The correlation between the CBR value and penetrability of pavement construction materials

Prepared for Transport for London (Street Management)

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CONTENTS

Executive Summary

The design of new and regenerated urban areas, particularly those alongside highways and streets, is essential to the success of wider initiatives to improve towns and cities as places where people live and work. The spaces alongside highways must support the growth of trees as well as bearing pedestrian traffic and the occasional overrun by delivery and emergency vehicles. The paucity of information on the growth requirements for trees in urban areas, where conventional construction materials are usually expected to also act as a growing medium, has resulted in the high failure rate of newly planted trees in these areas.

The aim of the project was to identify construction materials that could support the growth of trees whilst at the same time providing sufficient structural support to the pavement. Many of the existing problems relating to tree failure within urban areas lie below ground, and can only be resolved by treatment prior to planting.

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1 The correlation between California Bearing Ratio (CBR), density and penetrability (as measures of the structural strength of a backfill).

2 The effect of soil additives on the structural performance of a soil.

3 The rate of growth of tree roots in materials compacted to various densities.

A better understanding of the above would enable engineers to design and specify the construction of pedestrian pavements in terms of the level of compaction required for the various backfill materials, that would (a) provide sufficient structural support to a pavement and (b) permit the growth of tree roots. It would also allow site personnel to measure and control that level during construction.

The main objective of this report is to present and discuss the relations between the results of CBR and Dynamic Cone Penetrometer (DCP) tests undertaken on a range of materials each compacted over a range of densities. The effect of soil additives on these relations for a limited range of materials is also covered.

1 Introduction

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1.1 Terminology

The physical characteristics of soils, such as density and porosity, are defined differently by engineers and horticulturists. For example, in conventional soil mechanics practice, bulk density is taken as the ratio of the total mass of the material per unit volume, but in horticulture bulk density is taken to be the mass of solid (i.e. dried) material per unit volume: (in soil mechanics practice this ratio defines the dry density of a soil). Conventional soil mechanics definitions have been adopted in this report.

2 Details of materials used

To ensure that the results of the study had a broad applicability, the selected materials had a wide range of particle size distributions and, for each material, tests were undertaken over a range of densities. The selection covered most of the range of materials likely to be encountered in highway works.

A complete set of tests was undertaken on five materials, namely a heavy clay, an as-dug sand, a clay loam, a Type 1 sub-base, and a 6F1 capping material: both the Type 1 and 6F1 materials were crushed granite aggregates. The selected Type 1 sub-base and the 6F1 capping materials were towards the coarser and finer ends of the grading envelopes respectively. Some tests were also undertaken on a crushed brick fill, having a grading similar to the 6F1 capping, and a 'tree soil', namely urban soil, which is a mixture of quartz sand (about 95 per cent) and peat. The grading curves of all the materials are shown in Figure 1, whilst the percentages for each grading size are reported in Table 1.

3 Details of tests

3.1 Introduction

In general in the UK, the compaction of materials will be controlled by a method specification for general fill, for constructing earthworks for example, but an end-product specification for more critical applications such as fill to structures. The application of an end-product specification for general fill would require a quick and reliable means of determining the *in situ* density of the placed fill, but direct methods of measurement are not well suited for tree-growing schemes.

The object of this study was to compare the structural properties of a range of different soils and pavement materials as determined using TRL's *in situ* Dynamic Cone Penetrometer (DCP) and also as determined from laboratory CBR tests. A schematic representation of the TRL Dynamic Cone Penetrometer is shown in Figure A1 of Appendix A. This device was designed originally for the rapid *in situ* measurement of the structural properties of road pavements. The device allows measurements to be made down to a depth of 800 mm. Such an *in situ* method eliminates the problem of sample disturbance.

The relation between CBR value and penetration resistance has been established for a variety of materials, see for example Kleyn (1975), Smith and Pratt (1983) and Jones and Rolt (1986). By and large, correlations have been derived from tests undertaken on small samples but, because dense granular materials undergo dilation during shearing, some of the correlations might have been affected by scale effects. For this study it was decided to test large specimens to all but eliminate any possible effect of scale, but some tests were undertaken on small specimens to quantify its effect.
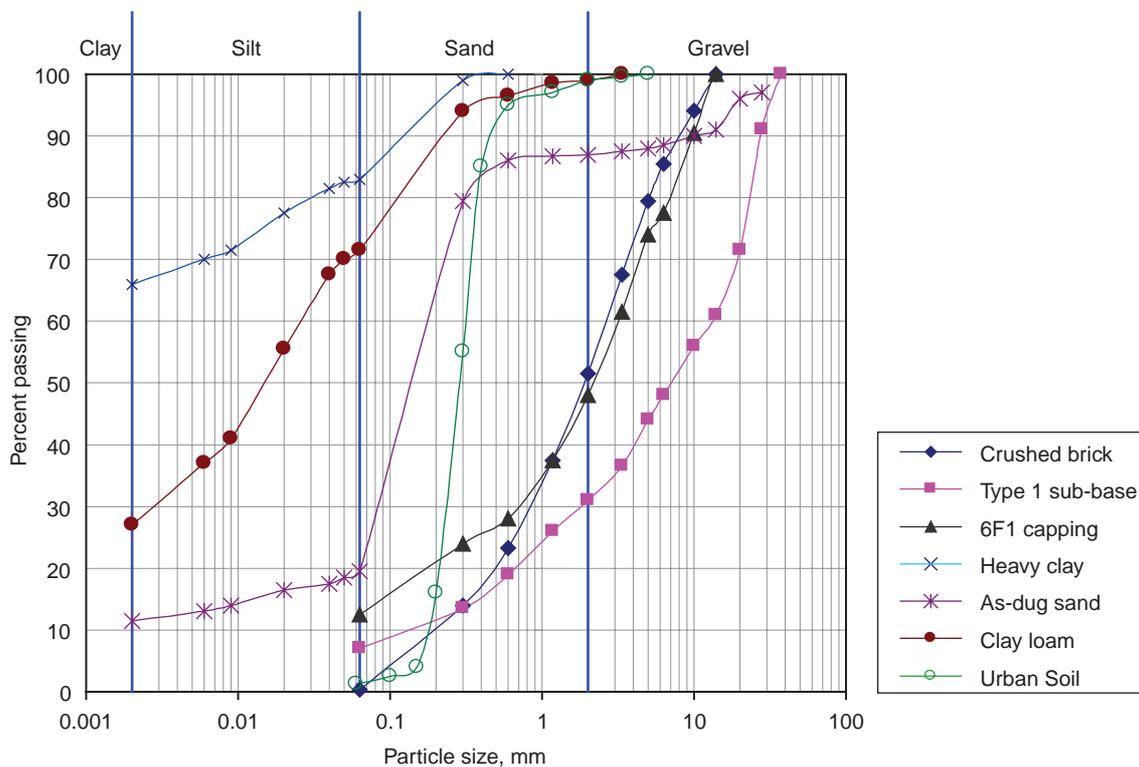
Figue 1 Grading curves of the materials

Table 1 Grading sizes of the materials

Number	Material	% Gravel	% Sand	% Silt	% Clay
1	Heavy clay	0	17	18	65
2	As-dug sand	13	68	7	12
3	Clay loam	1	28	44	27
4	Type 1 sub-base	70	23	7	0
5	6F1 capping	42	46	6	6
6	Urban soil	0	96	4 (as organic matter)	0
7	Crushed brick	50	50	0	0

3.2 Preparation of test specimens and test methods

Schematic representations of the set-up for testing large samples of materials 1 to 5 - as listed in Table 1 - are shown in Figures A2 to A4 of Appendix A. At each of the test bays, two DCP tests were undertaken: the mean result of each pair of tests is reported herein. Following the DCP tests, a CBR mould fitted with a cutting shoe was inserted into the undisturbed areas of the more cohesive of the materials to obtain a CBR test specimen, see Figure A5 of Appendix A. This sampling method was not viable for the more granular materials, and so the CBR test specimens for these were prepared in the laboratory.

The CBR tests were carried out in the laboratory according to BS 1377: Part 4 (BSI, 1990). The arrangement of a CBR test is shown in Figure A6 of Appendix A. However, as shown in Figure 1, about 10 per cent by weight of the Type 1 sub-base material was larger than 20 mm. According to the Standard, particles larger than 20 mm should be removed from the test sample. To

investigate the effect of this scalping of the grading, CBR tests were carried out on specimens prepared to the Standard, and also on specimens formed from the full grading of the material. The CBR value of the 20 mm-down 'scalped' specimens was significantly lower, by up to about 24 per cent, than the value obtained from the full grading. Unless otherwise stated, the CBR values quoted for the Type 1 sub-base are based on tests undertaken on the 20 mm-down scalped specimens.

The crushed brick and the urban soil are not conventional backfill materials. To investigate their structural characteristics, CBR and DCP tests were undertaken on specimens prepared in CBR moulds. However, the derived relation between the results of these tests might be influenced by scale effects.

The test bays were prepared at different densities by varying the compacted layer thickness (between 100 and 150 mm) and the number of passes per layer of a 50 kg vibro-tamper. A test specimen of each material was prepared according to the specification for the reinstatement of openings in highways (Department for Transport, 2002). According to this, to achieve the level of compaction necessary to support a pavement the materials should be compacted at their optimum moisture content either in 100 mm thick layers by 4 passes of a 50 kg vibro-tamper, or in 150 mm thick layers by 8 passes of the vibro-tamper.

3.3 Relations between CBR value and penetrability

The results of the CBR and DCP tests are presented in Figure 2. It can be seen, as might have been expected, that resistance to penetration increased with increasing CBR value. The relations are reasonably linear, but note that a
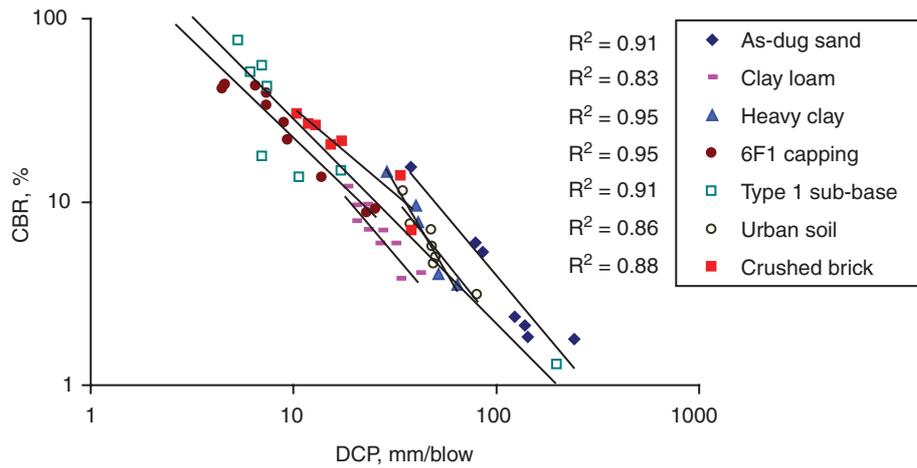
Figure 2 Relations between CBR value and penetrability

log-log plot has been used for convenience and that this tends to mask some of the variability of the data.

The correlation between the results of all the tests is shown in Figure 3.

Figure 4 compares the data obtained from this study with those presented by Kleyn and van Heerden (1983) and also by Jones and Rolt (1986). The results suggest that there is a good correlation between the results of CBR and DCP tests for a wide range of materials, at various moisture contents and dry densities.

The correlation can be improved, but only marginally, by taking account of the effect of moisture content.
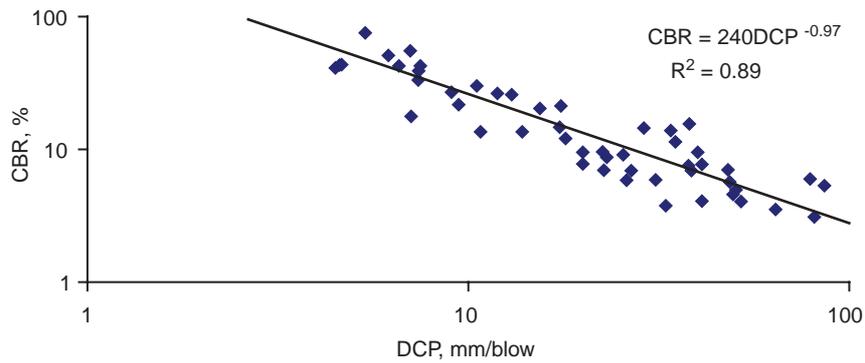
Figure 3 Consolidated relation between CBR value and penetrability
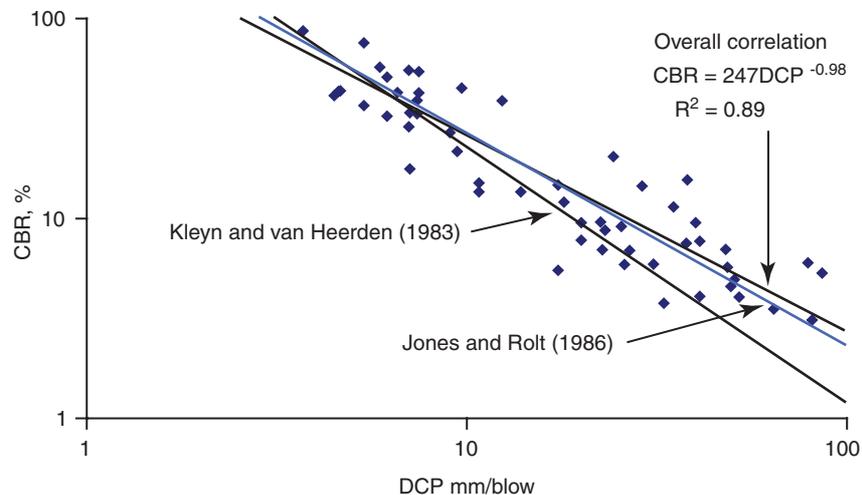
Figure 4 Comparison of correlations from different sources

Figure 5 presents the data obtained from this study with penetration resistance divided by $(1 + \omega)$, where ω is the moisture content expressed as a fraction.

The data presented in Figures 3, 4 or 5 could be used to estimate the *in situ* CBR value from the results of an *in situ* DCP test.

The relations given in Figure 2 have been used to estimate the number of DCP drops per 100 mm of penetration for various ranges of CBR values: these estimates are given in Table 2. The volume of air present in a densely compacted fine-grained material can be so low that it effectively prevents the growth of tree roots. Furthermore, there are physical limits to the density and CBR value that can be achieved. The range of CBR values given in Table 2 reflects these restrictions.

3.4 Relations between CBR value and dry density

Figure 6 shows the relations between the measured CBR value and the dry density for the various materials.

Correlations between the CBR value and dry density can be derived for various material types, for example as given in Figure 7 for the granular materials. Because of the large void content within the crushed brick fill, the data for this material have not been included in the figure.

A comparison of the data in Figures 5 and 7 shows that there is a better correlation between the results of the CBR and DCP tests than between the CBR value and dry density. Although the modes of failure are different, both the CBR and DCP tests are measures of the bearing capacity of a material. Dry density is a measure of the state of particle arrangement. The shear strength of a material, which is related to bearing capacity, is a function both of the state of packing and the level of stress. Thus, by itself, dry density might not correlate particularly well with the results of CBR or DCP tests.

3.5 Relations between penetrability and dry density

Relations between the results of the DCP tests and the dry density of the materials are shown in Figure 8. These have been used to derive the number of DCP blows required to penetrate 200 mm into the various materials for various ranges of dry density: these data are provided in Table 3. As with Table 2, the data given in Table 3 is limited to what can be physically achieved and also, for the heavy clay soil, to the range of dry densities that would support the growth of tree roots.

The relations given in Figure 8 are widely spaced and so a useful single correlation cannot be established between the results of the DCP tests and dry density. This is not unexpected given the widely differing nature of the materials. However, a useful correlation might be established for particular types of material.

3.6 Effect of grain size

As noted in Section 3.2, CBR tests were undertaken on 20 mm-down 'scalped' specimens of the Type 1 sub-base (in accordance with BS 1377: Part 4) and also on specimens prepared from the full grading. The scatter of the test data complicates comparison but, on average, for

$$CBR = 243[DCP/(1+w)]^{-1.01}$$
$$R^2 = 0.90$$

DCP/(1+w)
(with DCP expressed as mm/blow and w as a fraction)
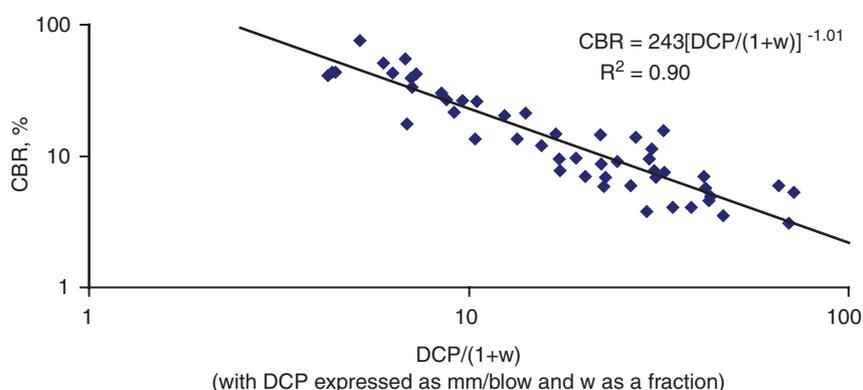
Figure 5 Comparison of data taking account of moisture content

Table 2 Number of DCP blows to penetrate 100mm

Material	CBR value (per cent)												
	1-4	*5-10*	*11-15*	*16-20*	*21-25*	*26-30*	*31-35*	*36-40*	*41-50*	*51-60*	*61-70*	*71-80*	*81-100*
Urban soil	< 2	2-3	3-4				Not achievable						
As-dug sand	1	2	2-3				Not achievable						
Clay loam	< 3	3-5	5-7	7-9			Not achievable						
Heavy clay	1-2	2-3	3	4	< 5		Not achievable						
Crushed brick	1	2-3	3-4	5-6	6-8	8-9	10-11	11-13	13 – 16	Not achievable due to grain crushing			
Type 1 sub-base	1-2	2-4	4-6	6-7	8-9	9-11	11-12	12-14	14-16	17-19	20-22	23-25	25-31
6F1 capping	1-2	2-5	5-7	7-9	9-11	11-13	14-15	16-17	18-21	22-25	26-29	30-33	34-41
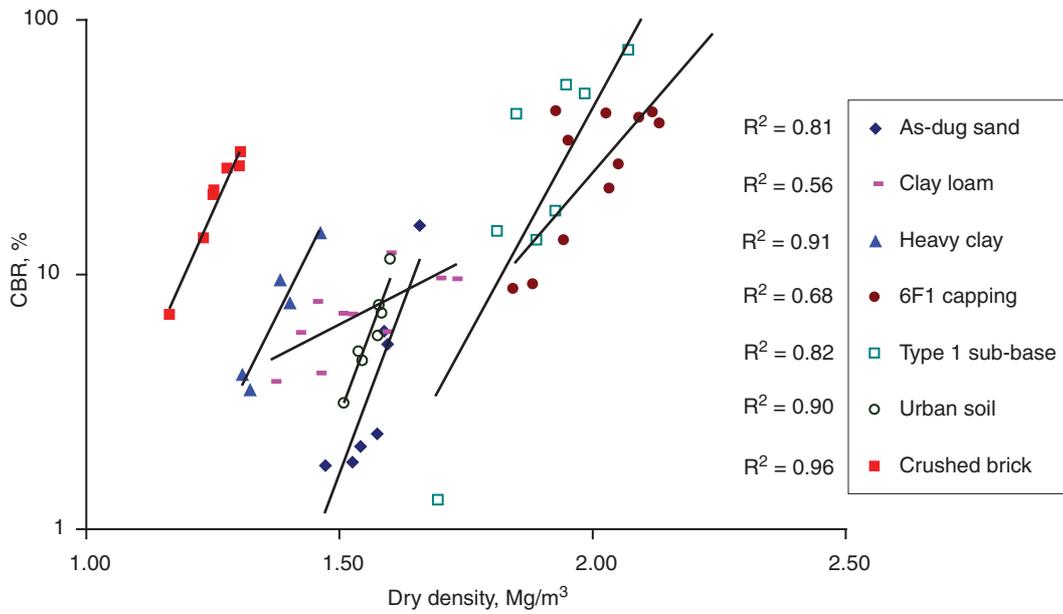
Figure 6 Relations between CBR value and dry density
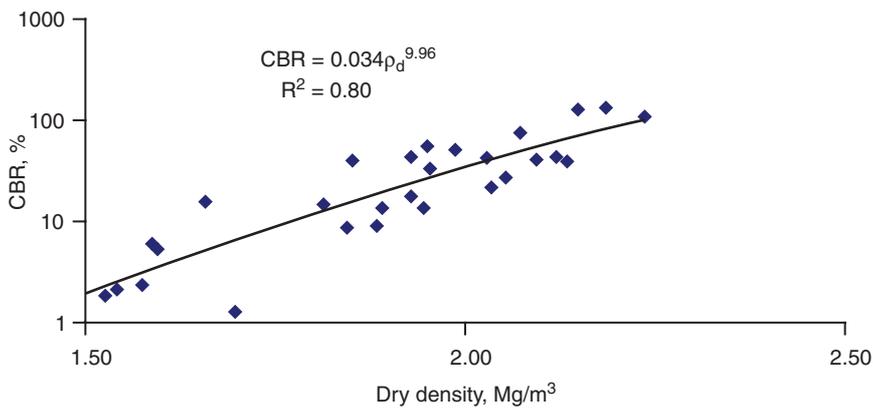
Figure 7 Relations between CBR value and dry density for granular materials
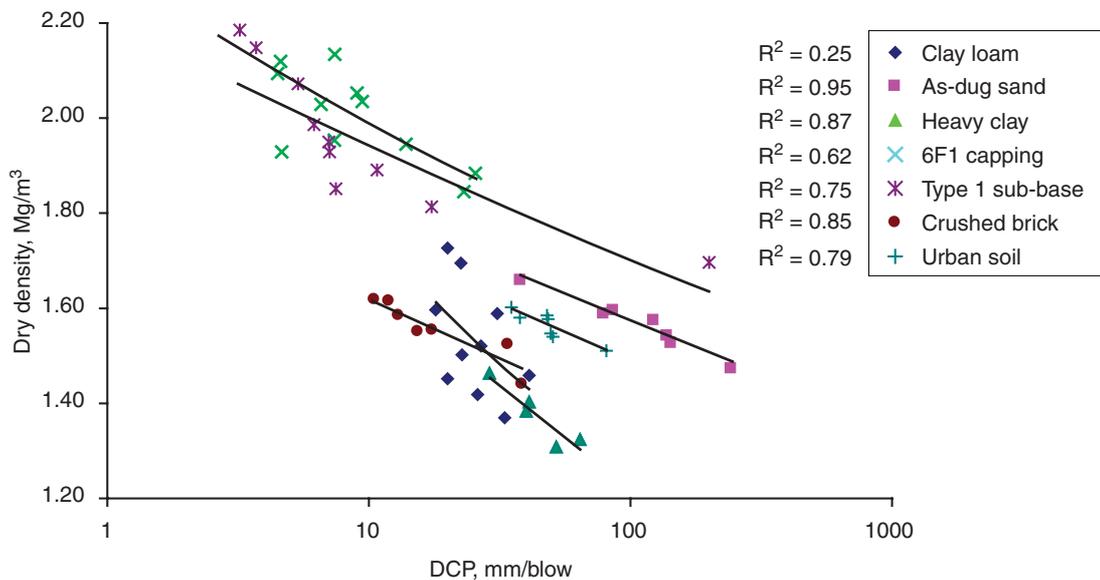
Figure 8 Relations between penetrability and dry density

Table 3 Number of DCP blows required for 200 mm penetration

	Dry density (Mg/m³)										
Material	1.15-1.20	1.21-1.30	1.31-1.40	1.41-1.50	1.51-1.60	1.61-1.70	1.71-1.80	1.81-1.85	1.86-1.90	1.91-1.95	1.96-2.00
Crushed brick	3-6	6-18	Not achievable due to grain crushing								
Loamy clay		1-3	3-4	5-7	Not achievable						
Urban soil		< 1		1-2	2-6	Not achievable					
As-dug sand			< 1		1-3	Not achievable					
Heavy clay	1-2	2-3	3-5	5-9	10-14	Achievable under moisture conditions well below optimum (not suitable for planting).					
Type 1 sub-base	Not achievable					1-2	2-5	6-9	9-14	15-22	22-34
6F1 capping	Not achievable					1-2	2-5	5-7	7-10	11-15	16-22

the same dry density the CBR value of the full grading was up to about 24 per cent higher than for the scalped grading.

Relations between the results of the various CBR tests and the DCP tests are shown in Figure 9. Although there is some scatter in the data, the two correlations are reasonably similar.

3.7 Effect of sample size

The results of previous studies showed that the dimensions of the test specimen could affect the measured penetration resistance of a granular soil, see for example Parkin and Lunne (1982) and Zohrabi (1993). To investigate this effect, DCP tests were undertaken on specimens of the 6F1 capping compacted into CBR moulds. The data from these tests and from those undertaken in the large bays are shown in Figure 10. The effect of confinement within the CBR mould had little effect for CBR values of less than about 15, or penetrability in excess of about 30 mm/blow. However, for higher CBR values the effect of confinement increased with increasing CBR value and increasing penetration resistance. The diameter of the zone of failed soil around a plunger or penetration cone increases with increasing strength of the material, and so this phenomenon is not unexpected.

3.8 Relations between the results of DCP and mexicone penetrograph tests

The DCP device was developed for conventional highway construction materials and was, therefore, not well suited for testing low density, weak materials such as the as-dug sand and the urban soil: in such soils the DCP probe would sink under its own weight. Thus a more suitable device was required with such materials.

The Mexicone penetrograph is a lightweight penetrometer that was developed for determining the penetration resistance of the soft ground. The penetrometer cone is pushed into the ground at a constant rate and the resistance to penetration is recorded automatically on a built-in chart recorder. This device can be fitted with a range of cones to suit the particular ground conditions, but the results obtained from the device need to be calibrated for a particular cone and material. Tests were undertaken

using this device on the as-dug sand and urban soil.

Previous studies yielded the following relations for the urban soil, WIMTEC (1998).

$$\text{Dry density (Mg/m}^3) = [0.036 \times \text{CBR (\%)}] + 1.505 \quad (1)$$

$$\text{CBR (\%)} = (1.85 \times \text{penetrograph reading}) - 1.55 \quad (2)$$

Combining the above,

$$\text{Dry density (Mg/m}^3)$$
$$= 0.067 \times \text{penetrograph reading} + 1.45 \quad (3)$$

Interpretation of the data was hindered by the variation in the measured cone resistance within a particular layer. However the mean reading recorded at the mid-height of a layer was taken as a measure of penetration resistance of that layer.

The results of the DCP and penetrograph tests were used to estimate the CBR value of the as-dug sand and the urban soil for various density states. The estimates are provided in Table 4.

Despite the problems of interpretation, there was good agreement between the CBR values estimated from the data obtained from the two penetrometers. Of the two sets of values, those derived from the penetrograph might be more reliable, particularly for the looser specimens.

3.9 Effect of additives on structural properties

The potential of some soils as a growing medium for trees might be enhanced by the introduction of various types of additive. For example, additives might be used to improve (a) the water retention properties of conventional coarse-grained backfills, and (b) the degree of aeration within fine-grained soils.

A series of tests was undertaken to determine the effect of adding one or other of two proprietary products on the CBR value and the penetrability of the 6F1 capping, the crushed brick and the urban soil. The additives were:

1 'Broadleaf P4 polymer' - this is a cross-linked polyacrylamide compound capable of absorbing up to 500 times its own weight of water. The rate of dosage is between 0.1 to 0.2 per cent by weight of the backfill. At such a low dosage, the additive should have little effect on the structural properties of a dry backfill.
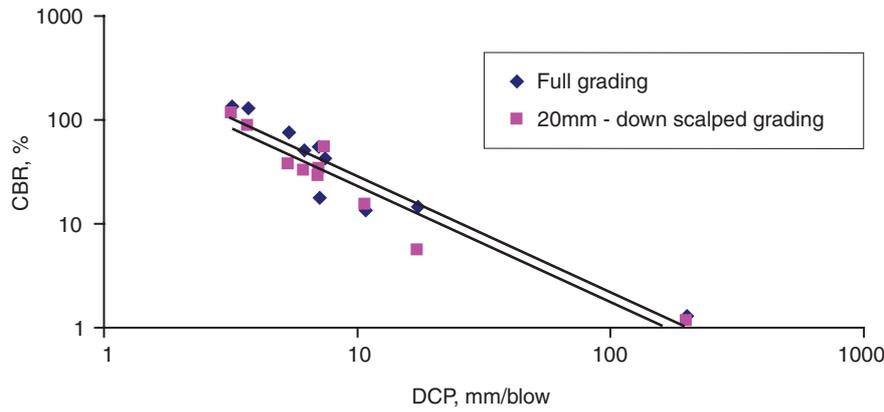
Figure 9 Relations between CBR value and penetrability for Type 1 sub-base
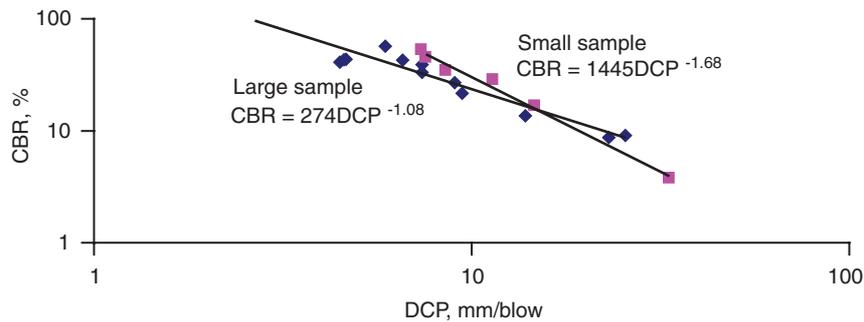
Figure 10 Effect of sample size on relations between CBR value and penetrability for 6F1 capping

Table 4 Comparison of CBR values derived from results of DCP and Penetrograph tests

Material, and density state	Average penetrograph reading	CBR by penetrograph, %	CBR by DCP, %
Urban soil, loose	1.1	1.0	2.5
Urban soil, medium dense	2.5	3.1	3.6
Urban soil, dense	3.3	4.5	5.0
As-dug sand, loose	1.4	1.3	1.3
As-dug sand, medium dense	1.6	1.8	1.8
As-dug sand, dense	3.0	4.0	4.5

2 'Moler' granules - these are calcined diatomite/ montmorillonite clay granules capable of absorbing a substantial quantity of water. The product is available in fine, standard and coarse grades, over which the granules range from 0.5 to 6 mm in diameter. The rate of dosage is about 10 per cent by weight of the backfill. At this rate, the additive might affect the structural properties of a dry backfill: it will, for example, modify the grading of the backfill.

A series of CBR and DCP tests were undertaken on specimens, with and without the additives, prepared at the natural moisture content of the materials, which ranged from 5 to 10 per cent. However the full potential of the additives would not be exploited at such low moisture contents, and so tests were also undertaken on similarly

prepared specimens but which were soaked for at least an hour prior to testing. For practicality, the DCP tests were undertaken on specimens prepared in CBR moulds.

3.9.1 6F1 capping

When mixed into the material at around its optimum moisture content, both additives seemed to increase the CBR value and penetration resistance of the material. This might be due to the additives absorbing water from the base material. The relations between the CBR value and penetrability for the material with and without the additives are shown in Figure 11.

The additives had a substantial and detrimental effect on the structural properties of the soaked specimens. Through soaking, the volume of the specimens in the CBR moulds increased by about 20 per cent. The expansion brought about by the addition of the P4 polymer effectively destabilised the material.

3.9.2 Urban soil

As above, at the optimum moisture content it seemed that both additives improved the structural characteristics of the soil. The relations between the CBR value and penetrability for the soil, with and without the additives, at around its optimum moisture content are shown in Figure 12.

But, as above, the additives had a substantial detrimental effect on the structural properties of the soaked material.

9
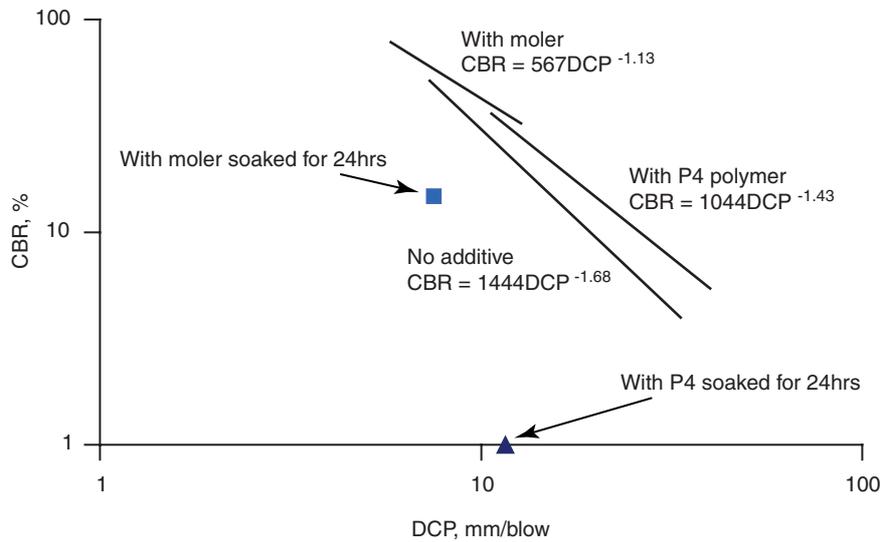
Figure 11 Effect of additives on the relation between CBR value and penetrability for the 6F1 capping
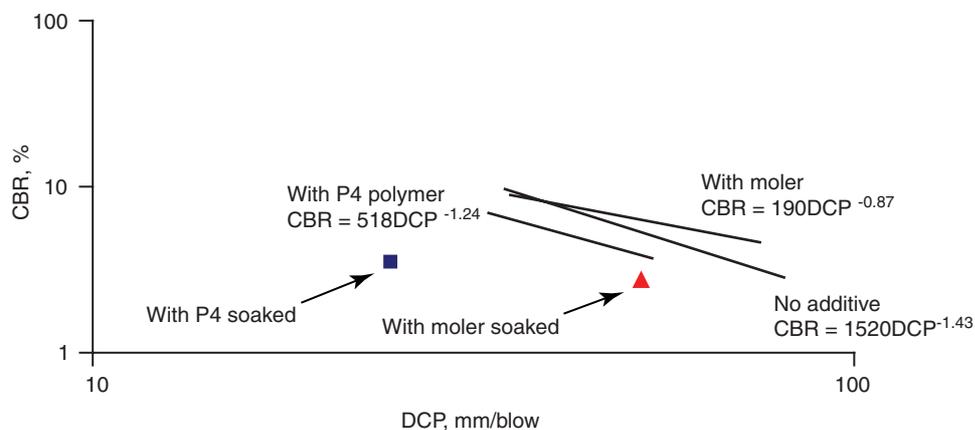
Figure 12 Effect of additives on the relation between CBR value and penetrability for the urban soil

3.9.3 Crushed brick

The data from tests undertaken on the crushed brick are shown in Figure 13. As with the other materials, at around the optimum moisture content the additives seemed to improve the structural characteristics of the material, but in the soaked condition they had a substantial detrimental effect on its properties.

3.10 Effects of layer densification

The reinstatement of an opening in a highway is covered by the 1991 Specification (Department for Transport, 2002); this requires pavement layers to be compacted in 100 mm thick layers. Some of the energy applied to the compaction of a layer of material will be transmitted to the underlying, previously compacted layers. For densely compacted materials, as required by the NRSWA Specification, any increase in density due to the compaction of overlying material will be small. However the level of compaction used in this study covered a wide range of densities. It was evident during the compaction of the test bays that the upper layers required a higher number of passes of a vibro-compactor than the lower

layers, indicating that some of the compaction energy applied to the upper layer was absorbed by the underlying layers.

Any such densification will affect the relation between the CBR value and penetrability of the materials. This effect was investigated by measuring the penetrability of 300 mm thick layers of the Type 1 sub-base, the 6F1 capping and the crushed brick both before and following the placement of a further 300 mm thick layer of the same material. The results of these tests showed that there was a minimum dry density of the lower layer above which the compaction of the overlaying layer did not have a significant effect. The minimum value varied from one material to another.

Using the various relations established above, the data from the crushed brick showed that the compaction of the overlying layer increased an initial CBR value of 12.5 by about 10 per cent, and an initial CBR value of 15 by 5 per cent. With the 6F1 capping, an initial CBR value of 12.5 was only increased by about 5 per cent. The minimum initial CBR value of the Type 1 sub-base was about 20 and no increase in CBR value was recorded as a result of compacting the overlying layer. Thus it would appear that there was little effect for these particular materials and layer thickness, where the initial CBR value was higher than about 17.5.
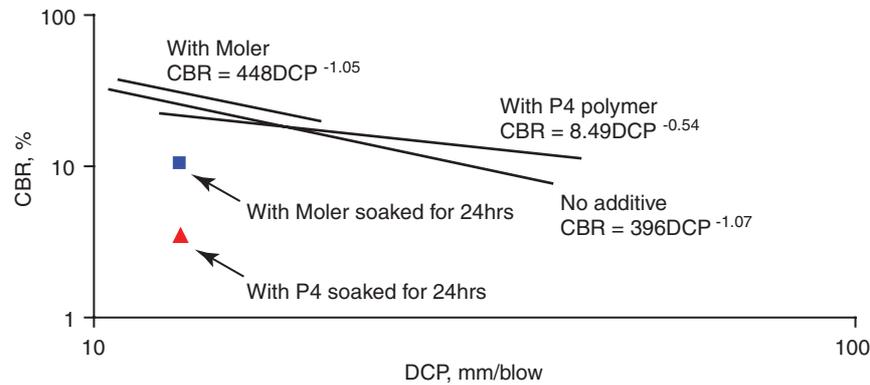
Figure 13 Effect of additives on the relation between the CBR value and penetrability for the crushed brick

4 Other methods of assessing *in situ* properties

Other methods of determining the density or stiffness of pavement layers are discussed below.

4.1 Nuclear density gauge

Nuclear density gauges are commonly used to determine the density of materials placed in earthworks and as backfill to structures. The devices emit and receive gamma radiation, the strength of the return signal can be calibrated against the density of the material.

4.2 Ground penetrating radar

Ground penetrating impulse radar (also known as ground radar) can be used to obtain information on the thicknesses of the various pavement layers, and on the presence of anomalies or defects in a foundation. The radar antenna transmits a pulse of electromagnetic radiation that travels as an energy wave through a pavement, as shown in Figure 14. Part of the energy is reflected at the interface between different materials, and the strength and timing of these reflections provides information on the various layers. The timing is a function of the thickness of the layer. The strength of the reflected signal depends mainly on the difference in the dielectric constant of the adjacent materials in a pavement; the constant can be related to the density or strength of the pavement layer. However, because of the limited sensitivity of the equipment, HD 29/94 (DMRB 7.3) recommends that radar surveys only be used to determine the thickness of the pavement layers, changes in construction form, and voids or wet patches beneath concrete slabs.

4.3 PANDA: ultra-light dynamic penetrometer

A schematic diagram of the PANDA device is shown in Figure 15. With this device, a blow from a 10 kg hammer, with a drop height of 0.5 m, is applied to the head of a penetration cone. Various sizes of cone are available. The speed of impact and the depth of penetration are recorded, by an on-board computer, and are used to calculate the dynamic cone resistance of the material; this is displayed as real-time data on the computer screen.

The boundary between different pavement layers might be identified by changes in penetration resistance. A knowledge of the characteristics of the pavement layers (grain size distribution, plasticity indices and moisture content) enables estimates to be made of their *in situ* properties.
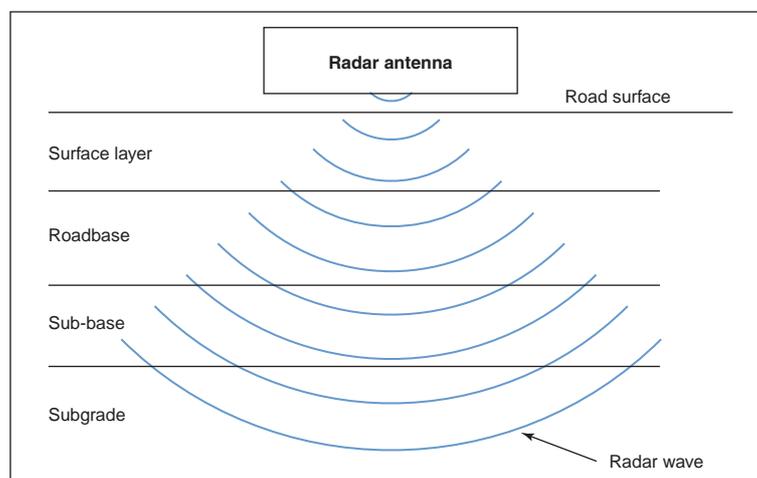
Figure 14 Ground penetrating radar
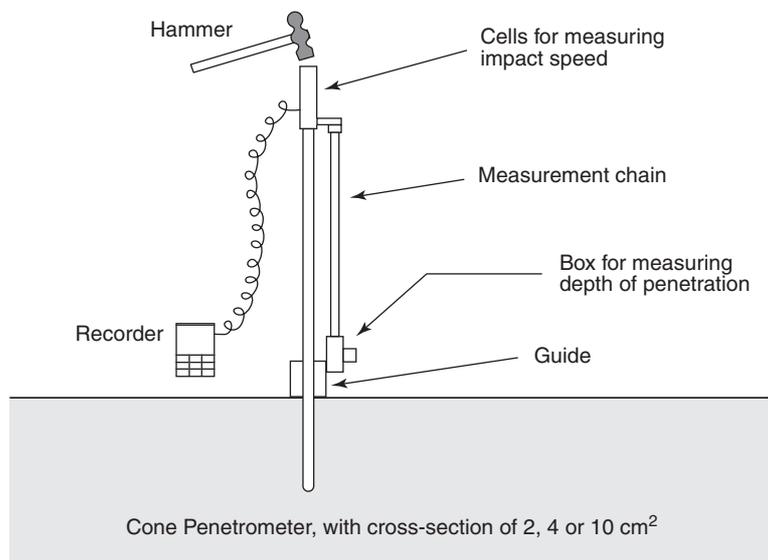
Figure 15 Schematic view of the PANDA device

4.4 Impact hammer

Impact hammers are used to determine the stiffness of both bound and un-bound pavement layers. In practice, a series of blows from an instrumented hammer are applied to the pavement. The blows need to be of uniform strength but not necessarily heavy because even a faint blow will create propagating frequencies. The resulting displacement and acceleration response is measured using an accelerometer or a geophone: the calculated velocities can be related to the stiffness of the pavement layers.

4.5 Clegg hammer

The Clegg hammer is commonly used for testing the integrity of trench reinstatements, Clegg (1976). A schematic layout of the device is shown in Figure 16. In use, the 4.5 kg mass falls 450 mm in a 50 mm diameter guide tube. The deceleration of the hammer head is measured and converted into a Clegg Impact Value (CIV), which is expressed in multiples of 10 g.

The device is cheap, portable and easy to use. However the area of the hammer head is rather small and so the contact stress is rather high. Also, because of this, there can be a wide scatter in the results of tests undertaken on materials having a maximum particle size comparable to the diameter of the head, see for example Thom (1988).
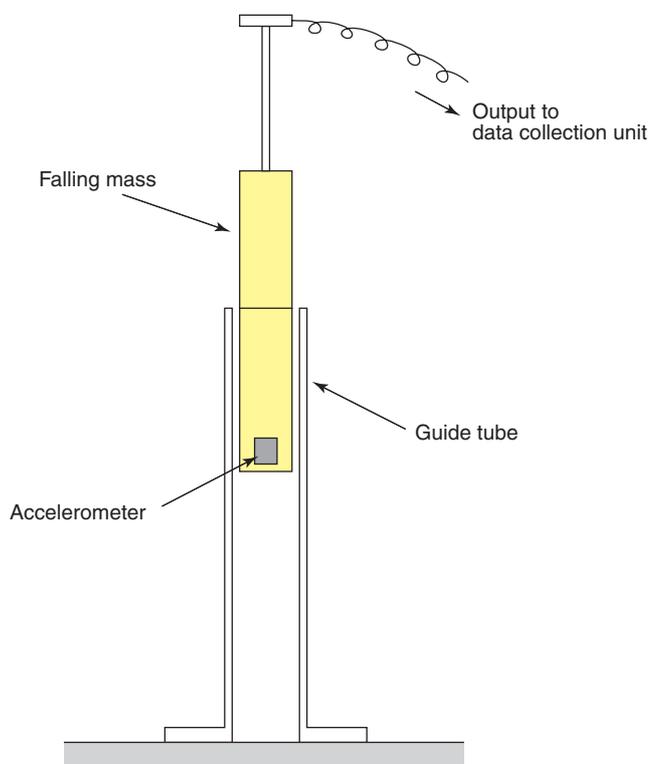
Figure 16 Schematic view of the clegg hammer

5 Conclusions

The following conclusions can be drawn from the results of the CBR and DCP tests:

1 There was a good correlation between the CBR value and penetration resistance of the wide range of soils tested. The relations were similar to those provided in other studies, such as by Jones and Rolt (1986).

2 The DCP device is a useful tool for predicting the *in situ* CBR value and/or the density of reasonably strong materials. The sensitivity of the device is insufficient for materials having a CBR value of less than about 10. In these cases the Mexicone penetrograph could be used for prediction purposes.

3 The use of soil additives might be of some limited benefit in well-drained sites, but in other cases they could lead to substantial heave and weakening of the pavement foundations.

4 For materials with a relatively low CBR value, the placement and compaction of a layer of material might lead to the densification of underlying, previously

compacted material. The possibility of over-compaction might need to be investigated to ensure that a reasonable degree of uniformity of density and strength of the construction layers is achieved.

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Appendix A: Details of CBR and DCP tests

KEY:-

1. Handle
2. Hammer (8kg)
3. Hammer shaft
4. Coupling
5. Hand guard
6. Clamp ring
7. Standard shaft
8. 1 metre rule
9. 60° cone

ϕ 20mm

60° inc
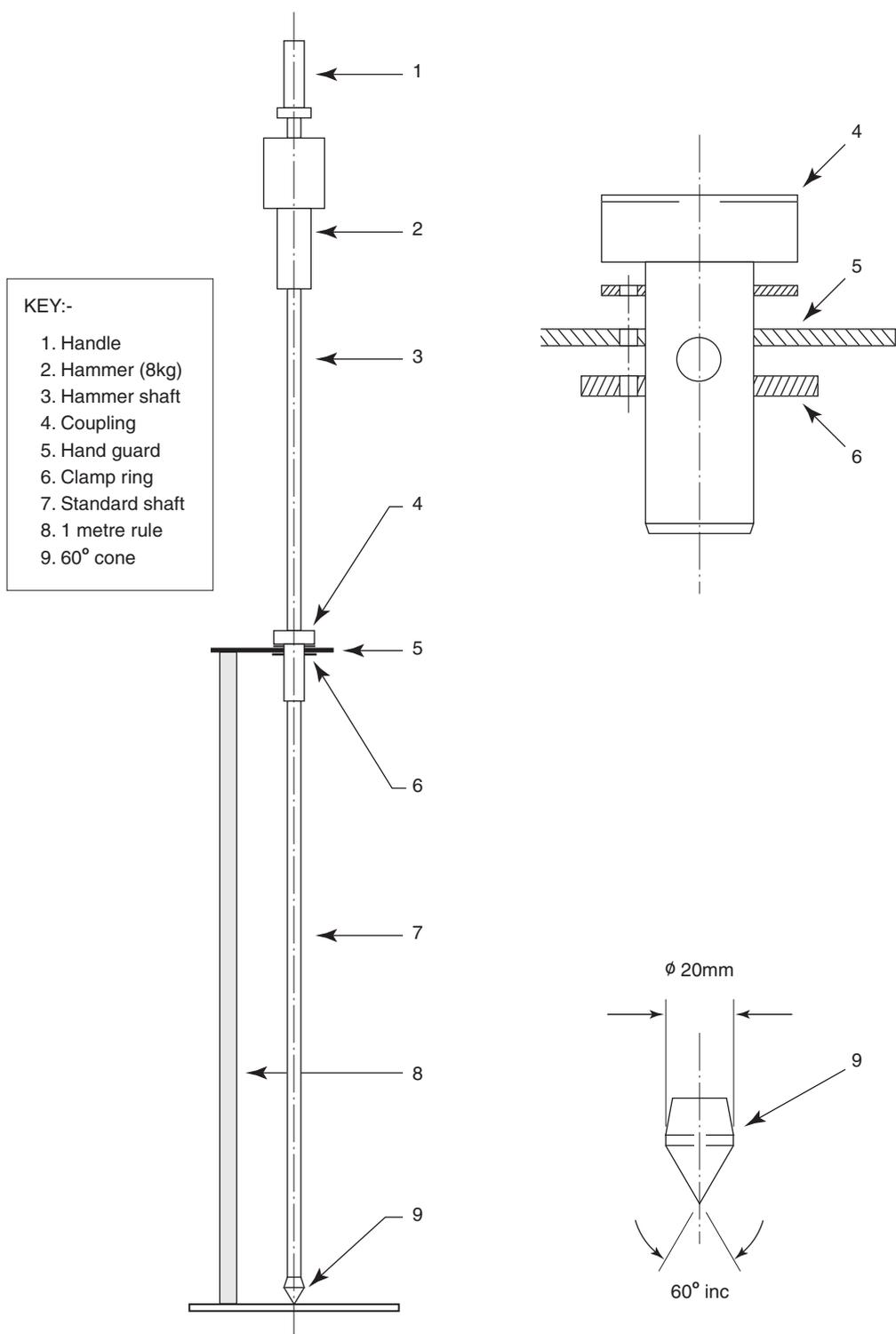
Figure A1 Layout of the TRL Dynamic Cone Penetrometer (after Jones and Rolt, 1986)
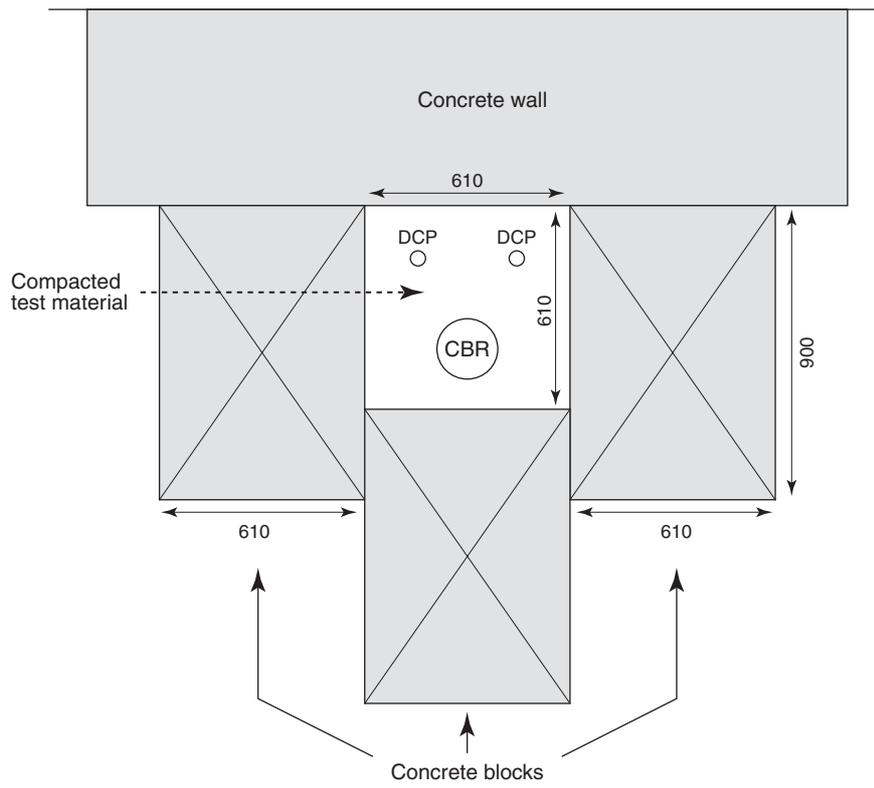
Figure A2 Plan of test bay for cohesive materials
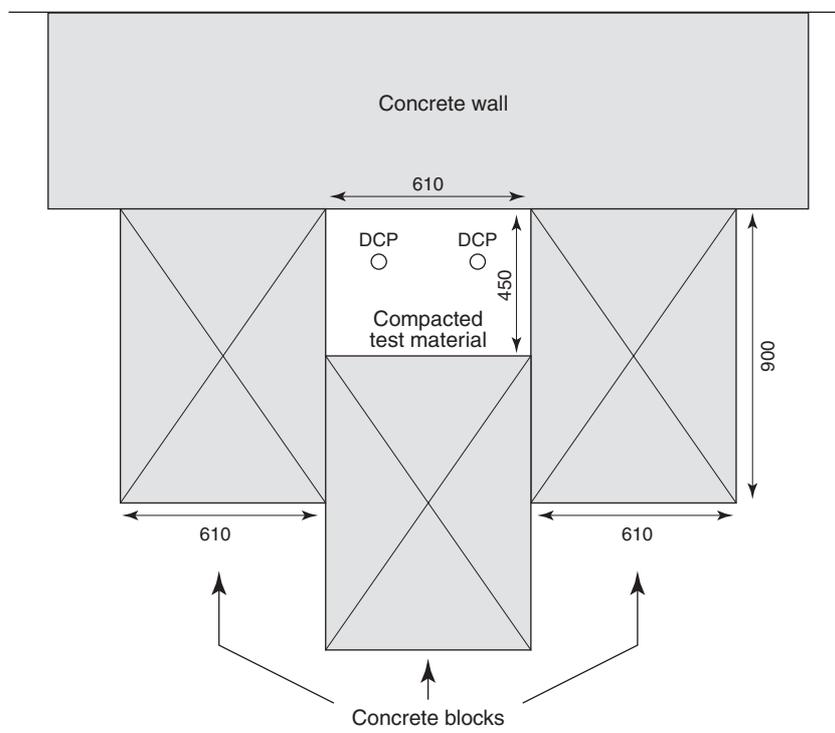
Figure A3 Plan of test bay for granular materials
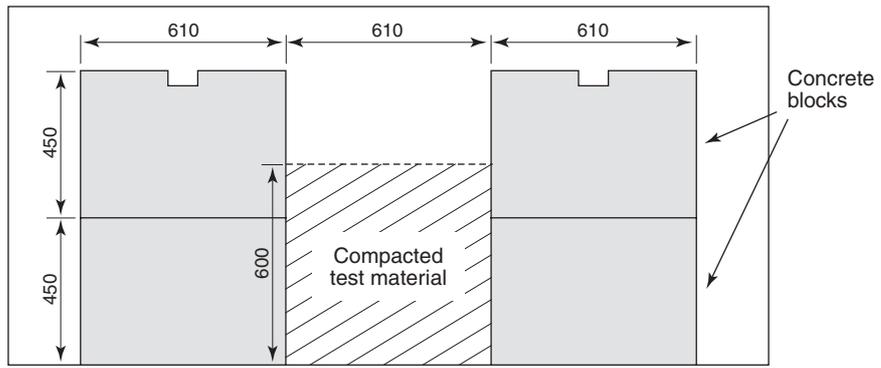
Figure A4 Elevation of the test bays

Figure A5 Arrangement of DCP test

Figure A6 Laboratory CBR test in progress

Abstract

This report presents and discusses the results of a series of laboratory Californian Bearing Ratio (CBR) tests and *in situ* Dynamic Cone Penetration (DCP) tests undertaken on seven materials. The materials ranged from a manufactured 'tree soil' of sand and peat, to crushed granite aggregates that met the requirements for a Type 1 sub-base and a 6F1 capping. The effect that the dry density of the materials had on the results of such tests was also investigated. It was found that reasonably robust correlations could be established between the results of CBR and DCP tests, and also between the results of these tests and the dry density of the materials. Such correlations enable the results of DCP tests to be used to estimate the *in situ* CBR or dry density of the materials.

This work has been undertaken as part of a research contract between Transport for London (Street Management) and a research team consisting of Richards, Moorehead & Laing Ltd, TRL Limited and the Tree Advice Trust.

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