1

Commonly Measured Properties

The purpose of this chapter is to introduce the more commonly measured properties and give outline descriptions of how they are measured. This will allow engineers and geologists who are specifying test schedules, but who may have little or no experience of soils laboratory work, to have a clear understanding of the procedures used to carry out the tests they are scheduling, along with any problems that might occur. This, in turn, should help them to choose the most appropriate tests and to fully appreciate any problems or shortcomings related to the various test methods when appraising the results. It may also give an appreciation of the complexity of some tests to determine seemingly straightforward properties. For clarity, some details have been omitted; test descriptions are not intended to give definitive procedures or to be of sufficient detail to allow them to be used for actual testing. Such details should be obtained directly from the test standards being used, and will normally be the responsibility of the testing laboratory unless specific variations from the standards are required.

Deeper discussions of the nature and meaning of the various properties, and how they relate to other properties, are given at the beginning of subsequent chapters.

Soil Properties and their Correlations, Second Edition. Michael Carter and Stephen P. Bentley.

1.1 Moisture Content

Moisture content has a profound effect on many properties, and moisture content determinations are carried out as a routine part of many tests; for example, during the determination of shear strength, compressibility, plasticity and California Bearing Ratio (CBR). An especially common use is during density determinations, where it is used to calculate dry density from measurements of bulk density.

To obtain a moisture content value, a soil specimen is simply heated until dry. By weighing the specimen before and after drying, the weight of dry soil and the weight of water driven off can be obtained, and moisture content is obtained from:

$$m = \frac{\text{weight of water}}{\text{weight of dry soil}} \tag{1.1}$$

expressed as a percentage.

Note that the definition relates moisture content to the weight of soil solids (dry soil) and not to the total weight of the wet sample. This means that for some soils, such as peat, where the weight of water may exceed the weight of soil solids, the moisture content may exceed 100%.

1.1.1 Test Methods

1.1.1.1 Standard Oven Drying

The standard laboratory procedure is by oven drying a specimen of between 30 g (fine-grained soils) and 3 kg (coarse-grained soils) in an open tin or tray at 105-110 °C for 18-24hours, or until a stable weight is obtained for at least 4 hours. This temperature is high enough to ensure that all free water is driven off but not so high as to break down the mineral particles within the soil. However, some variation in the method may be required for certain soils, especially those containing gypsum or anthracite (coal), which break down chemically at normal oven temperatures. For such soils, lower temperatures are used, typically 60 °C.

1.1.1.2 Quick Methods

Whist the standard oven drying method is satisfactory for normal ground investigation testing, the length of time taken to dry out the specimen can be a problem for quality control of earthworks, where results are needed quickly. To overcome this problem, a number of quick methods have been developed, some of which are outlined below. In all cases, the quick methods should be calibrated against oven-drying values for each soil type as not all methods work with all soils.

- *Microwave oven drying* works well for most soil types provided the soil is microwaved for the appropriate times – see, for example, Carter and Bentley (1986). Ceramic or glass dishes that do not absorb microwaves must be used, and some kind of dummy sample should be included that will continue to absorb microwaves after all the water has been driven off to avoid running the microwave with no load, which can damage it. Note that there is a risk that the dummy sample will get very hot.
- The *'Speedy' moisture tester* consists of a sealed cylindrical pressure flask with a pressure gauge mounted at one end. A fixed weight of soil is put into it along with calcium carbide powder, and the flask is shaken. Reaction of the powder with water in the soil produces acetylene gas, creating a pressure that is proportional to the amount of water in the specimen. The pressure gauge is calibrated directly in percentage moisture content. The tester is quick and simple to operate, requiring no specialised knowledge or equipment, and usually gives reasonably accurate results with granular soils but results can be erratic with clay soils. The method should be calibrated against oven-drying tests for each soil type, and some soils may not give consistent results at all, precluding use of this method.
- *Field density meters*, which measure the transmission or backscatter of radiation through the soil, may also be used to obtain moisture content values. These are an exception to the methods used by the other tests in that the soil is not dried out during testing. The operation of these devices is summarised later in this chapter in the 'Soil density' section.
- *Other methods* include heating the specimen over a hot tray of sand placed on a gas burner, mixing the specimen with methylated spirit (a mixture of methyl and ethyl alcohol) then setting it alight. However, these are rarely used now except in remote field locations where only primitive equipment is available and they are not without risks to the tester if not carried out carefully, so are not described here.

1.2 Grading

Grading, otherwise known as particle size distribution or PSD, gives a measure of the sizes and distribution of sizes of the particles that make up a soil. Grading is arguably the most fundamental of all properties, especially for coarse-grained soils with little or no clay particles.

Particle size distribution is used for a wide variety of assessments, especially where soil is to be used in remoulded form such as fills and embankments, and grading tests are specified in nearly all site investigation test schedules. Uses include: classifying fill materials for design purposes (Appendix A); assessment of permeability and drainage characteristics; and suitability for backfill to pipes. Grading characteristics are more important for coarse-grained soils (sands and gravels); for fine-grained soils (silts and clays), plasticity is more indicative of behaviour but, even for these soils, the proportion of coarser material present is important for assessing properties.

1.2.1 Test Methods

There are two main methods of grading soil.

- *Sieve analysis*: Coarse-grained soils, with soil particles down to 63 μm (fine sand size, defined as below 75 μm in some standards), can be separated out by sieving.
- *Sedimentation analysis*: Below 63 μm, particles are too fine to be sieved, and particle distribution is determined by the rates of settlement of particles suspended in water using Stokes's Law.

1.2.1.1 Sieve Analysis

British Standard (BS) and US sieves are circular with a square mesh; sieve specifications are defined in BS (2014) and ASTM (2015). The larger sizes are usually 300 mm diameter and the smaller sizes 200 mm. They are made to slot together, one on top of the other, to form a 'nest' (see Fig. 1.1) that can be shaken, usually on an electrically powered sieve shaker, but hand shaking may be used. Within a nest, the sieve aperture size decreases from top to bottom. The minimum sieve size is usually 63 μm or 75 μm, depending on the standard used, and a pan is held below the bottom sieve to catch the fines.

For granular soil (sand and gravel), the specimen may be simply sieved dry. However, soil with a significant amount of silt and clay will tend to form lumps which will be retained on the larger size sieves, so the fines must be washed out of the specimen first. This gives rise to two procedures: wet sieving and dry sieving.

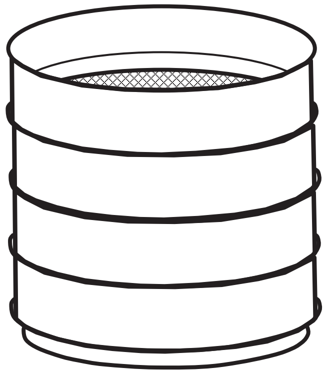

Figure 1.1 Nested sieves.

Wet Sieving

The procedure for wet sieving is as follows.

- The soil specimen is oven dried and weighed. A minimum of 200 g, 2 kg or 20 kg is used depending on whether the soil is fine, medium or coarse grained. (The laboratory will decide on this.)
- The dried specimen is sieved through a 20 mm sieve to separate out larger particles. (This step may be omitted for soils not containing particles above 20 mm.) Material retained on the sieve is sieved through larger sieves (>20 mm).
- Material passing the sieve is divided up, usually by riffling, to produce a suitable-sized sample for the smaller sieves.
- After weighing, this sub-sample is placed in a bucket or tray and covered with water containing a dispersing agent (typically sodium hexametaphosphate) and left to stand for an hour.
- The material is then washed, a little at a time, through a 2 mm sieve nested on a 63 μm sieve until the wash water runs virtually clear.
- Now that the silt- and clay-sized particles have been removed from the soil, the two portions (2–20 mm and 63 μm–2 mm) can be oven dried and dry sieved through a nest of appropriate sieve sizes.
- From the total weight of the sample and sub-samples, and the weights on each sieve, the proportions of the various sizes can be calculated.

This procedure appears rather complex for what is essentially a simple sieving process but it is necessary to ensure that sufficient material is used to obtain a representative specimen size for the larger particle sizes while not overloading the smaller sieves, and to wash out any silt- and clay-sized particles as described above. The need to oven dry the specimen initially, and again after washing out the fines, means that the test can take two or three days overall because each oven drying takes typically 12–24 hours with drying taking place overnight.

Dry Sieving

For clean aggregates or soils with minimal fines content, dry sieving may be used, in which the washing procedure is omitted, significantly simplifying the procedure.

1.2.1.2 Sedimentation Analysis

About 15 g of soil fines (<63 μm or <75 μm depending on the test standard) is boiled with distilled water to wet and break up the particles, then hydrogen peroxide is added to remove any organic matter.

The mixture is allowed to stand overnight and is then boiled again to remove the hydrogen peroxide. It is washed with more distilled water and either centrifuged or filtered before being oven dried and weighed.

The sample is shaken or stirred with sodium hexametaphosphate solution for 4 hours to ensure complete dispersion and washed into a 1 litre measuring cylinder. The volume is made up with distilled water to 1 litre and shaken vigorously, with a stopper in the top of the cylinder. As soon as the shaking has ceased and the cylinder stood on a level surface, a stop clock is started.

The rate of sedimentation is measured by one of two methods. The pipette method uses a pipette to take a sample from 100 mm below the surface at set time intervals. This is dried and weighed. The hydrometer method measures the average density of the suspension by inserting a hydrometer (similar to that used for home wine-making) at various time intervals. With either method, the rate of sedimentation is obtained for a range of time intervals. This can be related to the particle size distribution using Stokes's law, which gives a relationship between particle size and its rate of settlement through a liquid. Sedimentation analysis is not strictly comparable with sieving, especially since Stokes's law assumes the particles to be spherical whereas clay particles tend to be plate-like.

Knowing the percentage of clay particles may be useful in some investigations, but normally the important clay properties are better obtained from the liquid and plastic limit test. Given the complexity of the test, its shortcomings and the limited use of the results, it is worth considering whether sedimentation testing is really necessary before ordering it.

1.3 Plasticity

Plasticity is a measure of the range of moisture contents over which a soil is a mouldable solid. It is measured by two tests: the plastic limit test and the liquid limit test. Results are expressed as three moisture content values: the plastic limit; the liquid limit; and the plasticity index, which is the difference between the liquid and plastic limits.

The tests are carried out on only the fine fraction of a soil, which is normally material passing the 425 μm sieve depending on the test standard. Soils with no fines (granular soils) are not mouldable at any moisture content and are simply described as 'non-plastic'.

Plasticity results are not normally used directly in geotechnical analysis, but may be used in conjunction with correlations to infer a wide range of properties. Liquid and plastic limit values are also used in soil classification systems, as described in Appendix A.

1.3.1 Test Methods

1.3.1.1 Liquid Limit

Two methods are available for determining the liquid limit: the traditional Casagrande method and the cone penetrometer method which has largely superseded the Casagrande method in many regions.

In each case, soil must be initially prepared by drying it then sieving it through a 425 μm sieve and discarding the coarser material. About 200 g of soil is normally sufficient. Oven drying is normally used but this can affect results with some soils, especially tropical residual soils and those containing gypsum, for which air drying should be used.

Casagrande Method

The equipment is illustrated in Figure 1.2. Soil is placed in the cup, the surface scraped level and then grooved as illustrated using a special grooving tool. By turning a handle on the device, the cup is repeatedly raised 13 mm and then dropped on to the special rubber base, jarring the soil and causing the groove to close up. The number of blows required to cause the two sides of the groove to just touch over a 13 mm length is recorded. The soil is then

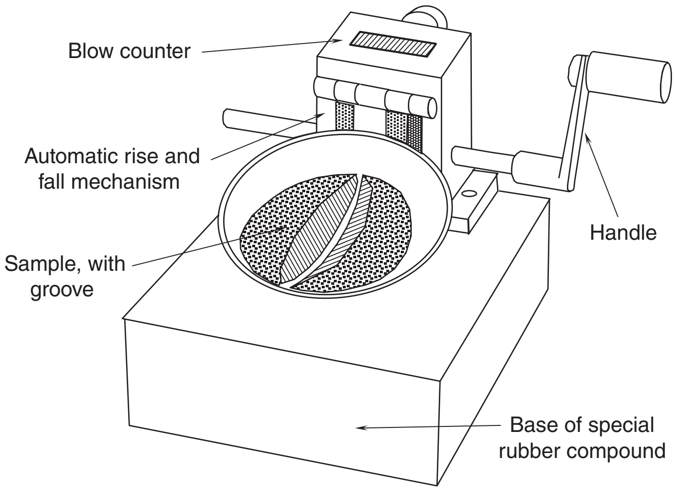

Figure 1.2 Casagrande liquid limit apparatus.

removed and a specimen taken for moisture content determination. The remainder is mixed with a little water and the test repeated. This process is continued until results are obtained for at least four moisture content values, with blow counts of between 50 and 10.

By plotting the number of blows (to a log scale) against moisture content (to a linear scale), the moisture content at which 13 mm of groove would close after 25 blows can be obtained. This is the liquid limit.

Cone Penetrometer Method

The prepared soil is placed in a cylindrical metal cup, scraped level with the rim and placed on the apparatus; the cone is then lowered to just touch the top of the soil, as illustrated in Figure 1.3.

The cone is released for five seconds before being re-clamped, and the cone penetration into the soil is measured to the nearest 0.1 mm with the dial gauge (see Fig. 1.3). The soil is then removed, a specimen taken for moisture content determination, the remainder mixed with a little water and the test repeated. This process is continued until results are obtained for at least four moisture content values, with cone penetrations of between 15 mm and 25 mm.

By plotting the penetration against moisture content (both on linear scales), the moisture content corresponding to 20 mm penetration can be obtained. This is the liquid limit.

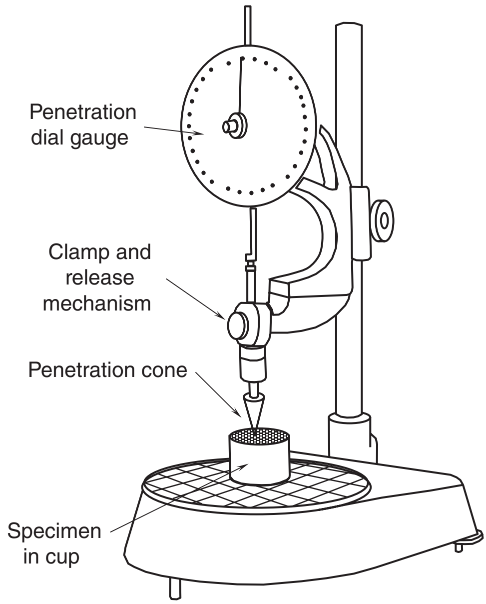

Figure 1.3 Cone penetrometer liquid limit apparatus.

Comparison of the Test Methods

A certain amount of skill and judgement is needed to carry out these tests and to estimate the amounts of water needed. The two tests give similar results but the cone penetrometer method is quicker and produces more consistent results. The Casagrande method, by comparison, can be affected by aging of the rubber base and even by the location of the apparatus on a worktop. For example, if performed on a poorly constructed wooden worktop, tests made with the apparatus mid-way between supports will give slightly different values from those with it placed directly over a support.

1.3.1.2 Plastic Limit

A 20 g specimen of soil, prepared as described for the liquid limit test, is mixed with a little distilled water until it becomes plastic enough to be shaped into a ball. Half the soil is then moulded and rolled between the fingers until the surface begins to crack as it slowly dries out. It is then repeatedly rolled on a glass plate into 3 mm diameter threads until they begin to crack longitudinally at a diameter of 3 mm. The process is repeated with the second half of the specimen and the moisture contents of the two separate portions are determined. The average is taken as the plastic limit provided the two values agree within 0.5%. This moisture content is the plastic limit.

This is an intrinsically simple test, requiring little equipment, but it relies heavily on the experience of the tester. At each re-rolling, the threads must be rolled back into 3 mm threads within 10 hand strokes. The temptation with inexperienced testers is to reduce pressure as the thread begins to break up and continue rolling, giving a plastic limit value that is too low.

1.3.1.3 Plasticity Index

This is simply the difference between the liquid and plastic limits.

1.4 Specific Gravity of Soil Particles

This method is used to determine the average density of the particles of soil. Results are expressed as a proportion of the density of water, that is, as specific gravity.

The specific gravity of the soil particles allows the proportion of voids in the soil to be calculated, and it is needed to calculate the proportion of air voids within a soil, a measure of the effectiveness of compaction methods. However, it is often specified unnecessarily whenever consolidation tests are carried out in the mistaken belief that it is necessary for the calculation of the coefficient of volume compressibility, m_v.

1.4.1 Test Method

The test requires a container that can be filled with water to a high degree of repeatability. Typically, a gas jar, a pyknometer or a specific gravity bottle are used, depending on how coarse-grained the soil is (Fig. 1.4).

The soil specimen is oven dried then weighed. The specimen size varies according to the coarseness of the soil and is typically between 20 g and 400 g. Next, the container is half-filled with water and the soil is placed into it and left to stand for about 4 hours, after which it is shaken vigorously to remove air. It is then filled with water and weighed. Finally, the container is washed out, filled with water and weighed again.

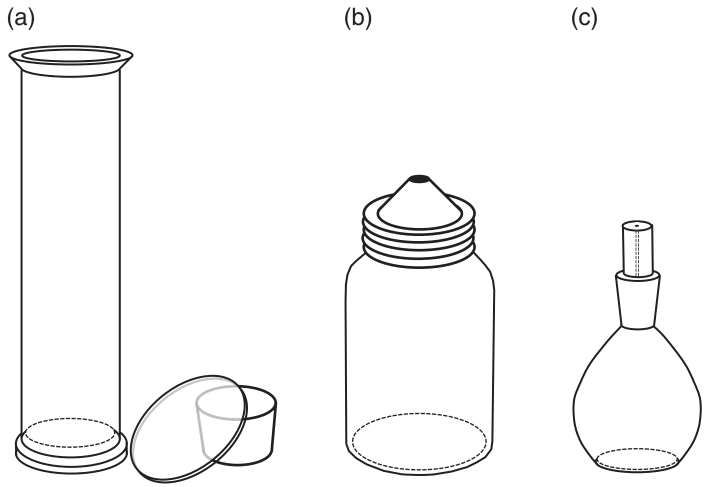

Figure 1.4 Specific gravity determination jars: (a) gas jar with stopper and glass plate; (b) pkynometer; and (c) specific gravity bottle.

The weight of water displaced by the particles can be obtained from the difference between the two container weights and the weight of the dry specimen. The specific gravity G_s is then calculated from:

$$G_s = \frac{\text{weight of soil}}{\text{weight of water displaced by soil particles}}. \tag{1.2}$$

1.5 Soil Density

Soil density values are used in several ways:

- *directly*, for instance to calculate forces on retaining walls and slopes, and the shear stresses and strengths of soils beneath foundations and behind slopes and retaining walls;
- *indirectly*, for instance to infer other properties such as compressibility and shear strength, using correlations; and
- *for quality control*, for instance to ensure that earthworks and pavements have been compacted as well as reasonably possible.

This wide range of uses means that density measurements are carried out in a variety of situations using various methods.

The presence of water in soil gives an added complication to the definition of soil density, and four types of soil density are used: bulk density, dry density, saturated density and submerged density, as defined and discussed in Chapter 3.

1.5.1 Test Methods

1.5.1.1 Common Laboratory Methods

Density is routinely measured as part of other tests: for instance, shear strength testing using triaxial and shear box equipment; consolidation testing using an oedometer (consolidometer); standard compaction testing; CBR testing; and permeability testing.

In all cases the soil is cut to a specific size or is contained within a mould of fixed dimensions so that determination of the soil volume is a matter of simple calculation. Once the soil is weighed, its bulk density can be readily determined. Once a specimen of the soil has been taken for a moisture content determination, its dry density can also be calculated.

1.5.1.2 Field Density Measurements

These are typically used to check the density of earthworks and pavements for quality control purposes.

Core Cutter Method

This is an intrinsically simple test in which a core of clay is taken by driving a cylindrical core cutter, typically of 150 mm or 200 mm diameter, into the surface. After driving to full depth, it is carefully removed and excess soil is trimmed off either end. Soil density is then obtained from weighings and knowledge of the volume of the cutter.

Care is needed to ensure that the soil completely fills the core cutter, and a special driving dolly is used to help drive the cutter well into the surface while allowing soil to protrude from the top. It also reduces the risk of the sample being compacted during driving which can be a problem with some soils, leading to an overestimation of density.

The method can work reasonably well in firm plastic clays but harder, more friable soils may break up and granular soils simply fall out of the cutter when it is removed. Also, with some soils, the sample may be compacted during driving, leading to an overestimation of density. Because of these difficulties, the range of soils for which this test can be used is limited.

Sand Replacement Method

All the methods described above rely on obtaining a specimen of a specified shape whose dimensions are accurately known. However, this is not always possible when checking the density of compacted earthworks. The sand replacement method overcomes this problem by using sand of known density to fill the volume of an excavated hole.

This, the traditional field test for earthworks, requires no sophisticated equipment; it is however slow and cumbersome, and may appear to be somewhat outdated by modern methods. However, it can be used for many different soil types and gives reasonably accurate values so it is still the standard against which other field density methods are judged. The equipment is illustrated in Figure 1.5.

An area of the surface is scraped level and the special plate with a hole in it (Fig. 1.5) is placed on the levelled surface. A circular hole is excavated using the plate as a template to the full depth of the layer being tested. The plate is used to catch any excavated material which is transferred to a

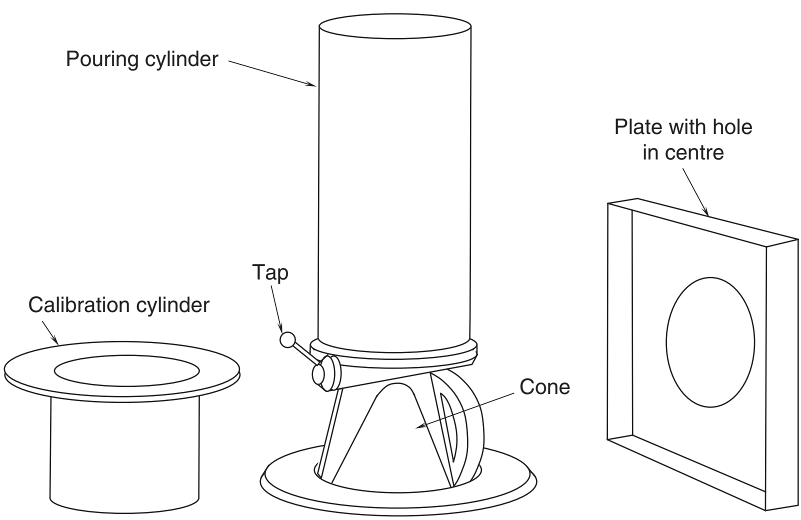

Figure 1.5 Sand replacement method equipment.

polythene bag for weighing and moisture content determination. The hole is trimmed reasonably smooth and any loose material is removed.

The plate is then moved away and the pouring cylinder is placed directly over the hole. This is partly filled with a known weight of special 'density sand' of known density and the tap is opened, allowing sand to flow into the hole, filling both the hole and the cone beneath the cylinder. Once the sand has stopped flowing, the tap is closed and the remaining sand transferred to a polythene bag for weighing.

Knowing the weight of sand used and allowing for the volume of the cone, the volume of soil removed can be calculated, hence the bulk density is obtained. Dry density can then be calculated from the moisture content value.

The density sand, which should be closely-graded (i.e. contain a small range of particle sizes) so that it gives a consistent density value, must be prepared and its density measured beforehand using a special calibration cylinder of known volume.

Equipment comes in various diameters, but is typically 150 mm diameter for fine-grained soils and 200 mm diameter for medium-grained soils. Hole depths are roughly equal to the diameter.

Nuclear Density Meter

The nuclear density meter is quick to use and gives virtually instant results without the need to wait for moisture content determinations. Bulk density is measured using a radioisotope source and a gamma ray detector. The meter is placed on the surface, which must be carefully levelled, and the detector records radiation that has passed through the ground from the source. There are two distinct methods of use, as illustrated in Figure 1.6:

- *direct transmission mode*, in which the source is inserted into the ground and the meter detects radiation that has passed through the soil; and
- *backscatter mode*, in which the source is kept on the surface and the meter detects radiation that has been reflected back.

Backscatter mode is quicker to perform because it does not require a hole to be made in the surface but it effectively checks only the upper few centimetres of soil, whereas direct transmission mode checks the whole layer to the depth of the radioisotope source.

In addition, radiation produces slow neutrons when gamma rays (fast neutrons) collide with hydrogen atoms in the soil. These can be measured

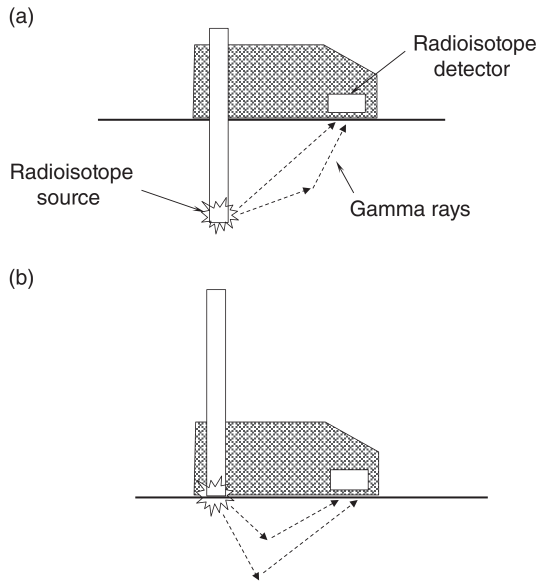

Figure 1.6 Nuclear density meter modes of operation: (a) direct transmission mode; and (b) backscatter mode.

by a slow neutron detector. Since nearly all the hydrogen in soil is normally due to the water present, this can be used to estimate moisture content, allowing dry density to be obtained immediately.

The instruments were originally used to check asphalt densities where the flat surface, lack of need to check a moisture content and requirement for speed make them ideal. However, care must be used in soils, since variations in soil composition can affect results, so they must be checked regularly for each soil type using soil compacted into a calibration box.

There is also a limitation regarding the soil types with which they can be used, especially if the moisture content facility is required, because soils containing organics will contain hydrogen atoms that are not part of the soil moisture. This includes many of the Coal Measures rocks found in Wales and the north of England. Soils containing gypsum will also contain water in the form of water of crystallisation in the gypsum crystals.

A further drawback is that the meters rely on radioactive sources which carry health hazards; although the amount of radioactivity is small, this risk should not be overlooked.

1.6 Permeability

Permeability is used in seepage calculations including seepage through dams, beneath cut-off walls and through the ground when estimating the extent of contamination in the ground. It is therefore limited to certain special types of problem, so permeability tests do not form part of most ground investigation testing.

There are basically two types of laboratory permeability test:

- *falling head tests*, in which a fixed amount of water flows through the specimen from a graduated cylinder, with the pressure head decreasing throughout the test; and
- *constant head tests*, in which water flows under a constant pressure through a soil specimen and the rate of flow is measured.

Falling head tests are more suitable for clay soils, whose low permeability means that the rate of flow is so slow that test times would be excessive. Constant head tests are more suitable for sands and gravels, whose higher permeability means that the falling head test, with its limited supply of water, would be over too quickly for accurate measurement.

In addition to the specific permeability tests described in the following sections, permeability may also be measured using triaxial test equipment and may be inferred from consolidation test results.

Permeability is often measured in field tests where the flow of water from or to a borehole or sometimes a trial pit is measured, again using falling/rising head or constant head tests depending on the ground permeability. Field testing is beyond the scope of this book, but it is worth considering the relative merits of field and laboratory tests.

Essentially, laboratory tests have the advantage that the soil geometry is controlled so all the parameters needed for permeability calculations are accurately known. This knowledge or control of the ground and the flow through it is absent in field testing, where the ground profile and flow patterns can often only be guessed at. However, the overall permeability of the ground is greatly affected by the macro-structure of the soil, with sometimes thin silt or sand layers within a clay taking most of the flow for instance. The resulting discrepancy can be huge, with overall ground permeability sometimes being 10 times or more that measured in laboratory tests.

These limitations mean that field testing tends to be preferred where the overall permeability of the ground is required, while laboratory testing is preferred to measure the permeability of specific materials such as those to be used as drainage layers.

1.6.1 Test Methods

1.6.1.1 Sample Preparation

Cohesive soil specimens are prepared by carefully trimming a sample to the correct diameter while pressing it into the test cylinder with a cutting edge at one end. Once inserted, the specimen is trimmed top and bottom and parings are taken for moisture content determination. Disturbed cohesive specimens may be formed by first compacting into a standard compaction mould and then forming the test specimen as described above. Granular soils are poured into the permeability test cylinder and tapped or vibrated until the required density is achieved.

Weighings are taken so that the soil density can be determined. Gauze end caps are placed at the top and bottom of the cylinder, which is then fixed into a frame with top and bottom end caps and lowered into a water bath to saturate the soil. A tube connects the upper end of the cylinder to a vacuum pump to aid with soil saturation.

1.6.1.2 Falling Head Permeameter

The specimen, still in the water bath, is connected via tubing to a glass cylinder filled with de-aired water as shown schematically in Figure 1.7.

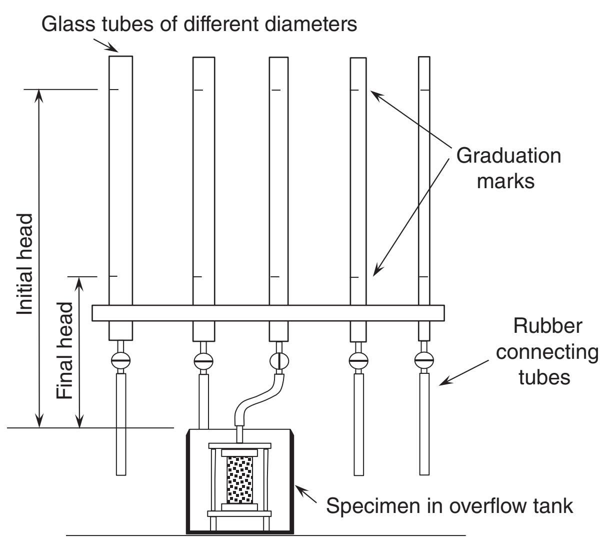

Figure 1.7 Basic layout of the falling head permeameter.

The water is allowed to run through the specimen and the time taken for it to fall between two marks on the graduated cylinder is taken. The soil permeability can then be calculated. The test is usually repeated three or four times.

The apparatus normally has a number of glass tubes of different diameters to allow for variations in permeability of the test specimen. The correct tube is selected by judgement and by trial and error, so that the test will take between about 15 seconds and 90 minutes.

1.6.1.3 Constant Head Permeameter

The sample, still in the water bath, is connected to a column of water maintained at a constant head by the arrangement shown schematically in Figure 1.8. Water flows through the specimen and is collected in a measuring cylinder so that the rate of flow can be determined.

The cylinder containing the soil specimen usually has a number of nipples along its side which can be connected to manometer tubes via flexible hosing, so that the piezometric head can be measured at various points along the specimen.

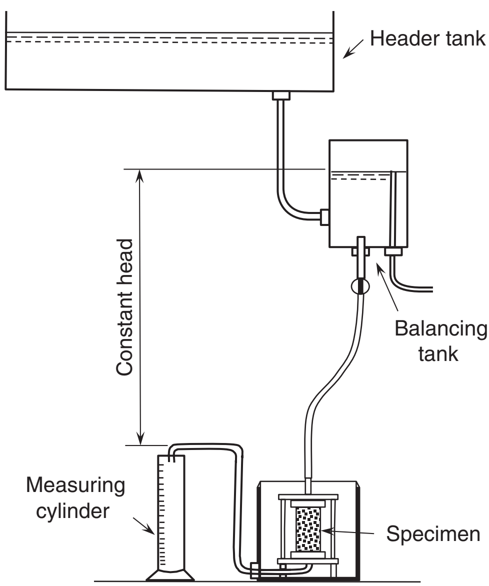

Figure 1.8 Basic layout of the constant head permeameter.

1.7 Consolidation

Consolidation testing is normally carried out by means of an oedometer or consolidometer, shown in Figure 1.9. The test measures two consolidation parameters: the coefficient of volume compressibility m_v, which is a measure of the amount by which a soil will settle; and the coefficient of consolidation c_v, which is a measure of the rate of settlement.

Since settlement of foundations and within fills and embankments is often an important design consideration, consolidation testing commonly forms part of ground investigations.

Experience has shown that values of m_v generally give reasonably good predictions of overall settlement, when appropriate correction factors are applied. It should be remembered, however, that soil becomes stiffer as it compresses, so the value of m_v is not constant but decreases as consolidation pressure increases. It is therefore essential that the m_v value used in settlement estimates is for the pressure change that will actually be experienced in the ground.

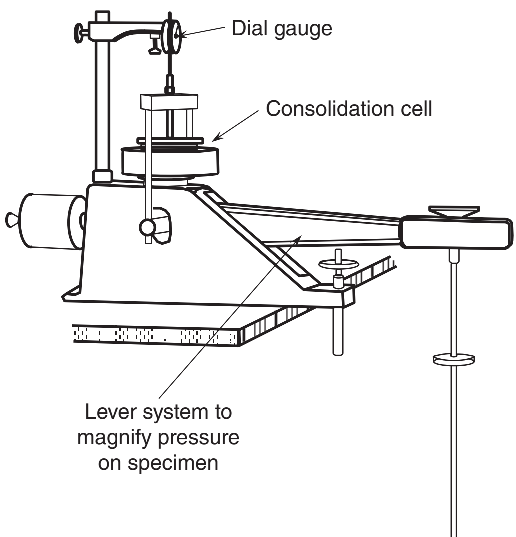

Figure 1.9 Consolidation test equipment.

An exception to this can occur in the case of overconsolidated clays, where m_v will show a sudden increase once the pressure reaches the previous overconsolidation pressure. Care is needed to avoid underestimating settlements in this case.

By contrast, c_v values often do not reflect actual settlement times, especially in highly stratified soils where rates of settlement may be much higher than predicted. This is because the small test specimen does not reflect the macrostructure of the soil, giving the same types of discrepancy as those described for permeability. To overcome this problem and obtain more realistic settlement rates, consolidation tests are sometimes combined with field permeability tests using the theoretical relationships between c_v and the coefficient of permeability.

A further note of caution is needed with some soils and climatic conditions: consolidation theory was developed with temperate conditions in mind, where soils are typically saturated. However, soils such as tropical residual clays and loess tend to be unsaturated, with open structures. This causes specimens to collapse in the initial stages of testing, requiring special testing procedures, and raises questions about the validity of consolidation theory for these soils. Similar problems can occur when testing poorly compacted fills.

1.7.1 Test Method

The soil specimen, usually a clay, is contained in a metal consolidation ring, typically 75 mm diameter and 19 mm deep, with a cutting edge at the bottom. Typically, a short length of sample is extruded from a sample tube and the consolidation ring is pressed into it, cutting around the edges with a palette knife then finally trimming it top and bottom. Good sample preparation is important, and requires care and skill.

For highly stratified soils, where horizontal permeability may be much greater than vertical permeability, pairs of tests may be performed; one with the specimen prepared as described above, and a second specimen in which the consolidation ring is pushed into the side of the sample, so that drainage from it will be along the horizontal layers within the soil. The value of the coefficient of volume compressibility will usually be little affected but the rate of consolidation, hence the coefficient of consolidation, may be greater in the second specimen if the stratification features are fine enough to be reflected in the specimen. However, larger-scale features may not be reflected in the small specimen, and field tests may be used to supplement laboratory testing as described above and in Chapter 4.

Where soil is to be used for fill, a sample can first be prepared by compacting it into a standard compaction mould to the required density then preparing the specimen as described above.

Once prepared, the specimen is placed into a consolidation cell which is fitted on to the load frame as indicated in Figure 1.9. Weights are added, then the consolidation cell immediately filled with water. Readings of displacement with time are taken until the rate of consolidation is very small. More weights are then added and the process repeated; usually four or five load stages are tested, then a final unloading stage may be specified if this is relevant for the design calculations, at which all the weights are removed and swell is measured.

Weights are usually calculated so that the loading pressures follow the sequence: 12.5, 25, 50, 100, 200, 400 kPa (kN/m^2), etc., the choice depending on the expected stress range at the project site. However, it is better to have the first stage below the expected pressure range, as initial settling-in problems can sometimes give less-accurate m_v values for the first load stage.

Readings are typically taken at 30 seconds, then 1, 2, 4, 8, 15 and 30 minutes, then 1, 2, 4, 8 and 24 hours. With five load stages, or four load stages and an unloading stage, the test typically takes a working week.

Graphs are plotted of displacement with time for each load stage, plus a graph of final displacement at each stage against pressure. Graphical constructions are used to obtain c_v.

1.8 Shear Strength

Shear strength testing is usually carried out using either triaxial tests or shear box tests, although other tests, such as ring shear, are occasionally used. Hand penetrometers are also used for quick indications on site, and a variety of shear vane tests may be used including hand-held vanes and vane test equipment for use down boreholes.

For both triaxial and shear box tests, there are a number of variations depending on whether the short- or long-term response of the soil is needed. These are noted in the test methods described below.

Shear strength values are needed for a wide variety of design calculations, including spread footing stability, pile capacity, retaining wall stability and slope stability. Shear strength tests are therefore a feature of most test schedules, although the type of test will depend on both the soils encountered and the design calculations to be carried out.

1.8.1 Test Methods

1.8.1.1 Triaxial Tests

Triaxial tests are usually carried out on undisturbed samples of silt, clay or soft rock. The test is unsuitable for granular soils as the test specimen is not contained within a mould, so non-cohesive specimens cannot be prepared. As noted above, there are a number of variations of the test and triaxial testing is the subject of many books and papers; the complexities of the test procedures and interpretation of results are therefore only discussed briefly in this book.

The apparatus includes a triaxial cell and a load frame, illustrated in Figure 1.10, along with associated control and measuring equipment.

Sample Preparation

Testing is often carried out using samples from 100 mm diameter sample tubes. For fine-grained soils, test specimens are usually 38 mm or 40 mm diameter (76 mm or 80 mm long), and three specimens can be prepared simultaneously by extruding soil from the tube directly into three specimen tubes.

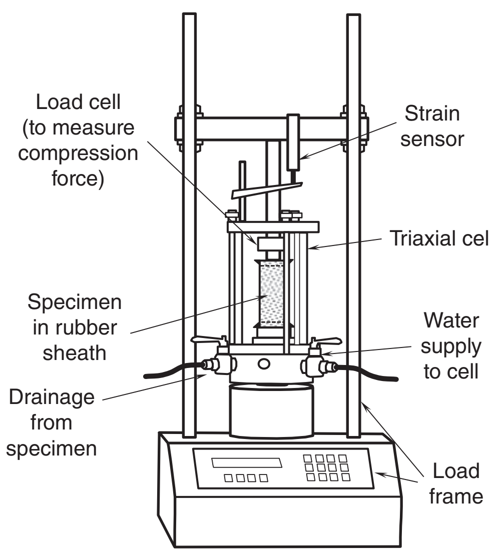

Figure 1.10 Triaxial test equipment.

Specimens are then extruded from the specimen tubes into a special split wall tube to be trimmed to length, then transferred to a third special tube which enables them to be covered in a rubber membrane. An end platen (a disc, which may be either solid or porous depending on the test type) is placed at either end.

In a variation of the test, used for medium-grained soils, a 100 mm diameter specimen is used, straight from the sample tube.

The 'Quick' Undrained Test

This is the simplest, quickest and most common form of the test and is used for footing and pile calculations, for which short-term stability is usually the most critical consideration.

The specimen, with solid end platens, is placed on the pedestal on the load frame and the perspex (plexiglass) triaxial cell is placed over it. Once fixed in place, the triaxial cell is filled with water which is pressurised to simulate pressure in the surrounding ground. The load frame is then adjusted so that the top plunger just touches the top of the specimen. Load is then applied, usually at a constant rate of movement, representing typically 2% strain per minute, up to 20% strain, when the test is normally terminated. Strain and load readings are taken throughout so that a stress-strain plot can be obtained.

The test is repeated on each of the two remaining specimens, each being tested at a different cell pressure. With most commercial laboratory equipment three specimens can be tested simultaneously, each within its own triaxial cell.

Where medium-grained soils are tested and a 100 mm diameter test specimen is used, it is usually not possible to obtain three specimens from a single sample tube. To overcome this problem, a modified form of the test is used in which the specimen is tested up to peak value for the first cell pressure, then the cell pressure is increased and the test continued to obtain a second peak; then similarly for the third cell pressure. This is difficult to perform and the results should be viewed with some scepticism; indeed, some engineers refuse to schedule this type of test.

Drained and Consolidated Undrained Tests

These tests are used to determine the long-term shear strength of the soil after consolidation has taken place. They consequently have to be carried out much more slowly than the 'quick' test, and include an initial consolidation stage after the triaxial cell has been brought up to pressure, before shearing takes place. A further difference from the quick test is that these tests give a measure of the stresses within the soil skeleton (the 'effective' stresses), whereas the quick test measures the combined soil skeleton and pore-water pressure stresses ('total' stresses).

In both tests porous end platens are used so that water can drain out of the specimen during the consolidation phase, which generally takes around 24 hours. In the drained test, drainage of the specimen is also allowed to take place during the loading stage. Loading is carried out sufficiently slowly to allow full dissipation of pore-water pressures during shearing, so the stresses measured represent those on the soil skeleton itself. The rate of testing depends on the permeability of the soil, and laboratories will normally advise on this; shearing typically takes several hours but can, with exceptional soils, take days.

In the consolidated undrained test, the specimen is not allowed to drain during testing so that measured stress includes both the soil skeleton stress and pore-water pressure. However, the pore-water pressure is measured so that, again, the stresses on the soil skeleton can be obtained. The rate of testing needs to be comparable with that of the drained test to allow pore-water pressures to equalise throughout the specimen during shearing, so they can be properly measured.

Specifying Cell Pressures

As described above, each of the three test specimens is tested at a different cell (or confining) pressure and these must be specified when scheduling a test. Pressures should normally cover the range of expected stresses in the soil. The first specimen would therefore be tested at overburden pressure, the third at a little above the maximum expected pressure after loading (e.g. overburden plus additional pressure to be exerted by a foundation), with the second specimen tested midway between. Tests should not be carried out below overburden pressure.

Interpreting the Results

Results are shown as individual stress-strain curves for each specimen and as a graph of shear strength against confining pressure, plotted as Mohr circles, as shown in Figure 1.11. For effective stress tests, additional graphs of the consolidation stage are given. A line is drawn tangential to the Mohr circles, as illustrated, to obtain the shear strength parameters, cohesion c and angle of shearing resistance ϕ (c_d and ϕ_d for drained tests; c' and ϕ' for consolidated undrained tests).

When viewing test results it should be remembered that, while the Mohr circles represent actual test measurements, the tangent line and resulting

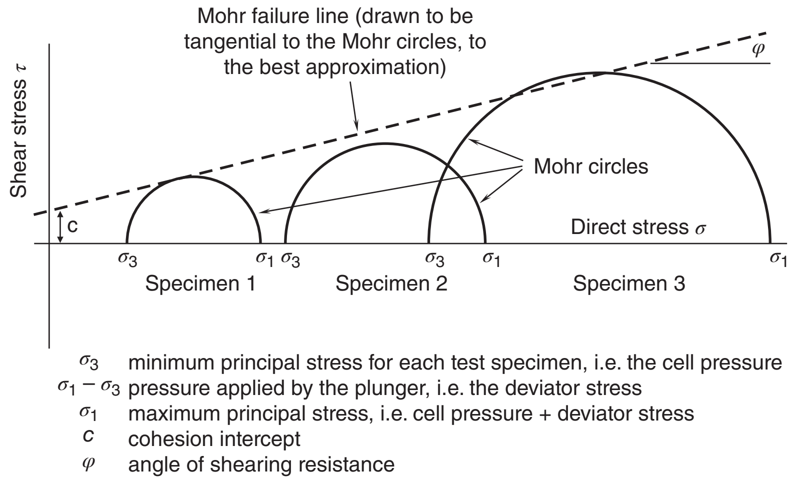

Figure 1.11 Example of a Mohr circle plot.

shear strength parameters represent an interpretation; one that may be open to doubt given that variability of the results may make it difficult to decide on where to plot the tangent line. For instance, the plot shown gives both cohesion c and angle of shearing resistance ϕ values but it is typically assumed that for total stresses in saturated clays the angle of shearing resistance is zero, giving a constant shear strength, and that sands and gravels are cohesionless, giving a purely frictional material with no cohesion intercept. Effective strength tests in overconsolidated clays often give both cohesion and friction (i.e. positive c and ϕ values) but the (usually small) cohesion value is sometimes ignored in calculations.

1.8.1.2 Shear Box Tests

The test is straightforward in its approach in that a specimen contained in a square-section split mould (the shear box) is simply sheared across its centre. The specimen and shear box arrangement is shown schematically in Figure 1.12.

Both the test procedure and the theory are simpler than for the triaxial test. Drainage conditions cannot be controlled or measured as much as they can in the triaxial test, and pore-water pressures cannot be measured. However, the test does have two significant advantages over the triaxial test: since the specimen is confined within a mould, it is easy to test granular

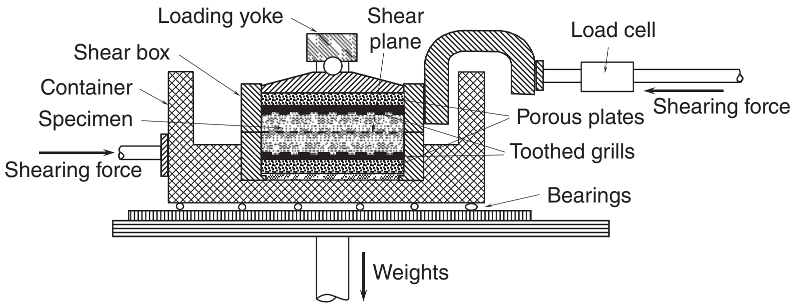

Figure 1.12 Schematic arrangement of a shear box.

soils; and shearing may be continued indefinitely by repeatedly reversing the movement allowing residual strengths to be measured, which is not possible with the triaxial test.

The specimen is usually 60 mm square and 20 mm thick and, for clays, is cut to shape by using a square specimen cutter of the same dimensions as the shear box, trimming with a palette knife. This is then put into the shear box. For sands or disturbed clay samples, the soil may be compacted directly into the shear box.

Once placed in the apparatus, the specimen is put under vertical (or normal) pressure using weights hanging from a loading yoke, and the shear box is flooded with water.

In the standard test, the specimen is sheared at typically 1.25 mm/min, usually for about 9 mm, to obtain peak shear strength. This gives undrained conditions for clays, but drained conditions for sands with their greater permeability. Drained shear strength parameters may be obtained for clays by simply slowing down the rate of shearing, testing over several hours or even days. Residual strength can be obtained by repeated back-and forth shearing. Changes in specimen thickness during shearing (caused by dilation along the shear plane) are measured.

Three test specimens are sheared during a set of tests, each at a different normal pressure, and a plot of shear stress against movement is made for each specimen, with a combined plot of peak (and possibly residual) shear stress against normal stress to obtain the shear strength parameters.

Larger shear boxes, typically 300 mm square, are used to test coarse material, but the large sample size and high normal forces needed create difficulties, especially since the weights required would be too great to be practicable, so a hydraulic loading system is normally used which greatly increases complexity and costs.

1.8.2 Choice of Shear Strength Test

Figure 1.13 gives an overview of the various types of triaxial and shear box test that are commonly used and suggests the appropriate test related to soil types and design considerations. This may provide a useful starting point for the selection of test type but should not be used as a substitute for experience and consideration of specific circumstances.

1.9 Standard Compaction Test

When soil is compacted the density obtained depends on the soil type, its moisture content and the compactive effort used. Standard compaction tests use a standard compactive effort (broadly comparable with that applied by compaction plant on site), and the sample is compacted at various moisture contents to determine the optimum moisture content that produces the maximum dry density. When used for quality control, this gives a standard against which field density results can be judged and an indication of the most appropriate moisture content for compaction. At the site investigation stage, the test gives a comparison between natural moisture content and optimum moisture content, indicating whether the soil is suitable for earthworks; a natural moisture content more than 1½-2% above optimum cannot be well compacted.

1.9.1 Test Method

Soil is compacted into a standard cylindrical mould to give a standard amount of compactive effort per unit volume of soil. A sketch of typical equipment is shown in Figure 1.14. Normally, compaction is carried out using a rammer of standard dimensions, weight and drop, but the use of a rammer for compaction has been found to give unrealistically low values for some sands and gravels; in which case a variation of the test may be used in which the soil is compacted using a vibrating hammer under a specified procedure, typically vibrating for 60 seconds with a force of 30–40 kg.

The standard test uses a 1-litre mould with soil compacted in 3 layers by 27 blows per layer of a 2.5 kg rammer falling through 300 mm; whilst a heavy standard uses a 2.3-litre CBR mould with soil compacted in 5 layers by 62 blows per layer falling through 450 mm. Note that these values are for UK practice, but variations in standards tend to be small and result in much the same compactive effort per unit volume of soil. For instance, the original Proctor test used a $\frac{1}{30}^{\text{th}}$ of a cubic foot (944 cm^3) mould with 25 blows per layer of a standard rammer weighing 5½ pounds (2.49 kg) falling through 1 foot (30.48 cm).

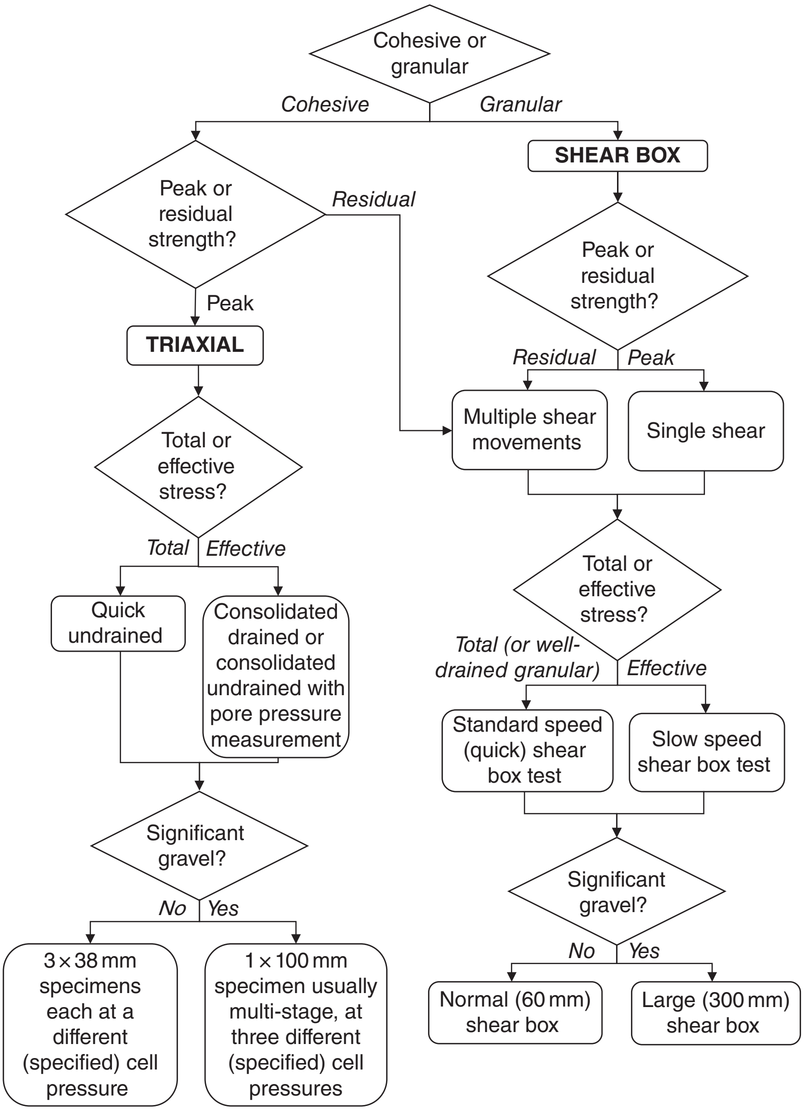

Figure 1.13 Shear test types and typical uses.

Since UK pavement design methods are based on the standard test, there is normally little point in carrying out the heavier standard test in the UK, but design standards elsewhere for both roads and aircraft pavements sometimes require the heavy standard.

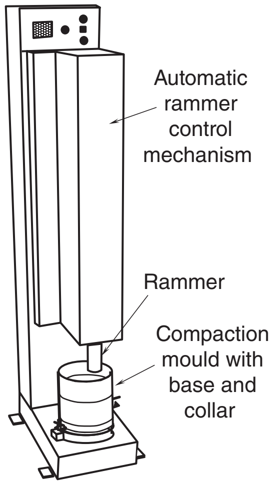

Figure 1.14 Standard compaction test equipment.

About 5 kg of soil is needed for the standard test, and about 12 kg if a CBR mould is used (see Section 1.10 below). The sample of soil is passed through a 20 mm sieve and mixed with a suitable amount of water (or dried out if it is too wet) for the first compaction point. The quantity of water added depends on the soil and must be judged from experience.

The soil is compacted into the mould as described above, using sufficient to fill the mould in three even layers (five for the heavier standard) to just above the base of the collar.

The collar is removed and the top surface carefully trimmed off level with the top of the mould using a steel straight-edge. The mould with contained soil is then weighed. Knowing the weight and volume of the mould allows the bulk density to be calculated. The soil is then extruded from the mould and two or three small specimens are taken for moisture content determination so that the dry density can be calculated.

The remaining soil is mixed with a little water and the test repeated. The test is further repeated, adding water each time, to give at least 5 compaction points. At first, adding water will result in an increase in the dry weight of the soil compacted into the mould, indicating it is dry of optimum. Eventually, however, additional water will result in a decrease in the dry weight compacted into the mould, indicating the soil is wet of optimum. There should be at least two compaction points either side of optimum.

Results are plotted as a graph of dry density against moisture content, on which a trend line may be drawn to obtain the maximum dry density and optimum moisture content. This is discussed further and illustrated in Chapter 3.

Traditionally, earthworks were required to attain a specified percentage of maximum dry density (usually 90% or 95%), but more recently compaction is specified in terms of the percentage of air voids, especially in wet climates where it is impractical to specify that soil be compacted at or near optimum moisture content. This still requires the standard compaction test, however, to determine reasonable, achievable values and compare its moisture content with the optimum value.

1.10 California Bearing Ratio

California Bearing Ratio (CBR) values are used to calculate the required thicknesses of pavement layers. As its name implies, the test was originally developed in California but, ironically, was used there for only a short time. The test does not measure any fundamental property of the soil, and is used only in pavement thickness design.

The test measures the resistance of soil to a cylindrical plunger of standard dimensions being pushed into the surface at a standard rate. It is therefore basically an indirect measure of shear strength, and for clays an approximate relationship exists with shear strength as discussed in Chapter 7.

Results are highly dependent on the method of sample preparation, so much so that the method is no longer used by many highways agencies, but it is still the basis for some design methods, especially for minor roads, car parks and storage areas. The test is intrinsically linked to pavement design methods, and test methods must follow those specified in the design standard being used. For instance, UK design methods generally require the test to be prepared to the moisture content that is likely to exist beneath the pavement in the long term and tested without soaking, whereas US design practice tends to favour soaking of the specimen, regardless of expected subgrade conditions, then applying a climatic correction factor.

1.10.1 Test Method

In the normal laboratory test, a sample is sieved (if necessary) to remove any material above 19 mm size, then compacted into a standard 2.3 litre mould – about 7 kg of sample is normally sufficient. In UK practice, the

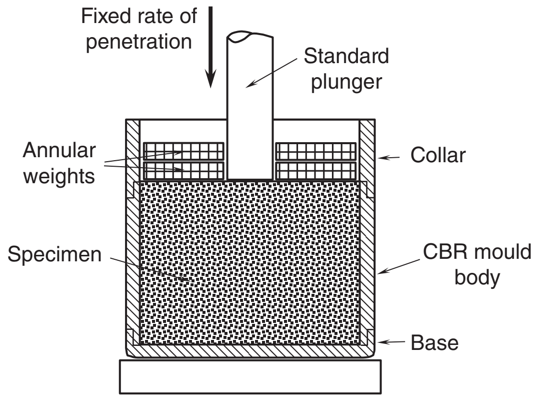

Figure 1.15 Test arrangement for CBR.

target compacted density is usually that which is expected to be achieved in the field, and compaction can be carried out either using a standard rammer (as for the compaction test), a vibrating hammer or by hydraulic jack. Compaction is normally in 3 or 5 layers.

Samples may be soaked, typically for 4 days, during which swell is measured. Soaking is standard in much US practice, but is not normal in the UK.

In the test itself, the plunger is pushed into the surface at 1 mm per minute using a load frame similar to that used for triaxial testing. The arrangement of mould and plunger is shown in Figure 1.15. Readings are taken and a graph plotted of force against penetration. After smoothing and possible corrections, the forces corresponding to penetrations of 2.5 mm and 5.0 mm are compared with a standard value for each penetration and expressed as a percentage; the higher percentage is the CBR value.

During testing (and soaking) annular weights are normally placed on the surface to simulate the weight of pavement that is expected above the layer being tested. These have little effect on clays but may have some effect on granular soil. Typically, two or three 2.27 kg weights are used.

Strictly, in the UK, the sample should be tested at both ends and the average CBR value taken, but some UK laboratories appear to test only at the top. Other design standards may require testing only at the bottom, especially if the specimen is soaked which can cause the top to become softened.

A variation of the test procedure is to use it in conjunction with standard compaction testing: standard compaction tests are performed in CBR moulds rather than standard moulds so that each test specimen can subsequently be tested for CBR. This shows the variation of CBR with moisture content, which can be useful when assessing the suitability of soils for subgrade material.

1.11 Other Properties

A wide variety of other tests are available to check specific properties, and a complete description of all possible tests and test variations is beyond the scope of this book. Three of the more common specialist properties are briefly described below.

1.11.1 Swelling Potential

Swelling potential is used to indicate the potential of a soil to swell and shrink with changes in moisture content. It is used, for instance, in conjunction with estimates of the depth of soil subject to seasonal moisture content changes to determine minimum founding depths for structures on expansive soils and in the proximity of trees.

Swelling potential is defined in terms of the swelling potential test, a modified form of consolidation test, as described in Chapter 8.

An alternative, simpler test, used to assess the propensity of a subgrade soil to swell, is the linear shrinkage test, in which a specimen of soil with moisture content at its liquid limit is pressed into a small trough then oven dried. The reduction in length of the specimen after drying is measured and expressed as a percentage of the original length to give the linear shrinkage value.

Although these tests give an indication of swelling potential, the actual swelling that will occur in the field depends on site conditions including seasonal moisture content changes and overburden pressures, so test results can be used only as an indication of relative swelling problems. Because of this, swelling potential is usually inferred from plasticity and grading tests which are simpler to carry out and based on standard laboratory practice, as discussed in Chapter 8. However, there is no universal agreement about the reliability of plasticity tests to predict swelling potential.

1.11.2 Frost Susceptibility

Frost susceptibility is a measure of the potential of a soil to swell when subjected to repeated cycles of freezing and thawing. It is used, for instance, in conjunction with climate data to determine the minimum thickness of pavements.

Direct measurements of the amount of swelling that can occur are tedious as they require repeated freezing and thawing and, like swelling potential described above, can give only an indication of potential problems, not the specific movement that may occur in the field. Therefore, frost susceptibility is often estimated from plasticity and grading tests, using correlations, as discussed in Chapter 9.

1.11.3 Combustible Content

Combustible content is important when assessing the propensity of a near-surface soil to catch fire when subjected to high temperatures. It is also used in conjunction with air voids content to assess the risk of spontaneous combustion in deeper soils, especially of colliery discard tips.

The propensity for combustion is usually measured by the 'calorific value' test but the simpler 'mass loss on ignition' test may also be used as there is a reasonable correlation between the two tests, as discussed in Chapter 10.

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