need to work with new materials (e.g., recycled aggregates, biosolids, mine tailings, and other alternative materials), new laboratory tests have been developed and old test procedures have been modified. These have resulted in the requirement for new laboratory test methods and revisions or updates of existing standards.

In geotechnical engineering, laboratory testing should not be limited to soils; there are rocks and aggregates. It is not always possible to avoid getting into rock mechanics, which is not covered in traditional geotechnical engineering education. Most smaller soil testing laboratories have no capacity to perform rock tests. Virgin and recycled aggregates of different sizes are being used in roadwork and often require tests that are not covered in most laboratory testing manuals.

This is the first book that covers the *laboratory tests of soils, rocks, and aggregates*. The objective of this book is to describe these tests in sufficient detail but in a concise manner without sacrificing the salient features of the tests. Sample data sheets are provided with all computations clearly explained. ASTM International (ASTM), originally known as the American Society for Testing and Materials, standards were followed wherever possible. For rock tests, the methods suggested by International Society for Rock Mechanics are followed closely and any deviations from ASTM are noted. Some of the aggregate tests are adopted from the British standards where they are covered more extensively. This book can be seen as a one-stop shop and the first point of reference for the main laboratory tests concerning soils, rocks, and aggregates. Irrespective of what is discussed in the book, the hardcore soil testers will still religiously adopt the specific standards they are required to follow.

Part A of the book covers the general introductory material on laboratory testing, equipment, measurements, and units. Parts B, C, and D cover the tests on soils, rocks, and aggregates, respectively. The authors have extensive experience in all phases of laboratory testing of soils, rocks, and aggregates, including an intimate knowledge of the laboratory equipment and the test procedures.

We are grateful to several people who have contributed to this book. Most importantly, Warren O'Donnell, the senior technical officer of the Soils and Rocks Laboratory at James Cook University, Townsville, critically reviewed most of the chapters of this book and made valuable suggestions. He also provided several photographs and datasheets included in this book.

N. Sivakugan, A. Arulrajah, and M.W. Bo

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Dr. A. Arulrajah is an associate professor in geotechnical engineering at Swinburne University of Technology, Melbourne, Australia. He completed his BSc in civil engineering at Purdue University, Lafayette, Indiana, in 1992; MEngSc at the University of Malaya, Malaysia, in 2003 and PhD from Curtin University, Australia, in 2005. Dr. Arulrajah is a Fellow of Engineers Australia, and a Chartered Professional Engineer in Australia. Prior to his first academic appointment in 2006, he worked for 14 years for various engineering consultants in Australia, Singapore, and Malaysia. Dr. Arulrajah was the first author of a journal paper on ground improvement that won the Telford Premium Prize (2009) from the Institution of Civil Engineers, United Kingdom. He is also the recipient of the Shamsher Prakash prize for excellence in the practice of geotechnical engineering (2010) and the recipient of three Swinburne University Vice-Chancellor Awards. He is the author of nearly 40 scientific and technical papers in refereed international journals and 40 more in refereed international conference proceedings. He has supervised three PhD candidates to completion in these areas of research. He is an editorial board member of the *International Journal of Geotechnical Engineering* and is an active reviewer for several international journals.

Dr. Myint Win Bo (BO Myint Win) is a senior principal/director (Geo-Services) at DST Consulting Engineers, Canada. He graduated with a BSc (geology) from the University of Rangoon and received a postgraduate diploma in hydrogeology from University College, London and an M.Sc degree from the University of London. He obtained his PhD in civil engineering (specializing in geotechnics) from the Nanyang Technological University, Singapore. He is a Fellow of the Geological Society, London, and a Fellow of the Institution of Civil Engineers, UK. He is also a professional engineer, professional geoscientist, international professional engineer, United Kingdom, and a chartered geologist, scientist, engineer, environmentalist, European geologist, and European engineer. Dr. Bo is also serving in several national and international professional societies as a committee member. Dr. Bo is an experienced practicing engineer as well as educator, and he has been giving several special lectures and workshops at international conferences, tertiary institutions, and professional associations. Additionally, Dr. Bo is an adjunct professor at the University of Ottawa and Lakehead University in Canada as well as adjunct professor at the Swinburne University of Technology in Australia. He is the author of more than 50 scientific and technical papers in refereed international journals, 70 more in refereed international conference proceedings, and three textbooks. Dr. Bo is an active reviewer for more than 6 international journals.

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Downloads for *Laboratory Testing of Soils, Rocks and Aggregates* consist of spreadsheets that can be used to develop laboratory specific datasheets for most tests and easily modified to your style and standards.

Introduction

Part A

Laboratory testing of soils, rocks, and aggregates is an integral part of the geotechnical design. The design parameters are derived from laboratory and in situ testing of the geomaterials. During the site investigation program, when the in situ tests (e.g., standard or cone penetration) are being carried out, it is a common practice to take samples from the ground at various locations for further laboratory tests.

The laboratory tests have certain advantages over in situ tests that include:

- Well defined boundary conditions that can also be controlled
- More rational interpretation
- Higher degree of accuracy in the measurements

On the other hand, in situ tests are quicker, test a larger volume of soil, and are relatively inexpensive. However, their boundary conditions are not well defined, and their interpretation is often empirical or semi-empirical. Does it make one better than the other? Not really. A good site investigation program will include both in situ and laboratory tests that complement each other. The use of one should not be at the expense of the other.

DISTURBED AND INTACT SAMPLES

The grains of a gravelly, sandy, or silty soil are equidimensional, where the dimensions in all three mutually perpendicular directions are of the same order of magnitude. In addition, they are nonplastic and noncohesive. Their packing density is measured by *relative density* (D_r) defined as:

$$D_r = \frac{e_{max} - e}{e_{max} - e_{max}} \times 100 \quad \text{(A.1)}$$

where e_{max} = void ratio at the loosest state and e_{min} = void ratio at the densest state (e = current void ratio at which the relative density is computed). D_r varies between 0 and 100%. At the loosest state, it is 0 and at the densest state it is 100%. Classification of granular soils based on packing density of the grains is shown in Figure A.1. The behavior of a granular soil subjected to external loading is highly dependent on the grain size distribution, relative density, and the angularity of the soil grains.

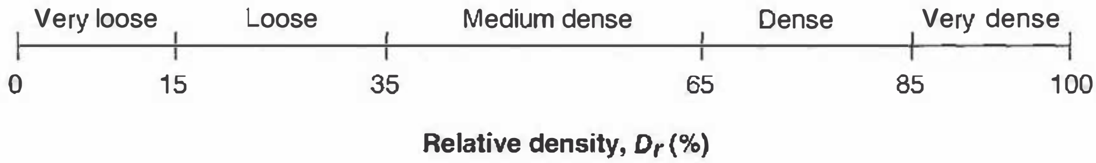

Figure A.1 Classification of granular soils based on relative density

Clay particles are one- or two-dimensional with shapes of needles or flakes and have a large *specific surface* (i.e., surface area per unit mass, measured in m^2/g). For example, *montmorillonite* clays can have a specific surface of 800 m^2/g. They are electrically charged with a net negative charge. In the presence of water, they are sticky and can exhibit plasticity and cohesion. Clayey soils can be classified on the basis of their plasticity and unconfined compressive strength as shown in Figures A.2 and A.3, respectively. Undrained shear strength (c_u) is half of the unconfined compressive strength (q_u). The term relative density is not applicable to clays.

Undisturbed samples literally means that the samples have the same characteristics (e.g., temperature and stresses) as in the in situ state. It is impossible to remove material from the ground without causing a disturbance to at least one of these characteristics. *Intact samples*, on the other hand, are the ones obtained using the best possible methods to minimize disturbance and still acknowledge that there is a degree of disturbance. The terms *samples* and *specimens* are misused commonly in practice. Samples are what we collect from the site, and from these samples we select specimens for specific laboratory tests. Specimen is a subset of sample.

It is difficult to collect good quality intact or undisturbed samples in granular soils. If required, there are some special techniques such as ground freezing, using resins, or attaching a core catcher to the sampling tube, among others. When laboratory tests are required on granular soils, it is common to perform them on *reconstituted* samples. Here, the granular soil grains

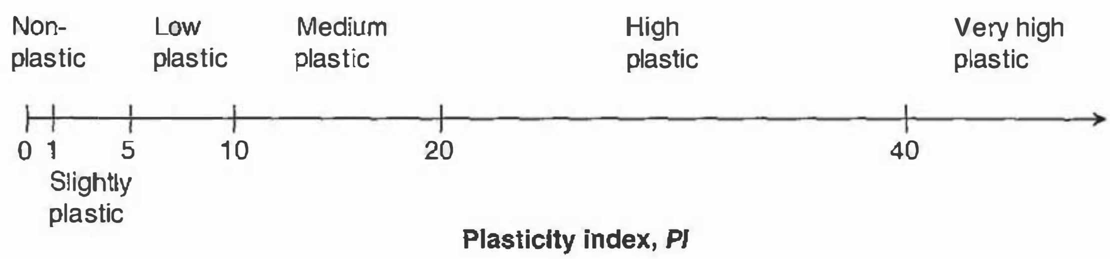

Figure A.2 Classification of clays based on plasticity (after Burmister 1949)

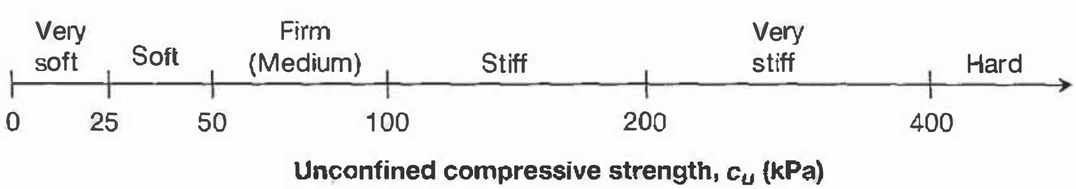

Figure A.3 Classification of clays based on unconfined compressive strength are repacked to densities that are representative of the field samples and hence replicate the field situation. Reconstituted cohesive soil specimens can be prepared in the *Harvard miniature compaction device* (Wilson 1970). This device provides a kneading action on the soil placed in layers and simulates compaction by a sheepsfoot roller. It can be used in the laboratory to produce specimens that can be tested directly in a triaxial or uniaxial compression setup without further preparation. Reconstituted clay samples can also be prepared by sedimenting the clay slurry, typically mixed at a water content of 1.5 to 2.5 times the liquid limit.

In cohesive soils, good quality intact samples are required for laboratory tests such as triaxial, direct shear, consolidation, and permeability tests. They can be obtained from boreholes or trial pits. The samples from boreholes are recovered from thin walled *Shelby tubes*™ or special samplers such as a *piston sampler*. Piston samplers are effective in very soft clays and organic soils such as peat. Hvorslev (1949) introduced area ratio A_R as an indirect measure of the degree of mechanical disturbance that can be expected. It is defined as:

$$A_R(\%) = \frac{D_o^2 - D_i^2}{D_i^2} \times 100 \tag{A.2}$$

where D_i and D_o are the inner and outer diameter of the sampler. For a good quality intact sample, A_R should be less than 10%. In very stiff or hard strata, it may be necessary to use tubes with greater wall thicknesses and, thus, significantly higher values of A_R. It is common to see *double* or *triple tube core barrel samplers* used in very stiff or hard soils for obtaining good quality intact samples. Hvorslev suggested that the length of the intact sample be limited to 10 to 20 times the diameter of the tube in cohesive soils. ASTM International (ASTM) D1587 suggests the maximum length to be 910 mm (36 in) for 50 to 75 mm (2 to 3 in) diameter tubes, and 1450 mm (57 in) for 127 mm (5.0 in) diameter tubes. The sampling tubes are made of mild, galvanized, or stainless steel, or brass. When sampling in environmental projects, to avoid chemical reactions with the metal, epoxy-coated steel or plastic liners can be used.

Sample disturbance occurs due to two separate factors, namely, *mechanical disturbance* and *stress-relief*. Mechanical disturbance is caused by the drilling equipment and the sampler that is inserted into the borehole. As seen in Equation A.2, the mechanical disturbance increases with the wall thickness. As a result, the outer annular region in the sample recovered from the borehole can be disturbed. Under such circumstances, it is a good practice to discard the annular region and use the core from the center. To overcome the effects of stress relief, the sample can be reconsolidated to the estimated in situ overburden stress. Block samples can be recovered from a wall or base of an excavation or trial pit.

Disturbed or remolded samples are adequate for the soil classification, Atterberg limits, water content, and specific gravity determination. They can also be used for compaction and California Bearing Ratio tests if available in sufficient quantity. The split-spoon sampler used in a standard penetration test has A_R in excess of 100%, and hence the samples are highly disturbed, rendering them suitable only for visual identification purposes. The split-spoon sampler can be equipped with a liner that will hold the samples intact. The liner can then be sealed and waxed at the ends before it is transported to the laboratory to preserve the natural water content and avoid oxidation. Sealable plastic bags and glass jars with air-tight lids are useful for preserving the samples at their natural water content. When filled with samples, they have to be properly labeled indicating the project, geographic location, sample depth, date, and other relevant information.

For safety reasons, it is a common practice to fill the borehole or trial pit with soil once the sampling and the associated in situ tests are completed.

ACCURACY, PRECISION, AND RESOLUTION

Let's define some simple terms associated with laboratory measurements. *Resolution* is the smallest change the measuring device can display (e.g., 0.01 g in a digital balance). In a digital display, the resolution is simply one digit of change in the last digit. The term *accuracy* can be split into two components: *precision* and *bias*. Precision is a measure of scatter about an average value of the measurements that need not be close to the true value. The difference between this average of the measured values and the true value is known as the bias of the instrument. *Sensitivity* refers to the response of a device to a unit input (e.g., 100 milli volts per mm movement of a linear variable differential transformer). Sensitivity applies to measuring devices such as transducers, load cells, or dial gages; resolution applies to the readout or display devices. *Repeatability* is slightly different from *reproducibility*. Repeatability is a qualitative measure of the variability between test results when the tests are repeated on identical specimens by the same person in the same laboratory under the same conditions. Reproducibility is a measure of variability between the test results when the tests are repeated in different laboratories, by different operators using different equipment.

The test measurements and computed results should be reported to appropriate *significant digits*. When reporting the mass of a soil sample as 142.3 g, there are four significant digits. Reporting too many digits can give a false sense of accuracy and demonstrates a lack of appreciation for the quality of measurements. The significant digits should be based on the sensitivity of the instrument, resolution of the measuring device, specimen size, and measured quantity. In geotechnical laboratory testing, it is sometimes specified by the relevant standards. For example, liquid or plastic limit and plasticity index are generally rounded to the nearest integers. Densities (in t/m^3 or Mg/m^3) and specific gravities are reported to 0.01.

SOME LABORATORY DEVICES

In this section, we discuss some common laboratory devices that are used frequently in the laboratory testing of soils, rocks, and aggregates.

Length Measuring Devices

Length measurement devices used in a geotechnical laboratory include a meter stick, ruler, measuring tape, Vernier calipers, micrometers, dial gages, and LVDTs, among others. Some of these are shown in Figure A.4. Vernier calipers and micrometers are used for precise one-off measurements of dimensions such as inner and/or outer diameters of a cylinder. Dial gages and LVDTs are used for precise continuous measurements of displacements or deformations during a test.

Mass Measuring Devices

Water content is one of the most common measurements in the geotechnical laboratory. It is carried out as a part of most laboratory tests and when collecting field samples on samples as

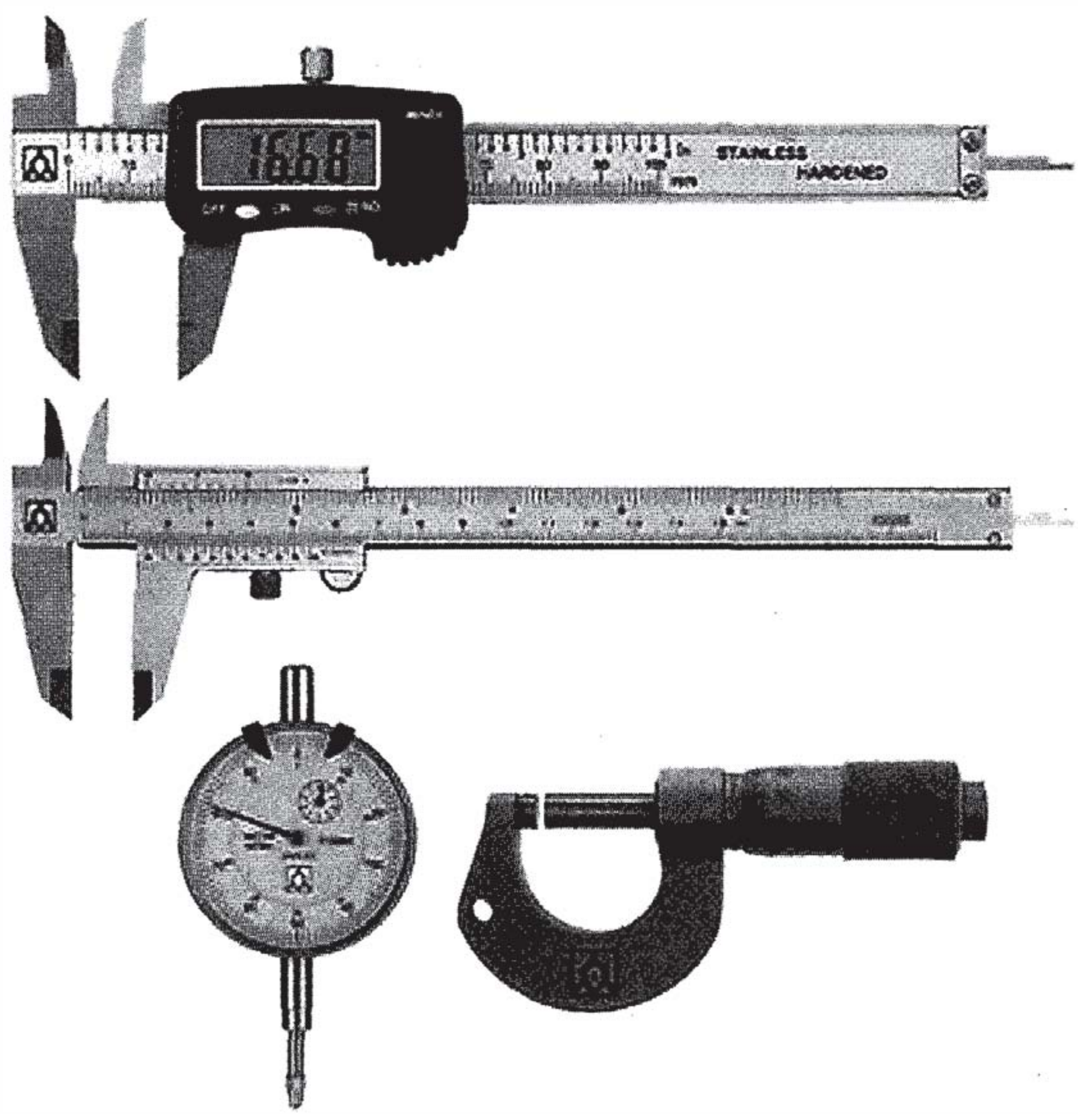

Figure A.4 Length measurement devices (Photograph: N. Sivakugan)

Figure A.5 Mass measurement devices (Photograph: N. Sivakugan)

small as 20 g in mass. A good balance (Figure A.5) capable of measuring the mass to 0.01 g resolution is preferable. This includes top pan balances and analytical balances. When dealing with larger soil samples, it may be necessary to use a coarse balance such as a semi-self-indicating scale or a heavy platform scale with lesser resolution.

Load Measuring Devices

Frequently, there is a requirement to measure the load acting on a specimen rather precisely. It is necessary to monitor the loads throughout the tests, especially in strength tests where the specimens are tested to failure. *Load cells* and *proving rings* are some of the common devices that are used for this purpose (Figure A.6). Pressures are generally measured by transducers.

Drying Equipment

To determine water contents and to dry soils in preparation for laboratory tests, it is necessary to dry out the soils completely. Laboratory drying ovens are useful for this purpose. They are usually set at 105 to 110°C for inorganic soils and somewhat lower for organic soils. Drying for 16 to 24 hours is usually sufficient. By plotting the dry mass with time, this can be verified. When the difference between successive weighings is less than 0.1% of the dry mass, it can be assumed that the soil has reached a constant mass. Metal trays, water content tins, and weighing bottles are suitable for drying soils in the oven. They should be transferred to the *desiccator* and cooled without absorbing any moisture before placing on a weighing scale or balance.

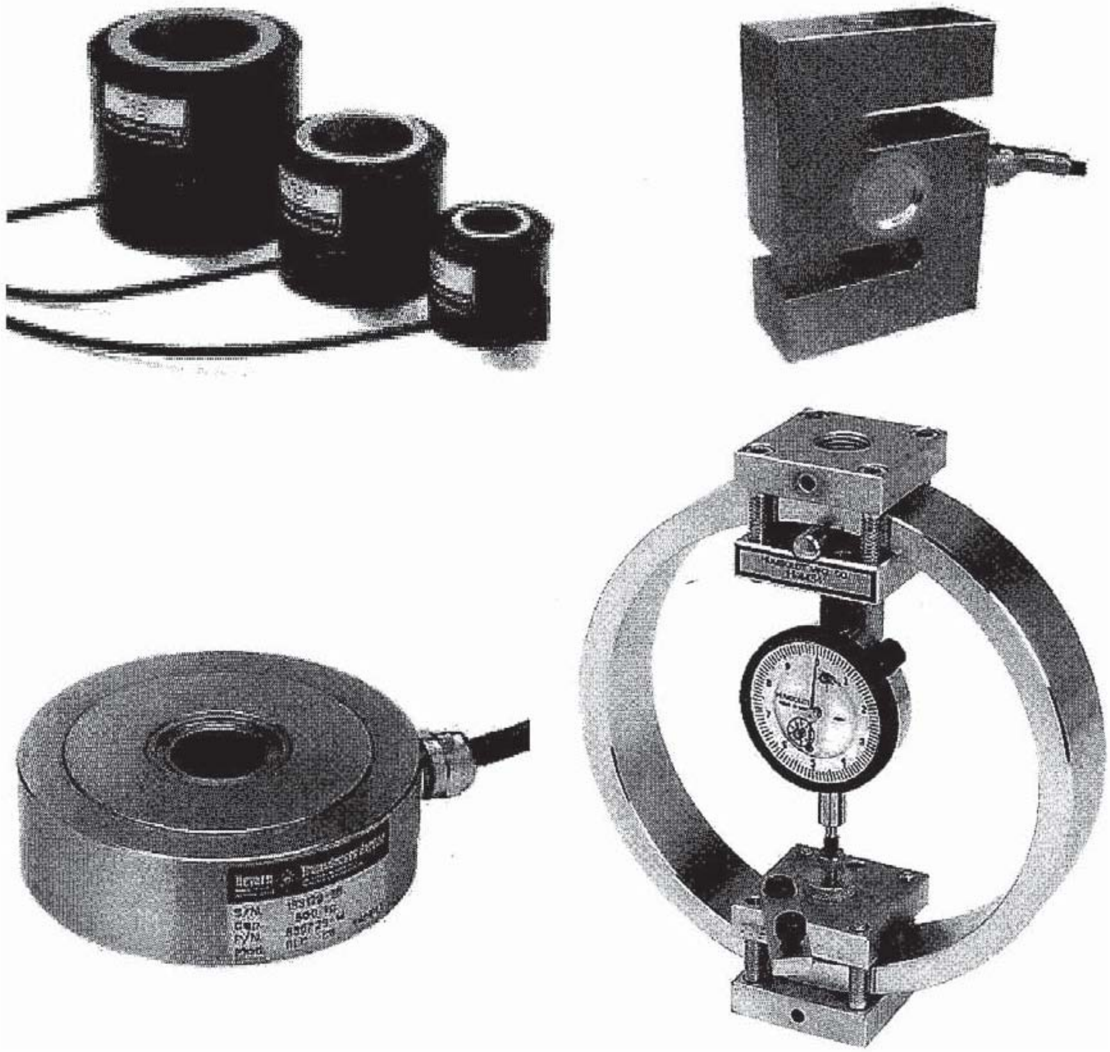

Figure A.6 Load cells and proving ring (Photograph: N. Sivakugan)

Desiccator

A desiccator (Figure A.7) is a glass enclosure that contains a desiccant (e.g., anhydrous silica gel) that keeps the air within the desiccator dry. It is used to cool a sample without absorbing moisture when removed from the oven. With its airtight seal, it can be used to contain the samples when applying vacuum. The silica gel, in the form of crystals, can be spread in a dish and kept below the perforated floor of the desiccator. The self-indicating crystals are blue in color when dry and slowly become colorless when they absorb moisture. By heating them in the oven at 110°C, they can be dried and reused. There are also cheaper nonindicating desiccants that do not change color. Desiccators can be useful for containing the soil specimens while de-airing through application of vacuum.

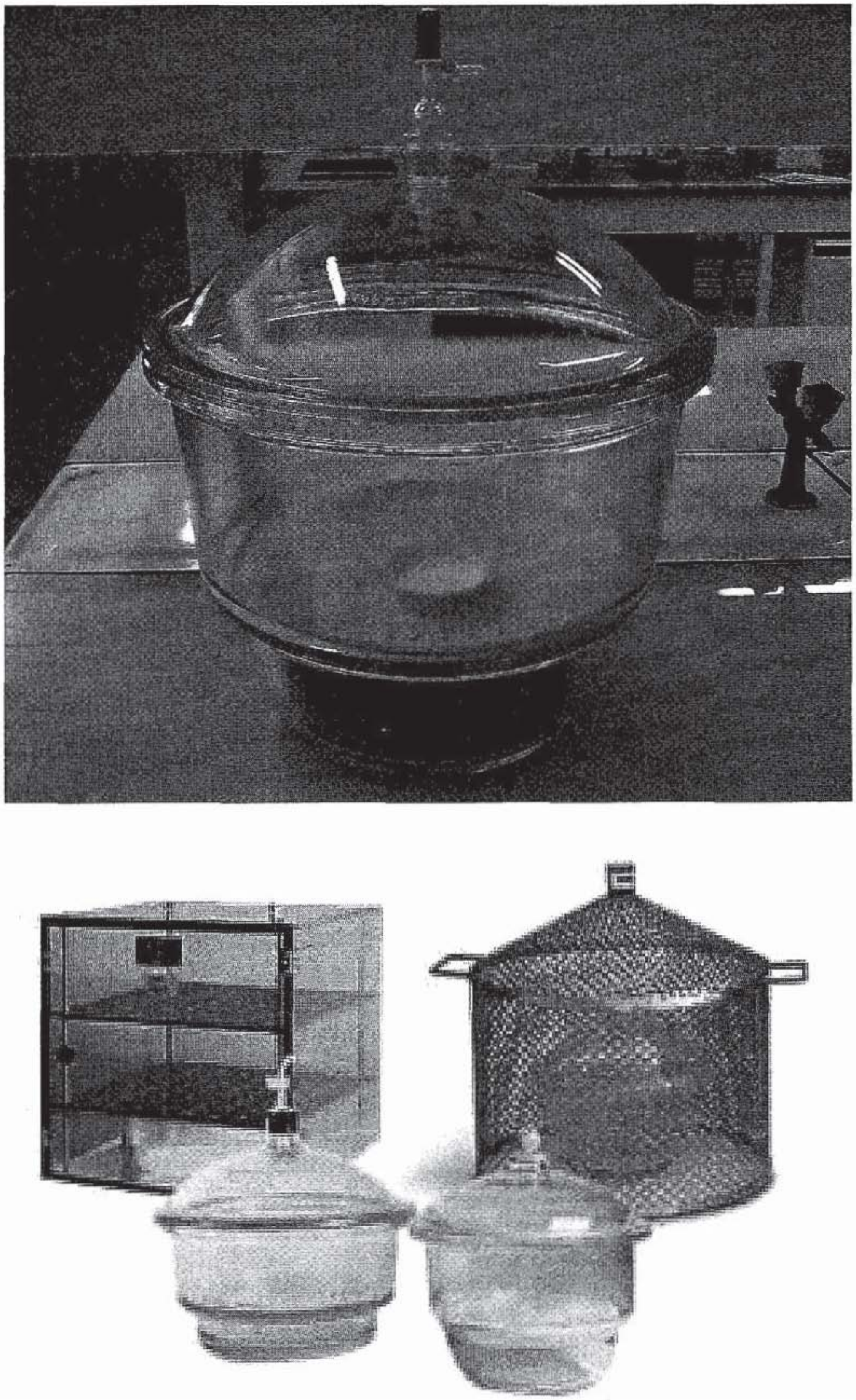

Figure A.7 Desiccator (Photograph: N. Sivakugan)

Constant Temperature Baths

For laboratory tests (e.g., hydrometer tests) that require a constant temperature environment for a long period of time, a constant temperature bath is useful.

Vacuum Pump

Often the laboratory tests are carried out on saturated soil specimens. De-airing water, soils, and soil-water mixes can be accomplished by applying vacuum and/or by heating. Remember that atmospheric pressure at sea level is 1 atm (= 760 mm Hg = 101.325 kPa = 1.01325 bar). Therefore, theoretically, the maximum vacuum one can apply is 101.325 kPa. A vacuum pump with a pressure gage for measuring the vacuum is a useful device in a geotechnical laboratory. Vacuum is commonly applied to specimens placed in a desiccator that can be covered by a protective cage for safety reasons.

Water Purification System

Tap water contains dissolved ions and bacteria that can react with the soil samples that are being tested. Therefore, it is necessary to use some purer forms of water such as *distilled* or *deionized water* for the laboratory tests. Distilled water has all of the impurities removed by boiling the water and condensing the steam. Deionized water has all of the mineral ions removed by running the water through a series of filters. In most soil testing systems, the tests are carried out on saturated specimens. To ensure no air is introduced into the system, *de-aired* distilled or deionized water is used. De-aired water does not have any dissolved air in it. De-airing can be carried out by applying vacuum to the water in a suitable vessel that can resist the atmospheric pressure from outside.

Wax Pot And Wax

Wax is effectively used for sealing samples in tubes or other containers, protecting them against any moisture changes until the tests are carried out. To avoid damage to the samples, wax with a low melting point is preferable. Wax with a high melting point tends to be more brittle and, hence, is prone to cracking. Paraffin is the most common wax that is used for sealing sampling tubes. It is inexpensive and is available from hardware stores. Being relatively brittle, this can crack after a few days and destroy the seal. Germaine and Germaine (2009) and Lambe (1981) recommend mixing paraffin with petroleum jelly in a 1:1 ratio. An electrically heated wax pot with thermostat control can maintain the molten wax at the right temperature while coating the samples and sealing tubes. A wire brush to apply the wax and a ladle for collecting wax from the wax pot are other items that can help in the use of a wax pot and wax. Samples can also be waxed by dipping them in the molten wax. Wax should not be heated to more than a few degrees above its melting point. Overheating can affect the sealing properties and the wax can become brittle.

STANDARDS

The laboratory and field tests are generally conducted according to some standards that are developed by specialists in the area. Some of these specialists are ASTM International (ASTM), International Standardisation Office (ISO), American Association of State Highway and Transportation Officials (AASHTO), Australian Standards (AS), and British Standards (BS).

ASTM standards (http://www.astm.org) cover a wide range of materials, including steel, concrete, soils, rocks, petroleum, paints, and water. The standards are published in more than 80 volumes. Luckily, all that concerns us are available in two volumes, each of which has more than 1000 pages. The volumes are also available separately on CDs. ASTM standards for soils, aggregates, and rocks are updated regularly by Committee D18 and are published in two volumes 04.08 and 04.09 that come under Section 4—Construction.

UNITS

Worldwide, two of the most commonly used systems of units are the *Imperial* (British) and *metric* systems. In addition to these two systems, there have been a few hybrids where the units were simply derived from these two. Since the 1950s, in an attempt to standardize the units across the globe, SI units have become increasingly popular. SI stands for "Le Système International d'Unités" (The International System of Units). It is the modern form of the metric system. The United Kingdom converted to SI in 1972, followed by Australia and New Zealand. In North America, both systems are still being used.

The SI system is based on the following seven base units:

- Length in meter (m)
- Mass in kilogram (kg)
- Time in second (s)
- Electric current in ampere (A)
- Thermodynamic temperature in Kelvin (K)
- Luminous intensity in candela (cd)
- Amount of substance in mole (mol)

Only the first three are commonly used in geotechnical engineering. The units for all other physical quantities are derived from all of the seven basic units. Some of the derived quantities have been given specific names. For example:

- Newton (N) = Force required to accelerate a mass of 1.0 kg at the rate of 1.0 m/s^2
- Pascal (Pa) = N/m^2
- joule (J) = Work done when a force of 1 Newton moves a distance of 1 m.
- watt (W) = joule/s

Other special names, not necessarily SI but worth noting are:

- Ångström (Å) = 10^{-10} m
- bar = 10^5 Pa
- British (short) ton = 2000 lb
- British (long) ton = 2240 lb
- dyne = 10^{-5} N
- hectare (ha) = 10000 m^2
- hertz = 1.00 cycle/s
- hundred weight (UK) = 112 lb
- hundred weight (US) = 100 lb
- kilopond = kilogram-force
- kip = 1000 lb-force (lbf)
- metric ton (tonne) = 1000 kg
- nautical mile = 1852 m
- poundal = Force required to accelerate a mass of 1.0 lb at the rate of 1.0 ft/s^2
- stone (US) = 12.5 lb; stone (UK) = 14.0 lb

Some unit conversions that are commonly used in geotechnical engineering are:

Length:

- angstrom = 10^{-10} m
- foot (ft) = 0.3048 m
- inch = 2.5400×10^{-2} m
- mil = 1/1000 inch = 2.54×10^{-5} m
- mile = 1.609344 km
- nautical mile = 1852 m
- yard = 3.00 ft = 0.9144 m

Area:

- acre = 4840 sq. yard = 4046.8564224 m^2
- hectare (ha) = 10,000 m^2
- perch = 25.29285264 m^2
- square = 9.290304 m^2

Volume:

- gallon (U.S.) = 3.785412×10^{-3} m^3
- gallon (U.K.) = 4.546090×10^{-3} m^3
- liter = 1.0×10^{-3} m^3

- ounce (U.S. fluid) = 2.957353×10^{-5} m^3
- pint (U.S. fluid) = 4.731765×10^{-4} m^3

Mass:

- British ton (short) = 2000 lb
- British ton (long) = 2240 lb = 20 hundredweight
- hundredweight (U.K.) = 112 lb
- hundredweight (U.S.) = 100 lb
- metric ton (or tonne) = 1000 kg
- ounce (mass) = 28.34952 g
- pound (mass) = 0.4535924 kg
- U.S. ton = 2000 lb

Force:

- dyne (dyn) = 1.00×10^{-5} N
- kilogram-force = 1.00 kilopond = 9.80665 N
- kip-force (1000 lbf) = 4448.222 kN
- poundal = 0.13825495 N
- pound force (lbf) = 4.448222 N

Pressure:

- atmosphere (760 mm Hg) = 1.013247×10^5 Pa
- bar = 1.0×10^5 Pa
- kgf/cm^2 = 98.06650 kPa
- lbf/in^2 (psi) = 6.894757 kPa
- kips/in^2 (ksi) = 6.894757 MPa
- ton-force (short)/sq. ft = 95.760518 kPa
- ton-force (long)/sq. ft = 107.251780 kPa

Work or Energy:

- Btu = 1055.0559 J
- calorie = 4.186800 J
- erg = 1.00×10^{-7} J
- joule (J) = 1.000 N(m
- kilowatt-hour = 3600 kJ

Dynamic viscosity:

- poise (P) = 0.1 Pa·s
- centipoise (cP) = 0.001 Pa·s

Kinematic viscosity (dynamic viscosity divided by density):

- Stoke (St) = 1.0 cm^2/s = 1.0×10^{-4} m^2/s
- Centistoke (cSt) = 1.0×10^{-6} m^2/s

Prefixes indicate orders of magnitude in steps of 1000 and provide a convenient way to express small and large numbers. The prefixes used with SI units are summarized in Table A.1. Some notes from ASTM that should be observed when expressing SI units are:

a. In derived units formed by multiplication, use *raised* dots (·) between the symbols. For example; N·m or Pa·s, for example. The unit names should be written as Newton meter, Pascal second, and so forth with space between the different unit names.
b. In derived units formed by division, use only one solidus (/) per expression and parentheses to avoid ambiguity.
c. SI symbols are not abbreviations and hence no period should follow them except at the end of a sentence.
d. Unit is the same whether singular or plural.

Table A.1 SI prefixes used with units

Factor	Prefix	Symbol
10^{24}	yotta	Y
10^{21}	zeta	Z
10^{18}	exa	E
10^{15}	peta	P
10^{12}	tera	T
10^{9}	giga	G
10^{6}	mega	M
10^{3}	kilo	k
10^{2}	hecto	h
10^{1}	deca	da
10^{-1}	deci	d
10^{-2}	centi	c
10^{-3}	milli	m
10^{-6}	micro	µ
10^{-9}	nano	n
10^{-12}	pico	p
10^{-15}	femto	f
10^{-18}	atto	a
10^{-21}	zepto	z
10^{-18}	yocto	y

e. Leave a space between the value and the symbol. For example, 5 m, not 5m. An exception is for the plane angle degree which is expressed as 73° and not 73°. Symbol for degree Celsius is °C.
f. Do not place a space or hyphen between the prefix and the unit name. For example, kilogram, not kilo-gram.
g. Choose a prefix so that the number lies between 0.1 and 1000.

LABORATORY REPORT

All the salient findings from a laboratory testing program must be documented clearly in a laboratory report that is submitted to the client. The information presented should be factual, nonambiguous, and should include:

- Name and address of the laboratory
- Name of the client, project, and sample location
- Visual classification and description of the test samples
- Standards followed and deviations in the procedure (if any)
- Properly completed datasheets
- Analysis and interpretation of the test results
- Name and signature of the tester with date

Use of spreadsheets can streamline the calculations involved in the test. Most commercial laboratories would prefer using their standardized spreadsheet for this purpose. Table A.2 lists the Greek symbols that are used to denote some variables in engineering in general.

SAFETY

These days we are realizing the value of workplace health and safety more and more. Laboratories with machinery, equipment, and hazardous material are some of the high risk areas prone to accidents. Material Safety Datasheets must be used to assess whether special protective clothing and/or eye protection are required. Hazardous chemicals should be disposed of in an appropriate manner. We must take every possible step to minimize the risk. There are designated workplace health and safety officers to give induction for the beginners and ensure that those working in the laboratories follow the best practices as far as the workplace health and safety is concerned.

FURTHER READING

The late Professor T. W. Lambe of Massachusetts Institute of Technology wrote the first reference book *Soil Testing for Engineers* in 1951. There were no further updated editions of this book,

Table A.2 Greek alphabet

Name	Symbol		Name	Symbol	
	Uppercase	Lowercase		Uppercase	Lowercase
alpha	Α	α	nu	Ν	ν
beta	Β	β	xi	Ξ	ξ
gamma	Γ	γ	omicron	Ο	ο
delta	Δ	δ	pi	Π	π
epsilon	Ε	ε	rho	Ρ	ρ
zeta	Ζ	ζ	sigma	Σ	σ
eta	Η	η	tau	Τ	τ
theta	Θ	θ	upsilon	Υ	υ
iota	Ι	ι	phi	Φ	φ
kappa	Κ	κ	chi	Χ	χ
lambda	Λ	λ	psi	Ψ	ψ
mu	Μ	μ	omega	Ω	ω

and it is currently out of print. This 165-page book has remained a valuable source of reference in many geotechnical laboratories worldwide. The U.S. Army Corps of Engineers produces numerous design manuals and guidelines that are available free and can be downloaded from their website http:///www.usace.army.mil/publications/eng-manuals. This includes *Laboratory Soil Testing* (USACE 1986). The U.S. Naval Facilities Engineering Command produces excellent design manuals that are widely used in geotechnical engineering. The three most commonly used manuals are: *DM7.01-Soil Mechanics*, *DM7.02-Foundations and Earth Structures*, and *DM7.03-Soil Dynamics and Special Design Aspects* downloaded from their website http://www.navfac.navy.mil. The U.S. Bureau of Reclamation produces *Earth Manual* which covers earthwork and the associated lab and in situ testing and construction control. This can be downloaded free from http://www.usbr.gov/pmts/writing/earth/earth.pdf. The American State Highway Transportation Officials (AASHTO) produces their standards in *Standard Specifications for Transportation and Methods of Sampling and Testing*. This can be purchased from AASHTO. The three volume series by K.H. Head, *Manual of Soil Laboratory Testing*, can be a useful reference source in a soil testing laboratory. They are quite comprehensive and cover the nuts and bolts of the test procedures and equipment.