Chapter 6

Compaction tests

6.1 Introduction

6.1.1 Scope

Many civil engineering projects require the use of soils as fill material. Whenever soil is placed as an engineering fill, it is nearly always necessary to compact it to a dense state in order to obtain satisfactory engineering properties that would not be achieved with loosely placed material. Compaction on site is usually effected by mechanical means such as rolling, ramming or vibrating. Control of the degree of compaction is necessary to achieve a satisfactory result at a reasonable cost. Laboratory compaction tests provide the basis for control procedures used on site.

Compaction tests furnish the following basic data for soils:

1. The relationship between dry density and moisture content for a given degree of compactive effort.
2. The moisture content for the most efficient compaction i.e. at which the maximum dry density is achieved under that compactive effort.
3. The value of the maximum dry density so achieved.

Item 1 is expressed as a graphical relationship from which items 2 and 3 can be derived. The latter are the moisture and density criteria, against which the compacted fill can be judged if *in situ* measurements of moisture content and density are made.

There are several different standard laboratory compaction tests. The test selected for use as the basis for comparison will depend upon the nature of the works, the type of soil and the type of compaction equipment used on site. This chapter describes the tests accepted in Britain as standard practice and two tests of American origin that have special applications.

Tests that are carried out on site to determine the density and other characteristics of the compacted fill are not described here.

6.1.2 Development of test procedures

A test to provide data on the compaction characteristics of soil was first introduced by Proctor in the USA in 1933, in order to determine a satisfactory state of compaction for soils being used in the construction of large dams, and to provide a means for controlling the degree of compaction during construction. The test made use of a hand rammer and a cylindrical mould with a volume of 1/30 ft^3, and became known as the standard Proctor compaction test (Proctor, 1933; Taylor, 1948). The test now known as the British Standard light compaction test is very similar, although the equipment used differs in some details.

At that time it was believed that the Proctor test represented in the laboratory the state of compaction that could be reasonably achieved in the field. But with the subsequent introduction of heavier earth-moving and compaction machinery, especially for the construction of large dams, higher densities became obtainable in practice. A laboratory test using increased energy of compaction was then necessary to reproduce these higher compacted densities, so a test was introduced which used a heavier rammer with the same mould. This intensified procedure became known as the modified Proctor test. It is similar to the British Standard heavy compaction test. The 'Proctor' mould of 1/30 ft^3 (944 cm^3) is used in ASTM standards. When the British Standard changed to SI units in 1975 the volume of the mould was rounded up to 1000 cm^3, and this is known as the one-litre compaction mould. The dimensions and masses of rammers were rationalized to metric units at the same time. It is essential to appreciate that the BS and ASTM tests, although similar in principle, require different apparatus and use procedures which differ in some details.

Details of the BS and ASTM compaction moulds are summarised in Table 6.1, and data for compaction rammers are included in Table 6.2.

Granular soils, especially gravels, are most effectively compacted by vibration. A laboratory test using a vibrating hammer was introduced into British Standards in 1967 to establish the compaction characteristics for these conditions. Because particles up to coarse gravel size are necessary to represent these materials as closely as possible in the test, a large mould (the CBR mould) is used. This procedure is known in this country as the British Standard vibrating hammer compaction test.

Dry densities measured on compacted soils *in situ* are still often expressed as a percentage of the maximum dry density for a specified degree of compaction. This percentage is called the relative compaction of the soil. When the dry density required on site is greater than the BS light maximum dry density, the field density is more usually related to the BS heavy maximum dry density, rather than quoting values of relative compaction in excess of 100%.

Table 6.1 Details of compaction moulds: Internal dimensions

Type of mould	*Diameter*		*Height*	*Internal volume*	
	(mm)	*(in)*	*(mm)*	*(cm^3)*	*(cu ft)*
BS 1 litre	105		115.5	1000	
CBR	152		127	2305	
ASTM 4 in	101.6	(4)	116.4	944	(1/30)
6 in	152.4	(6)	116.4	2124	(0.075)

Table 6.2 Compaction procedures

Type of test	*Mould*	*Rammer* *Mass* (kg)	*Drop* (mm)	*No of Layers*	*Blows per layer*	*Refer to section*
BS light	One litre	2.5	300	3	27	6.5.3
	CBR	2.5	300	3	62	6.5.5
ASTM (5.5 lb)	4 in	2.49	305	3	25	
	6 in	2.49	305	3	56	6.5.7
BS heavy	One litre	4.5	450	5	27	6.5.4
	CBR	4.5	450	5	62	6.5.5
ASTM (10 lb)	4 in	4.54	457	5	25	
	6 in	4.54	457	5	56	6.5.7
BS Vibrating hammer	CBR	32–41*		3	(1 min)	6.5.9

* Downward force to be applied.

6.2 Definitions

Compaction The process of packing soil particles more closely together, usually by rolling or mechanical means, thus increasing the dry density of the soil.

*Optimum moisture content (*OMC) The moisture content of a soil at which a specified amount of compaction will produce the maximum dry density.

Maximum dry density The dry density obtained using a specified amount of compaction at the optimum moisture content.

Relative compaction The percentage ratio of the dry density of the soil to its maximum compacted dry density determined by using a specified amount of compaction.

Dry density-moisture content relationship The relationship between dry density and moisture content of a soil when a specified amount of compaction is applied.

Percentage air voids (V_a) The volume of air voids in a soil expressed as a percentage of the total volume of the soil.

Air voids line A line showing the dry density–moisture content relationship for a soil containing a constant percentage of air voids.

Saturation line (*Zero air voids line*) The line on a graph showing the dry density–moisture content relationship for a soil containing no air voids.

6.3 Theory

6.3.1 Process of compaction

Compaction of soil is the process by which the solid soil particles are packed more closely together by mechanical means, thus increasing the dry density (Markwick, 1944). It is achieved through the reduction of the air voids in the soil, with little or no reduction in the water content. This process must not be confused with consolidation, in which water is

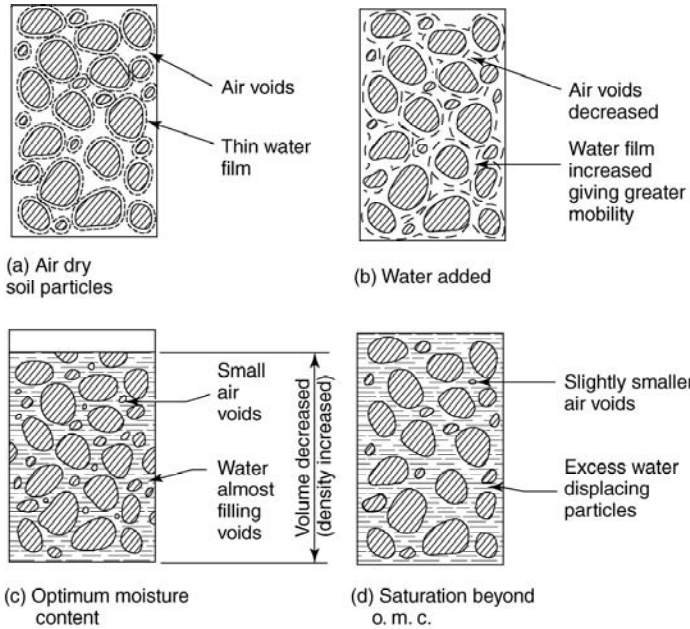

Figure 6.1 Representation of compaction of soil grains

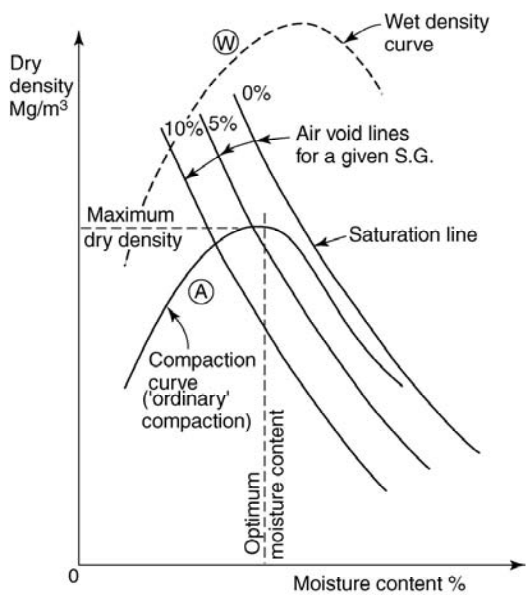

Figure 6.2 Dry density–moisture content relationship for soils

squeezed out under the action of a continuous static load. The air voids cannot be eliminated altogether by compaction, but with proper control they can be reduced to a minimum. The effect of the amount of water present in a fine-grained soil on its compaction characteristics, when subjected to a given compactive effort, is discussed below.

At low moisture content the soil grains are surrounded by a thin film of water, which tends to keep the grains apart even when compacted (Figure 6.1(a)). The finer the soil grains, the more significant is this effect. If the moisture content is increased, the additional water enables the grains to be more easily compacted together (Figure 6.1(b)). Some of the air is displaced and the dry density is increased. The addition of more water, up to a certain point, enables more air to be expelled during compaction. At that point the soil grains become as closely packed together as they can be (i.e. the dry density is at the maximum) under the application of this compactive effort (Figure 6.1(c)). When the amount of water exceeds that required to achieve this condition, the excess water begins to push the particles apart (Figure 6.1(d)) so that the dry density is reduced. At higher moisture contents little or no more air is displaced by compaction, and the resulting dry density continues to decrease.

If at each stage the compacted dry density is calculated and plotted against moisture content, a graph similar to curve A in Figure 6.2 is obtained. This graph is the moisture–density relationship curve. The moisture content at which the greatest value of dry density is reached for the given amount of compaction is the optimum moisture content (OMC), and the corresponding dry density is the maximum dry density. At this moisture content the soil can be compacted most efficiently under the given compactive effort. The relationship between bulk (wet) density and moisture content is shown by the dotted curve (W) in Figure 6.2. This curve is not generally plotted, except perhaps as a guide during a compaction test before the moisture contents are measured.

A typical compaction curve obtained from the British Standard light compaction test (Section 6.5.3) is shown in Figure 6.3 as curve A. If a heavier degree of compaction corresponding to the BS heavy compaction test (Section 6.5.4) is applied at each moisture content, higher values of density and therefore of dry density will be obtained. The resulting moisture–density relationship will be a graph such as curve B in Figure 6.3. The maximum dry density is greater, but the optimum moisture content at which this occurs is lower than in the light test.

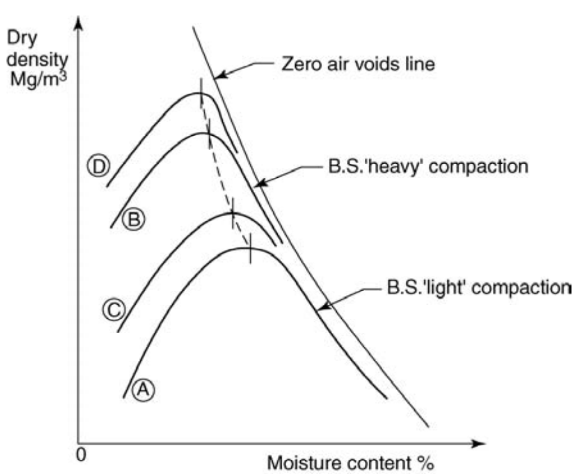

Figure 6.3 Dry density–moisture curves for various compactive efforts

Every different degree of compaction on a particular soil results in a different compaction curve, each with unique values of optimum moisture content and maximum dry density. For instance, a compaction test similar to the BS light test but using, say, 50 blows per layer instead of 27 would give a graph similar to that shown by curve C in Figure 6.3. A test similar to the heavy compaction test but using a greater number of blows would give a graph similar to curve D. It can be seen that increasing the compactive effort increases the maximum dry density but decreases the optimum moisture content.

6.3.2 Air voids lines

A compaction curve is not complete without the addition of air voids lines. An air voids line is a (curved) line showing the dry density–moisture content relation for soil containing a constant percentage of air voids. A set of air voids lines can be drawn from calculated data if the particle density of the soil grains is known; three are indicated in Figure 6.2. The derivation of the equation relating dry density to moisture content for a given percentage of air voids V_a is given below. Note that V_a is the volume of air voids in the soil expressed as a percentage of the total volume of soil, as in BS 1377: 1990: Part 1: 2.2.37, and not as a percentage of the voids. V_a is not the same as (100 – S), where S is the saturation expressed as a percentage of the total voids.

If all the air voids are removed, so that the total voids between solid particles are filled with water, the soil reaches the fully saturated condition. The equation relating the saturated dry density to moisture content, from which the zero air voids line can be drawn, can be derived by setting V_a equal to zero.

The notation is the same as that used in Section 3.3.2, with some additional symbols:

Volume of solids	= 1
Volume of air voids	= a
Volume of water in voids	= b
Total volume = V	$= \overline{1 + a + b}$
Mass of solids = 1 × ρ_s	= ρ_s
Mass of air = a × 0	= $\underline{0}$
Total dry mass	= ρ_s

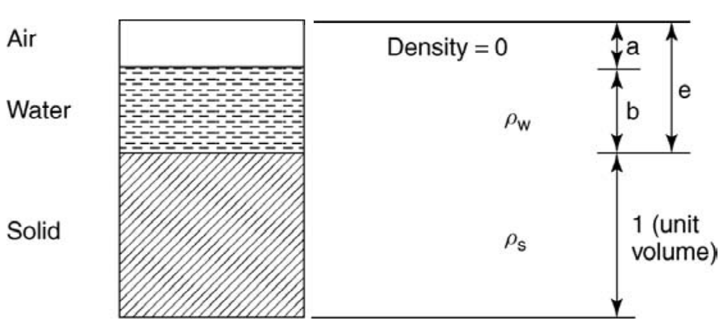

Figure 6.4 Representation of soil with air voids

$$\text{Mass of water, from moisture content} = \frac{w}{100} \times \rho_s$$

Therefore,

$$\text{Volume of water} = \frac{w\rho_s}{100\rho_w} = b \tag{6.1}$$

Volume of air voids, a, expressed as a percentage of the total volume, is denoted by V_a. i.e.

$$V_a = \frac{a}{V} \times 100 = \frac{100a}{1 + a + b} \tag{6.2}$$

Hence

$$a = \frac{V_a(1+b)}{100 - V_a}$$

therefore

$$\begin{aligned} V &= 1 + \frac{V_a(1+b)}{100 - V_a} + b \\ &= \frac{(1+b)(100 - V_a) + V_a(1+b)}{100 - V_a} \\ &= \frac{100(1+b)}{100 - V_a} \end{aligned} \tag{6.3}$$

Substituting for b from Eq. (6.1),

$$\begin{aligned} V &= \frac{100\left(1 + \dfrac{w\rho_s}{100\rho_w}\right)}{100 - V_a} \\ &= \frac{1 + \dfrac{w\rho_s}{100\rho_w}}{1 - \dfrac{V_a}{100}} \end{aligned} \tag{6.4}$$

$$\text{Dry density } \rho_D = \frac{\text{dry mass}}{\text{volume}} = \frac{\rho_s}{V}$$

$$= \rho_s \cdot \frac{1 - \dfrac{V_a}{100}}{1 + \dfrac{w\rho_s}{100\rho_w}}$$

i.e.

$$\rho_D = \frac{\left(1 - \frac{V_a}{100}\right)\rho_w}{\frac{\rho_w}{\rho_s} + \frac{w}{100}} \tag{6.5}$$

Using SI units and setting ρ_w = 1 Mg/m³ gives the equation

$$\rho_D = \frac{1 - \frac{V_a}{100}}{\frac{1}{\rho_s} + \frac{w}{100}} \quad \text{Mg/m}^3 \tag{6.6}$$

For the fully saturated condition (no air voids), $V_a = 0$. Therefore,

$$\rho_{D(sat)} = \frac{1}{\frac{1}{\rho_s} + \frac{w}{100}} \rho_w \ \text{Mg/m}^3 \tag{6.7}$$

This equation defines the zero air voids line, or the saturation line. It is impossible for a point on a compaction curve (in terms of dry density) to lie to the right of this line, whatever degree of compactive effort is applied.

Curves for 0, 5 and 10% air voids (i.e. V_a = 0, 5, 10%) are shown in Figure 6.2. These curves are defined only by the particle density of the soil grains. Sets of standard curves can be drawn up for various particle densities, so that the set applicable to a particular soil can be selected, either by use of the data given in Table 6.3 or direct from equations (6.6) and (6.7). The air voids lines do not apply to the wet density curve (W) in Figure 6.2.

6.3.3 Compactive efforts

The procedures used for various types of BS and ASTM compaction test are summarised in Table 6.2.

The mechanical energy applied in each type of BS test, in terms of the work done in operating the rammer, is derived and compared below.

BS Light compaction test

$$(2.5 \text{ kg}) \times \frac{(300 \text{ mm})}{1000} \times 27 \times 3 = 60.75 \text{ kg m}$$

$$= 60.75 \times 9.81 \text{ Nm} = 596 \text{ J}$$

(kg m × 9.81 = newton metres = joules).

Volume of soil used = 1000 cm³ = 0.001 m³. Therefore,

$$\text{work done per unit volume of soil} = \frac{596}{1000} \text{ J/cm}^3 = 596 \ \text{kJ/m}^3$$

BS Heavy compaction test

$$4.5 \times \frac{450}{1000} \times 27 \times 5 \times 9.81 = 2682 \text{ J, or } 2682 \text{ kJ/m}^3$$

Table 6.3 Data for constructing air voids lines*

Moisture content w(%)	*Air voids, V_a(%)*	*Particle density ρ_s Mg/m³* 2.60	2.65	2.70	2.75	2.80
0	0	2.60	2.65	2.70	2.75	2.80
	5	2.47	2.52	2.57	2.61	2.66
	10	2.34	2.39	2.43	2.48	2.52
5	0	2.30	2.34	2.38	2.42	2.46
	5	2.19	2.22	2.26	2.30	2.33
	10	2.07	2.11	2.14	2.18	2.21
10	0	2.06	2.09	2.13	2.16	2.19
	5	1.96	1.99	2.02	2.05	2.08
	10	1.86	1.89	1.91	1.94	1.97
15	0	1.87	1.90	1.92	1.95	1.97
	5	1.78	1.80	1.83	1.85	1.87
	10	1.68	1.71	1.73	1.75	1.77
20	0	1.71	1.73	1.75	1.77	1.79
	5	1.63	1.65	1.67	1.69	1.71
	10	1.54	1.56	1.58	1.60	1.62
25	0	1.58	1.59	1.61	1.63	1.65
	5	1.50	1.51	1.53	1.55	1.56
	10	1.42	1.43	1.45	1.47	1.48
30	0	1.46	1.48	1.49	1.51	1.52
	5	1.39	1.40	1.42	1.43	1.45
	10	1.31	1.33	1.34	1.36	1.37
35	0	1.36	1.37	1.39	1.40	1.41
	5	1.29	1.31	1.32	1.33	1.34
	10	1.23	1.24	1.25	1.26	1.27

* Dry densities (Mg/m³) corresponding to various moisture contents for soils of different particle densities

Light compaction in CBR (California bearing ratio) mould

$$\text{Volume} = 2305 \text{ cm}^3$$

$$2.5 \times 0.3 \times 62 \times 3 \times 9.81 = 1368 \text{ J}$$

$$\frac{1368}{2305} \times 1000 = 594 \text{ kJ/m}^3$$

Heavy compaction in CBR mould

$$4.5 \times 0.45 \times 62 \times 5 \times 9.81 = 6158 \text{ J}$$

$$\frac{6158}{2300} \times 1000 = 2672 \text{ kJ/m}^3$$

The calculations verify that for the light compaction tests, whether carried out with the one-litre mould or the CBR mould, the compactive energy per unit volume of soil is about the same.

For the heavy test the energy is similar with both procedures. The energy applied per unit volume in the heavy test is 4.5 times as much as that used in the light test (2682/596 = 4.5 exactly).

Vibrating hammer compaction (see Section 6.5.9)

Assume a 600 W motor and that 50% of the electrical input is converted to mechanical energy, half of which is absorbed by the soil sample (the other half being taken mainly by the operator), then

$$\text{energy applied to sample} = 600 \times \tfrac{1}{2} \times \tfrac{1}{2} \times 60 \times 3\text{J}$$

$$= 27\,000 \text{ J}$$

$$\frac{27000}{2300} \times 1000 = 11\,739 \text{ kJ/m}^3$$

The ratio of the calculated energy applied by the vibrating hammer to that applied by the heavy compaction test is 11 739/2672 = 4.39, which is of the same order of magnitude as the ratio (4.5) of the heavy to the light compactive effort.

6.3.4 Effect of stone content

In the laboratory compaction tests using the one-litre mould only the fraction of soil passing a 20 mm sieve is used. Particles larger than 20 mm that are removed before test may consist of gravel, fragments of rock, shale, brick or other hard material, and are collectively referred to below as stones. The soil actually tested is called the ‘matrix’ material.

The density achieved on site for the total material cannot be compared directly with the results of laboratory compaction tests on the matrix material only. If the matrix material is compacted to reach a particular density, the presence of stones will give the total material a higher density, as the stones have a greater density than the matrix material they displace. The resulting *in situ* density of the whole material can be calculated from the equation derived below, provided that (a) the proportion of stones in the total material is known and (b) this

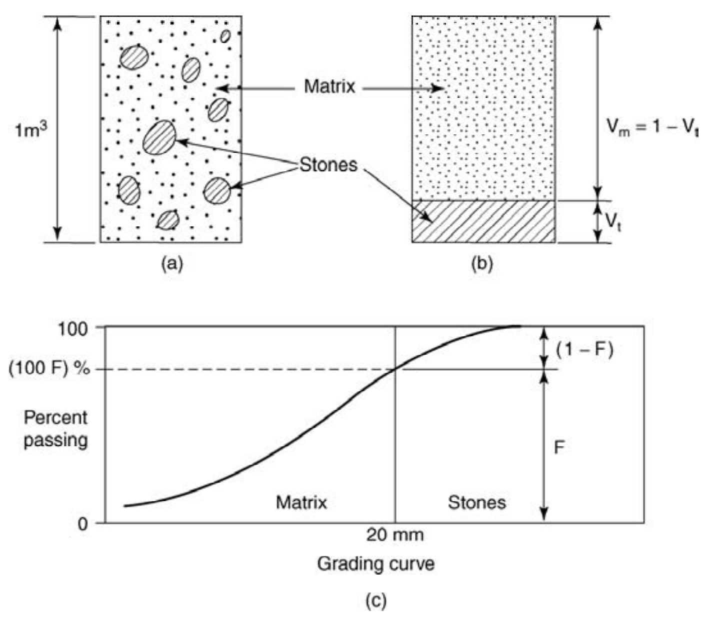

Figure 6.5 Representation of stony soil

proportion is not large (i.e. not more than about 25% of the total by dry mass), so that the stones are distributed within the matrix in such a way that they are not in contact with each other (Maddison, 1944; McLeod, 1970).

In practice, the presence of stones requires additional compactive effort to achieve the same degree of compaction of the matrix as when the matrix is compacted alone. However, this effect is not great for small percentages of stones and does not affect these calculations. If the percentage of stones is quite large, there may not be sufficient matrix materials completely to fill the voids between the stones, and this could be an unsatisfactory fill material for many purposes.

A unit volume of stony soil is represented diagrammatically in Figure 6.5(a), and the stones are imagined to be fused together in one piece occupying a volume V_t, as in Figure 6.5(b). The idealized grading curve of the whole material is shown in Figure 6.5(c). The proportion of material finer than 20 mm, expressed as a decimal fraction, is denoted by *F*.

The symbols used in the expressions below are summarised in Table 6.4. Four relationships can be written in the form of equations, as follows.

The total dry mass in a unit volume is equal to $\rho_D = m_m + m_t$ (6.8)

The mass of matrix materials is equal to its density multiplied by its volume i.e.

$$m_m = (1 - V_t)\rho_{mD} \quad (6.9)$$

The mass of stones is equal to the volume of solid material multiplied by the density of that material i.e.

$$m_t = V_t \rho_t \quad (6.10)$$

From the grading curve, the fraction of the matrix material to the whole is equal to the ratio of its dry mass to the total dry mass i.e.

$$F = \frac{m_m}{m_m + m_t} \quad (6.11)$$

Table 6.4 Symbols for stone content equations

Soil properties	*Matrix material*	*Stones*	*Total material*
Dry density	ρ_{mD}		
Particle density	ρ_s	ρ_t	
Volume	V_m	V_t	1
Mass in a unit volume of soil	m_m	m_t	$(m_m + m_t)$

From these equations the relationship between the dry density of the material containing stones ρ_D and the dry density of the matrix material measured in the laboratory ρ_{mD} can be derived, and is as follows:

$$\rho_D = \frac{\rho_t}{(1 - F) + F\left(\dfrac{\rho_t}{\rho_{mD}}\right)} \quad (6.12)$$

Using customary SI units and setting ρ_w = 1 Mg/m^3 this equation becomes

$$\rho_D = \left[\frac{\rho_t}{(1-F)\rho_{mD} + F\rho_t} \right] \rho_{mD} \tag{6.13}$$

This is the theoretical dry density to be expected *in situ*, derived from the dry density, ρ_{mD} of the matrix material measured in the laboratory.

The overall moisture content of the total material will differ from that of the matrix, owing to the presence of the stones. The stones themselves may absorb a certain amount of moisture, which will be removed by the normal oven drying procedure. Let w_m = moisture content of matrix, and w_t = moisture content (absorbed moisture) of stones. This absorbed moisture does not alter the volume of the stones. Moisture contents are expressed as decimal fractions. Other notation is as before.

Mass of water contained in matrix

$$= w_m m_m = w_m F(m_m + m_t)$$

$$= w_m F \rho_D$$

Mass of water contained in stones

$$= w_t m_t = w_s(1-F)\rho_D$$

Therefore, total mass of water contained in unit volume of combined material

$$= W = w_m F + w_t(1-F)\rho_D$$

Moisture content of total material

$$= w \frac{W}{\text{dry mass}} = \frac{W}{\rho_D}$$

Therefore,

$$w = Fw_m + (1 - F)w_t \tag{6.14}$$

If the stones contain no absorbed water (e.g. if they consist of pieces of quartz gravel), the value of w_t is zero and w is simply equal to $F \times w_m$.

Relationships similar to the above are given in ASTM Standards, D 4718.

6.4 Applications

6.4.1 Objectives of proper compaction

Soils may be used as fill for many purposes, the most usual being:

1. To refill an excavation, or a void adjacent to a structure (such as behind a retaining wall).
2. To provide made-up ground to support a structure.
3. As a sub-base for a road, railway or airfield runway.
4. As a structure in itself, such as an embankment or earth dam, including reinforced earth.

Compaction, by increasing the density, improves the engineering properties of soils. The most significant improvements, and the resulting effects on the mass of fill as a whole, are summarised in Table 6.5.

Table 6.5 Effects of proper compaction of soils

Improvement	*Effect on mass of fill*
Higher shear strength	Greater stability
Lower compressibility	Less settlement under static load
Higher CBR value	Less deformation under repeated loads
Lower permeability	Less tendency to absorb water
Lower frost susceptibility	Less likelihood of frost heave

6.4.2 Construction control

The relationship between dry density and moisture content for soil subjected to a given compactive effort, established by laboratory compaction tests, provides reference data for the specification and control of soil placed as fill. On many projects the laboratory compaction tests are supplemented by field compaction trials by using the actual placing and compacting equipment that is to be employed for construction (Williams, 1949).

Sometimes it is necessary to adjust the natural moisture content of a soil to a value at which it can be most effectively compacted, or at which it has the highest strength. The required moisture content, and the dry density to be achieved, can be assessed on the basis of the dry density–moisture content relationship derived from laboratory compaction tests on samples taken from the borrow area.

While compaction *in situ* needs to be of a sufficient degree to obtain the required density, it is equally important not to over-compact fine-grained soils. Overcompaction not only is wasteful of effort, but should be avoided because overcompacted soil, if not confined by overburden, can readily absorb water, resulting in swelling, lower shear strength and greater compressibility. Tops and sides of embankments are particularly sensitive to this effect.

6.4.3 Design parameters

When the compaction characteristics of a soil are known, it is possible to prepare samples in the laboratory at the same dry density and moisture content as that likely to be attained after compaction in the field. These samples can be subjected to laboratory tests for the determination of their shear strength, compressibility and other engineering properties. Design parameters derived from these tests enable the stability, deformation and other characteristics of the fill to be assessed. They can also provide the basis for the initial design of an embankment or earth dam.

More elaborate tests can be carried out on compacted samples to measure the changes of pore pressure due to changing conditions of applied stress. During construction, pore pressures can be monitored in order to ensure that they do not at any time exceed certain limiting values established by the tests.

A specification for compacted fill may require a certain relative compaction (measured in terms of dry density) to be achieved, within specified limits of moisture content. More usually a specification defines the maximum air voids permitted in the compacted soil within the required dry density range. For this reason it is necessary to determine the density of soil particles so that air voids lines can be added to the compaction test graphs.

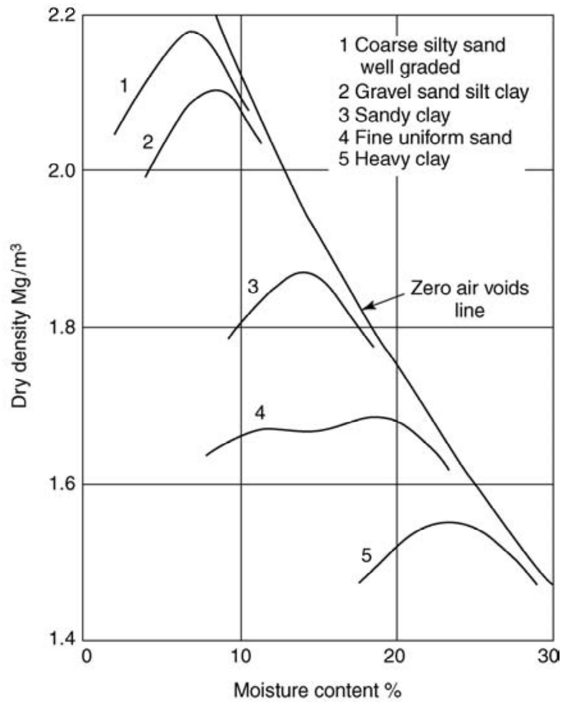

Figure 6.6 Compaction curves for some typical soils

6.4.4 Types of compaction curve

The form of compaction curve for five typical materials is shown in Figure 6.6. For ease of comparison they have been related to a common zero air voids line by adjusting the curves to the same particle density. These curves relate to BS or ASTM light compactive effort.

In general, clay soils and well-graded sandy or silty soils show a clearly defined peak to the compaction curve. Uniformly graded free-draining soils, consisting of a narrow range of particle sizes, give a flatter compaction curve from which the optimum condition is not easy to define. A double peak is often obtained from uniformly graded fine sands. For these materials a moisture content for optimum compaction is not easy to define. The results of laboratory tests can be meaningless or misleading, and provide a poor guide to field compaction behaviour. A higher dry density can often be obtained in the field, and a maximum density test (Section 3.7.2 or 3.7.4) might be more appropriate.

6.4.5 Compaction of chalk

Chalk is a very variable material which in its natural state exists as a virtually saturated porous rock. When excavated and recompacted its properties and behaviour can range from those of rock to those of soil, depending on the proportion of putty chalk formed as a result of breakdown of the natural material (see Section 2.4.3).

If the proportion of putty chalk is high enough to control the behaviour of the mass, the fill material will be weak and unstable and may be difficult to compact at all.

The extent to which chalk is likely to break down during earth-works construction processes can be assessed from the chalk crushing value (CCV). The test to obtain this value was developed at TRL when it was realized that other methods of test for soil and rock could not realistically represent the susceptibility of chalk to crushing. The CCV, together with the saturation moisture content (see Sections 2.4.3 and 2.5.4) enables the chalk to be classified as to whether it is suitable for use as fill, and if so to assess the appropriate construction methods to use (Ingoldby and Parsons, 1977).

6.5 Compaction test procedures

6.5.1 Types of test

The tests described in the following sections are those given in BS 1377: 1990: Part 4 as the recognised tests for the determination of the moisture–density relationship of soils. Very similar tests, except for the vibrating hammer method, are also given in ASTM Standards, and their differing features are outlined in separate sections:

1. Light compaction: Section 6.5.3 (BS clause 3.3) and Sections 6.5.5–6.5.7 (ASTM D 698).
2. Heavy compaction: Section 6.5.4 (BS clause 3.5) and Section 6.5.7 (ASTM D 1577).
3. Compaction of soils containing large particles, in CBR mould: Section 6.5.5 (BS clauses 3.4 and 3.6, and ASTM D 698 and D 1577).
4. Compaction using vibrating hammer: Section 6.5.9 (BS clause 3.7).

The British Standard describes these tests under the title ‘Determination of dry density/moisture content relationships’. The ASTM title is ‘Moisture-density relations’.

Preparation of soil for the BS tests is given in Section 6.5.2, and for the ASTM tests in Section 6.5.6.

The use of an automatic compaction apparatus as an alternative to hand compaction (Section 6.5.8) is included.

It is important to refer to the test designation in full when reporting results or when quoting the tests, including whether reference is made to British or ASTM Standards.

6.5.2 Preparation of soil for BS compaction tests

General

The method of preparation of test samples from the original soil sample depends upon

(a) the size of the largest particles present in the original sample

(b) whether or not the soil particles are susceptible to crushing during compaction.

Criterion (a) is assessed by inspection, or by passing the soil through sieves in the gravel-size range. The amount of coarse material determines the size of mould to be used, i.e. whether the one litre (4 in) or the CBR (6 in) mould should be used.

Criterion (b) can sometimes be assessed by inspection and handling, but trial compaction may be desirable, with sieving tests on the soil before and after compaction to determine whether any particles break down during the process. Breakdown of particles results in a change in the soil characteristics, and if a single batch of soil is compacted several times that change will be progressive during the test. A separate batch of susceptible soil is needed for each determination of compacted dry density; consequently a much larger sample is required.

Cohesive soils need to be broken down into small pieces before adjusting the moisture content for compaction. These soils should not be dried first, but should be chopped with a suitable knife, or shredded using a cheese-grater, while at natural moisture content. The extent of chopping or shredding should be consistent, because the results of a compaction test depend on the size of pieces. In any case the results will not necessarily relate directly to results obtained *in situ* because the extent of breaking down is quite different from that obtained in the laboratory. Typical methods are to chop the soil into pieces to pass a 20 mm sieve or to shred it to pass a 5 mm sieve. The method used should be recorded.

Grading Criteria For the purpose of compaction tests, soil is divided into six zones on the particle size chart, depending on the percentages retained on the 20 mm and 37.5 mm sieves. The six grading zones are designated and defined as follows.

Zone 1. No particles retained on (i.e. 100% passing) the 20 mm sieve.

Zone 2. 100% passing the 37.5 mm sieve, and not more than 5% retained on the 20 mm sieve.

Zone 3. 100% passing the 37.5 mm sieve, and between 5% and 30% retained on the 20 mm sieve.

Zone 4. 100% passing the 63 mm sieve, and not more than 5% retained on the 37.5 mm sieve, and not more than 30% retained on the 20 mm sieve.

Zone 5. 100% passing the 63 mm sieve, and between 5% and 10% retained on the 37.5 mm sieve, and not more than 30% retained on the 20 mm sieve.

Zone X. More than 10% retained on the 37.5 mm sieve, or more than 30% retained on the 20 mm sieve.

The criteria (in terms of percentages retained on each sieve) are summarised in Table 6.6. These zones are also shown diagrammatically in Figure 6.7, which represents the relevant portion of a particle size distribution chart. If the grading curve passes through more than one zone, the highest-numbered zone applies. If the grading curve passes through zone (X), the soil is not suitable for these tests unless the coarse material is removed.

If appropriate, soils in grading zones 1 and 2, which would normally be compacted in the one litre mould, may be compacted in the CBR mould provided that there is enough material. This procedure is useful when CBR tests (see Volume 2) are to be performed on the compacted soil over a range of moisture contents.

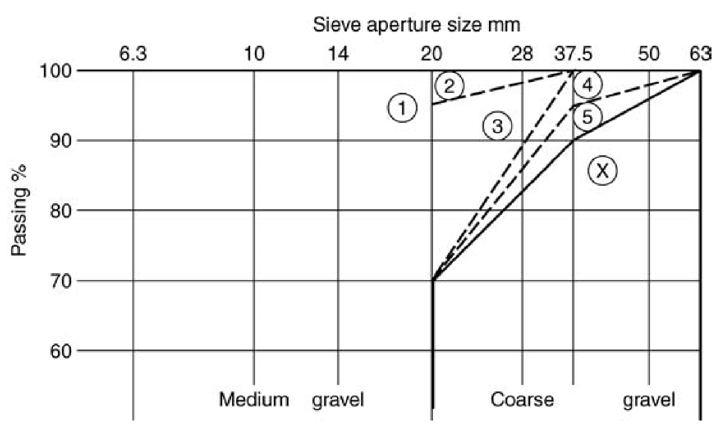

Figure 6.7 Summary of soil grading zones

Table 6.6 Grading criteria for BS compaction tests

Grading zone	*Retained on sieves* (%)		*Min mass reqd*		Mould used	*Mass for each determination*
	37.5 mm	20 mm	(*a*)	(*b*)		
1	0	0	6 kg	15 kg	one litre	2.5 kg
2	0	0–5				
3	0	5–30	15 kg	40 kg	CBR	6 kg
4	0–5	0–30				
5	5–10	5–30				
X	>10 or	>30	Tests not applicable			

(a) Single batch — soil particles not susceptible to crushing.
(b) Multiple batches — soil particles susceptible to crushing.

Method of preparation (BS 1377: Part 4: 1990: 3.2)

1. *Grading zone*

   Determine the grading zone to which the soil belongs, by sieving on the 37.5 mm and 20 mm sieves as appropriate. Use undried soil for this assessment, and determine the dry mass of soil passing the 20 mm sieve from the moisture content measured on a representative portion.

   The amount of soil used for this preliminary sieving should be not less than the mass indicated in Table 4.5. If enough soil is available a separate representative portion may be used for sieving, and that portion may be dried if it is not to be used for the compaction test.

   The sample is dealt with as follows, according to the grading zone to which it is allocated.

   Zone 1: Can be compacted in the one-litre mould.
   Zone 2: Either remove the material retained on the 20 mm sieve and compact in the one-litre mould, or compact in the CBR mould.
   Zone 3: Compact in the CBR mould.
   Zone 4: Remove the material retained on the 37.5 mm sieve and compact in the CBR mould.
   Zone 5: Remove and weigh the material retained on the 37.5 mm sieve. Replace this material by the same mass of similar material passing the 37.5 mm sieve and retained on the 20 mm sieve. Compact in the CBR mould.
   Zone X: Not suitable for these tests.

   Any coarse material removed should be weighed and the mass recorded.

2. *Susceptibility to crushing*

   Assess whether the soil particles are susceptible to crushing under the degree of compaction to be applied in the test. Soils susceptible to crushing contain granular material of a soft nature e.g. soft limestone, sandstone, chalk, or other minerals likely to be broken down by compaction. If necessary, compact a portion of the soil by the appropriate method. If in doubt, assume that soil particles are susceptible to crushing.

Table 6.7 Moisture contents for compaction tests (Note: w_p is the plastic limit of the fraction finer than 425 µm).

Type of soil	Suggested lowest value		Increments for subsequent stages
	2.5 kg test	*4.5 kg test*	
Sandy and gravelly	4 to 6	3 to 5	1 to 2
Cohesive	$(w_p - 10)$ to $(w_p - 8)$	approx $(w_p - 15)$	2 to 4

Whenever practicable the procedures described for susceptible material should be followed for all soils.

3. *Mass of soil for test*
   The mass of soil to be prepared for the test is obtained from Table 6.6 when the grading zone and susceptibility to crushing of particles have been established. A considerably larger initial sample is required if the particles are susceptible to crushing. Obtain the required representative mass from the original sample (after removing coarse material if necessary) by riffling or quartering, as described in Section 1.5.5.
4. *Adjustment of moisture content*
   The lower end of the moisture content range for a test, and suitable increments of moisture content for each stage, should be judged from experience. The values given in Table 6.7 provide a general guide.
5. *Single batch of soil* (*BS 1377: Part 4: 1990: 3.2.4 and 3.2.5*)
   It is often convenient to make the first determination with the soil at the moisture content 'as received'. For subsequent determinations, adjust the moisture content as follows.
   (a) To obtain a lower moisture content, allow the soil to partially air-dry to the moisture content at which it is to be compacted. Do not allow the soil to dry more than necessary, and mix frequently to prevent local over-drying. Estimate the moisture content by inspection, or by weighing at intervals.
   (b) To obtain a higher moisture content, mix additional water thoroughly into the soil as described in 6 below.
   Place the soil in an airtight container if it is not to be used immediately. For a cohesive soil, leave it in the container for a maturing period of at least 24 hours to allow for a uniform distribution of water in the sample.
6. *Multiple soil batches* (*BS 1377: Part 4: 1990: 3.2.6 & 3.2.7*)
   Multiple batches are essential when soil particles are susceptible to crushing. Subdivide the prepared soil sample to give five or more representative specimens for test. Each specimen should be of about 2.5 kg for the one-litre mould, or 6 kg for the CBR mould (see Table 6.6).

   Add a different amount of water to each specimen, in order to cover the required range of moisture contents (see Table 6.7). The range should provide at least two values on either side of the optimum moisture content at which maximum dry density occurs.

   Thorough mixing with the water is especially important with cohesive soils. After mixing, a cohesive soil should be allowed to mature for at least 24 hours in a sealed container.

6.5.3 Light Compaction Test (2.5 kg rammer method) BS 1377: Part 4: 1990: 3.3

This test is suitable for soils containing particles no larger than 20 mm. The detailed procedures depend on whether or not the granular material is susceptible to crushing during compaction. Use procedure (a) if not susceptible and (b) if particle crushing is likely.

If the soil contains particles larger than 20 mm, refer to Section 6.5.5.

Apparatus

1. Cylindrical metal mould, internal dimensions 105 mm diameter and 115.5 mm high. This gives a volume of 1000 cm^3. The mould is fitted with a detachable baseplate and removable extension collar (see Figure 6.8).
2. Metal rammer with 50 mm diameter face, weighing 2.5 kg, sliding freely in a tube which controls the height of drop to 300 mm (see Figure 6.9).
3. Measuring cylinder, 200 ml or 500 ml (plastics).
4. 20 mm British Standard sieve and receiver.
5. Large metal tray e.g. 600 × 600 × 60 mm deep.
6. Balance, 10 kg capacity accurate to 1 g.
7. Jacking apparatus for extracting compacted material from the mould.
8. Small tools: palette knife, steel straight-edge, 300 mm long, steel rule, scoop or garden trowel.
9. Drying oven and other equipment for moisture content determination.

   Compaction test equipment is shown in Figure 6.10. If a mechanical compaction apparatus is available, refer to Section 6.5.8. The procedure described below is the same in principle whether compaction is effected by the hand rammer or by the machine.

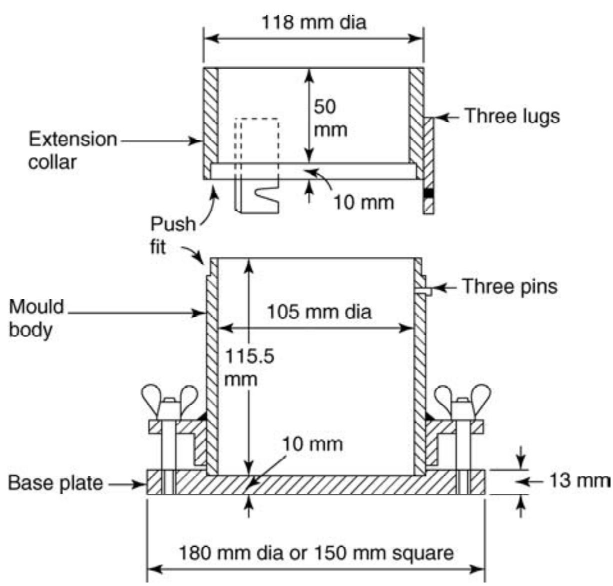

Figure 6.8 British Standard one-litre compaction mould

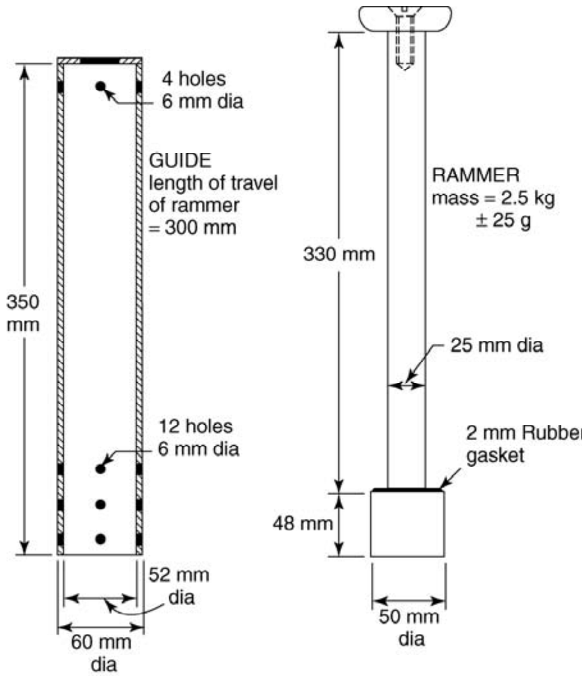

Figure 6.9 Rammer for BS 'light' compaction test

Procedural stages

1. Prepare apparatus
2. Prepare test sample or samples
3. Place soil in mould
4. Compact soil into mould
5. Trim off
6. Weigh
7. Remove soil from mould
8. Measure moisture content
9. *Either* (a) break down the soil for re-use or (b) discard
10. *Either* (a) repeat stages 3–8 and 9(a) after mixing in more water with sample *or* (b) repeat stages 3–8 and 9(b) using the next batch; a total of at least five compactions in either case.
11. Calculate
12. Plot graph
13. Read off optimum values
14. Report results.

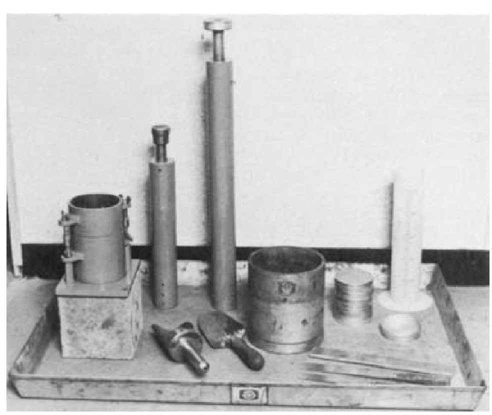

Figure 6.10 Equipment for compaction tests

Test procedure (a) — Particles not susceptible to crushing (BS 1377:Part 4:1990: 3.3.4.1)

1. *Prepare apparatus*

   Verify that the mould, baseplate, extension collar and rammer to be used are those that conform to BS 1377. Check that the mould, extension collar and baseplate are clean and dry. Weigh the mould body to the nearest 1 g (m_1). Measure its internal diameter D mm and length L mm in several places to 0.1 mm using vernier calipers, and calculate the mean dimensions. Calculate the internal volume of the mould V cm^3 from the equation

   $$V = \frac{\pi \times D^2 \times L}{4000}$$

   The mould is designed to give a volume $V = 1000$ cm^3, but this may change slightly with wear.

   Check that the lugs or clamps hold the extension collar and baseplate securely to the mould, and assemble them together. A wipe with a slightly oily cloth on the internal surfaces will assist removal of soil afterwards. A disc of thin filter paper may be placed on the baseplate for the same purpose.

   Check the rammer to ensure that it falls freely through the correct height of drop, and that the lifting knob is secure.

2. *Preparation of sample*

   Prepare the soil as described in Section 6.5.2, to provide the single sample of about 6 kg (step 3), and adjust the moisture content to the desired starting value (step 5).

3. *Place into mould*

   Place the mould assembly on a solid base such as a concrete floor or plinth or a concrete cube. A resilient base may result in inadequate compaction.

   Add loose soil to the mould so that after compaction the mould will be one-third filled.

4. *Compaction in mould*

   Compact the soil by applying 27 blows of the rammer dropping from the controlled height of 300 mm (Figure 6.11).

   

   Figure 6.11 Compacting soil into mould

   Take care to see that the rammer is properly in place before releasing. The hand that holds the tube must be kept well clear of the handle of the falling rammer. Do not attempt to grab the lifting knob before the rammer has come to rest; a finger or thumb trapped between knob and tube can sustain a nasty injury.

   The first few blows of the rammer, which are applied to soil in a very loose state, should be applied in a systematic manner to ensure the most efficient compaction and maximum reproducibility of results. The sequence shown in Figure 6.12(a) should be followed for the first four blows, in order that the effort dissipated in displacing loose material is kept to a minimum. After that the rammer should be moved

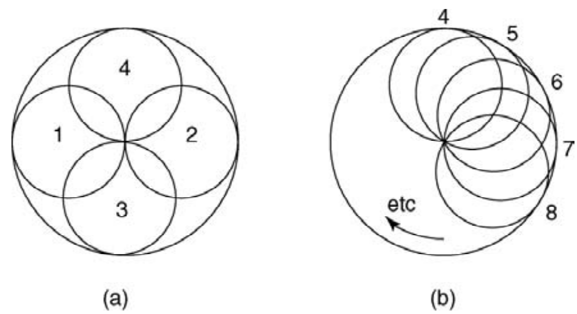

Figure 6.12 Sequence of blows using hand rammer

progressively around the edge of the mould between successive blows, as indicated in Figure 6.12(b), so that the blows are uniformly distributed over the whole area. Soil must not be allowed to collect inside the tube of the rammer, because this will impede the free fall of the rammer. Make sure that the end of the tube is resting on the soil surface and does not catch on the edge of the mould before releasing the rammer. The guide tube must be held vertically. Place the tube gently on the soil surface; the rammer does the compaction, not the tube.

If the correct amount of soil has been used, the compacted surface should be at about one-third of the height of the mould body i.e. approximately 77 mm below the top of the mould body, or 127 mm below the top of the extension collar. If the level differs significantly (by more than, say, 5 mm) from this, remove the soil, break it up, mix it with the remainder of the prepared material and start this stage again.

Lightly scarify the surface of the compacted soil with the tip of a spatula or point of a knife. Place a second, approximately equal, layer of soil in the mould, and compact with

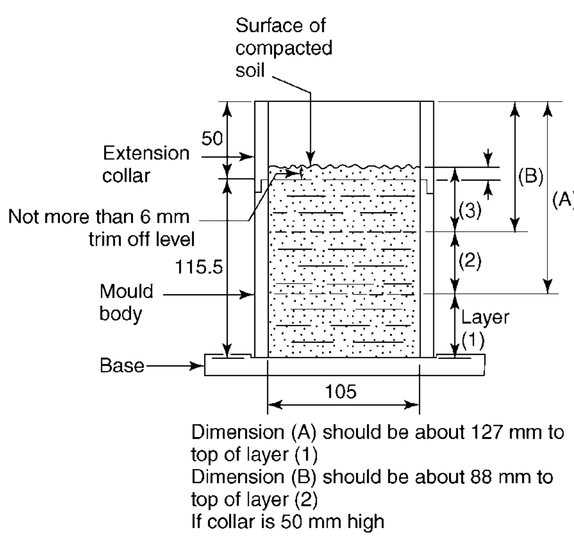

Figure 6.13 Soil in mould after compaction

27 blows as before. Repeat with a third layer, which should then bring the compacted surface in the extension collar to not more than 6 mm above the level of the mould body (see Figure 6.13). If the soil level is higher than this, the result will be inaccurate, so the soil should be removed, broken up and remixed, and the test repeated with slightly less soil in each layer.

5. *Trim off*
   Remove the extension collar carefully. Cut away the excess soil and level off to the top of the mould, checking with the straight-edge. Any small cavities resulting from removal of stones at the surface should be filled with fine material, well pressed in.
6. *Weigh*
   Remove the baseplate carefully, and trim the soil at the lower end of the mould if necessary. Weigh soil and mould to the nearest 1 g (m_2).

   The British Standard procedure does not call for the removal of the baseplate before weighing. If the soil is granular and will not hold together well, the baseplate is best left on. In this case the mass m_1 refers to the mould with baseplate. If the soil is cohesive enough to hold together, it is preferable not to include the baseplate in the weighings, because the mould with baseplate weighs substantially more than the soil it contains.
7. *Remove soil*
   Fit the mould onto the extruder and jack out the soil (Figure 6.14). Alternatively, remove the soil by hand, but this can be difficult with gravelly soils containing a clay binder. Break up the sample on the tray.
8. *Measure moisture content*
   Take up to three representative samples in moisture content containers for measurement of moisture content, using the standard procedure described in Section 2.5.2. This must be done immediately, before the soil begins to dry out. The average of the three measurements is denoted by w%.

   Alternatively, moisture content samples may be taken, one from each layer, as the soil is placed in the mould for compaction.
9. *Break up and remix*
   Break up the material on the tray, by rubbing through a 20 mm sieve if necessary, and mix with the remainder of the prepared sample. Add an increment of water, described approximately as follows:

   Sandy and gravelly soils: 1–2% (50–100 ml of water to 5 kg of soil).

   Cohesive soils: 2–4% (100–200 ml of water to 5 kg of soil).

   Mix in the water thoroughly.

Figure 6.14 Jacking soil out of mould

10. *Repeat with added water*
    Repeat stages 3–9 for each increment of water added, so that at least five compactions are made. The range of moisture contents should be such that the optimum moisture content (at which the dry density is maximum) is near the middle of that range. If necessary to define the optimum value clearly, carry out one or more additional tests at

suitable moisture contents. Keep a running plot of dry density against moisture content so as to see when the optimum condition has been passed.

Above a certain moisture content the material may be extremely difficult to compact. For instance, a granular soil may by then contain excessive free water, or a clay soil may be very soft and sticky. In either event the optimum condition has been passed and there is no point in proceeding further.

Test procedure (b) — Particles susceptible to crushing (BS 1377: Part 4: 1990: 3.3.4.2)

1. As step 1 above.
2. *Preparation of sample*
   Prepare the soil as described in Section 6.5.2, to provide a sample of about 15 kg (step 3), from which five (or more) separate batches of about 2.5 kg are obtained and made up to different moisture contents (step 6).

3–8 Treat the first batch as described in steps 3–8 of the 'non-susceptible' procedure. The whole compacted sample can be used for the moisture content determination if it is not required for further tests.

9. Discard the material as no longer being representative of the original sample. If it is to be retained in store, it should be clearly labelled as such, with a record of the test performed and the date.
10. Repeat stages 3–9 for each batch in turn. If necessary, make up another batch or batches and test them if other points are required on the compaction curve

The following stages refer to both of the above test procedures:

11. *Calculate*
    Calculate the bulk density of each compacted specimen from the equation

$$\rho = \frac{m_2 - m_1}{1000} \mathrm{Mg}/\mathrm{m}^3$$

where m_1 = mass of mould (and base if included) and m_2 = mass of soil and mould (and base if included). If the volume of the mould is not 1000 cm^3 but is V cm^3, then

$$\rho = \frac{m_2 - m_1}{V} \mathrm{Mg}/\mathrm{m}^3$$

Calculate the average moisture content w% for each compacted specimen.

Calculate the corresponding dry density from the equation

$$\rho_D = \left(\frac{100}{100 + w}\right) \rho \ \mathrm{Mg}/\mathrm{m}$$

Typical density and moisture content data and calculations are given in Figure 6.15.

Calculate the percentage of stones retained on the 20 mm sieve.

12. *Plot graph*
    Plot each dry density ρ_D against the corresponding moisture content w. Draw a smooth curve through the points. The curves for 0, 5 and 10% air voids may be plotted as well.

    A typical graph, together with other test data, is shown in Figure 6.16, which includes three air voids lines.

Compaction test
Work sheet

D.S. 1377		Location: Easthampstead	Loc No. 1998
No. of layers: 3	Rammer 2.5 kg	Soil description: Brown sandy clay with a little fine gravel	Sample No. 27/4
Blows per layer: 27	Drop 300 mm	Sample type: Bulk bag; Operator: C.B.A.	Date started. 10. 3. 78
Compacted by hand/machine		Sample preparation: Air dried and riffled	
One-litre/CBR/cylinder no. 7		No. of separate batches: 5; Special techniques: Separate batches used	
DENSITY	Volume of cylinder (V) 1002 cm^3		

Measurement no.	(1)	(2)	(3)	(4)	(5)
Cylinder & soil A g	3786	3907	3999	3962	3908
Cylinder B g	1917	1917	1917	1917	1917
Wet soil A – B g	1869	1990	2082	2045	1991
Wet density ρ Mg/m^3	1.865	1.986	2.078	2.041	1.987

MOISTURE CONTENT

Container no.	64	44	18
Wet soil & container g	104.12	97.48	89.67
Dry soil & container g	96.02	90.42	82.76
Container g	9.36	16.58	9.51
Dry soil g	88.66	73.84	73.25
Moisture loss g	8.10	7.06	6.91
Moisture content $w_{1,2,3}$ %	9.35	9.56	9.44

$$\rho = \frac{A - B}{V}$$

$$W = \frac{W_1 + W_2 + W_3}{3} \qquad \rho_D = \rho \times \frac{100}{100 + W}$$

	(1)	(2)	(3)	(4)	(5)
AVERAGE MOISTURE %	9.45	12.55	15.95	18.71	21.47
DRY DENSITY ρ_D Mg/m^3	1.704	1.765	1.792	1.719	1.636

Figure 6.15 Compaction test data and calculations (BS 1377: Part 4: 1990: 3.3)

13. *Read off optimum values*

Ascertain the point of maximum dry density on this curve, and read off the maximum dry density value. The maximum value may lie between two plotted points, but the peak should not be exaggerated when drawing the curve. Read off the corresponding moisture content, which is the optimum moisture content for this degree of compaction.

14. *Report results*

The report should state that the test was carried out in accordance with Clause 3.3 of BS 1377: Part 4: 1990, and should include the following:

- The graphical plot, showing the experimental points and giving a description of the soil.
- Method of preparation of the sample, and whether a single sample or separate batches were used, and if relevant the size of lumps or pieces to which a cohesive soil was broken down.
- The percentage by dry mass (to the nearest 1%) of the original material retained on the 20 mm and 37.5 mm sieves.
- The maximum dry density for the degree of compaction used, to the nearest 0.01 Mg/m^3.
- The optimum moisture content, to two significant figures.
- The particle density used for constructing the air voids lines, and whether measured (if so, the method used) or assumed.

6.5.4 Heavy Compaction Test (4.5 kg rammer method)—BS 1377: Part 4: 1990: 3.5

This test gives the dry density – moisture content relationship for a soil compacted in five layers in the same mould as used in the light compaction test, using 27 blows per layer with a 4.5 kg rammer falling 450 mm. The total compactive energy applied is 4.5 times greater

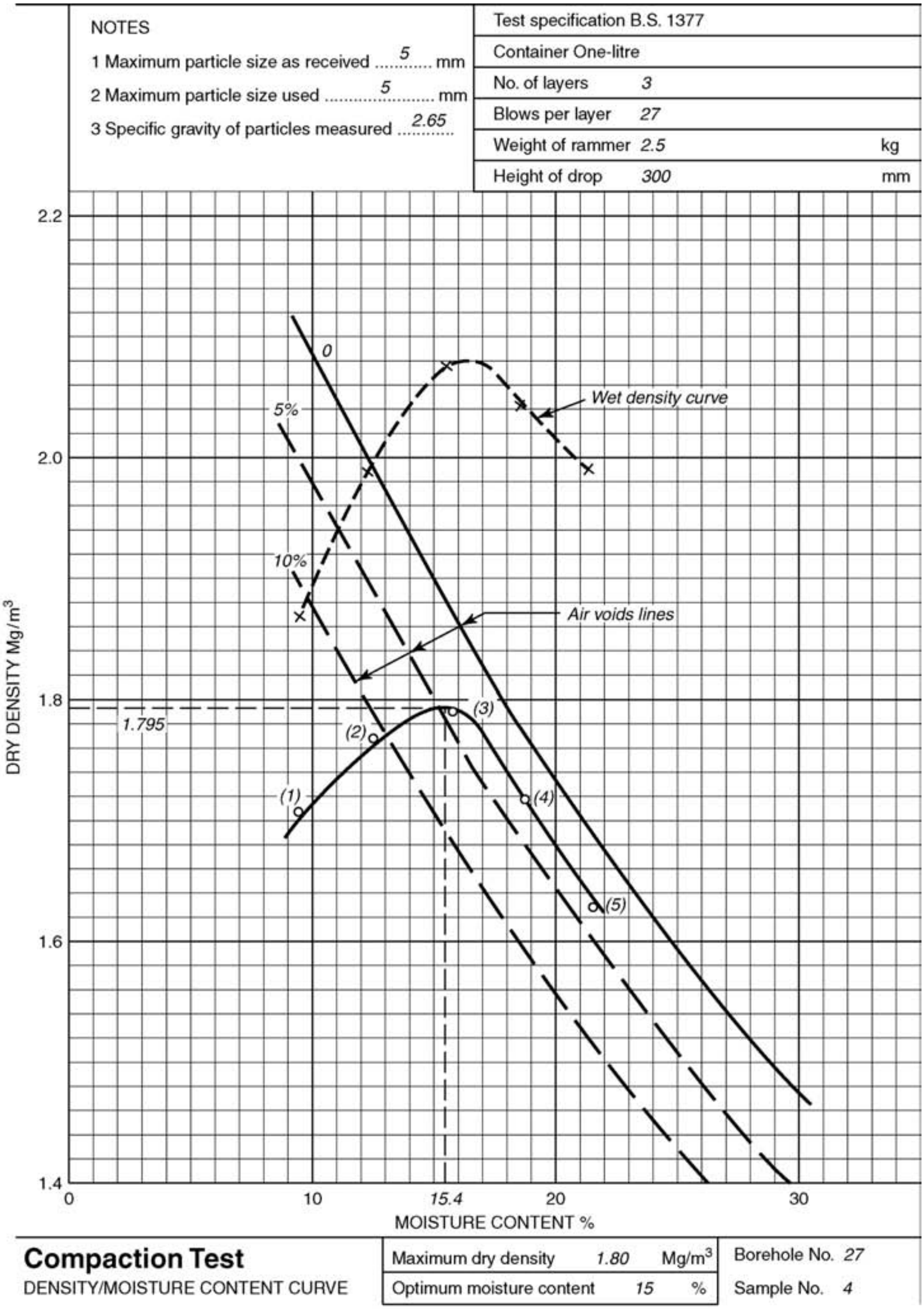

Figure 6.16 Dry density—moisture content test results and graph (the wet density curve is not normally plotted) (BS 1377: Part 4: 1990: 3.3)

than in the light test. From the density–moisture curve the optimum moisture content and the maximum dry density for this heavier degree of compaction can be determined.

As with the light test, this procedure is suitable for soils containing particles no larger than 20 mm, and the details depend on whether or not the particles are susceptible to crushing. If the soil contains particles larger than 20 mm, refer to Section 6.5.5.

Apparatus

1. Mould, as for the light compaction test (Section 6.5.3).
2. Metal rammer with 50 mm diameter face, weighing 4.5 kg, and a controlled height drop of 450 mm (see Figure 6.17). Otherwise, it is similar to item 2 of Section 6.5.3.

3–9 As for the light test (Section 6.5.3).

Procedural stages

The stages are similar to those given in Section 6.5.3 for the light test.

Test procedure

The procedure is similar to that described in Section 6.5.3, with the exception of the detailed modifications referred to below. As in Section 6.5.3, the test is carried out either on a single sample of soil (a) or on separate batches (b), depending on the nature of the soil particles.

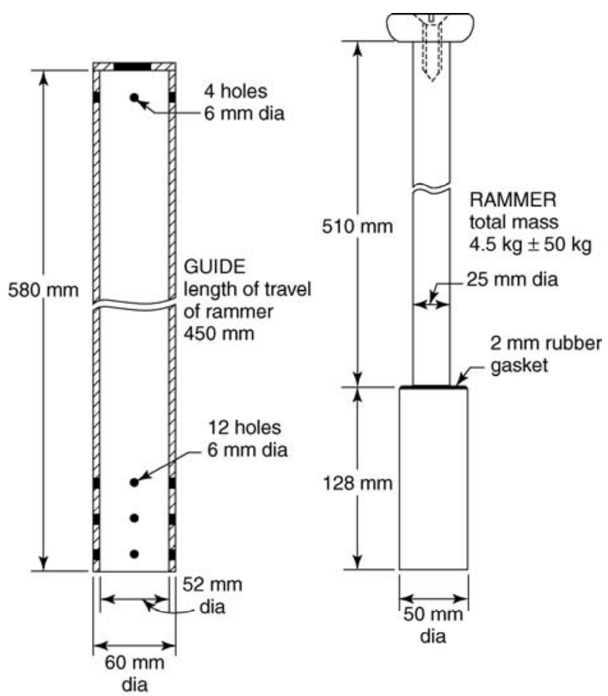

Figure 6.17 Rammer for BS 'heavy' compaction test

1–2 *Sample preparation* As for the light test, depends upon whether the soil particles are susceptible to crushing. The quantity of water to be added to the sample initially, or to the first batch is a little less than for the light test (see Table 6.7).

3–4 *Compaction* Carried out in five layers instead of three, the 4.5 kg rammer with a drop of 450 mm being used, with 27 blows for each layer. Take extra care when using this rammer to ensure that it is properly in place before releasing. See stage 4 of Section 6.5.3.

If the correct amount of soil has been used for compacting the first layer, the compacted surface should be at about one-fifth of the height of the mould body i.e. approximately 92 mm below the top of the mould body, or 142 mm below the top of the extension collar. If significantly different from this, remove the soil and start this stage again.

Compact four more equal layers into the mould as before. The final compacted surface should be not more than 6 mm above the top of the mould body (see Figure 6.13). If it is higher than this, remove the soil, break it up and repeat this stage, using slightly less soil in each layer.

5–10 As for Section 6.5.3. Moisture content increments are similar to those suggested in stage 9.

11–13 *Calculation, plotting and reporting* These are as described in Section 6.5.3, except that the reported procedure is in accordance with Clause 3.5 of BS 1377: Part 4: 1990.

6.5.5 Compaction of stony soils

For soils containing gravel-size fragments larger than 20 mm, a calculated correction can be applied to the maximum dry density to estimate the corresponding maximum dry density in the field. The principle is explained in Section 6.3.4, but applies only if the stone content does not exceed about 25%.

For soils containing larger proportions of coarse material, the only satisfactory method of obtaining the compaction characteristics is to carry out a test in a larger container so that a larger maximum particle size can be used. A CBR mould, as used in the vibrating hammer test (Section 6.5.9), is used for this purpose. The nominal volume of this mould is 2305 cm^3, but this may change slightly with wear and the dimensions should be checked as described in Section 6.5.3. When this mould is used for compaction tests, up to 30% of particles retained on a 20 mm sieve can be included in the test sample. Verify that the BS mould is used.

Either the equivalent light or the equivalent heavy standard compaction test may be carried out with the CBR mould. The total quantity of material passing the 37.5 mm sieve required is 25 kg, or five batches each of 8 kg if the particles are susceptible to crushing. The procedures are the same as those described in Sections 6.5.3 and 6.5.4, except that 62 blows are required in each layer instead of 27. This is because of the increased volume of soil compared with the smaller mould (see Table 6.2). Weighings are made to the nearest 5 g instead of 1 g.

Application of the first few blows should be done systematically, but the pattern differs from that used for the one-litre mould because of the larger size. The first two blows should be applied at the edge and diametrically opposite each other, the next two half-way between and the fifth at the centre (see Figure 6.18). The next four (numbered 6, 7, 8, 9) are placed between those already applied. After that, work systematically around the mould and across the middle so that the whole area is uniformly compacted.

The test report should state that the procedure is in accordance with Clause 3.4 or 3.6 (as appropriate) of BS 1377: Part 4: 1990.

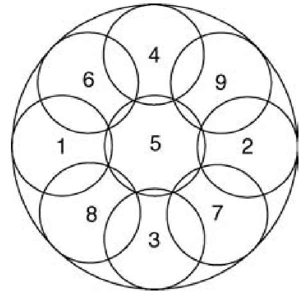

Figure 6.18 Sequence of blows using hand rammer in CBR mould

6.5.6 Preparation of soil for ASTM tests

In ASTM test designations D 698 (5.5 lb rammer method) and D 1557 (10 lb rammer method), three categories of soil are recognised, depending on the largest sizes of particles remaining after initial preparation. These categories relate to the following test methods.

Methods A: Use if 20% or less by mass of the material is retained on a no. 4 (4.75 mm) sieve. If Method A is not specified, this material may be tested using Method B or C.

Method B: Use if more than 20% by mass of the material is retained on a no. 4 (4.75 mm) sieve and 20% or less by mass is retained on a 3/8 in (9.5 mm) sieve. If Method B is not specified, this material may be tested using Method C.

Method C: Use if more than 20% by mass of the material is retained on a 3/8 in (9.5 mm) sieve and less than 30% by mass is retained on a 3/4 in (19.0 mm) sieve.

If the material contains more than 5% by mass retained on the 3/4 inch (19.0 mm) sieve and is not included in the test sample, corrections to the density and moisture content must be applied as described in ASTM D 4718.

If the amount of material retained on the 0.75 in (10.0 mm) sieve is 30% or more, the test methods for the determination of maximum dry density or optimum moisture content are not applicable.

For method A and B, the 4 inch compaction mould is used, and a test sample of about 11 kg is required. For method C the 6 in mould is used, and test samples of about 23 kg are required. In all cases the test sample is divided into at least four portions for compaction, each of which is brought to a different moisture content so as to bracket the optimum moisture content. Otherwise, the method of test preparation is generally similar to that described in Section 6.5.2.

6.5.7 ASTM Compaction test procedures (ASTM D 698 and D 1557)

The ASTM compaction test procedures are similar in principle to the corresponding British Standard procedures described in Sections 6.5.3, 6.5.4 and 6.5.5.

Verify that the mould, baseplate, extension collar and rammer are those that conform to ASTM D 698 or D 1557 as appropriate, whether the 4 in or 6 in mould is used.

In Test Designation D 698, the 5.5 lb (2.49 kg) rammer with a 12 in (305 mm) drop is used. Soil prepared by Method A or B (Section 6.5.6) is compacted into the 4 in (101.6 mm) diameter mould (944 cm^3) in 3 layers applying 25 blows of the rammer on each layer. Soil prepared by Method C requires the 6 in (152.4 mm) diameter mould (2124 cm^3), and is compacted in 3 layers with 56 blows of the rammer on each layer.

In Test Designation D 1557, the 10 lb (4.54 kg) rammer with a drop of 18 in (457 mm) is used. Soil prepared by Method A or B (Section 6.5.6) is compacted into the 4 in (101.6 mm) diameter mould (944 cm^3) in 5 layers applying 25 blows of the rammer on each layer. Soil prepared by Method C requires the 6 in (152.4 mm) diameter mould (2124 cm^3), and is compacted in 5 layers with 56 blows of the rammer on each layer.

An automatic compaction device as described in Section 6.5.8, suitably designed to give the compactive efforts required for the ASTM procedures, may be used in place of the hand rammer in any of these tests.

In all cases the whole compacted sample, after removal from the mould, should be used for the determination of moisture content if the soil is of high permeability, such that the moisture content is not uniformly distributed throughout the sample.

Calculations, plotting and reporting are similar to the requirements for the BS tests.

6.5.8 Use of automatic compactor

An automatic compaction apparatus eliminates much of the physical effort required for carrying out compaction tests. However, it has been found that the densities achieved by machine are often less than those obtained by hand compaction. This is partly because the blow pattern differs from that recommended in Sections 6.5.3 and 6.5.5, and partly because the base not only rotates but also has to provide horizontal movement when a CBR mould is being used so that its whole area may be covered by the rammer. This results in the mould support being less rigid than a concrete base.

A machine of the type shown in Figure 6.19 incorporates the following features:

1. The blow pattern closely follows the recommended pattern; widely spaced blows to flatten the soil surface, followed by overlapping blows.
2. The area of a CBR mould is covered by shifting the position of the rammer assembly instead of moving the base.
3. The rotating base is supported by an inertia block offering a machined annular surface of large area, which provides a very rigid support.

Separate machines are designed specifically for the BS and the ASTM compaction tests, and the machine used must be to the correct specification.

The performance of an automatic compaction machine can be assessed by performing parallel tests on duplicate samples using a hand rammer and the machine with the appropriate setting. If the density obtained by the machine is within ± 2% of the density obtained by using the hand rammer, the machine is satisfactory and meets the requirements of BS 1377.

Figure 6.19 Automatic compaction apparatus (photograph courtesy of ELE International)

6.5.9 Compaction by vibration (BS 1377: Part 4: 1990: 3.7)

This test is applicable to granular soils passing the 37.5 mm sieve. It is not suitable for cohesive soils. The principle is similar to that of the rammer procedures, except that a vibrating hammer is used instead of a drop-weight rammer, and a larger mould (the standard CBR mould) is necessary.

Apparatus

1. Cylindrical metal mould (CBR) internal dimensions 152 mm diameter and 127 mm high. The mould can be fitted with an extension collar and baseplate. Details of two types of mould are shown in Figures. 6.20 and 6.21. (Note: The mould shown in Figure 6.21 must not be confused with the similar ASTM compaction mould which is 116.4 mm high.)
2. Electric vibrating hammer, power consumption 600–800 W, operating at a frequency in the range 25–60 Hz. To comply with safety regulations, the hammer should operate on 110 V, and an earth-leakage circuit breaker (ELCB) should be included in the line between the mains supply and the hammer. A check test to verify whether the hammer meets the requirements of the British Standard is described below. A special supporting frame for the hammer may be used for easier operation, as shown in Figure 6.22.

   Electric vibrating hammers other than the above may be used providing it can be demonstrated that they comply with the calibration requirement specified in BS 1377: Part 4: 1990: 3.7.3.
3. Steel tamper for attaching to the vibrating hammer, with a circular foot 145 mm diameter (see Figure 6.23).
4. 37.5 mm BS sieve and receiver.
5. Depth gauge or steel rule accurate to 0.5 mm.
6. Laboratory stop-clock accurate to 1 sec.

Also required are items 3–9 as listed in Section 6.5.3, except that a balance of higher capacity is required for which accuracy to 5 g is adequate.

Procedural stages

Alternatives marked (a) are for soils containing particles not susceptible to crushing, (b) if crushing by compaction is likely.

1. Prepare apparatus
2. Prepare test sample or samples
3. Place soil in mould

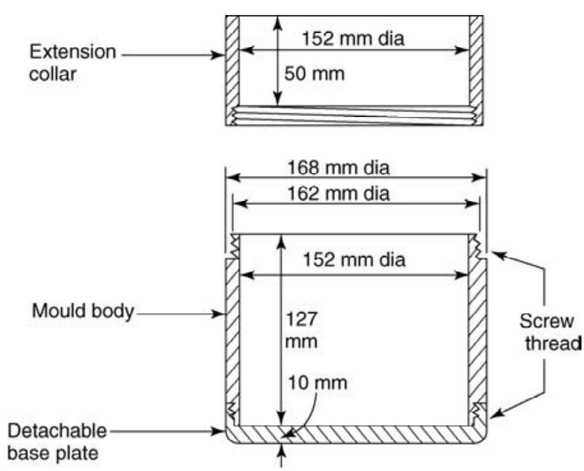

Figure 6.20 CBR mould, screw type (BS)

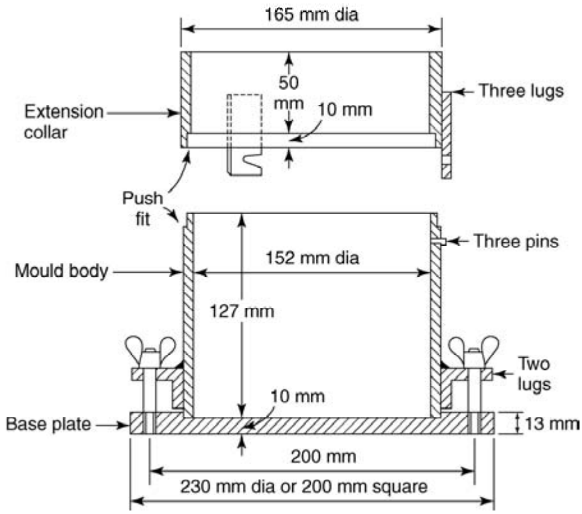

Figure 6.21 CBR mould, clamp type (BS)

Figure 6.22 Vibrating hammer in supporting frame

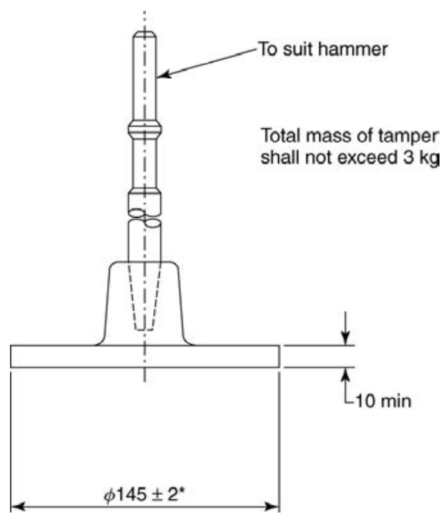

Figure 6.23 Tamper for vibrating hammer (courtesy of BSI, London)

4. Compact into mould in layers
5. Measure height
6. Weigh
7. Remove soil from mould
8. Measure moisture content
9. *Either* (a) break down the soil for re-use *or* (b) discard the material

10. *Either* (a) repeat stages 3–8 and 9(a) after mixing in more water with the sample *or* (b) repeat stages 3–8 and 9(b) using next batch; a total of at least five compactions in either case.
11. Calculate
12. Plot graph
13. Read off optimum values
14. Report results.

Test procedure (a) — Particles not susceptible to crushing (BS 1377: Part 4: 1990: 3.7.5.1)

1. *Prepare apparatus*

   See that the component parts of the mould are clean and dry. Assemble the mould, baseplate and collar securely, and weigh to the nearest 5 g (m_1). Measure the internal dimensions of the assembly, and calculate the internal volume, as described in Section 6.5.3. The nominal dimensions of the mould give an area of cross-section of 18 146 mm^2 and a volume of 2304.5 cm^3 (say 2305 cm^3), but these may change slightly with wear. The inside height of the mould with collar is recorded as h_1 (mm).

   The comments regarding preparation of the compaction mould given in Section 6.5.3 apply equally to the CBR mould. It is particularly important to ensure that the lugs and clamps holding the mould assembly together are secure and in good condition, in order to withstand the effects of vibration. If the mould has screw-on fittings (Figure 6.20), the threads must be kept clean and undamaged. Avoid cross-threading when fitting the baseplate and extension collar, and make sure that they are tightened securely as far as they will go without leaving any threads exposed. Screw threads and mating surfaces should be lightly oiled before tightening.

   Ensure that the vibrating hammer is working properly, in accordance with the manufacturer's instructions. See that it is properly connected to the mains supply, and that the connecting cable is in sound condition. The supporting frame, if used, must move freely without sticking. The hammer should have been verified as described below.

   The tamper stem must fit properly into the hammer adaptor, and the foot must fit inside the CBR mould with the necessary clearance (3.5 mm all round).
2. *Preparation of sample*

   Prepare the soil as described in Section 6.5.2, to provide a single sample of about 15 kg (step 3), and adjust the moisture content to the desired starting value (step 5). A typical moisture content for a sandy and gravelly soil would be about 3% to 5% but the actual value should be judged from experience.
3. *Place into mould*

   Place the mould assembly on a solid base, such as a concrete floor or plinth. If the test is performed out of doors because of noise and vibration problems, place the mould on a concrete paved area, not on unpaved ground or on thin tarmac. Any resilience in the base results in inadequate compaction.

   Add a quantity of soil to the mould, such that after compaction the mould is one-third filled. A preliminary trial may be necessary to ascertain the correct amount of soil. A disc of polyethylene sheet, of a diameter equal to the internal diameter of the mould, may be placed on top of the layer of soil. This will help to prevent sand particles moving up through the annular gap between the tamper and the mould.

4. *Compaction into mould*
   Compact the layer with the vibrating hammer, fitted with the tamper, for 60 s, applying a firm pressure vertically downwards throughout. The downward force, including that resulting from the mass of the hammer and tamper, should be 300–400 N. This force is sufficient to prevent the hammer bouncing up and down on the soil. The correct force can be determined by standing the hammer, without vibration, on a platform scale and pressing down until a mass of 30–40 kg is indicated. With experience the pressure to be applied can be judged, but an occasional check on the platform scale is advisable. If the hammer-supporting frame is used, the hand pressure required is much less but should be carefully checked.

   Repeat the above compaction procedure with a second layer of soil, and then with a third layer. The final thickness of the compacted specimen should be between 127 mm and 133 mm; if it is not, remove the soil and repeat the test.
5. *Measure height*
   After compaction, remove any loose material from the surface of the specimen around the edge so that the surface is reasonably flat. Clean off the top edge of the mould collar. Lay the straight-edge across the top of the collar, and measure down to the surface of the specimen with the steel rule or depth gauge to an accuracy of 0.5 mm. Take readings at four points spread evenly over the surface and 15 mm from the side of the mould. Calculate the average depth (h_2 mm). The mean height of the compacted specimen, h, is given by

$$h = (h_1 - h_2)\text{mm}$$

6. *Weigh*
   Weigh the mould with the compacted soil, collar and baseplate to the nearest 5 g (m_2).
7. *Remove soil*
   Remove the soil from the mould and place on the tray. A jacking extruder makes this operation easy if fittings to suit the CBR mould are available. Sandy and gravelly (non-cohesive) soil should not be too difficult to break up and remove by hand, however.
8. *Measure moisture content*
   Take two representative samples in large moisture content containers for measurement of moisture content. This must be done immediately after removal from the mould, before the soil begins to dry out. The moisture content samples must be large enough to give results representative of the maximum particle size of the soil (see Section 2.5.2). The average of the two moisture content determinations is denoted by w%.
9. *Break up and remix*
   Break up the material on the tray and rub it through the 20 mm or the 37.5 mm sieve if necessary. Mix in with the remainder of the sample. Add an increment of water so as to raise the moisture content by 1 or 2% (150–300 ml of water for 15 kg of soil). As the optimum moisture content is approached it is preferable to add water in smaller increments.
10. *Repeat with added water*
    Repeat stages 3–9 for each increment of water added. At least five compactions should be made, and the range of moisture contents should be such that the optimum moisture

content is within that range. If necessary, carry out one or more additional tests at suitable moisture contents.

Above a certain moisture content the soil may contain an excessive amount of free water, which indicates that the optimum condition has been passed.

Test procedure (b) — Particles susceptible to crushing (BS 1377: Part 4: 1990: 3.7.5.2)

1. As step 1 above.
2. Prepare the soil as described in Section 6.5.2, to provide a sample of about 40 kg (step 3), from which five (or more) separate batches of about 8 kg are obtained and made up to different moisture contents (step 6).

3–8 Treat the first batch of soil as described in steps 3–8 above.

9. Discard the material as no longer being representative of the original sample. If it is to be retained in store, it should be clearly labelled as such, with a record of the test and the date.
10. Repeat steps 3–9 on each batch of soil in turn. If additional points are required to define the optimum condition on the compaction curve, make up additional 8 kg batches at appropriate moisture contents and compact each batch as above.

The following stages apply to both the above procedures:

11. *Calculate*

    Calculate the bulk density of each compacted specimen from the equation

    $$\rho = \frac{m_2 - m_1}{18.15 \times h} \text{ Mg/m}^3$$

    where m_1 = mass of mould, collar and baseplate; m_2 = mass of mould, collar and baseplate with soil; h = height of compacted soil specimen = $h_1 - h_2$.

    The above equation applies only if the average diameter of the mould is 152 mm. If it is not, and is represented by D mm, use the area of cross-section A (= $\pi D^2/4$) in the equation

    $$\rho = \frac{m_2 - m_1}{A \times h} \times 100 \text{ Mg/m}^3$$

    Calculate each dry density from the corresponding moisture content w% from the equation

    $$\rho_D = \frac{100}{100 + w} \times \rho \text{ Mg/m}^3$$

    Calculate the percentage of coarse material retained on the 37.5 mm sieve.
12. *Plot graph*

    Plot the values of dry density ρ_D against moisture content w and draw a smooth curve through the points. The curves corresponding to 0, 5 and 10% air voids may be plotted as well.
13. *Read off optimum values*

    Read off the maximum dry density and the corresponding moisture content from the compaction curve.

14. *Report results*
    The report should state that the test was carried out in accordance with Clause 3.7 of BS 1377: Part 4: 1990, and should include the following:
    - The graphical plot, showing the experimental points and giving a description of the soil.
    - Method of preparation of the sample, and whether a single sample or separate batches were used.
    - The percentage by dry mass (to the nearest 1%) of the original material retained on the 37.5 mm sieve.
    - The maximum dry density for the degree of compaction used, to the nearest 0.01 Mg/m^3.
    - The optimum moisture content, to two significant figures.
    - The particle density used for constructing the air voids lines, and whether measured (if so the method used) or assumed.

Verification of vibrating hammer (BS 1377: Part 4: 1990: 3.7.3)

The following procedure may be used to ascertain whether the vibrating hammer used for the above test complies with the requirements of BS 1377:1990 and is in satisfactory working order.

About 5 kg of an unused sample of clean, dry silica sand from the Woburn Beds of the Lower Greensand in the Leighton Buzzard district is required. The specified grading requires 100% passing the 850 μm sieve, at least 75% passing 600 μm, at least 75% retained on 425 μm, and 100% retained on 300 μm. The sand must be dry and free from flaky particles, silt, clay and organic matter.

Sieve this sand through a 600 μm sieve and discard the retained material. Add water to the sieved sand to bring its moisture content to 2.5% (125 ml of water to 5 kg of dry soil). Mix the water in thoroughly and check the actual moisture content, which should not differ from the stated value by more than 0.5%.

Compact the sand into the CBR mould in three layers with the vibrating hammer, as described in stage 4 of the above test procedure. Measure the height of the compacted sample, weigh and determine the compacted dry density to the nearest 0.002 Mg/m^3, as described above. Repeat twice on the same sample of sand, making three tests in all.

If the range of values of dry density exceeds 0.01 Mg/m^3, repeat the above procedure. The vibrating hammer is satisfactory for the vibrating compaction test if the mean dry density achieved exceeds 1.74 Mg/m^3.

This test is valid only for the sand specified above. Other types of sand will give different results.

6.5.10 Harvard Compaction Method

The Harvard compaction test procedure is given in ASTM STP 479 (Wilson, 1970) as a suggested method for determining the compaction characteristics of fine-grained soil when only a small quantity of material is available. The action of the apparatus differs from the drop-weight principle of the conventional compaction tests in that the soil is subjected to kneading rather than impact. Results from the Harvard test may not be directly comparable with the BS or ASTM tests, and is not intended as a substitute for them.

This small-scale procedure can be useful in the laboratory for the preparation of small recompacted specimens for use in other tests. The controlled degree of compaction which it provides gives results which are more reproducible than those obtained by arbitrary hand tamping methods.

Apparatus

The compaction device consists of a hand-held spring-loaded tamper and special mould, which are shown in Figure 6.24. The spring is compressed by means of the adjusting nut to a compression of 40 lb (18.2 kg or 178 N), so that a small increase of force above that value will compress the spring further. Springs of different stiffnesses can be substituted. The metal tamper rod is 0.5 in (12.7 mm) diameter.

The mould used has an internal diameter of 33.34 mm and is 71.5 mm high, giving a volume of 62.4 cm^3. This volume was selected because the mass of soil, in grams, is equal to its density in pounds per cubic foot. An extension collar about 38 mm high may be added to the mould, both of which can be fitted to a detachable baseplate.

The Harvard compaction procedure can be modified to provide additional or lesser degrees of compaction, but the relationship to the BS or ASTM compaction efforts can only be determined experimentally for a particular soil.

A specially designed jig (the collar remover) enables the compacted soil to be held in place and kept intact while the extension collar is being removed.

A sample ejector quickly and easily removes the compacted specimen from the mould.

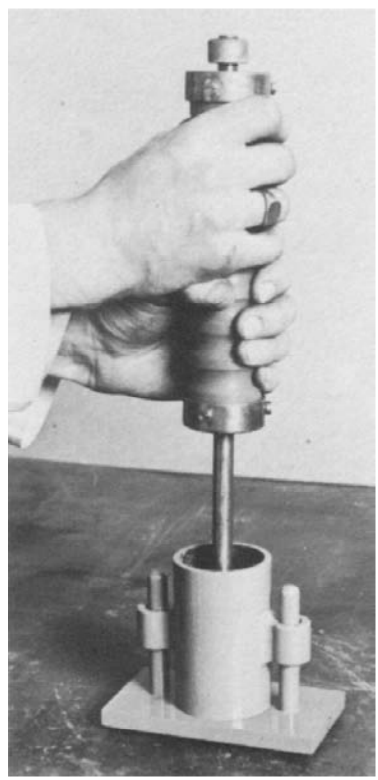

Figure 6.24 Harvard compaction apparatus (photograph courtesy of ELE International)

Soil sample

Soil for use with this apparatus should contain particles no larger than 2 mm. The usual procedure for sub-dividing, sieving, mixing and curing should be followed.

If a complete moisture–density relationship test is to be done, separate batches should be used for each moisture content, and a compacted specimen should not be remixed and reused.

Compaction procedure

Compaction is effected by placing the plunger on the soil surface and pressing down with the hand grip until it can be felt that the spring is just starting to compress, and then releasing and moving to the next position. The first four tamps should be applied in opposite quadrants touching the edge of the mould, followed by one at the centre (see Figure 6.25). The next four should be in a similar pattern but spaced between the first four, then at the centre. This sequence is repeated until the required number of tamps have been applied, at a rate of about one tamp every 1.5 s.

With a 40 lb (178 N) spring, compaction in three layers with 25 tamps per layer is roughly equivalent to BS light compaction, but this is given only as a general guide and not an established relationship.

Measurement of density and moisture content and calculations are done in the same way as for the compaction tests described above. Results of a moisture–density relationship test should include a note reporting the type of test, size of mould and compression spring used.

Apart from its use for determining the moisture–density relationship, the Harvard tamping device provides a convenient means of preparing small reproducible test specimens for shear strength and other tests on recompacted soil.

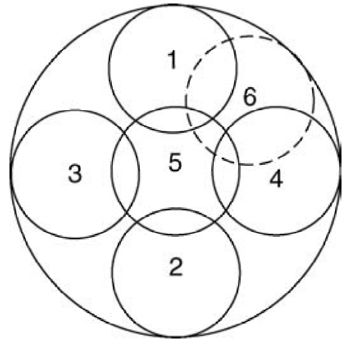

Figure 6.25 Sequence of tamps using Harvard apparatus

6.6 Moisture condition tests

6.6.1 Scope

Purpose of tests

The procedure for determining the moisture condition value (MCV) of a soil was developed at the Transport and Road Research Laboratory as a rapid means of assessing the suitability of soil for use in earthworks construction in relation to the specified limits of moisture content or strength (see TRL Reports by Parsons, 1976; Parsons and Boden, 1979; Parsons and Toombs, 1987; Matheson and Winter, 1997; Winter, 2001). Because of the variability of materials encountered on a typical earthworks construction site it is not usually possible to assign unique values of soil parameters such as moisture content, plastic limit and optimum moisture content. This causes difficulties in the control of the quality of earthworks, and it is these difficulties that the MCV test attempts to overcome.

The merits of the MCV test can be summarised as:

1. It provides an immediate result, without having to wait for the determination of moisture content or other parameters.
2. The test is applicable to a wide range of soil types, usually with the exclusion of granular soils containing no fines.
3. Some variations within a given soil type are not critical.
4. The test can be performed on site as well as in the laboratory, using the same size of test specimen, and test results are compatible provided that the same method of interpretation of test data is used.
5. Test results show good reproducibility.
6. The likelihood of operator error is small.
7. Variability associated with sampling is not excessive because a reasonably large sample is used.
8. The test can provide a useful indicator of the engineering quality and of some aspects of the soil behaviour.

It is possible that relationships can be derived between MCV and laboratory-measured soil parameters such as undrained shear strength and CBR value, as well as soil classification.

MCV, CBR and moisture content are all inter-related. The MCV could also be related to the performance of earthmoving plant, and could indicate where high degrees of compaction are likely to be difficult to achieve, or where excess pore water pressures might be produced by over-compaction.

Types of test

The procedures given in clause 5 of BS 1377: Part 4: 1990 comprise the following.

1. Determination of the MCV of a sample of soil at the moisture content as received (Section 6.6.3.)
2. Determination of the relationship between MCV and moisture content, known as the Moisture Condition Calibration (MCC) (Section 6.6.4).
3. Rapid assessment of whether or not a sample of soil is suitable for compaction by comparison with a previously determined criterion (Section 6.6.5.).

In the MCV test the soil is repeatedly compacted into a rigid mould under the blows of a falling rammer. The apparatus used is a modification of the machine used for the determination of the aggregate impact value, described in BS 812: Part 112: 1990. The minimum compactive effort required to produce near-full compaction of the soil fraction passing a 20 mm sieve is determined.

The relationship between MCV and moisture content for a particular soil type can be determined. A criterion can then be established against which a rapid assessment test can determine whether or not a similar soil complies with the pre-calibrated standard. Further comments on the test and its applications, especially to the use of glacial tills in earthworks, are given by Winter (2004).

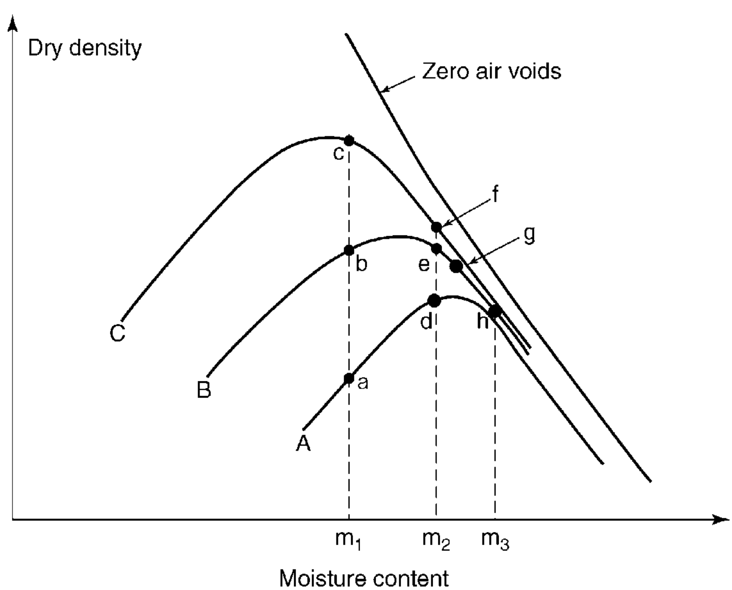

Figure 6.26 Idealized compaction curves for three different compactive efforts

6.6.2 Principles

The MCV test is based on the principles of compaction of soil described in Section 6.3.1. If a soil is subjected to compaction tests using different compactive efforts, as the moisture content increases the curves relating dry density to moisture content tend to converge. They lie close to the zero air voids line, as shown in Figure 6.3. Compaction curves for a soil when three different compactive efforts are used, denoted by A, B and C (A being the lightest, C the heaviest) are shown diagrammatically in Figure 6.26.

When the soil is at moisture content m_1, compactive effort A gives a dry density corresponding to point a; effort B to point b; and effort C to point c. Increasing the compactive effort results in corresponding increases in dry density at this moisture content.

At the higher moisture content m_2, compactive effort B still gives a higher dry density than effort A (points e and d respectively). However effort C (point f) gives a relatively insignificant increase compared with effort B because point e is already close to the zero air voids line. Thus at moisture content m_2, compactive effort B is sufficient to produce very nearly full compaction of the soil. Increasing the moisture content a little more (point g), curves B and C virtually coincide and effort B gives full compaction.

Increasing the moisture content further to m_3 and beyond, no significant increase in dry density can be achieved by using compactive efforts B or C compared with effort A. At this moisture content (point h), effort A is sufficient to produce full compaction.

It can be seen that the higher the moisture content of the soil, the lower is the compactive effort required beyond which no significant increase in dry density occurs i.e. the lower is the effort required to give full compaction. A measure of the moisture condition can be obtained by determining the lowest compactive effort beyond which the increase in dry density is not significant.

In the test the change in height of the sample (which is related to change in density) in the mould is determined by measuring the penetration of the rammer. The change is considered to be insignificant when the change in penetration due to additional compaction is 5 mm or less.

The bulk density and dry density are not required to be calculated in the BS test. However the determination of these values, although liable to some error, requires little additional effort and they provide further useful data for comparison with other test results

6.6.3 Moisture Condition Value (MCV) test (BS 1377: Part 4: 1990: 5.4)

The test is carried out on soil containing particles passing a 20 mm sieve. It is particularly relevant to cohesive soils, but for non-cohesive (granular) soils there may be difficulties in interpretation of results, especially if particles are susceptible to crushing.

Apparatus

1. Moisture condition apparatus complete with mould, separating disc and a means of measuring the penetration or protrusion of the rammer. A typical apparatus is shown in Figure 6.27, and the main features are shown diagrammatically in Figure 6.28.

   Full specification details are given in BS 1377: Part 4: 1990: 5.2. Essential requirements are:

   (a) Mass of base of frame: at least 31 kg

   (b) Mould with detachable permeable base:

Internal diameter 100 mm
Internal height at least 200 mm
Internal surface with protective coating
Permeability of base to allow water discharge of 4 to 7 litres per minute when the water level in the mould is maintained at a head of 175 mm above the base.

(c) Rammer: falling mass 7 kg, diameter of face 97 mm, height of drop 250 mm.
(d) Scale and vernier to measure penetration or protrusion of rammer to 0.1 mm.
(e) Fibre disc to separate soil from rammer: minimum diameter 99.10 mm.
(f) Lifting system to release rammer at pre-set level, fitted with automatic counter.
(g) Drop height control to regulate the height of drop in the range 100 mm to 260 mm, to within ± 5 mm.

Figure 6.27 Apparatus for moisture condition test (photograph courtesy of ELE International)

It is not necessary to stand the apparatus on a plinth or inertia block as the specified mass of the base provides enough inertia.

The energy per blow delivered by the rammer is $2\frac{1}{3}$ times that delivered by the BS 2.5 kg rammer. The energy delivered per unit volume of soil per blow is about 3 times that of the 2.5 kg rammer, or about 11% more than that of the BS 4.5 kg rammer.

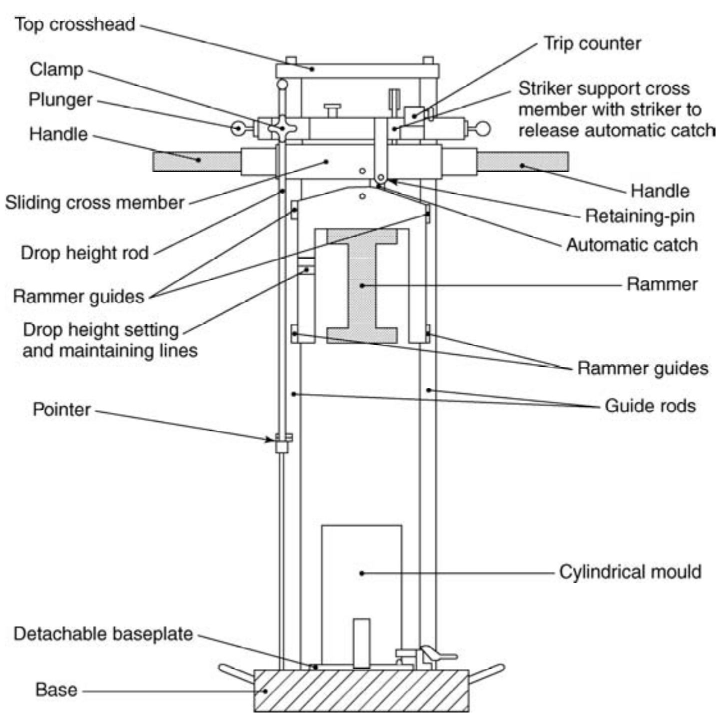

Figure 6.28 Main features of moisture condition apparatus (courtesy of BSI, London)

2. Balance, 2 kg capacity accurate to 1 g.
3. 20 mm sieve and receiver.
4. Large metal tray e.g. 600 × 600 × 60 mm deep.
5. Drying oven and other equipment for moisture content determination.
6. Jacking apparatus for extracting compacted soil from the mould.

Procedural stages

1. Check apparatus
2. Prepare test sample
3. Place soil in mould
4. Fit mould
5. Apply blows and measure penetrations
6. Remove sample
7. Calculate
8. Plot graph.

Derivation of the MCV, and reporting of results, are described under separate headings.

Test procedure

1. *Checking apparatus*

   Ensure that the rammer drops freely.

   Adjust the height of drop of the rammer to give a fall of 250 mm to the top of the rigid disc when placed in the mould on the machine base, in accordance with the manufacturer's instructions. (A smaller height of drop may be appropriate in some tests in which higher moisture contents are used; if so the height of drop should be clearly stated.)

   Ensure that all components of the apparatus are secure.

   Check that the mould and its components are clean and dry, and that the internal protective coating has not been worn away by abrasion.

   Measure the internal dimensions of the mould.

   For safety, when checking or adjusting the apparatus or placing the mould and fittings with the rammer in the raised position, ensure that it is securely held by the retaining pin.

   Check that the separating disc passes freely through the bore of the mould.
2. *Preparation of test sample*

   Sieve the original sample of soil on a 20 mm sieve, break down any aggregations of retained particles, and remove individual particles retained on the sieve.

   Weigh the sample and the removed material to 1 g if the proportion of coarse particles is to be reported.

   Take a representative portion of soil passing the 20 mm sieve for determination of moisture content.

   Subdivide the soil passing the sieve to give a representative test sample of about 1.5 kg (± 20 g). Do not break down any aggregation of particles in this sample.

   If compacted densities are to be measured (not a requirement of the BS, but useful for comparisons), weigh the test sample to the nearest 1 g.

3. *Placing soil in the mould*

   Place the 1.5 kg sample of soil as loosely as possible in the mould. If necessary, push the soil in if it would otherwise overflow the rim, but push only enough for the surface of the loose soil to finish within about 5 mm of the top of the mould.

   The loose condition can be achieved by pouring the soil into the mould, through a funnel if necessary. If the soil is not placed in its loosest condition the reproducibility of the result can be affected.

4. *Fitting mould*

   Secure the rammer of the apparatus in the raised position with the retaining pin.

   Place the mould in position on the base of the apparatus and place the fibre disc on top of the sample.

   Adjust the automatic counter to zero.

   Holding the rammer steady, remove the retaining pin and lower the rammer gently onto the disc covering the loose sample. Allow the rammer to penetrate into the mould under its own weight until it comes to rest.

   Set the height of drop to 250 mm.

5. *Application of blows*

   Raise the rammer until it is released by the automatic catch, so that one blow is applied to the sample. Measure the depth of penetration of the rammer inside the mould, or the distance to the top of the rammer from the rim of the mould i.e. the protrusion, to 0.1 mm using the depth gauge and vernier.

   It is immaterial whether penetration (which will increase with further blows) or protrusion (which will decrease) is measured, because the plotting is based on changes in measurements. Measurement of protrusion using a depth gauge is usually easier, and the test data given below are based on that type of measurement, but reference is also made to penetration.

   Reset the height of drop of the rammer to 250 mm. Apply further blows, and when appropriate make corresponding measurements, as described above. Reset the height of drop to 250 mm as necessary, and continue until there is no further significant increase in penetration, or until 256 blows have been applied.

   Measure the penetration or protrusion after the blows numbered as follows.

   1 4 16 64 256
   2 8 32 128
   3 12 48 192
   6 24 96

   In each line of this sequence, every number is 4 times the previous number. The criterion for 'no significant increase in penetration' has been arbitrarily set at a change of not more than 5 mm between the application of n blows and $4n$ blows (see Section 6.6.2 above).

   Enter the readings opposite the blow number in the second column of the form shown in Figure 6.29. If the material is very dry and more than 256 blows would be required, report the MCV as 'more than 18'.

Moisture condition

Single sample/separate batches*	
Initial sample mass	g
Moisture content	g
Dry mass	g
Mass retained on 20 mm sieve g	%

Location		Job ref.	
		Borehole/ Pit no.	
Soil description		Sample no.	
		Depth	
Test method	BS 1377 : Part 4 : 1990 : 5	Date	

* Delete as appropriate

Total number of blows n	Penetration or protrusion mm	Change in penetration n to $4n$ mm
1		
2		
3		
4		
6		
8		
12		
16		
24		
32		
48		
64		
96		
128		
192		
256		

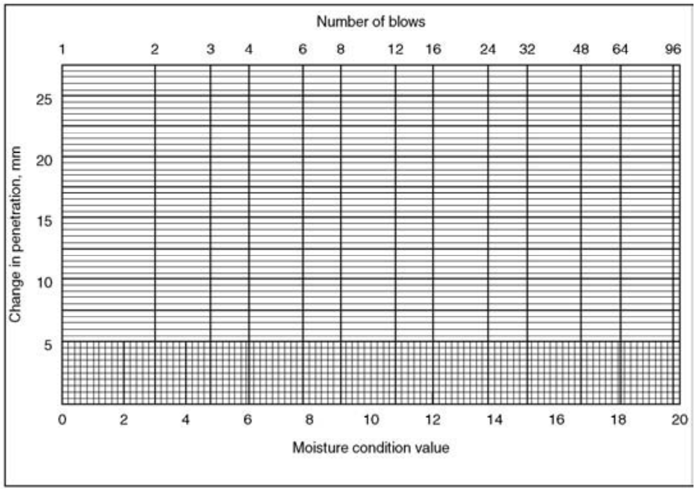

Figure 6.29 Form for recording moisture condition value test (courtesy of BSI, London)

When all the required blows have been applied, raise the rammer carefully and secure it with the retaining pin.

6. *Removal of sample*
   Remove the mould from the base of the apparatus, take off the base and extract the sample. Clean and dry the mould ready for its next use.

   Although not required by the British Standard, a representative sample may be taken for determination of moisture content.
7. *Calculation*
   Calculate the change in penetration between a given number of blows n and four times as many blows $4n$.

   Enter the difference in the third column of the table in Figure 6.29 opposite n blows. For example, enter the difference between 4 and 16 blows on the same line as 4 blows.

   If desired, calculate the approximate density of the compacted soil from the known mass of soil used. The height of the compacted sample can be determined from the mould and rammer measurements and the final penetration or protrusion measurement. If the height is denoted by H (mm), and the mass of soil used is 1.5 kg, the density is equal to $191/H$ Mg/m^3.

   From the density and moisture content calculate the dry density using equation (3.12) in Section 3.3.2. This value, although not a requirement of the BS, enables the tested sample to be related to the moisture/density relationship obtained from a compaction test.

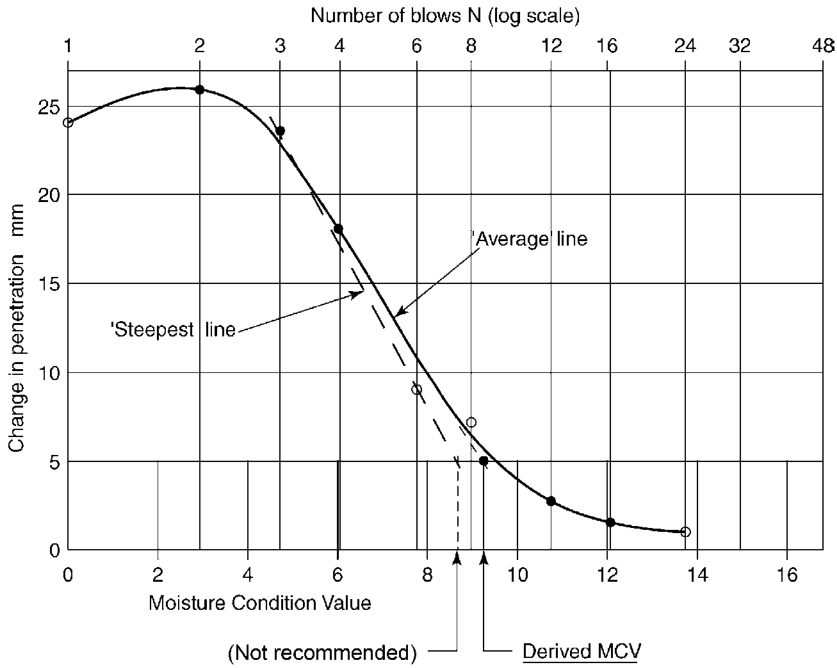

Figure 6.30 Typical plot of change in penetration against number of applied blows (logarithmic scale)

8. *Plotting graph*

   Plot each change of penetration, on the linear scale, against each initial number of blows, *n*, on the logarithmic scale, using a form similar to that shown in Figure 6.30. Use the value of penetration change on the same line as the number *n*.

   Draw a smooth continuous curve through the plotted points. Interpretation of this graph differs according to the requirements of different authorities, as described below.

Derivation of MCV

(a) BS 1377 method

This method of derivation of the MCV from the graph is given in Clause 5.4.2.3 of BS 1377: Part 4: 1990. It is in line with the procedure described in SR522, Section 11 (Appendix). It is sometimes referred to as the English method.

Draw the steepest average straight line through the plotted points immediately before the 5 mm change in penetration value. Extend this line, if necessary, to intersect the horizontal line corresponding to 5 mm change. Read off the number of blows (*B*), to two significant figures, at the intersection point. The procedure is illustrated in Figure 6.31. The MCV is then defined as 10 $\log_{10} B$, in which B=B_1.

The flattening out of the curve, which for many soils found in the UK occurs after, or only a little before, the 5 mm change in penetration is reached, reflects the increasing difficulty of expelling air from the soil as the state of full compaction is approached. The steepest straight line interpretation helps to minimize this effect.

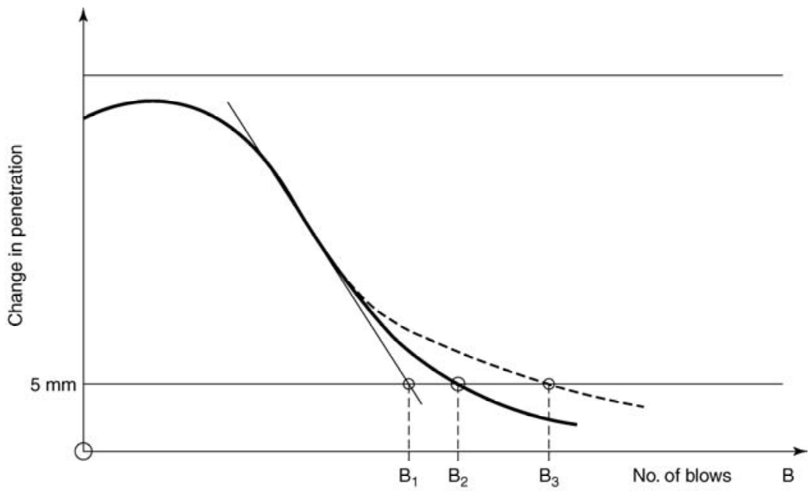

Figure 6.31 English and Scottish methods of interpretation of penetration curve from MCV test

In Figure 6.30, an arithmetical scale of 0 to 20 for the range of blows from 0 to 100 has been added along the bottom. This scale enables the MCV to be read off directly to the nearest 0.1.

The Note to the above clause in BS 1377 draws attention to problems that may arise with interpretation of the graph, some of which are covered in (c) below.

(b) Scottish method

This method is advocated by Matheson and Winter (1997) because it appears to be more suitable for the granular tills found in Scotland. It was given in the original TRRL document LR750, and appears in Section 3 of SR522.

Determine the point at which the plotted curve intersects the line representing 5 mm change in penetration. Read off the number of blows ($B = B_2$ in Figure 6.31) corresponding to this point and calculate the MCV as described above or read off the MCV directly from the arithmetical scale.

The English method can give appreciably lower, and therefore more conservative, MCV results than the Scottish method when the flattening out of the graph begins above the 5 mm change line, as illustrated by the dashed curve in Figure 6.31. This curve gives $B = B_3$, which is significantly greater than B_1. Winter (2004) recommends that the best-fit curve (giving point B_2 in Figure 6.31) should be used for all soils.

(c) Other interpretations

When using the English method, the line of interpretation should be the steepest sensible straight line, obtained by averaging the points if there is some scatter. A reasonable interpretation is shown by the full line in Figure 6.30. The line should not be obtained by joining only two of the plotted points to give the greatest possible slope, illustrated by the broken line in Figure 6.30.

With some soil types, notably granular soils, the relationship between change in penetration and number of blows may be of the form shown in Figure 6.32. Here

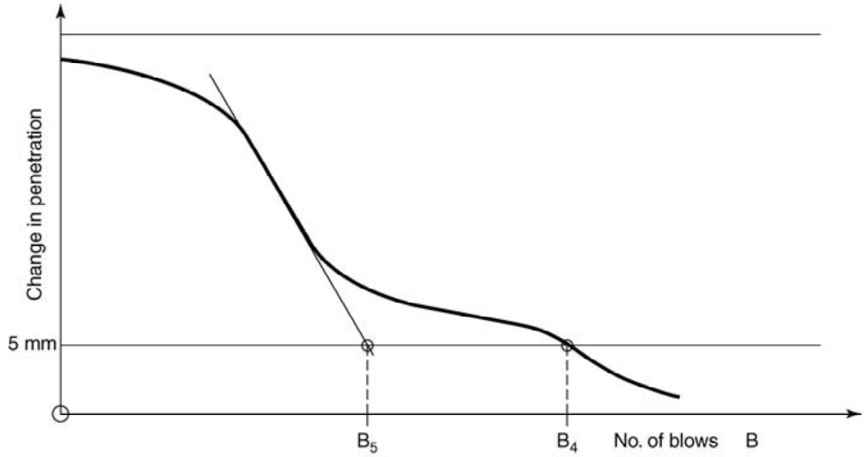

Figure 6.32 Type of MCV curve sometimes obtained for granular soils

the slope of the curve decreases and then increases again, before reaching the 5 mm change line. This is probably due to factors other than reaching full compaction, such as expulsion of water and crushing of soil particles. The latter is very likely with sandy gravel soils. If it is unlikely that crushing of particles will occur during compaction in the field, it would be unreasonable to apply the Scottish method, which gives $B = B_4$, to this type of curve. On the other hand, the English method, giving $B = B_5$, could produce an unreasonably conservative MCV. Interpretation of a curve of this type should be avoided unless adequate field data are also available.

In general, MCV tests on granular soils are difficult to interpret. Fine to medium sands in particular are not amenable to this test. Very low MCV results may be obtained for granular soils, indicating that they are apparently not suitable for earthworks, whereas in fact they may be good free-draining material.

When comparing test results, for example data from a main laboratory with data from site, the same method of interpretation must be used in both cases. Interpretation of MCV test results is discussed in more detail by Dennehy (1988) and Winter (2004).

Reporting results

The plot of change in penetration against logarithm of the number of blows should normally form part of the test report. The method of interpretation of the graph should be clearly stated.

The report should also include:

- The method of test (BS 1377: Part 4: 1990: 5.4).
- The moisture condition value (MCV) of the soil, to the nearest 0.1.
- The percentage moisture content at which the soil was tested if required, and whether it represents the natural moisture content.
- The proportion by dry mass of particles larger than 20 mm (if any) which were removed from the initial sample.

6.6.4 MCV/Moisture Content Relationship (BS 1377: Part 4: 1990: 5.5)

This is a calibration procedure for a given soil, and is referred to here as the Moisture Condition Calibration (MCC) test. This procedure is not suitable for free-draining soils (Winter, 2004).

The MCV test is first carried out on the soil over a range of moisture contents.

Apparatus

As for the MCV test, Section 6.6.3.

Preparation of test sample

If the soil contains particles which are susceptible to crushing during compaction, or includes clay of low permeability requiring at least 24 hours after mixing with water to ensure uniform distribution of water, a separate batch of soil should be prepared for compaction at each moisture content (method 1). Otherwise a single sample may be prepared, and reused after mixing with further increments of water (method 2). The soil should not be dried to a moisture content that is less than the lowest value required for the test. The effects of sample preparation procedures, for Swedish glacial tills, are discussed by Lindh and Winter (2003).

1. *Separate batches*

   Prepare the soil as described in stage 2 of Section 6.6.3, after partially air-drying to the lowest moisture content required for the test. Do not allow the soil to dry completely. At least 10 kg of soil passing the 20 mm sieve is required.

   Sub-divide the soil to give at least 4 test samples of about 2.5 kg each. Mix each sample with a different amount of water to give a suitable range of moisture contents, providing MCVs from approximately 3–14. Samples of cohesive soil should be stored in sealed containers for at least 24 hours before testing.

2. *Single batch*

   Prepare the soil as described in stage 2 of Section 6.6.3, to give a sample of about 4 kg. The initial moisture content should produce an MCV of 13–15 (full compaction after 20 to 32 blows of the rammer). Reduce the moisture content by partial air drying, or add water and mix well in, if it is already too dry, to achieve this condition.

Test procedure

1. *Separate batches*

   Determine the MCV of each sample in turn, using the procedure described in Section 6.6.3.

   After extracting each sample from the mould, take a representative portion for the determination of the moisture content. The remainder of each sample may be discarded.

2. *Single batch*

   Take a representative sample of 1.5 kg (± 20 g) of the prepared soil and carry out the MCV test as described in Section 6.6.3.

   After extracting the soil from the mould, take a representative portion for the determination of moisture content. Break up the remainder of the soil and mix with the remains of the original sample. Add a suitable amount of water and mix in thoroughly.

Repeat the MCV test after each increment of moisture content, to make at least four determinations in all. The moisture contents should give MCVs ranging from about 3–14.

Plotting

Plot the moisture content of each compacted sample against the MCV for the sample, and draw the best-fit line through the points. A typical relationship is of the form shown by the full line in Figure 6.33, which is plotted above the curves obtained from the individual MCV tests. For clarity only three MCV curves are shown, but in practice 6 or 8 MCV tests would be performed to derive the calibration curve.

The MCC for a granular soil, or a clayey soil with a high gravel content, may provide points marked X lying on a second calibration line or curve at low moisture content, as indicated by the dashed curve in Figure 6.33. These points are below an 'optimum MCV'. This branch of the curve represents non-effective calibration, and should not be used.

The effective calibration for clay soils might be in the form of a curve. This can reflect

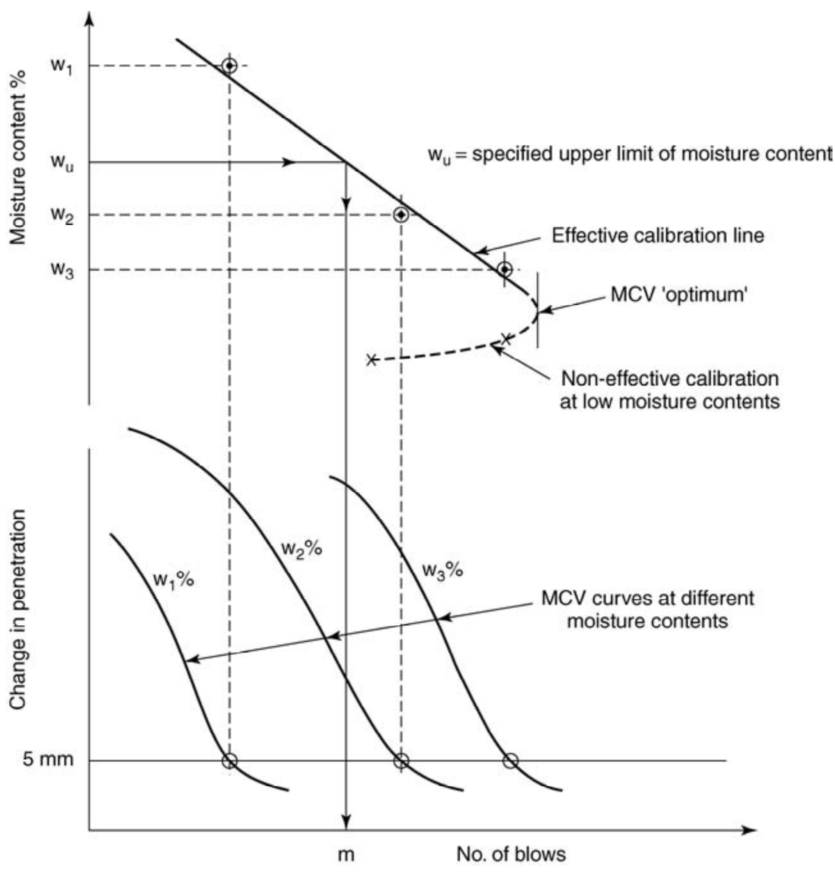

Figure 6.33 Idealized curves from moisture condition calibration (MCC) tests

the extent to which the clay structure is broken down before testing, and often occurs with overconsolidated clays. A linear calibration is more likely if the clay has been worked more before testing, but excessive breaking down and working of clay in the laboratory would not usually represent field conditions, and a non-linear curve might be more representative.

Reporting

The graphical calibration plot, which may be added above the curves obtained from the individual MCV tests (see Figure 6.33), forms part of the test report. The method of test, and other information listed under Reporting for the MCV test (Section 6.6.3), should also be reported.

6.6.5 Assessment of soil strength (BS 1377: Part 4: 1990: 5.6)

This procedure provides a rapid method, which can be carried out on site, for the assessment of the condition of a soil, regarding its acceptability for use in earthworks construction. It is based on the results of an MCC test on similar soil, using the procedure given in Section 6.6.4, from which a calibration standard in terms of MCV has already been derived. This rapid test indicates only whether the soil is acceptable or unacceptable without indicating the degree to which it exceeds or fails to meet the precalibrated standard. The result is normally insensitive to small variations in soil properties.

The normal procedure given here relates to a limit at the wet end of the moisture content range. This method can also be used to relate the moisture condition of the soil to the dry end limit. If penetration measurements are taken after 6, 24 (or 25) and 100 blows it can be assessed immediately whether the MCV of the soil lies between 8 and 14.

Apparatus

As for the MCV test, Section 6.6.3. For a site assessment test, item 2 can be replaced by a balance such as a robust spring balance accurate to 20 g and item 5 is not necessary.

Determination of precalibrated standard

The procedure for deriving a precalibrated standard MCV for a given soil can be summarized as:

1. Carry out the appropriate moisture–density relation test (2.5 kg or 4.5 kg rammer method) and determine the optimum moisture content (OMC).
2. For cohesive soils, determine the plastic limit w_p.
3. Select the upper limit of moisture content w_u to be specified for *in situ* compaction.
4. Carry out the MCC test (Section 6.6.4) on a representative sample of the soil.
5. From the calibration curve, read off the MCV and initial number of blows corresponding to w_u.

The selected upper limit of moisture content will depend on the type of soil, method of compaction, field conditions and other factors. It can be related to the OMC or plastic limit, and the following relationships have sometimes been used as a general guide.

$$\text{For clays, } w_u = 1.2 \times w_p\%$$

$$\text{For other soils, } w_u = (\text{OMC} + 1.5)\%$$

Alternatively, the upper limit may be more easily related to a correlation already established between MCV and CBR value or shear strength. The criterion to be used must be decided by the engineer responsible for the works.

A typical MCC calibration plot is shown in Figure 6.33. The upper limit of moisture content w_u is marked on the moisture content scale and projected across to the calibration curve. The number of blows corresponding to this value *m* is read off from the horizontal scale. The corresponding MCV can also be derived if required. The number *m* (blows) corresponds to the precalibrated standard MCV.

Preparation of test sample

Prepare a representative sample of the soil to be tested as for the MCV test, Section 6.6.3.

Test procedure

Place the sample in the mould and apply blows as in the MCV test, Section 6.6.3, up to the total number of blows *m* equivalent to the MCV of the precalibrated standard, re-setting the height of drop as necessary. Measure the penetration or protrusion of the rammer to 0.1 mm.

Apply additional blows equal to three times the number already applied (i.e. 3 *m* blows, making a total of 4 *m* blows), without further adjustment to the height of drop of the rammer. Measure the penetration or protrusion of the rammer as above.

Assessment

Calculate the difference in penetration or protrusion between the application of *m* blows and 4 *m* blows to the nearest 0.1 mm.

If this difference exceeds 5.0 mm, the soil is stronger than the pre-calibrated standard, and is in a suitable condition for compaction. If the difference is less than 5.0 mm, the soil is weaker than the standard.

6.7 Chalk crushing value

6.7.1 Scope

This procedure was developed at the TRL to enable the strength of chalk, in terms of its resistance to crushing, to be measured. In the test, intact lumps of chalk are subjected to crushing by the action of the rammer in the MCV apparatus and the rate at which the chalk lumps are crushed provides the chalk crushing value (CCV). The CCV can be used in conjunction with the saturation moisture content of the intact lumps (Section 2.5.4) to classify the chalk with regard to its behaviour as a freshly placed fill material (for details see Ingoldby and Parsons, 1977).

6.7.2 Chalk Crushing Value (CCV) test (BS 1377: Part 4: 1990: 6.4)

The following procedure is described for a single sample of chalk lumps, but normal practice should be to prepare and test at least 6 representative samples and derive the mean value.

Apparatus

1. Moisture condition apparatus complete with accessories, as described in Section 6.6.3.
2. Balance of 2 kg capacity accurate to 1 g.
3. Hammer, such as a 2 1b club hammer.
4. 20 mm and 10 mm sieve and receiver.
5. Large metal tray e.g. 600 × 600 × 60 mm deep.
6. Jacking apparatus for extracting compacted soil from the mould (optional).

Test Procedure

1. *Preparation of test sample*

   Take a representative sample of the intact chalk lumps and sieve them on the 20 mm and 10 mm sieves. A sample of 1 kg of material passing the 20 mm sieve and retained on the 10 mm sieve is required. Determine the percentage of the whole sample, by mass, of material retained on the 10 mm sieve. If necessary, break down lumps of chalk larger than 20 mm, using the hammer, to provide enough material for the test sample.

   Do not include in the sample any coagulated lumps of chalk fines, fragments of flint, or any other non-chalk material.

   The degree of saturation of the chalk lumps is not significant, but the chalk should not be oven-dried.
2. Place the prepared sample loosely in the clean, dry mould of the MCV apparatus, and place the separating disc on top of the chalk.
3. With the rammer held in the raised position by the retaining pin, place the mould in position on the base of the apparatus, and adjust the automatic counter to read zero.
4. Hold the rammer steady and remove the retaining pin. Lower the rammer gently onto the separating disc and allow it to penetrate into the mould under its own weight until it comes to rest. Set the height of drop at 250 mm ± 5 mm.
5. Apply one blow of the rammer to the sample by raising the rammer until it is released by the automatic catch. Measure the penetration of the rammer into the mould, or the length of rammer protruding from the mould, to 0.1 mm. (See the comment in step 5 of Section 6.6.3). Record the readings on a test form similar to that used for the MCV test (Figure 6.29) but with the appropriate listing of the number of blows (see below).
6. Re-set the height of drop to 250 mm.
7. Repeat steps 5 and 6, taking readings of penetration or protrusion after selected accumulated numbers of blows and resetting the height of drop to 250 mm as necessary.

   The cumulative numbers of blows after which readings are taken should comprise at least the following, which provide a reasonable spacing of points when plotted on a logarithmic scale.

   1, 2, 3, 6, 8, 12, 20, 30, 40.

   Readings may be taken after intermediate numbers of blows if appropriate.
8. Stop the test when water starts to ooze from the base of the mould, no further penetration occurs or a maximum of 40 blows is reached. Carefully raise the rammer and insert the retaining pin.
9. Remove the mould from the apparatus, take off the base and extract the crushed chalk.

Plotting and Calculations

10. Plot the penetration or protrusion of the rammer (mm) on a linear scale against the number of blows on a logarithmic scale.
11. The greater part of the relation should form a straight line, the slope of which represents the rate at which the chalk was crushed. The Chalk Crushing Value (CCV) is taken as one-tenth of the slope of the straight line.

$$\text{CCV} = \frac{P_a - P_b}{10(\log a - \log b)}$$

where P_a is the penetration or protrusion (mm) after *a* blows of the rammer as read from the straight line; P_b is the penetration or protrusion (mm) after *b* blows of the rammer as read from the straight line.

For ease of calculation it is convenient to use values of *a* and *b* such that $a = 10b$. Then $\log a - \log b = 1$ and

$$\text{CCV} = \frac{P_a - P_b}{10}$$

The CCV should be expressed as a positive number.

Reporting Results

12. The test report should include the following:
    - The chalk crushing value (CCV) to two significant figures.
    - The plot of penetration against logarithm of the number of blows, if required.
    - The percentage of material in the original sample retained on a 10 mm BS test sieve.
    - The saturation moisture content of the chalk, when appropriate.
    - The method of test (clause 6.4 of BS 1377: Part 4: 1990).

6.8 Compactibility test for graded aggregates

This test was developed at the TRL (Pike, 1972; Pike and Acott, 1975) and is a method for assessing the compactibility of graded aggregates, particularly those used in road bases and sub-bases. The standard compaction tests used for soils were found to be unreliable when applied to some of these materials, and this procedure aims to provide a standardised approach to compactibility testing.

The principle of the test is similar to the vibrating hammer test described in Section 6.5.9. However, a more powerful vibrating hammer is used, in a standardised manner. It is mounted in a loading frame and the sample is compacted in a special heavy-duty mould. The test results are presented in the usual form of a moisture content–dry density relationship, but the dry density can also be expressed in items of a volumetric equivalent.

The following special apparatus is required, in addition to standard soil-testing equipment:

1. Compaction mould, comprising body, base, filter assembly and anvil. The latter covers the whole area of the sample, and may be fitted with an optional vacuum release plug. Any excess water is permitted to drain downwards.
2. Electric vibrating hammer, power consumption 900 W, frequency 33 Hz, fitted with a

tool to mate with the anvil.

3. Loading frame to support the hammer and mould, providing a steady downward force of 360 ± 10 kN.

The mould assembly and its component parts are illustrated in Figure 6.34. The load frame and mould, preferably housed, set up for use in a noise-reducing cabinet, are shown in Figure 6.35.

The procedure is not described here, but it is given in Clause 2.1.5 of BS 1924: Part 2: 1990.

It is suggested that this apparatus could provide a means of determining the maximum density (minimum porosity) of granular soils including silty sands, an alternative to the procedure described in Sections 3.7.2 and 3.7.3.

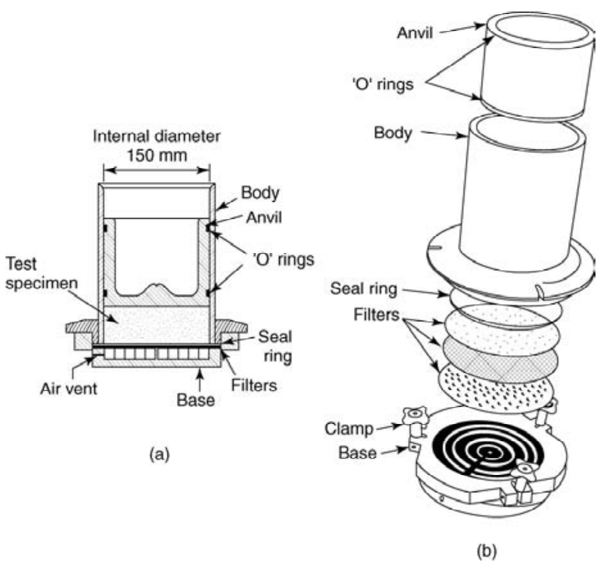

Figure 6.34 Mould and anvil for compactibility test (courtesy of Transport Research Laboratory)

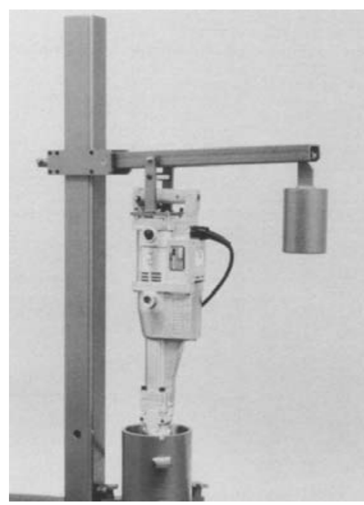

Figure 6.35 Equipment for compactibility test

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