THE STRENGTH OF CLAY FILL SUBGRADES: ITS PREDICTION IN RELATION TO ROAD PERFORMANCE

by

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Any views expressed in this Report are not necessarily those of the Department of the Environment or of the Department of Transport

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ABSTRACT

The suction method for estimating the shear strength of softs from plasticity data and moisture content has been examined in the light of a wide range of experimental evidence; it is concluded that the method predicts changes in strength of a wide range of soils satisfactorily.

The method has been used to quantify the likely changes in moisture content and strength under a range of site conditions. Very wet weather during construction on a poorly drained site reduces markedly the ultimate equilibrium strength of subgrades of low plasticity; equilibrium values are less than half the values associated with construction in dry weather. Heavy clays are much less affected.

Deflection studies indicate that the life of a pavement built in very wet weather may be reduced by up to 50 per cent of the life expected of a pavement constructed during average weather conditions.

1. INTRODUCTION

The stiffness and strength of soil subgrades play an important part in determining the performance of flexible roads. Deformation in the subgrade is controlled by the strength of the subgrade in relation to the traffic stresses transmitted to it and these are greatly influenced by the stiffness of the subgrade itself. The stiffness of the subgrade also influences the stresses generated by traffic within the layers of the pavement.

In the design of new roads in the United Kingdom the design parameter used to describe the soil is a measure of both its stiffness and strength. The California Bearing Ratio or CBR strength is determined with the soil at the equilibrium value of moisture content that is considered to persist under the road pavement throughout the life of the road. In actual practice the moisture conditions during construction are often much more adverse and seasonal variation also occurs under the in-service road.

Because the relation between soil suction and the wetting and drying of soils exhibits hysteresis, a subgrade that becomes wet during construction can be shown to attain a higher equilibrium moisture content than one that has been protected from the weather. The consequent reduction in subgrade strength (and stiffness) shortens the life of the road. Low subgrade strength during construction can result in poorly compacted granular sub-bases and roadbases which deform relatively easily under traffic. If a poorly compacted sub-base placed on a weak subgrade does not provide an adequate platform for the effective compaction of cement-bound and bituminous-bound roadbases road performance will again be adversely affected.

Because of the importance of the effect of subgrade strength and stiffness on both the structural quality and the in-service performance of road pavements, the present Report quantifies the likely changes in moisture
content and strength of the subgrade under a range of site conditions. The changes in moisture content are relatively independent of whether the soil is undisturbed or in well compacted fill and the suction method is used to assess the associated changes in soil strength. The effect of these changes on the structural life of pavements is assessed using relationships established between the structural performance of road pavements and their deflection under a rolling wheel measured in a standard manner.

2. THE SUCTION METHOD

The suction method estimates the California Bearing Ratio, CBR, of remoulded cohesive soils from plasticity data. It is based on experimentally established correlations between the plasticity indices, remoulded soil suctions and effective friction angles of soils. It was shown in reference 1 that the CBR correlated well with the product of the soil-moisture suction (in lb/in²) and one-tenth of the bearing-capacity factor when these two parameters were estimated from plasticity data. Comparison of estimated and measured CBR values for various British and African soils showed that the method was capable of predicting changes in strength due to changes in soil-moisture content and soil type with considerable accuracy and gave a reasonable idea of the absolute CBR to be expected; results are presented in Figure 1. If precise absolute values rather than relative values of CBR were required some calibration was necessary.

In order to use the same curves relating CBR and plasticity data for estimating shear strengths, the relation between CBR of remoulded soil and the undrained shear strength, Cu, was required.

In metric units the CBR of a soil is defined as the pressure on the CBR plunger, in kPa, at 2.5 mm penetration divided by 69.

\[ \text{CBR} = \frac{1}{69} \times \frac{1}{2} \times \frac{\text{qu}}{\text{penetration}} \]  

From model footing studies the pressure on a footing the size of the CBR plunger at a penetration of 2.5 mm is equal to about half of the pressure, qu, at ultimate bearing capacity of the soil. This differs from the assumption in reference 1; the evidence for the change is discussed in the Appendix.

Hence\[ \text{CBR} = \frac{1}{2} \times \frac{\text{qu}}{69} \]  

As the undrained shear strength is related to the ultimate bearing capacity of cohesive soils by the relation \[ \text{qu} = 6 \times \text{Cu} \], Equation 2 becomes

\[ \text{CBR} = \frac{\text{Cu}}{23} \]  

This applies when the CBR is measured on remoulded clays. When the CBR is inferred by the suction method as in reference 1, better correlation was found between estimated and measured shear strength if the equation was written

\[ \text{Cu} = (23 \times \text{CBR} + 1) \text{ kPa} \]  

This is a negligible correction at strengths typical of road subgrade soils but is necessary for correlation with strength near the liquid limit. It may reflect the fact that at zero suction, such as when a soil is immersed in water, most soils still cohere; this implies that some force other than suction is operating.
The relations obtained between Cu, CBR and plasticity data are given in Figure 2.

The prediction ability of the method has since been further evaluated on a wide range of soils whose index and strength properties are described in references 3, 4, 5 and 6. Reference 3 comprised a comprehensive series of vane shear strength measurements on artificial soils created by mixing different proportions of sand with Kaolinite and also Montmorillonite minerals. The plasticity indices of these soils ranged from 9 to 91 per cent; references 4 and 5 compared vane shear tests on remoulded soils, London Clay, Brick earth, Keuper Marl, etc; reference 6 includes similar tests including tests on other European soils. The comparison between measured strengths and strengths estimated by the suction method is given in Figure 3. Full details are given in the Appendix. Strength comparisons are made at the liquid limit and the plastic limit (some by extrapolation) and also at moisture contents mid-way between these limits. The 45° line in Figure 3 which is the line of equality between measured and estimated strengths is quite a good fit through the points. It confirms that the estimation method, on average, correctly estimates changes in the shear strength resulting from moisture-content changes, although, if a close estimate of strength is required, calibration will be required.

The Appendix demonstrates that much of the scatter in Figure 3 is as likely to be the result of experimental inconsistencies in measuring strength as of shortcomings of the suction method; in particular errors in measured values are considered likely to have arisen from pore pressures generated during compaction of the specimens. Although the information necessary to make numerical corrections for these inconsistencies is not available, the sense of these corrections is such as to reduce considerably the scatter in Figure 3.

A method of estimating the moisture changes which bring about changes in soil strength during and after construction is also required if the suction method is to be used to predict these strength changes. This is considered below, on a comparative basis.

3. ESTIMATION OF CHANGES IN MOISTURE CONTENT

The relationship between moisture content, overburden pressures, and water-table positions has been fully dealt with elsewhere. It has been shown that moisture content changes with the suction in the pore water of the soil and suction can be calculated using the equation

\[ \alpha P + S = U \]

\[ (5) \]

U is the pore-water pressure in the soil which is controlled by the position of the water table when equilibrium has been attained.

S is the soil moisture suction, or pore-water pressure at zero overburden pressure.

P is the overburden pressure.

\( \alpha \) is the proportion of the overburden pressure which is effective in changing the pore-water pressure (it is 1 for a heavy clay and 0 for sand at typical subgrade moisture contents).

Except in the case of sands, soil suction at equilibrium is therefore controlled both by the depth of the water table and by the surcharge imposed by the pavement.
Moisture-content changes in the subgrade can then be established from the results of extensive laboratory studies made of the relations between soil suction and moisture content of a range of soils, described in reference 8. This information has been used to develop a series of suction/moisture-content relations for soils with plastic indices of between 5 and 90 per cent. Different curves are obtained depending on whether the soil is drying-out or wetting-up and the characteristic hysteresis shape accounts for the important fact that the moisture content of a soil in equilibrium with a water table at a given depth under a given pavement, can be at one of two values as the result of one cycle of suction change. In practice an infinite number of hysteresis loops are possible, depending on the range and absolute values of suction at the ends of the wetting and drying phases.

It should be noted that, if a soil is at any given suction and the soil is wetted and dried back to the same suction, it will have a moisture content at the end which is greater than that at the beginning. The amount of the hysteresis usually lies between 1 per cent and 3 per cent moisture content for all soils. In the case of low plasticity soil, this amount of hysteresis is a large proportion of the moisture necessary to change a soil from its plastic limit to its liquid limit and therefore has a dominant effect on the ultimate equilibrium strength of low-plasticity soils subjected to different amounts of wetting during road construction. An example of two drying curves which start from two different suctions for a soil of plasticity index of 10 per cent are shown dotted in Figure 4.

The suction/moisture-content curves in Figure 4 are typical average values for soils that satisfy a line on the Casagrande Plasticity chart typical of cohesive softs with an equation

\[ \text{PI} = 0.838 \text{ LL} - 14.2 \] .......................... (6)

When soils satisfy this equation, the moisture content of the soil is an 'effective moisture content' and suction can be read directly from Figure 4 from measured moisture contents. If soils do not satisfy Equation 6 then an effective moisture content must be calculated, which differs from its actual moisture content. It can be calculated from the equation:

\[ \text{Effective moisture content} = \text{actual moisture content} + \frac{(\text{PI} + 14.2)}{0.838} - \text{LL} \] .......................... (7)

4. PREDICTION OF EQUILIBRIUM STRENGTHS OF ROAD SUBGRADES

The suction method can be used in conjunction with the equation \( \alpha P + S = U \) and the curves of Figure 4 to estimate strength of various soils that are subjected to different degrees of wetting or drying during and after construction. It is assumed in each analysis that the final equilibrium suction in winter under all road pavements and in all soil types is 180 cm of water. The justification for UK conditions is discussed in reference 1. This suction corresponds to the highest winter water-table level normally permitted in good construction practice, i.e. the water table should not be closer to the top of the subgrade than about 600 mm.

4.1 The effects of very dry weather

The first case considered is that of subgrades that are drier than their equilibrium suction at the earthwork stage and remain drier throughout construction of the pavement. Ultimately the soil wets up and comes into equilibrium with the water table. The predicted equilibrium strength of soils of various plasticity index is shown in Figure 5a, line 1. This is however unlikely to be often achieved in practice because of the
vagaries of our weather. Equilibrium strengths likely to be achieved as the result of construction conditions more typical of the United Kingdom are therefore calculated and compared with the ideal conditions represented by Line 1 Figure 5a. Two cases are considered, (1) the effect of very wet weather during construction and (2) the condition on a well drained site.

4.2 The effects of very wet weather

In normal practice a road sub-base cannot be laid unless the subgrade has adequate strength to carry the construction machinery without gross distortion of the soil surface. Hence the effects of wet weather on the soil need not be considered at this stage as any wetted soil will normally be removed and replaced with selected fill before construction begins. However, heavy rain after the sub-base has been laid must be considered.

It will be assumed in the analysis that the sub-base thickness has been laid according to Road Note 29, i.e. there will be a minimum sub-base thickness of 150 mm on low plasticity soils which we assume to be of high strength, increasing to a thickness of between 500 and 600 mm on the heaviest soils; the exact thickness of course, depends on the expected amount of traffic on the completed road. It is also assumed that sufficient rain had fallen to create a water table in the sub-base 150 mm above formation level; this would require about 50 mm of rain. Even on an embankment this is a possibility because the water table has to be above formation level before there is sufficient head for it to run off over the sides of the embankment. The lightest soils are known to be sufficiently permeable to reach moisture equilibrium to a depth of between 300 to 600 mm in a matter of days; in heavy soils the depth is much less. Equilibrium strengths at the surface of the subgrade are given as Line 2 in Figure 5b; the CBR strength of about 2 per cent obtained for most soil drops rapidly below that value as the plasticity of the soil decreases below 25 per cent. From experience it is known that at a CBR value of about 2 per cent the minimum sub-base thickness of 150 mm would be insufficient to carry construction machinery and under these conditions a minimum thickness of sub-base of about 300 mm is required. This implies that any soil of plasticity index of 25 per cent or less would be liable to produce difficult construction problems in wet conditions and this is, of course, borne out by site experience.

As a consequence of hysteresis in the suction/moisture-content relation (Figure 4), it can be seen that once the soil has become very wet it will follow a drying curve which ensures that the soil will always remain wetter at equilibrium than on the same soil which was never allowed to become so wet. Curve 3 of Figure 5b shows that the final equilibrium CBR under the finished pavement may be as little as one-half of the ideal shown as Curve 1 for low-plasticity soils.

Very-low-strength soil beneath the sub-base may lead to soil being forced into the lower 50–75 mm of granular material during construction of the road sub-base and base. This will be particularly liable to happen with the higher grades of sub-base which are low in fines and are therefore easily penetrated by soil. Intrusion of clay into a sub-base virtually reduces its effective depth by the depth of the intrusion.

4.3 Conditions on a well drained site

If both the effects of adverse weather and of penetration of the subgrade into the sub-base are to be avoided, then unimpeded drainage would be required at the earthworks stage to maintain the water table at an adequate depth beneath the prepared subgrade; this is particularly so with lighter soils. In fill it is quite easy for a perched table to form and drainage of an embankment is as important as drainage in cut.
In addition the soil surface should be laid to a good fall and waterproofed. It is not unlikely that a waterproofed and drained subgrade might reduce the urgency to lay the sub-base as soon as possible, which means that the soil would wet up from below with no counteracting effect on the suction, and hence strength, from the surcharging effect of the sub-base. The resulting CBR of the soil could then be as shown in Line 4 in Figure 5c. At equilibrium under the finished road, the resultant equilibrium CBR is likely to be as shown in Line 5 of Figure 5c.

Both of these curves are unlikely to occur in practice, the reason being the time necessary to attain equilibrium when the soil is fairly dry and dependent on drawing up water from the water table to achieve its equilibrium value. It has been assumed that only the lightest soil at a PI of 10 per cent will achieve these equilibrium values, because such soils are more permeable and will therefore more readily achieve equilibrium. Therefore the curves shown dotted as Line 4A and Line 5A have been sketched in as more probable relations.

Above a plasticity index of 50 per cent it can be seen that the various effects of wetting and drying, including those from the ideal and the very wet sites, have little effect on the final equilibrium strength because the moisture-content difference between the wetting and drying curves is a small proportion of the amount of water necessary to change the soil from its liquid limit to its plastic limit.

If the weather during construction of a road is moderate, which is usually the case, the extreme conditions described in Figure 5b will only rarely occur. In our variable weather, alternating wet and dry periods would be unlikely to raise the water table much and some surface wetting would be quickly removed by natural drainage and by drying winds. It is suggested that, under such conditions, the soil, not waterproofed, but surcharged with a sub-base related to the soil type, would very likely attain equilibrium conditions during and after construction not dissimilar to the curves shown as 4A and 5A in Figure 5C.

An alternative to waterproofing the soil, or hoping for at least reasonable weather, would of course be to increase the depth of sub-base.

To achieve the same CBR values as a well drained waterproofed site would require a minimum depth of construction of 370 mm of sub-base instead of 150 mm. This alternative permits the relative economics of each solution to be investigated.

4.4 Seasonal strength changes

The equilibrium strength Line 1 in Figure 6 is appropriate to winter water-table levels when the soil wets up to its equilibrium value. If the soil wets up to the equilibrium associated with the lower depth of water table that is possible in summer, Line 6 is appropriate. The latter line was based on the assumption that the summer water table under a pavement is up to 1 metre deeper than in winter and causes an increase in suction of the soil of one metre of water. This is typical of the change that can be expected in heavy clays and in the absence of more definite information it has also been accepted for all clay soils. The difference between the winter and summer equilibrium strength only exceeds 10 per cent at plasticity indices of less than 20 per cent and this is the maximum change likely to occur. The change in strength due to seasonal rise and fall of the water will be less than this value because the slope of the solid wetting or drying curves of the suction/moisture-content relationship in Figure 4 used for the calculations will be considerably less than those associated with seasonal movements of water table (a drying curve is shown as a dashed line).
4.5 Effects of pavement leakage on soil strength

In the event of cracking of a pavement which results in water leaking into the subgrade it has been shown that \(^{11}\) the water table in heavy clays can readily rise to formation level. In lighter soils the effect is not quite so great \(^{10}\) but for the purpose of this analysis it was assumed that they would be equally affected. The reduction in strength can be seen in Figure 7 by comparing Line 1, the ideal equilibrium-strength line, and Line 7, the possible equilibrium produced by leaks. In fact the effect of some leakage appears to create a soil strength similar to that of Line 5A, Figure 5C, which was considered to be typical of expected strengths at equilibrium under roads constructed in variable weather.

If drainage of the sub-base is impeded and leakage permits saturation of the sub-base, the much lower soil strengths would be predicted as shown in Line 8 of Figure 7. This approaches the expected equilibrium strength line experienced under pavement construction in adverse weather, Line 3, Figure 5b. In lighter soils it can be seen that impeded drainage could reduce the strength of the soil by 60 per cent.

Sometimes rapid deterioration of roads in a cracked condition is attributed to this loss of strength of the subgrade but the subgrade is not always to blame. It is possible for the surface to be disrupted by high pore-water pressures caused by the action of traffic on some saturated layer of granular roadbase or even of a deteriorating cement-bound roadbase, without the lowest layer of the road being involved.

4.6 Summary and conclusions on moisture conditions

Best estimates of the strength of softs at various plasticity indices during and after construction are summarised in Figure 8. The line numbers are consistent with those in Figures 5 to 7.

**Lines 1 and 6.** These are the likely strengths of soils wetting to winter and summer equilibrium respectively under a completed pavement when the subgrade has been prepared and the road built while the soil is drier than its final equilibrium. In UK climate this condition is likely to be exceptional.

**Line 5A.** This is the estimated most likely relation between plasticity index and soil strength for roads constructed in moderate weather. The estimate is based on the highest water table being at least 600 mm below formation level. It also predicts the strength that the soil would more reliably attain if the site was well drained and the soil waterproofed.

**Line 3.** This is considered to be the lowest equilibrium strength that is likely to occur under a pavement constructed in very adverse weather. It also estimates the likely strength in the soil if the sub-base becomes water-logged through impeded drainage.

**Lines 2 and 4A.** These lines represent strength in the subgrade soil during pavement construction. Line 2 represents the lowest likely strength that will occur if adverse weather follows the construction of the sub-base. For soils lighter than a plasticity index of 25 per cent, no roadbase construction could take place without first permitting the site to dry out. Line 4A is the equilibrium strength of waterproofed soil with a controlled water table. It also probably represents the strength of the soil under a sub-base during variable weather when some rain alternates with drying conditions; this curve could be considered typical for 'normal' conditions in the UK.
The curves in Figure 8, which relate CBR and plasticity index, can be compared with the equilibrium CBR values given in the official guide to the structural design of pavements for new roads, Road Note 29\textsuperscript{9}.

In Road Note 29 are given typical CBR strengths for soils of different plasticities in equilibrium with the different water-table conditions. The table was based on laboratory and field tests on soil at its natural moisture content\textsuperscript{7}, the moisture content that occurs in natural soil at a depth of 1 m or so, a depth at which there is normally little seasonal change of moisture content, or at the equilibrium condition measured under a pavement. The Road Note 29 values of CBR are reproduced in Table 1 below.

### Table 1

<table>
<thead>
<tr>
<th>Soil type</th>
<th>Plasticity index per cent</th>
<th>CBR per cent Depth of water table below formation level</th>
</tr>
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<tbody>
<tr>
<td></td>
<td></td>
<td>Depth of water more than 600 mm</td>
</tr>
<tr>
<td>Heavy clay</td>
<td>70</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>2.8</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>3</td>
</tr>
<tr>
<td>Silty clay</td>
<td>30</td>
<td>5</td>
</tr>
<tr>
<td>Sandy clay</td>
<td>20</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>7</td>
</tr>
<tr>
<td>Silt</td>
<td>–</td>
<td>2</td>
</tr>
</tbody>
</table>

The relations between CBR strength and plasticity index for the two water-table conditions quoted in the Table are shown as dotted lines in Figure 8.

Line 5A, which has been labelled as the typical equilibrium that might on the average be expected in our climate, roughly follows, and is a lower boundary to, the Road Note 29 strength for the deeper water-table condition. Line 3, which gives the lowest predicted equilibrium strength for roads constructed in very adverse conditions, approximates to the strength quoted in Road Note 29 for sites with shallow water tables, except for soils whose plasticity indices are greater than 50 per cent, where Road Note 29 suggests very low strengths that are below that predicted.

It therefore appears that the equilibrium CBR values actually achieved in service are likely to be considerably lower than measured values used for design if adverse moisture conditions are encountered during construction.
The suction method has not been properly calibrated below a plasticity index of 10 per cent and no comparison has therefore been made between estimates and measured CBR values in this range.

The very low strengths quoted for non-plastic silts in Road Note 29 reflect the fact that even in normal weather there can be sufficient rain during construction to so lower the strength of these materials that the road cannot be constructed to take advantage of the probable quite high equilibrium strengths. Sub-base thicknesses must therefore be designed for the construction phase, ie to the very low strength that may occur during construction; allowance is made for this in Table 1 of Road Note 29.

6. EFFECT OF SUBGRADE STRENGTH ON THE STRUCTURAL PERFORMANCE OF FLEXIBLE PAVEMENTS

Any mismatch between the design strength of a subgrade and the equilibrium strength developed under the road will be reflected in the life of the road achieved under traffic. In Road Note 29 only the design thickness of sub-base is related to the subgrade strength and it is not possible to deduce the effect on pavement life of a mismatch between design and achieved strength.

A major combined in-situ and laboratory study is at present in progress to evaluate the equilibrium subgrade conditions under the major full-scale road experiments built by the Laboratory. The aim is to characterise strengths in terms of conventional in-situ CBR/shear-strength as an essential input to revising design recommendations. Information is also being obtained relating to the fundamental behaviour of subgrades primarily by testing recovered samples in repeated triaxial loading designed to simulate as far as possible the stress conditions generated by moving traffic; the information is required as part of a wider programme aimed at developing a structural method of design based on a knowledge of the real behaviour of road materials and subgrades in service. In relation to the subgrade the approach will take account of the fact that conditions in the road are very different from those obtaining in either the CBR test or at failure in a conventional measurement of soil strength; the actual subgrade is subjected to a range of magnitudes of soil stress repeatedly applied with the moisture conditions within it responding to the presence of a water table and to the applied stresses. Progress in this field should lead to better design but is beyond the scope of this Report.

The study in terms of in-situ subgrade strength although in its early stages, is yielding results that indicate the importance of subgrade strength in influencing the performance of flexible roads. The work is considered in the following sections of the Report.

6.1 Measurement of subgrade strength

Cores of 150 mm diameter have been taken from the wheelpath zones of a number of experimental sections constructed. Three or six cores in each section provided accurate measurements of construction thicknesses and also access to the subgrade whose strength was measured by means of a static penetrometer calibrated in terms of CBR values. Strengths were averaged over the 0.75 m of subgrade below formation level.

6.2 Assessment of associated pavement performance

The structural performance of a flexible pavement can be correlated with the deflection of its surface under a dual-wheel load moving at creep speed. From systematic measurements of deflection made with
the Deflection Beam on full-scale road experiments over a period of years deflection histories have been developed: these relate deflection to pavement deterioration under traffic expressed in terms of equivalent standard axles of 8,175 kg. Well defined relations between deflection and pavement life (in standard axles) up to the stage when the pavement has deteriorated to a critical condition requiring overlaying, i.e., when it retains much of its structural integrity and therefore does not require reconstruction, have been obtained; they are of the form

\[ \text{Life} = \frac{A}{(\text{deflection})^{n}} \]  

(8)

where \( A \) is a function of the type of roadbase and \( n \) has a value close to 3, irrespective of the type of roadbase: other pavement parameters such as the thickness of pavement layers and strength of the subgrade over a wide range have no significant effect on the deflection/performance relationship. The deflection concerned is the value measured in the early life of the pavement when moisture equilibrium in the subgrade has been established and after any traffic compaction and cementing action in the granular layers of the road has taken place.

6.3 Correlation between deflection and CBR strength

Equilibrium deflections measured on a number of experimental sections of similar type vary systematically according to the strength of the subgrade. The limited number of results so far available for pavements constructed with road bases of dense bituminous materials are shown in Figure 9. Not all the pavements have the same thickness of roadbase; the deflection values have, therefore, been adjusted to a standard roadbase thickness of 200 mm using the overlay correction curves in reference. Figure 10 gives similar results for experimental pavements constructed with slag wet-mix roadbases and having the same nominal thickness.

A further check on the validity of the relations in Figures 9 and 10 has been obtained from sections of road experiments where the CBR strength of the subgrade at the time of construction and the associated deflection values were substantially different from the equilibrium values of these parameters. The actual change in deflection between construction and equilibrium will reflect the compaction and possibly cementing action in granular road layers as well as changes in subgrade strength and great accuracy cannot therefore be expected in using the relations in Figures 9 and 10 to predict the deflection at construction from knowledge of the changes in subgrade strength. However, the results obtained on five experimental sections, given in Table 2 and plotted as the solid points in Figure 11, show good agreement.

The corresponding data are also shown for equilibrium conditions used to develop the curve in Figure 9.

### Table 2
Comparison of initial and equilibrium deflections

<table>
<thead>
<tr>
<th>Section No.</th>
<th>Thickness of bituminous roadbase and surfacing</th>
<th>CBR</th>
<th>Deflections</th>
<th>Estimated</th>
<th>Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Initial</td>
<td>Final</td>
<td>Initial</td>
<td>Final</td>
</tr>
<tr>
<td>1</td>
<td>180</td>
<td>9</td>
<td>2.6</td>
<td>28</td>
<td>72</td>
</tr>
<tr>
<td>2</td>
<td>250</td>
<td>3.8</td>
<td>2.2</td>
<td>36</td>
<td>52</td>
</tr>
<tr>
<td>3</td>
<td>350</td>
<td>12</td>
<td>8</td>
<td>11</td>
<td>13</td>
</tr>
<tr>
<td>4</td>
<td>300</td>
<td>12</td>
<td>7.2</td>
<td>14</td>
<td>17</td>
</tr>
<tr>
<td>5</td>
<td>250</td>
<td>8</td>
<td>6</td>
<td>20</td>
<td>25</td>
</tr>
</tbody>
</table>
6.4 Implication for pavement life

Given the sensitivity of pavement life to the level of equilibrium pavement deflection indicated by Equation (8), the relations in Figures 9 and 10 point to significant changes in pavement life as the result of changes in CBR strength. The greatest likely change in CBR strength resulting from varying weather conditions during construction has been shown to be in soils of low-to-medium plasticity.

The example given in Table 3 indicates predicted equilibrium deflections and critical lives of a road having a roadbase of dense bituminous macadam of 150 mm thickness surfaces with 100 mm of rolled asphalt. It is constructed on a 180 mm thickness of granular sub-base on a soil with a plastic index of 10 per cent. The estimated critical life for a road built in very wet weather is only about half of that of a road built under average conditions; in turn a road built in favourable conditions is capable of achieving a life which is double that of the 'average' road.

<table>
<thead>
<tr>
<th>Conditions during construction</th>
<th>Equilibrium deflection mm x 10^{-2}</th>
<th>Critical life standard axles x 10^6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil drier than equilibrium during road construction (Curve 1)</td>
<td>19</td>
<td>42</td>
</tr>
<tr>
<td>Average construction weather (Curve 5a)</td>
<td>25</td>
<td>22</td>
</tr>
<tr>
<td>Very wet weather during construction (Curve 4a)</td>
<td>31</td>
<td>13</td>
</tr>
</tbody>
</table>

The thickness design curves in Road Note 29 relate to lives associated with total failure of the roadbase and surfacing; these would be expected to be about 30 per cent greater than the critical lives, which are related to the onset of deterioration in these pavement layers. The predicted critical lives are considerably greater than those indicated by Road Note 29; the latter, however, include a factor of safety whereas the critical lives quoted were derived from curves which estimate life in terms of a 0.50 probability of achievement.

7. SUMMARY AND CONCLUSIONS

1. Evidence is presented that the suction method, which relates the moisture content of a soil to its undrained strength, can be used in conjunction with relations between soil-suction and moisture content to analyse strength changes in subgrades under roads.

2. There are elements of the suction method that are not rigorously justifiable. The in-depth comparison of measured and predicted shear-strength values presented in the Appendix indicates that much of the mismatch between the two is as likely to be the result of experimental inconsistencies in the measured values as of shortcomings arising from the suction method.

3. The method has been used to quantify the effect of hysteresis observed in the suction/moisture-content relations on soil strength resulting from various moisture conditions that may occur during construction and subsequently under the completed pavement.
4. For average weather conditions during construction, typical equilibrium CBR strengths are similar to the values recommended in Road Note 29 for deeper water-table conditions.

5. Very wet weather during construction on a poorly drained site reduces markedly the ultimate equilibrium strength achieved in soils of low plasticity. Equilibrium strengths are less than half values associated with dry-weather construction and design should always be for the most adverse drainage conditions indicated in Road Note 29. To guarantee that problems during construction in very wet weather are avoided, the thickness of sub-base used on soils of low plasticity should be increased further; for soil of plastic index of 10 per cent, thicknesses of about 370 mm are required.

Alternatively effective drainage and water-proofing can maintain strengths associated with, at least, average construction conditions.

6. Seasonal variations in the level of water table under the completed road change the strength of the soil by less than 10 per cent.

7. The lives of pavements constructed in very wet weather, on poorly drained soils of low plasticity, may be reduced by as much as 50 per cent compared with pavements constructed during average weather conditions.

8. ACKNOWLEDGEMENTS

The work described in this report was carried out in the Pavement Design Division (Division Head: Mr N W Lister) of the Highways Department of TRRL.

9. REFERENCES


Fig. 1 COMPARISON OF ESTIMATED AND MEASURED CBR's of UNSATURATED SOILS (a) and (b) AT VARIOUS DRY DENSITIES, AND (c) TO (f) AT VARIOUS COMPACTIVE EFFORTS
Fig. 2 RELATION BETWEEN SHEAR STRENGTH, CBR AND PLASTICITY DATA

Consistency index = \( \frac{LL - w}{LL - PL} \)
Fig. 3 COMPARISON OF MEASURED SHEAR STRENGTHS WITH VALUES ESTIMATED BY THE SUCTION METHOD
Fig. 4 RELATION BETWEEN SUCTION AND MOISTURE CONTENT FOR VARIOUS SOILS

Equilibrium suction
Final equilibrium
Soil drying from here
Wettest condition
Fig. 4(b) line 2
Plasticity index
Liquid limit
Effective moisture content (per cent)

Suction (cm water)
Suction (cp)
Fig. 5 EFFECT OF WEATHER AND DRAINAGE ON THE SUBGRADE STRENGTH DURING AND AFTER COMPLETION OF PAVEMENT

Fig. 6 SEASONAL CHANGE IN STRENGTH OF SOIL BENEATH IMPERMEABLE PAVEMENT

Fig. 7 EFFECT OF WATER TABLE ABOVE NORMAL EQUILIBRIUM LEVEL
Fig. 8 SUMMARY OF EQUILIBRIUM SUBGRADE STRENGTHS DURING CONSTRUCTION AND FINALLY UNDER THE FINISHED ROAD
Fig. 9 RELATIONSHIP BETWEEN EQUILIBRIUM DEFLECTION AND EQUILIBRIUM SUBGRADE CBR FOR EXPERIMENTAL ROADS WITH BITUMINOUS ROAD BASES

Fig. 10 RELATIONSHIP BETWEEN EQUILIBRIUM DEFLECTION AND EQUILIBRIUM SUBGRADE CBR FOR AN EXPERIMENTAL ROAD WITH UNBOUND ROADBASES

Fig. 11 COMPARISON OF MEASURED AND ESTIMATED DEFLECTIONS
Shear strength (kPa) = \( \frac{2S + 1}{6} \)

Shear strength (kPa) = \( (1.2\tan \theta \cdot N_c + S N_d + 0.67 R N_r) + 1 \)

Fig. 12: Comparison of two methods of estimating bearing capacity

Effective moisture content (per cent)

Low plasticity (LP)

High plasticity (HP)

LL

P.I. 10

P.I. 20

P.I. 30

P.I. 50

P.I. 70

P.I. 90

LL
RESULTS FROM DUMBLETON AND WEST Ref. 3

Fig. 13 COMPARISON OF MEASURED AND ESTIMATED SHEAR STRENGTHS
RESULTS FROM DUMBLETON AND WEST Ref. 3

Fig. 14 COMPARISON OF MEASURED AND ESTIMATED SHEAR STRENGTHS
RESULTS FROM LEWIS AND ROSS Ref. 4

(Soil 12 only)
Effective moisture content (per cent)

Undrained shear strength (kPa)

Effective moisture content (per cent)

Fig. 15 COMPARISON OF MEASURED AND ESTIMATED STRENGTHS
Fig. 16 COMPARISON OF MEASURED AND ESTIMATED STRENGTHS
RESULTS FROM SCHOFIELD AND WROTH Ref. 6

- Measured strength
- Estimated strength

Fig. 17 COMPARISON OF MEASURED AND EFFECTIVE STRENGTHS
10. APPENDIX 1

DISCUSSION ON THE SUCTION METHOD

10.1 Modification of the suction method

The suction method was devised to estimate the CBR values of soil; in its derivation it was stated that the ultimate bearing capacity of soil, $q_u$, could be taken as equal to $S N_q$ where $S$ is the suction of the remoulded soil and $N_q$ the bearing-capacity factor used in the well-known bearing-capacity formula

$$q_u = 1.2c N_c + \gamma D N_q + 0.63 R N_q \gamma \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (9)$$

It was therefore reasonable for Rodin to use Equation (9) and combine it with the equation,

$$q_u = 6C_u \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (10)$$

to deduce an undrained shear strength for the soil ($C_u$). Rodin's conclusions were discussed by Forde who correctly deduced that $S N_q$ was not equal to bearing capacity. Forde also heavily criticised all the assumptions used in the suction method.

This appendix explains how in the original paper the ultimate bearing capacity was underestimated by approximately a factor of two. If this is allowed for, the suction method is capable of predicting undrained shear strength and its variations with useful accuracy.

It was known at the time of writing reference 1, that $S N_q$ was approximately one-half of bearing capacity calculated using the whole of Equation (9). A comparison of shear strength derived from Equation (9) and from $2 S N_q$ (to each of which has been added 1 kPa, see Section 2 of the main Report, is given in Figure 12. The agreement is probably as good as can be expected when values of the bearing-capacity factors have been taken from published data. Because the agreement is good, throughout this Appendix the calculations of undrained shear strength have used the simpler calculation $q_u = 2S N_q + 1$ kPa.

Although it was appreciated that $S N_q$ gave values of only one-half of those calculated from Equation (9), this value correlated well with a clear change of slope of the pressure/penetration curve used to derive CBR at about 2.5 mm penetration. This change of slope was wrongly deduced as bearing-capacity failure. Examination of 20 CBR curves taken to a penetration of 12.5 mm showed that the pressure on the plunger at 2.5 mm penetration is approximately half (47–52 per cent) of that at ultimate bearing capacity, which occurred close to the deeper penetration. This agrees reasonably well with the model footing tests carried out by Skempton where the comparable figure in remoulded soil was about 60–65 per cent of ultimate bearing capacity at similar penetration/diameter ratios.

If it is assumed that the pressure on the CBR plunger at 2.5 mm penetration is equal to half of that at the ultimate bearing capacity, this leads to the correlation $CBR = C_u/23$, given in Section 2 of this Report. Some experimental confirmation of this relationship is provided by Scala who, on the basis of six tests, derived a relationship $CBR = C_u/27.6$, and by Wiseman, on the basis of 150 tests, who showed that $CBR = C_u/24.5$. 

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Because Figure 1 indicates that the general pattern of changes of CBR with moisture content and density of different softs can be inferred by the suction method, it is concluded on the basis of the relationship CBR = Cu/23, that Cu should also be capable of estimation with useful accuracy. The accuracy is indicated in Figure 3 of this Report.

10.2 Comparison of estimated and measured shear strengths

Measured shear strengths were taken from references 3, 4, 5 and 6. In the cases of references 3 and 4, access was available to the laboratory note books and the original data were used; in a few cases these differ marginally from published data. The correlations between measured and estimated strengths are given in Figures 13–17. In each case strength is plotted against effective moisture content

\[ We = W_m + \left( \frac{Pl + 14.2}{0.838} - LL \right) \]  

where \( We \) = effective moisture content  
\( W_m \) = measured moisture content  
\( LL \) and \( PI \) are the liquid and plastic limits, respectively.

Details of all the soils used in the analysis are given in Table 4 which also includes the moisture-content correction, i.e. the term within the brackets in Equation (11) above.

**TABLE 4**

Plasticity data for softs used in strength correlations

<table>
<thead>
<tr>
<th>Source (Reference No.)</th>
<th>Figure No.</th>
<th>Soil No.</th>
<th>Soil type</th>
<th>LL</th>
<th>PL</th>
<th>Moisture-content correction %</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>13</td>
<td>1</td>
<td>Kaolinite: sand</td>
<td>25:75</td>
<td>26</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>2</td>
<td>Kaolinite: sand</td>
<td>50:50</td>
<td>42</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>3</td>
<td>Kaolinite: sand</td>
<td>75:25</td>
<td>59</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>4</td>
<td>Montmorillonite: sand</td>
<td>25:75</td>
<td>51</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>5</td>
<td>Montmorillonite: sand</td>
<td>50:50</td>
<td>84</td>
<td>27</td>
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<td></td>
<td>6</td>
<td>6</td>
<td>Montmorillonite: sand</td>
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<td>117</td>
<td>39</td>
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<tr>
<td>3</td>
<td>14</td>
<td>7</td>
<td>Kaolinite</td>
<td>82</td>
<td>43</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>8</td>
<td>Montmorillonite</td>
<td>143</td>
<td>52</td>
<td>91</td>
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<tr>
<td>4</td>
<td>15</td>
<td>9</td>
<td>Keuper Marl</td>
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<td>21</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>10</td>
<td>Sandy clay (H'orth brickearth)</td>
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<td>18</td>
<td>13</td>
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<tr>
<td></td>
<td>11</td>
<td>11</td>
<td>Silty clay (H'orth brickearth)</td>
<td>46</td>
<td>20</td>
<td>26</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>12</td>
<td>Gault clay</td>
<td>78</td>
<td>32</td>
<td>46</td>
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<tr>
<td></td>
<td>13</td>
<td>13</td>
<td>London clay (Heathrow)</td>
<td>78</td>
<td>29</td>
<td>49</td>
</tr>
<tr>
<td>5</td>
<td>16</td>
<td>14</td>
<td>Horten clay</td>
<td>30</td>
<td>16</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>15</td>
<td>London clay</td>
<td>73</td>
<td>25</td>
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<td>Gosport clay</td>
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<td>17</td>
<td>17</td>
<td>Shellhaven clay</td>
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<td>32</td>
<td>65</td>
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<tr>
<td>6</td>
<td>17</td>
<td>18</td>
<td>Weald clay</td>
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<td>18</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>19</td>
<td>19</td>
<td>Wiener Tegel V</td>
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<td></td>
<td>20</td>
<td>20</td>
<td>Kaolín</td>
<td>74</td>
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<td>32</td>
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<tr>
<td></td>
<td>21</td>
<td>21</td>
<td>London clay</td>
<td>78</td>
<td>26</td>
<td>52</td>
</tr>
<tr>
<td></td>
<td>22</td>
<td>22</td>
<td>Klein Belt Ton</td>
<td>127</td>
<td>36</td>
<td>91</td>
</tr>
</tbody>
</table>
The correlations are discussed in Figure No. order.

10.2.1 Results from Dumbleton and West (reference 3) in Figure 13. These measurements comprised a careful study of the shear strength of remoulded artificial softs using a miniature vane. A range of plasticities (from 9–90 per cent) were achieved by mixing different proportions of sand and either pure kaolinite or pure montmorillonite in the proportion given in Table 4. In the figure the symbols denote measured strengths and the full lines the estimated strength of soil of the same plasticity index. Over a wide range of plasticities the estimation method broadly indicates soil strength, particularly in the range of practical road subgrade strengths of 20 to 150 kPa.

10.2.2 Results from Dumbleton and West (reference 3) in Figure 14. These further measurements were made on the pure clay minerals kaolinite and montmorillonite. The good correlation between estimated and measured strengths in Figure 13 obviously does not apply here. In particular the relation between moisture content and strength shows a pronounced change of slope at strengths of between 10 and 20 kPa. It was known that the method of sample preparation was not the same at all soil strengths. Weak soils were 'buttered' into the mould and stronger soils were tamped-in; the change of slope of the curves coincides with the change in compaction method. Reference back to Figure 13 shows that the change of slope was also present there but to a lesser degree. Comparison of Soils 3 and 4 in Figure 13 shows that Soil 3 which contained 75 per cent clay, indicated a change of slope whereas Soil 4 with only 25 per cent clay indicated no change of slope. When considered together with the very marked effects shown in Figure 14, the indications are that the change of slope is the result of a changed method of compaction, the degree of the change depending on clay content. It is almost certain that the change is caused by excess pore pressures generated during compaction that easily dissipate in the more open sandy soils but persist for some time in the finer soils. No 'curing' time for the dissipation of excess pore pressure were specified for these tests. As this is a well known mechanism that is allowed for in samples prepared for CBR testing in the British Standard, the connection between reduced strength and excess pore pressure will be assumed in later comments.

This reduced slope at higher strengths of the experimental relationships, seen particularly in Figure 14 and also in later figures in the Appendix, is normally attributed to errors in the estimation method. If an adequate time for the dissipation of excess pore-water pressure were allowed, it is certain that agreement between measured and estimated strengths would improve. This was clearly seen in the CBR/moisture content correlations of Figure 1 where the agreement between estimated and measured slopes was consistently good. Care was taken in all those tests to see that the soils were allowed adequate time for equilibrium pore pressure to be attained. Even if the 24-hour delay allowed for in CBR testing is observed, errors may still occur; it is known that a week may not be long enough to guarantee complete dissipation in some soils compacted in a CBR mould.

10.2.3 Results of Lewis and Ross (reference 4) in Figure 15. These were vane shear tests on real soils. Once again the symbols denote measured strengths and the full lines the estimated strengths at the same plasticity index. Excellent agreement between measured and estimated values is obtained up to a plasticity index of 26 per cent. For plasticity indices of greater than 26 per cent, the effects of excess pore pressures are even more evident than in the measurements from reference 3. There are three reasons for this.

a) The reference 4 measurements were made immediately after compaction with the minimum of delay, whereas in the measurements in reference 3 this was not the case. Although no dissipation time was
specifically laid down in the latter case, there was usually an interval between sample preparation and testing.

b) The test samples in reference 3 were smaller than those in reference 4 permitting faster pore-pressure dissipation.

c) The air contents in the tests given in reference 4 were between 5 and 9 per cent at the lower moisture contents, compared with 2 to 3 per cent in the soils quoted in reference 3.

No corrections to strength to allow for the effects of air voids were made to the results plotted in Figure 15; such a correction would have brought the estimated and measured strengths 40 per cent closer.

10.2.4 Results of Skempton and Northey (reference 5) in Figure 16. These were also vane tests on real soils. No experimental points were given and the published measured relationships are shown as chain-dotted lines. The agreement between measurement and estimation is good for the soils of low plasticity but less so for soils of high plasticity. It is reasonable to suggest that excess pore-water pressure may also have been present in the test samples.

10.2.5 Results for Schofield and Wroth (reference 6) in Figure 17. Here also no experimental points were given. The dotted lines were derived from the critical-state lines obtained by triaxial and shear-box tests on various soils. In the case of soil numbers 18 and 19 (PI values 25 and 52) there is good agreement in the strength range of 10 to 150 kPa. Clearly the agreement is poor in the other cases. It is known that Soils 18 and 19 were remoulded but Soils 20–22 (giving poor agreement) had been remoulded as slurries and normally consolidated before testing. It is likely that the latter soils had not deformed to reach their critical state throughout the sample at the time strength measurements were made.
ABSTRACT

The strength of clay fill subgrades: its prediction in relation to road performance:
W P M BLACK AND N W LISTER: Department of the Environment Department of Transport, TRRL Laboratory Report 889: Crowthorne, 1979 (Transport and Road Research Laboratory). The suction method for estimating the shear strength of soils from plasticity data and moisture content has been examined in the light of a wide range of experimental evidence; it is concluded that the method predicts changes in strength of a wide range of soils satisfactorily.

The method has been used to quantify the likely changes in moisture content and strength under a range of site conditions. Very wet weather during construction on a poorly drained site reduces markedly the ultimate equilibrium strength of subgrades of low plasticity; equilibrium values are less than half the values associated with construction in dry weather. Heavy clays are much less affected.

Deflection studies indicate that the life of a pavement built in very wet weather may be reduced by up to 50 per cent of the life expected of a pavement constructed during average weather conditions.

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