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SUB-SOIL DRAINAGE AND THE STRUCTURAL DESIGN OF ROADS

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ABSTRACT

The purpose of longitudinal drains under roads and their effectiveness in lowering the water table are discussed. The effect of lowering the water table on the strength of road subgrades, and hence on the design thickness of flexible pavements, is examined.

Shallow longitudinal drains are used to drain the road structure and also to remove surface water. Deeper drains in permeable soils can be used to lower the water-table and thus to increase the strength of the sub-grade. However in saturated soils of low permeability, such as heavy clays, deep drains are ineffective in lowering the water-table below formation level and do not significantly increase the strength of the soil.

1. INTRODUCTION

Water has a damaging effect on most of the materials used in road construction particularly where freezing conditions prevail for part of the year as in the United Kingdom. In recent years, examination of several road failures has shown that water was responsible for weakening the roads, and thus that the measures adopted for the protection of roads from water have not proved to be sufficient.[1] Many engineers, learning from such failures, have paid increasing attention to road drainage and there is undoubtedly great scope for improvements in both the design and construction of drainage works.[2]

The purpose of this paper is to draw attention to the effectiveness of drainage in increasing the strength of some subgrade soils and to its ineffectiveness in other soils. The paper should therefore assist the making of decisions needed for the correct use of drainage measures.

2. THE PURPOSE OF LONGITUDINAL ROAD DRAINS

2.1 During construction

The main function of longitudinal drains during construction is to remove surface water and to lower the ground water table to facilitate the use of machinery during the construction of earthworks and of the pavement. To be effective such drains must lower the water table fairly quickly and are therefore most effective with soils of high permeability.

Several methods are available for the estimation of draw down times and considerable research has been carried out into methods of field drainage for agricultural purposes.[3] The results of road drainage studies by McClelland[4] provide a particularly useful guide to road engineers and, as pointed out by Barber and Sawyer,[5] the experimentally determined relations can be summarised in dimensionless ratios as in Fig. 1.

In normal practice drains are required to lower the water table distances of 30 cm to 1 m below the surface in order to obtain an appreciable drying of the soil and facilitate working of constructional traffic. The formula indicates that drains placed at a depth of 1 m and 10 m apart will lower the water table 37 cm in (y/k) days (k the coefficient of permeability is expressed in metres per day, and y is the volume of drainable water per unit volume of soil usually of the order of 0.1).

In permeable soils, which may have interspersed layers of gravel and sands, and where k is of the order of 1 m/d, sufficient drainage will normally take place in less than one day. For the less permeable soils, such as uniform silts and fine sands where k may be between 10^{-2} m/d to 10^{-4} m/d, the time taken for the drainage may be of the order of a few days to several weeks. On very heavy soils, such as clays where the permeability may be as low as 10^{-5} m/d, the drainage may take many months and hence drainage of clays is often impracticable unless the clay is naturally fissured or holed by soil boring animals and worms and therefore has a higher permeability than might be expected from its grain size distribution.[6]

2.2 Completed road

When the road has been completed, the drains near the edges of the carriageways provide means of draining the surface water and any water which may have penetrated through the road surfacing into the road structure. They also serve to prevent the level of the water table rising to the formation level and therefore allow the designer to take advantage of a higher soil strength in assessing the required thickness of the sub-base.

After the road has been constructed and the moisture conditions in the subgrade have stabilized, the level of the water table will depend on the relative permeabilities of the road surfacing and the subgrade soil in addition to the depth and spacing of the drains. Two cases need to be considered :-

(1) Where the permeability of the road surfacing is greater than the permeability of the subgrade,

and (2) where the permeability of the road surfacing is less than the permeability of the subgrade.

2.2.1 Permeability of surfacing greater than permeability of subgrade. This condition may arise when roads are constructed over subgrades of low permeability since, although a good surfacing will have a permeability of less than 10^{-5} m/d, some heavy clay soils also have permeabilities of the same order. The quantity of water passing through the road surface will depend on many factors including the amount and duration of rainfall. However it is easily seen that if water penetrates the road surfacing over a long period at a rate equal to the permeability of the subgrade then the water table will rise and ultimately reach the surface of the subgrade. Similarly, if water penetrates the road surfacing at a faster rate than the permeability of the soil then this water will accumulate in the road structure and the subgrade will be saturated even though subsoil drains may be present. Such considerations show that deep road drainage is not effective in soils of very low permeability and point to the need for better methods of draining the upper layers of road structures founded on impervious subgrades.

2.2.2 Permeability of surfacing less than permeability of subgrade. In circumstances where the road surfacing is less permeable than the soil, the water flow to the drains is mainly in a lateral direction from outside the road. In the case of longitudinal drains which penetrate into underlying soil whose permeability is less than one tenth of the permeability of the top soil, the flow of water through the lower soil strata can be ignored completely.[3] The longitudinal drain will then act as an effective cut-off drain and if the permeability of the surfacing is very much less than the permeability of the top soil then the final level of the water table will tend towards the level of the bottom of the drains.

The data given in Fig. 1 can be used to estimate the levels of the water table for given infiltration rates together with the depth and spacings of drains since the discharge rate q can be taken to equal the rate of infiltration of water through the road surfacing. Further research is needed however, to categorise the various drainage situations which arise on roads and to provide methods for the clear identification of the drainage characteristics of types of subgrade and road structure. For the present time some consideration of the strength increases which can be achieved by lowering the water table will help in the making of correct decisions about drainage and this is dealt with in the following section.

3. DRAINAGE AND STRENGTH OF SOIL

Drainage increases the strength of soil by reducing the soil moisture content. The California Bearing Ratio (C.B.R.) of a soil is a measure of its strength and is used to decide the design thickness of flexible road pavements built over the soil.[7] The C.B.R. value of the soil is normally determined by laboratory test but can be estimated from a knowledge of its suction and plasticity characteristics together with the true angle of friction.[8]

Using the latter approach the relations between C.B.R. value and suction were calculated for saturated soils in the undisturbed state with plasticity indices ranging from 10 to 80. The relations are given in Fig. 2 and show that at low suctions considerable increases in the C.B.R. value occur as the suction increases with all soils but the effect is less marked at higher suctions with the more plastic soils.

The suction of the soil is related to the position of the water table, as explained in the Appendix, and the influence of water table depth on the necessary thicknesses of flexible road pavement can be calculated. Examples of this type of calculation are also given in the Appendix.

Table 1 gives the sub-base requirement for flexible road pavements designed to carry the lightest and heaviest traffic categories in the United Kingdom over undisturbed soils with varying water table levels.

TABLE 1

Thickness of sub-base required (cm) over undisturbed soil

Type of road pavement	Type of subgrade	Plasticity index (per cent)	Thickness of sub-base (cm) water table depth from top of subgrade		
			0	60 cm	120 cm
Design Chart 1 of RN.29 (more than 4,500 commercial vehicles per day 20 years after construction)	Heavy clay	80	44.5	40.5	39.0
		40	39.5	34.0	30.5
	Silty clay	30	38.0	28.0	20.0
	Sandy clay	20	48.0	30.5	19.0
		10	66.0	40.5	18.0
Design Chart 6 of RN.29 (0.45 commercial vehicles per day 20 years after construction)	Heavy clay	80	25.5	23.0	20.0
		40	25.5	20.0	18.0
	Silty clay	30	25.5	18.0	11.5
	Sandy clay	20	28.0	18.0	9.0
		10	46.0	24.0	7.5

The results indicate that the effect of drainage in decreasing the thickness of sub-base material is limited in the case of heavy clays but substantial reductions could result from drainage of silts and sandy clays. In making the calculations it is assumed that the soil is at its natural in situ density and that with the water table near the surface bad drainage conditions preclude the use of compaction plant. With sandy and silty clays the use of drains to lower the water table will result in the soil drying and hence enable compaction plant to be used. The increased density will result in a further increase in C.B.R. value and thus a further reduction in the sub-base thickness required.

The effect of compaction on the moisture content of soil in equilibrium with a water table depends on the soil type and its natural structure. In the case of the majority of British clays which are overconsolidated, the shear and breakdown of the soil structure results in the compacted soil having a greater affinity for water than the undisturbed soil and consequently the compacted clays will increase in moisture content and ultimately be weaker than the natural soil.

With soils containing a small amount of clay sized particles and a greater proportion of silt and sand, the increased strength derived from better intergranular friction is greater than the loss of stability due to the loss of natural structure. Thus for such soils compaction results in lower moisture contents and in increased strength. In the case of sands, the state of compaction is the major factor determining the strength of the soil.

The moisture content of compacted soil in equilibrium with a water table cannot at present be predicted from a knowledge of the soil index properties but some guidance can be given, based on experience, and this has been tabulated in Road Note 29.

Table 2 is based on the information given in Road Note No. 29 and gives the sub-base requirement for flexible road pavements designed to carry the lightest and heaviest traffic categories in the United Kingdom over compacted soils and for two drainage conditions.

TABLE 2

Thickness of sub-base required (cm) over compacted soil

Type of road pavement	Type of subgrade	Plasticity index per cent	(Thickness of sub-base/cm)	
			Poorly drained (water table depth 60 cm)	Well drained (water table depth 60 cm)
Design Chart 1 of RN.29 (more than 4,500 commercial vehicles per day 20 years after construction)	Heavy clay	80	51.5	51.5
		40	51.5	37.0
	Silty clay	30	37.0	19.0
	Sandy clay	20	25.5	15.0
		10	19.0	15.0
Design Chart 6 of RN.29 (0-45 commercial vehicles per day 20 years after construction)	Heavy clay	80	29.0	29.0
		40	29.0	18.0
	Silty clay	30	18.0	7.5
	Sandy clay	20	10.5	7.5
		10	7.5	7.5

The considerable saving due to drainage and compaction of sandy and silty clays can easily be seen from Tables 1 and 2. In the case of lightly trafficked roads the potential saving will be reduced because many silty soils are likely to be frost susceptible and in these cases a minimum sub-base thickness of 25 cm (10 in) is specified.

In the case of concrete roads the effect of improved drainage is more problematical but it should be noted that Road Note No. 29 suggests that on soils other than heavy clays the thickness of construction may be reduced when the water table is lower than 2 ft (60 cm) beneath formation level.

4. DISCUSSION

Sub-soil drains form part of a road drainage system which has several functions ; the most common of which are to remove surface water and permit the drainage of the upper layers of the road structure. Comparatively shallow longitudinal drains which penetrate to depths of less than 0.5 m into the road subgrade can perform these functions provided suitable gradients are provided for the pipe lines.

Deeper drains may be necessary to lower a high water table to a level that results in an appreciable increase in the strength of the subgrade. It has been shown however that deep drains are largely ineffective in both lower the water-table and in increasing the strength in relatively impermeable soils such as highly plastic clays. Drainage can be used effectively in the more permeable soils such as sandy clays and silts to increase the strength and also enable further compaction to be carried out.

In flat areas with high water-tables, difficulties can arise in obtaining suitable gradients for both surface water and sub-soil drainage, due to lack of outlet facilities. Cases undoubtedly occur however where the soil can be drained. without engineering difficulties and these are particularly likely to occur in undulating or side-long ground.

High water-tables often occur during winter months in undulating or side-long ground where a layer of permeable soil overlies impermeable hard pan or clay, and lateral movement of water, i.e. seepage, is the only natural drainage. Such soils may dry sufficiently during the summer months to allow compaction plant to operate but longitudinal drains may be required to prevent the water table rising to the formation level during the winter. Cut-off drains are particularly effective in such circumstances if they penetrate down to the impermeable layer.

Difficulties with construction traffic and earth moving machinery have also been reported as due to seepage of water, often in deposits with interspersed layers of gravel, sand and clay. Deep drains installed on either side of cuttings in such conditions before excavation has started can ensure that work proceeds during the winter and result in the spoil being dry, easily moved and suitable for use in embankments elsewhere.

Where a water table is close to the surface the usual solution adopted is to design for the increased thickness of construction by raising the road on a shallow embankment. The use of the embankment method of construction usually simplifies the drainage of surface water and any water penetrating the road structure.

Areas with high water tables are often subjected to flooding and here again embankments are likely to be of more benefit to the road user than increased drainage.

It is difficult to generalise about costs of drainage and embankment construction because these vary according to locality but it would seem that even where the soil is a sandy clay or silt there is little difference in economic terms between the costs of deep drainage and the cost of extra sub-base thickness if deep drains are not installed. The decision as to whether deep drains should be installed or the road raised must therefore rest with the designer with his detailed knowledge of site conditions and local costs of materials.

Circumstances may arise where the road cannot be raised on embankment and consideration of the benefits of drainage may show that deep longitudinal drains are worthwhile rather than the use of excavation plant and pumps, together with the more expensive and stronger road sub-base material which will have to be used if the water table is not prevented from rising. On existing roads, consideration has sometimes to be given to the possible benefits which may be derived from lowering the water table by improving the drainage. In both cases the approach outlined in this paper may prove useful in deciding whether drainage is likely to be of benefit and hence assist in the making of rational decisions.

5. CONCLUSIONS

Shallow longitudinal drains are adequate to drain the road structure and remove surface water run-off. Deeper drains may be used to lower the water table and in permeable soils with a Plasticity Index of less than 30 per cent, deep drains can be effective in lowering the water table rapidly. Thus they can be of benefit during construction as well as increasing the strength of the subgrade. In most cases however, where roads are to be constructed in areas of high water table the most practical and economic solution is likely to be to raise the road on a shallow embankment.

The major use for deep drains is to cut off seepage water in sloping ground where the soil consists of interspersed permeable and impermeable layers.

Further research is required on the drainage characteristics of subgrades and the layers of the road structure, and on methods for the identification of the various drainage situations which arise on roads.

6. REFERENCES

1. CRAM, I. A. Developments in the materials and techniques of road construction. Public Works and Municipal Services Congress, Nov. 1964.
2. NATIONAL ECONOMIC DEVELOPMENT OFFICE. Efficiency in Road Construction. London 1966 (H. M. Stationery Office).
3. LUTHIN, J. N. Drainage Engineering. 1965 (John Wiley & Sons Inc., New York).
4. McCLELLAND, B. Large scale model studies of highway subdrainage. Proc. H. R. B. Vol. 23, 1943.
5. BARBER, E. S. and C. L. SAWYER. Highway subdrainage. Proc. H. R. B. Vol. 31, 1952.
6. GREEN, R. D. and G. P. ASKEW. Observations on the biological development of macropores in soils of Romney Marsh. J. Soil Sci. No. 16 MAR. 1965.

7. ROAD RESEARCH LABORATORY. A guide to the structural design of flexible and rigid pavement for new roads. Road Note No. 29, 2nd Edition, London, 1965 (H.M. Stationery Office).

8. BLACK, W. P. M. A method of estimating the California Bearing Ratio of cohesive soils from plasticity data. Geotechnique. Dec., 1962.

9. BLACK, W. P. M. D. CRONEY and J. C. JACOBS. Field studies of the movement of soil moisture. Department of Scientific and Industrial Research, Road Research Laboratory Technical Paper No. 41, London, 1958 (H. M. Stationery Office).

10. RUSSAM, K. The distribution of moisture in soils at overseas airfields. Department of Scientific and Industrial Research, Road Research Laboratory Technical Paper No. 58, London, 1962 (H. M. Stationery Office).

7. Appendix

SOIL SUCTION AND THE LEVEL OF THE WATER TABLE

The construction of an impervious pavement prevents moisture changes in the subgrade due to rainfall and evaporation and this results in a fairly stable moisture distribution particularly away from the pavement edge. It has been shown both in the United Kingdom[9] and in tropical countries[10] that the subgrade moisture under the pavement tends toward equilibrium with the ground water table when this close to the surface.

Under these circumstances the pore water pressure, u, at any point in the soil x units above the water table, is less than atmospheric pressure by the hydrostatic pressure exerted by x units of water. If atmospheric pressure is taken as the reference level then the suction of the soil free from stresses due to the overburden and road structure is given by the relation

$$s = \alpha P - u$$

where P is the vertical pressure due to the overburden etc. on the soil "in situ", and α is the fraction of this pressure transmitted to the soil water.

α can be measured in the laboratory where it may be found to vary slightly with moisture content but it is mainly dependent on the plasticity characteristics of the soil and can be estimated as follows :

Plasticity Index < 5 ; $\alpha = 0$

Plasticity Index > 40 ; $\alpha = 1$

$5 \leqslant$ Plasticity Index $\leqslant 40$; $\alpha = 0.027$ P.I. $- 0.12$

Under equilibrium condition therefore the suction at any depth in the soil under a road pavement can be easily calculated from a knowledge of the P plasticity characteristics of the soil, the density of the soil and pavement, and the position of the water table.

EXAMPLES OF THE CALCULATION OF THE EFFECT OF DRAINAGE ON PAVEMENT DESIGN

Example 1.

A road pavement of average bulk density 2.16 g/cm^3 consists of 5 cm thickness of bituminous surfacing, 15 cm thickness of base and 28 cm thickness of sub-base. The subgrade is a silty clay of plasticity index 25 per cent. Estimate the depth to which the water table should be lowered to enable the road to carry up to 250 commercial vehicles per day.

The design requirements for the road are given by Design Chart No. 4 of Road Note 29 and show that the road structure will be adequate if the subgrade has a CBR value of 3.2.

The suction s, at which a silty clay of P.I. 25 has a CBR value of 3.2 is, from Fig. 2, 117 cm of water.

$$\alpha \text{ for the soil} = 0.027 \times 25 - 0.12 = -.55$$

The overburden pressure P is due to the pavement only and

$P = 104\ g/cm^2$, equivalent to 104 cm of water.

Since $s = \alpha P - u$

$117 = -.55 \times 104 - u$

$u = -60$ cm of water

Thus the water table should be lowered to a depth of 60 cm below the top of the subgrade.

Example 2.

Calculate the reduction in sub-base thickness required for a road pavement designed according to the maximum thicknesses given in Design Chart 2 of Road Note 29 if the water table is lowered 60 cm from its present level at the top of the formation. The soil is a silty clay of plasticity index 25 per cent and the bulk density of the pavement can be taken as 2.20 g/cm^3.

The CBR of the subgrade will be less than 30 so in the first instance the sub-base thickness is taken as 15 cm.

The total thickness of pavement is thus 45 cm and

$P_1 = 99\ g/cm^2$, equivalent to 99 cm of water

$\alpha = 0.55$ as before

and $u = 0$

Thus $s_1 = P_1 - u_1 = 0.55 \times 99 = 54$ cm of water

At a suction of 54 cm of water the CBR value of the soil is 1.9 giving a sub-base requirement of 48 cm as the first approximate estimate.

Recalculating, the new overburden pressure P_2, due to 78 cm of pavement is equivalent to 172 cm of water and the new suction $s_2 = 0.55 \times 172 = 95$ cm of water. The revised estimate for the CBR value of the subgrade is 2.7 necessitating 37 cm of sub-base.

A final repeat of the process gives the sub-base requirement as 40 cm when the water table is in the surface of the foundation.

When the water table is lowered to a depth of 60 cm the pore water pressure at the top of the subgrade is - 60 cm of water.

Repeating the successive approximation as above, taking the initial sub-base thickness as 40 cm and P therefore as 154 g/cm^2.

	u (cm water)	P (cm water)	S (cm water)	CBR (per cent)	Sub-base (cm)	New P (cm water)
1st approximation	- 60	85	145	3.9	25	121
2nd approximation	- 60	67	127	3.4	30	132
3rd approximation	- 60	73	133	3.6	27.5	

Thus the effect of the drainage is to reduce the sub-base requirement from 40 cm to 27.5 cm.

If it can be assumed that the soil can be compacted then Road Note 29 indicates that the subgrade strength will be CBR 3.5 when the water table rises close to the surface and CBR 5.5 if the water table is kept at a depth of 60 cm. The corresponding thickness of sub-base are 30 cm and 15 cm indicating that the effect of drainage in reducing the sub-base requirement is similar for both compacted and natural soils of this type.

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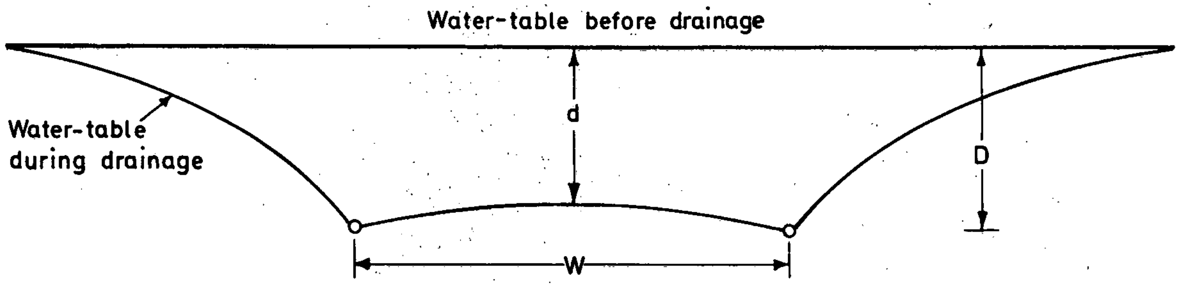

q = discharge per unit length per unit time

t = time since beginning of drainage

k = coefficient of permeability

y = volume of drainable water per unit volume of soil

Dimensionless ratios		
$\frac{tkD}{yW^2}$	$\frac{d}{D}$	$\frac{q}{kD}$
0·001	0·06	0·80
0·01	0·37	0·47
0·1	0·79	0·25

Fig. 1. DIMENSIONLESS RATIOS FOR DRAINAGE BY TWO PARALLEL PIPES

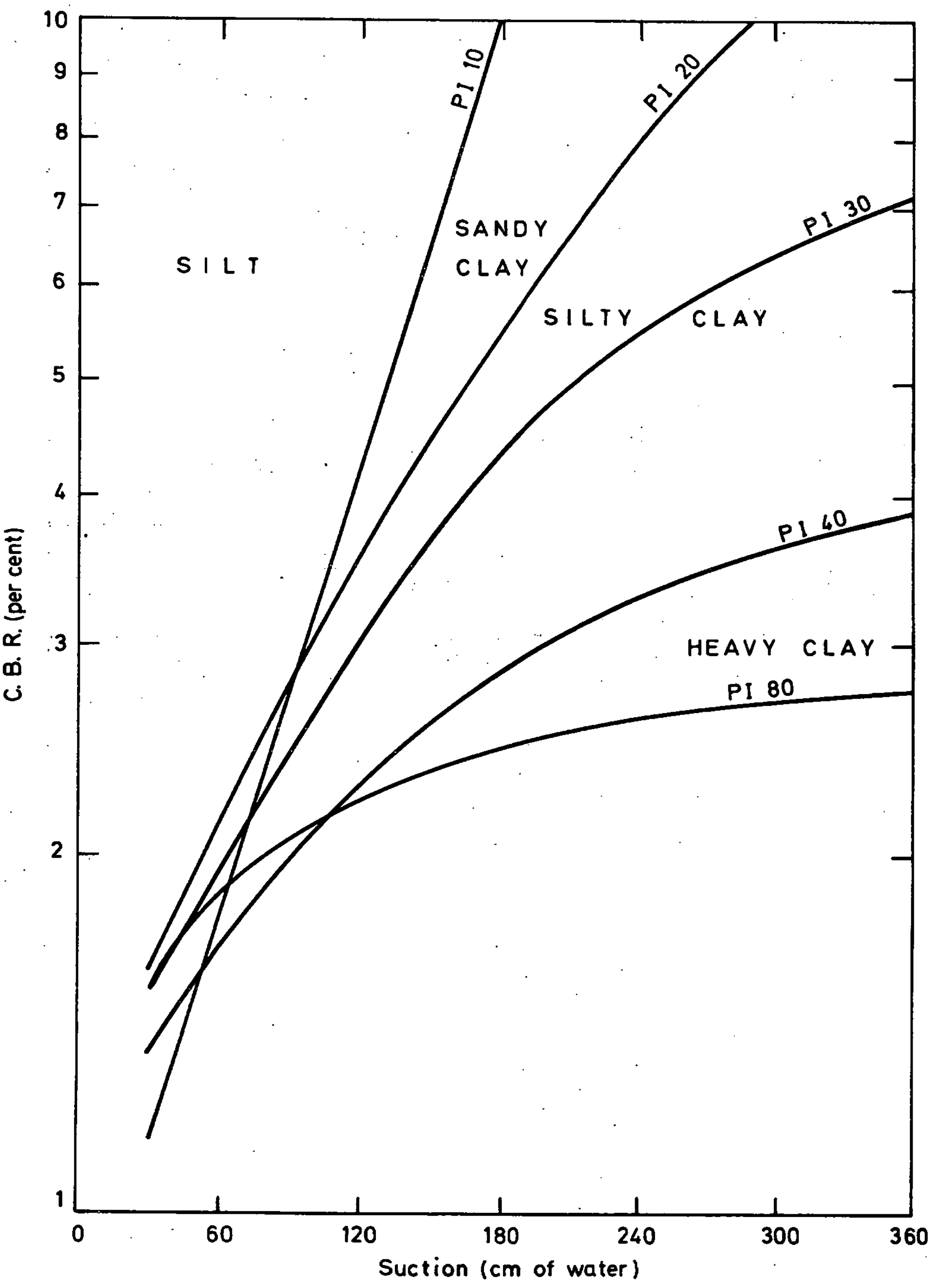

Fig. 2. RELATIONS BETWEEN C. B. R. VALUE AND SUCTION FOR SOILS OF VARIOUS PLASTICITIES