Since the load on the concrete slab is best approximated by the uniform pressures, it follows that for a wheelload of 45 ton the found flexural strength of at least 15 kg/cm$^2$ is not exceeded. For a wheel load of 67.5 ton this is only the case at places with a low modulus of subgrade reaction.

With regard to the strength of the layers above the concrete slab it followed from loading test on the test section that plastic deformation may only be expected at a contact pressure exceeding about 9 kg/cm$^2$.

Therefore it may be concluded from this first series of tests, that the bearing capacity of the combined rigid-flexible runway construction as applied at Schiphol Airport is sufficient for the requirements, without cracks occurring in the concrete slab and plastic deformations in the layers above. Since stresses in the concrete slab and in the layers above reach their safe limiting values almost simultaneously the construction as applied constitutes a well balanced system.

ACKNOWLEDGMENTS.

The authors wish to thank ir. C. van der Veen of the Delft Laboratory of Soil Mechanics for his assistance in evaluating the test results, also ir. C. van der Poel and M. de Kruyf of the Laboratory of the Bataafse Petroleum Maatschappij for their assistance at the tests.

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# SUB-SECTION VIII e

## INVESTIGATIONS ON FAILURES, DRAINAGE AND FROST ACTION

VIII e 5

## THE CAUSES AND CONTROL OF SUBGRADE MOISTURE CHANGES

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SUMMARY.

In this paper consideration is first given to the fundamental factors which control the movement of moisture in soil and on which a satisfactory subgrade drainage technique must be based. Distinction is drawn between movements occurring under the action of gravity and those resulting from suction or vapour pressure differences in the soil. The influence of moisture content, grading and temperature on the suction and vapour pressure characteristics of soil is considered in detail.

On the basis of this discussion an analysis is made of the principal ways in which water can enter and leave the road subgrade, viz:-
1) through a pervious or cracked road surface
2) by seepage from surrounding high ground
3) as a result of suction differences (a) between the subgrade and the verge, and (b) between the subgrade and the soil beneath
4) as a result of water vapour movements associated with temperature gradients in the road foundation.

Existing and proposed methods for controlling the moisture changes which arise from these sources are reviewed.

It is considered that long term records of the moisture distribution, temperature gradients and water table level under an experimental road would be of particular value in correlating laboratory and field data. A new electrical moisture meter designed to record the *in situ* moisture content of soil for use in this connection is described. This incorporates a moisture gauge using concentric electrodes.

## INTRODUCTION

The moisture content of a road subgrade should remain, throughout the life of the road, as near as possible to its value at the time of construction. The tendency of subgrade moisture conditions to vary with the season of the year leads, in the case of clay subgrades, to surface movements; more serious however is the progressive change in moisture content, sometimes called regression, which may take place over a period of years and which results in a gradual deterioration of subgrade strength.

An understanding of the factors which govern the movement of water in soil is necessary before consideration can be given to the question of controlling subgrade moisture. These factors are reviewed in the first part of this paper. The various ways in which water can enter and leave the subgrade are then analysed and methods of moisture control applicable to each case are examined.

## CLASSIFICATION OF SOIL WATER

Soil water can be broadly divided into three catagories, (1) Gravitational water, (2) Ground water and (3) Held water.

Gravitational water, on entering the soil moves freely towards the water table under the action of gravity. Ground water fills completely the voids and fissures in the soil below the water table. Held water is retained in the soil by surface tension and adsorptive forces after the flow of Gravitational water has ceased.

## FACTORS WHICH GOVERN THE MOVEMENT OF SOIL WATER

### Gravitational and Ground Water

Gravitational and ground water can both be removed from the soil by the installation of suitable drains.

The movement of gravitational water depends largely on the structural characteristics of the soil. It may be deflected during its passage to the water table by interposed layers of impermeable soil.

Ground water movements are generally assumed to follow Darcy's law of saturated flow. This states that the velocity of flow of water through a column of saturated soil is proportional to the hydraulic gradient (difference in head per unit length of soil), the constant of proportionality being defined as the coefficient of saturated permeability.

### Held Water

Held water is retained in the soil pores by surface tension forces and on the surface of the particles by forces of adsorption. The amount of water held solely by adsorption is greatest in clays owing to the large surface area per unit mass of soil particles, but its magnitude, even in a heavy clay, is unlikely to exceed a few per cent of the dry weight.

The forces by which the water is held impart to it a state of reduced pressure or suction. This suction is manifested by the curvature of the air-water interfaces in the soil interstices, and by a reduction in the vapour pressure of the soil water.

Relationship between soil suction and moisture content - There is a characteristic relationship between soil moisture suction and soil moisture content, which appears to be continuous from oven dryness to saturation. Over this moisture range the variation in suction is extremely great and it is essential therefore to use a logarithmic suction scale when the moisture content/suction relationship is considered as a whole. In this connection the pF scale introduced by Schofield (1) is frequently used. If the suction is expressed in terms of the height of a suspended water column, the common logartihm of this height, measured in centimetres, is equivalent to the pF of the soil water. Fig. 1 shows experimental curves obtained at the Road Research Laboratory for a number of lightly compacted soils having different clay contents. From these curves it will be seen that the soil suction increases with decreasing moisture content for all the soils, and that for a fixed suction the moisture content of the soils increases with clay content.

In a homogeneous soil held water moves from regions of low suction (high moisture content) to regions of higher suction (lower moisture content). It will be appreciated from Fig. 1, however, that soils of different type in suction equilibrium may have widely different moisture contents.

The rate at which moisture movements due to suction gradients occur depends on the unsaturated permeability of the soil which itself is a function of the soil moisture content 2). In comparatively dry soils (below the plastic limit) the movements are likely to be so slow that equilibrium conditions may only be reached after a period of years.

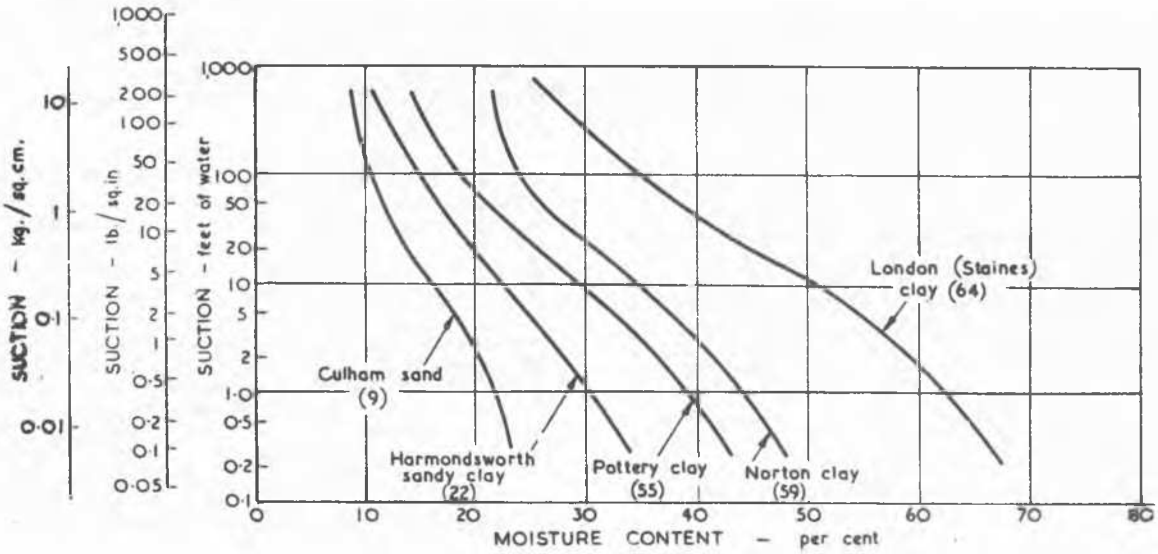
Soil moisture suction in the soil above the water table causes an upward movement of water generally termed capillary rise. If the soil water films can be regarded as continuous above the water table, a linear relationship between suction and height can be assumed once equilibrium conditions are reached i.e. the suction at x centimetres above the water table can be assumed equal to x centimetres of water. The soil moisture content/suction relationship can then be used directly to obtain the moisture distribution above the water table. In Fig. 2(a) a comparison is made between the moisture distribution obtained in this way for a loam soil and the actual distribution determined by boring and sampling. The moisture content/suction curve obtained on undisturbed samples of the soil is shown in Fig. 2(a).

Relationship between soil suction and vapour pressure - The suction of soil water causes its vapour pressure to be lower than that of free water at the same temperature. The driving force causing movements of held water can in fact be regarded either as a difference in soil suction or as a difference in relative humidity in adjacent parts of the soil, soil moisture suction and relative humidity being related thermodynamically by the equation:

$$h = \frac{-R\theta}{Mg} \cdot \log_e \frac{H}{100} \qquad (1)$$

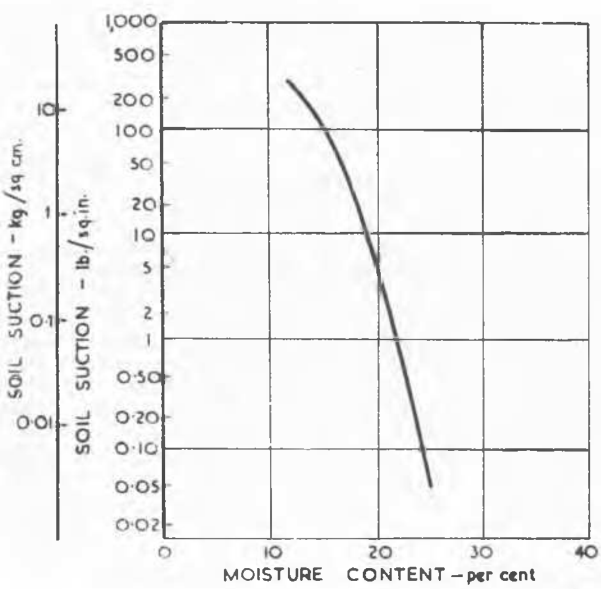
where h is the height of equivalent water column

R, universal gas constant,
θ, absolute temperature,
M, molecular weight of water vapour,
g, gravitational acceleration,
and H, percentage relative humidity



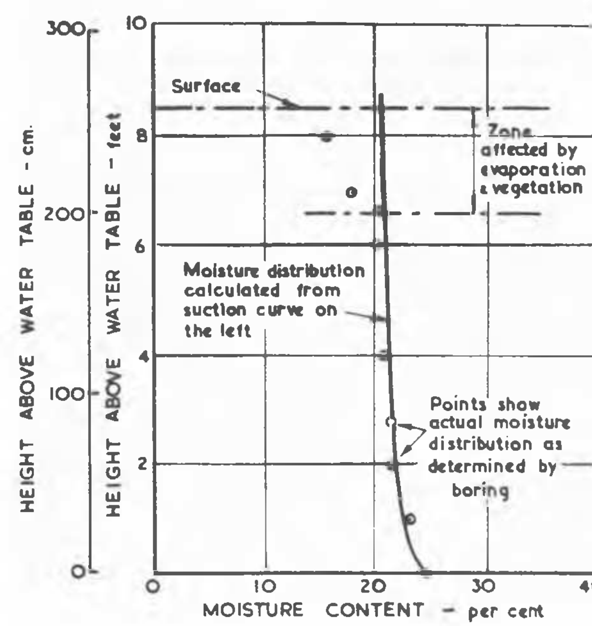

Relationship between soil suction and soil moisture content for five soils. (The clay content of each soil is shown in brackets)

FIG.1




Moisture content/suction relationship for undisturbed Harmondsworth soil.

FIG. 2 a




Comparison between moisture distribution calculated from suction curve on the left, and actual moisture distribution.

FIG.2 b

$$\left\{\frac{\text{Vapour pressure of soil water} \quad X \ 100}{\text{Vapour pressure of saturated water vapour}}\right\} = H$$

at the same temperature

In terms of the pF function equation (1)becomes:

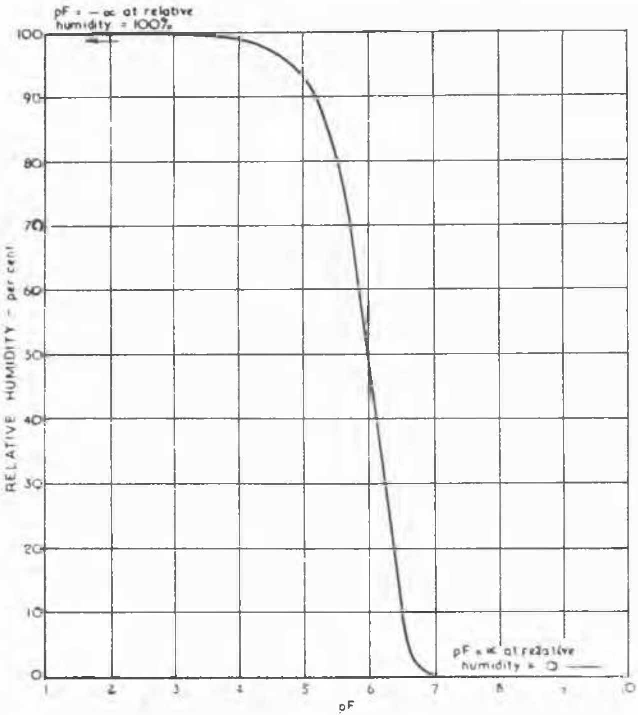
$$pF = \log_{10}\left\{2.303\,\frac{Re}{Mg}\right\} + \log_{10}\left\{2 - \log_{10}H\right\}$$

where R, e, M and g are in C.G.S. units. This relationship is shown plotted in Fig. 3.

Fig. 4 shows the relative humidity/moisture content relationship for a sand and a heavy clay soil. It will be observed that only at low moisture contents is the vapour pressure of soil water greatly different from that of free water at the same temperature.

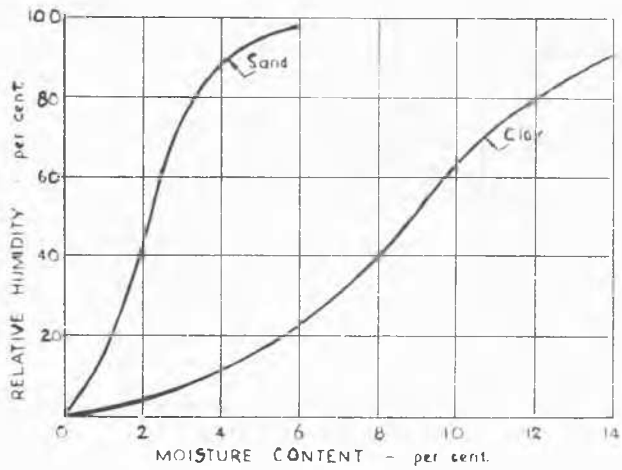
Influence of temperature gradients on the movement of held water - Within the temperature range of interest to the soils engineer the factor $\frac{Re}{Mg}$ increases slightly with temperature, whilst the relative humidity factor $- \log_e H/100$ (equation 1) decreases slightly. The value of the soil suction is as a consequence little affected by temperature changes. The theoretical effect of temperature on the pF of soil water is shown in Fig. 5.

If the relative humidity of soil water vapour is assumed not to vary with temperature and its value is known at a given soil moisture content, the vapour pressure/temperature relationship at that moisture content can be deduced from the vapour pressure/temperature relationship for free water. Further, from the relative humidity/moisture content relationship, a family of curves can be drawn showing the variation of vapour pressure with temperature at a number of different moisture contents. The curves shown in Fig. 6 have been




Relationship between $p^F$ and relative humidity of soil at 20°C.

FIG. 3



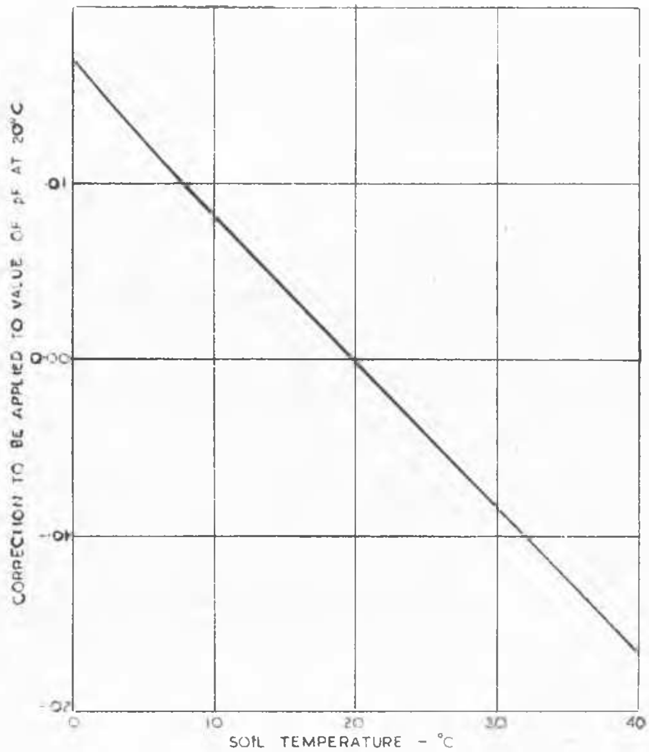

Relative humidity/moisture content curves for a sand and a clay.

FIG. 4

constructed in this manner from the relative humidity/moisture content curve shown in Fig.4.

Whilst the existence of a temperature gradient in a soil of uniform moisture content does not create an appreciable suction gradient, the vapour equilibrium in the soil is disturbed. Moisture transferred in the vapour phase to restore the vapour equilibrium, evaporates from regions of high temperature (high vapour pressure) to regions of lower temperature (lower vapour pressure), the movement being accompanied by a latent heat exchange tending to reduce the temperature gradient.

If free movement of the vapour in the soil is prevented or partly prevented, for example by the soil pores being occupied by wa-




Correction to be applied to $p^F$ of soil at 20°C. to obtain $p^F$ at other temperatures.

FIG. 5

ter in the liquid phase no transfer, or a limited transfer only, of moisture is possible. Fig. 7 gives some results obtained in the course of a research into vapour movements carried out at the Road Research Laboratory. Compacted cylindrical samples of a clay soil having the same density and a range of initial moisture contents were subjected to the same temperature gradient. The curves show the distribution of moisture after approximately three days when the rate of movement had become very small. The specimens were sealed to prevent evaporation. The research showed that in cohesive soils moisture movements resulting from temperature gradients were negligible when the moisture content was above the plastic limit.

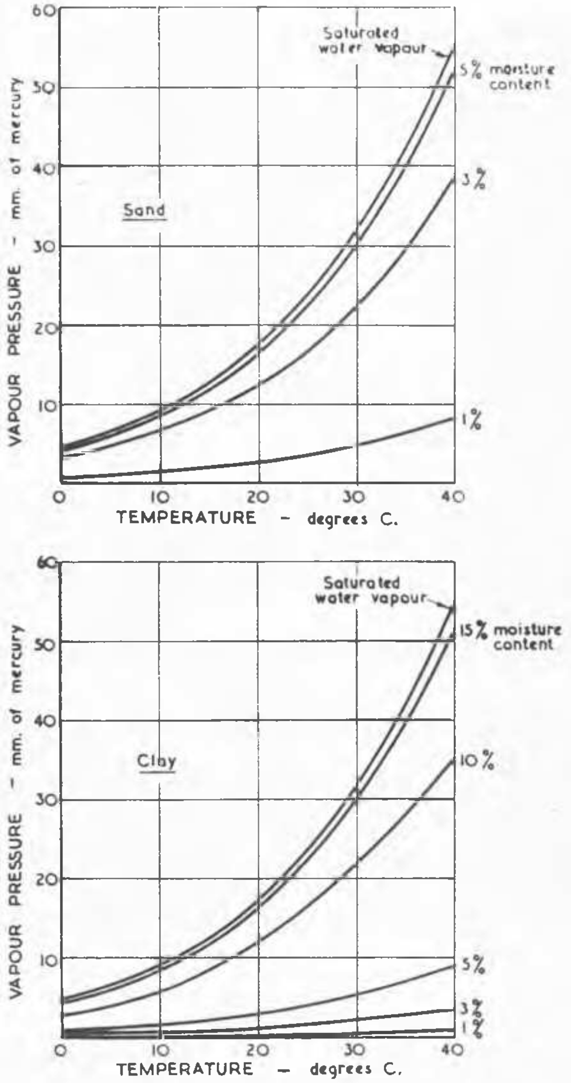
## WAYS IN WHICH WATER MAY ENTER AND LEAVE ROAD SUBGRADES

The various ways in which moisture can enter or leave the road subgrade are shown in Fig. 8. They may be tabulated as follows:

1) Through a pervious or cracked road surface
2) By seepage from surrounding high ground
3) As a result of suction differences (a) between the subgrade and the verge and (b) between the subgrade and the soil beneath in moisture equilibrium with the water table.
4) As a result of water vapour movements associated with temperature gradients in the road foundation.

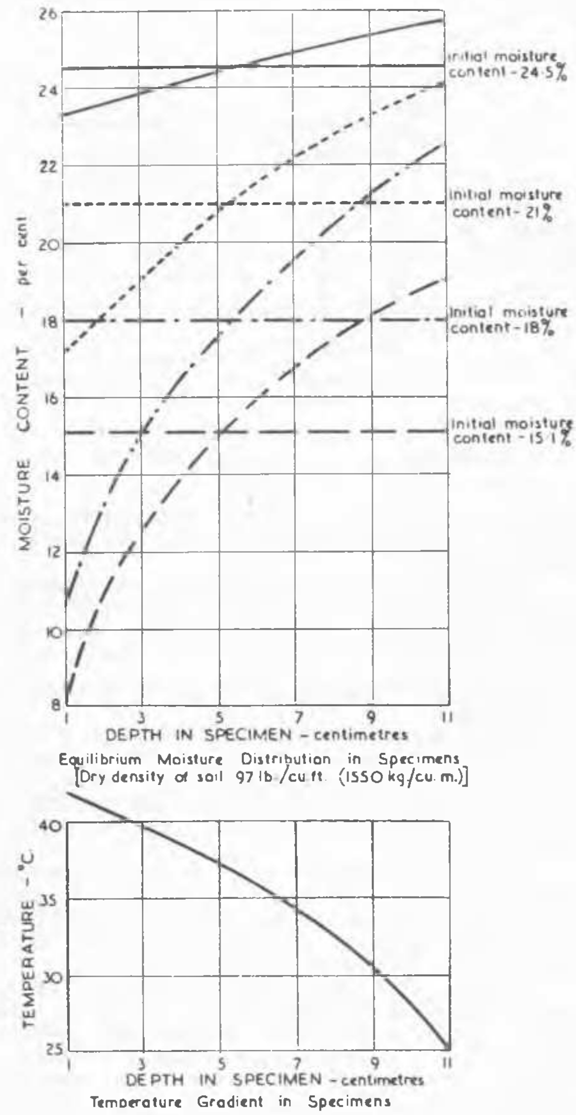
## CONTROL OF SUBGRADE MOISTURE

Drainage methods are usually employed to intercept or control the flow of gravitational and ground water. The water held in the soil by surface forces cannot however be removed directly by drains, although the latter may influence indirectly the amount of held water in the soil, e.g. by water table lowering. Since vapour movements, resulting from temperature



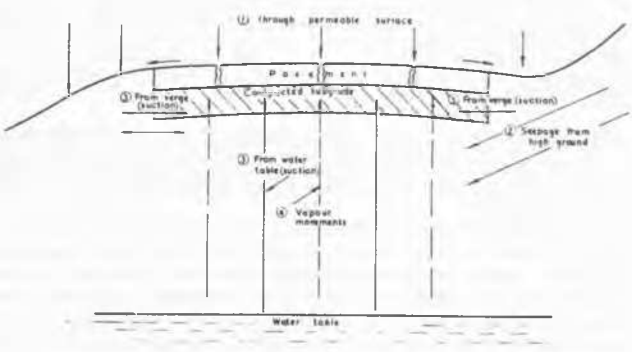

Vapour pressure/temperature curves deduced from the humidity/moisture content curves shown in fig 4.

FIG. 6



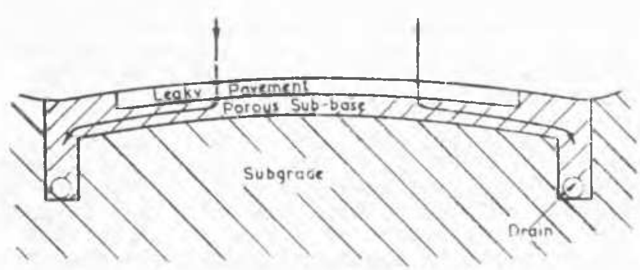

Equilibrium moisture distribution in cylindrical clay specimens of different initial moisture contents, when subjected to the same temparature gradient.

FIG. 7



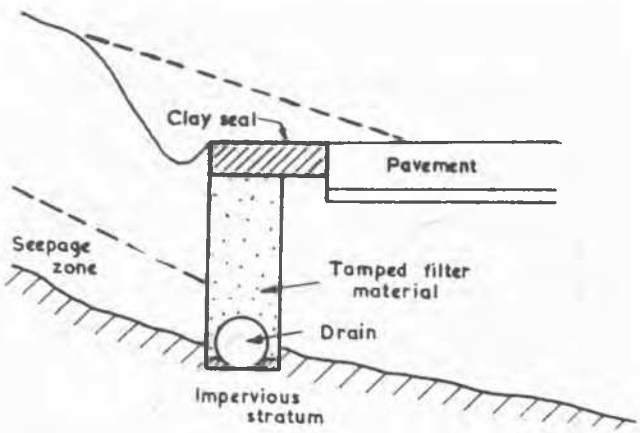

Ways in which water can enter and leave road subgrades.

FIG. 8




Use of porous sub-base to prevent subgrade regression due to pavement leakage.

FIG. 9




Interception of shallow seepage zone.

FIG.10

gradients, may occur from a considerable depth ordinary drainage methods cannot be used in their control.

The ways in which moisture may enter or leave the subgrade have been enumerated above. These will now be considered in greater detail and possible methods of control discussed.

1) Ingress through a pervious or cracked road surface

The ingress of moisture through a pervious road surface can cause serious foundation failures, by decreasing the subgrade strength. In concrete roads, for instance, inadequate sealing of cracks and joints may lead to mud-pumping.

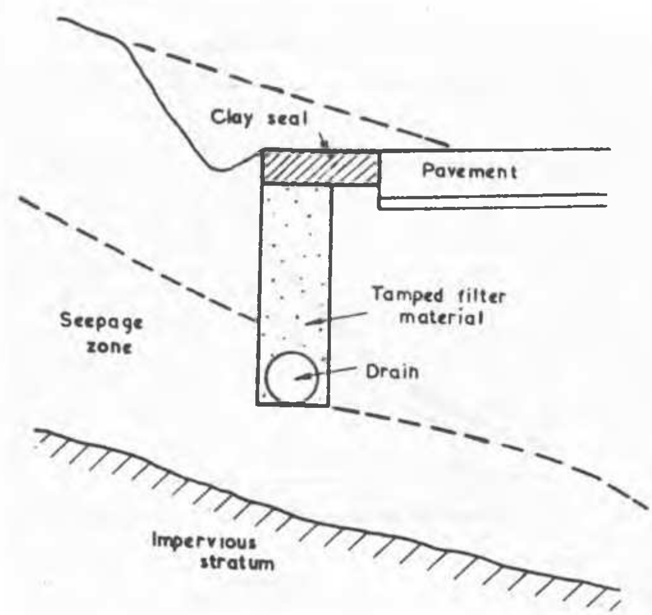
Since in practice a completely impermeable road surface is difficult to maintain, methods of dealing with water entering the subgrade in this manner must be considered. Three of these methods are discussed below:

Porous sub-base - In the case of relatively impermeable subgrades, e.g. clay, the installation of a porous sub-base has been used as a means of controlling surface-leakage. The sub-base consist of 6-12 inches of compacted porous material (sand, gravel, cinders etc.) laid on a cambered subgrade, and connected to drainage trenches in the verges, Fig. 9. In some cases transverse drain trenches have also been used.

Unless careful attention is given to the shaping and cambering of the subgrade most of the water which passes into the porous sub-base is trapped in irregularities in the surface of the subgrade, and consequently does not enter the drain. It would appear therefore that the main value of the porous sub-base lies in the increased stability which it may give to the road construction.

Stabilized sub-base - Stabilization of the top 6-9 inches of the subgrade with cement prevents loss of subgrade stability due to the ingress of water. Where the soil type is suitable, stabilization of a similar depth with water repellant agents minimises the absorption of water through surface cracks. Either method of stabilization should therefore provide a safeguard against subgrade deterioration arising from the entry of surface water.

Bituminized Strips - The use of waterproof strips of bituminous hessian under the joints in concrete roads has been suggested as a method of sealing the joints. To be effective the material would have to be in close contact with the underside of the concrete, and it is possible that slab movements would cause fracture of the strips.




Partial interception of deep seepage zone.

FIG.11

2) Seepage flow from surrounding high ground

Seepage flow is liable to occur in undulating country where impermeable strata are present in the subsoil. The water drains through the pervious surface soil and is deflected on reaching an impermeable stratum. To prevent seepage flow which would otherwise enter the subgrade of a road, intercepting drains are used.

If the seepage zone is near the surface, the intercepting drain should be located just in the impermeable stratum underlying the seepage zone, Fig. 10. This method traps completely all the seepage water.

In the case of a deep seepage zone it may be impracticable to intercept all the seepage flow. In this circumstance the depth chosen for the drains should be such as to prevent regression in the subgrade due to capillarity, Fig. 11.

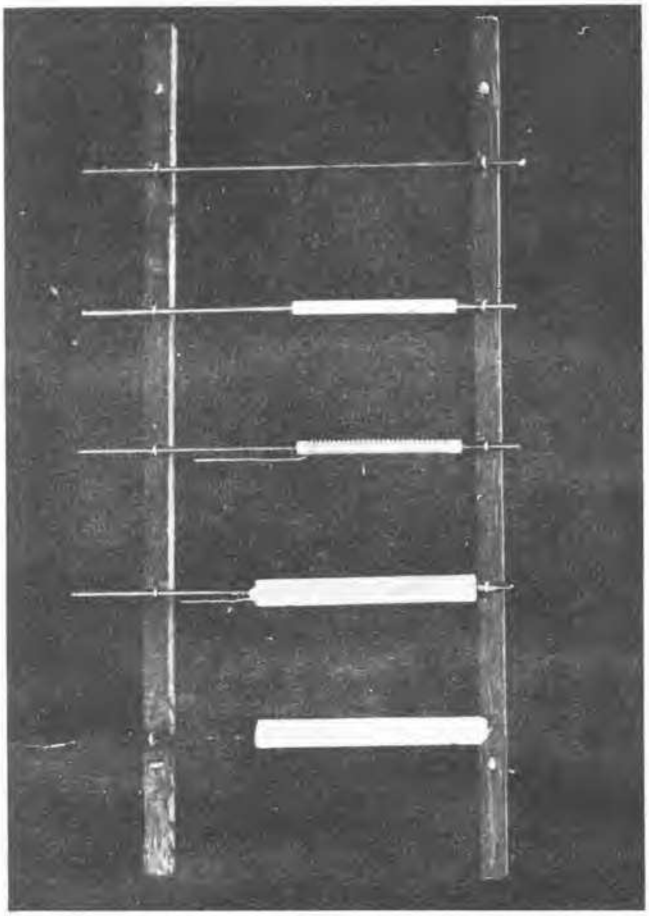
Where the gradient of the road is steeper than that of the surrounding high ground it may be necessary to install transverse intercepting drains.

It is important with intercepting drains to use correctly graded backfill in the drain trench, particularly when the subgrade contains an appreciable amount of silt (particle size 0.02 to 0.002 mm).

3) Unsaturated flow resulting from differences in soil suction between (a) the subgrade and the soil beneath, and (b) the subgrade and the verge

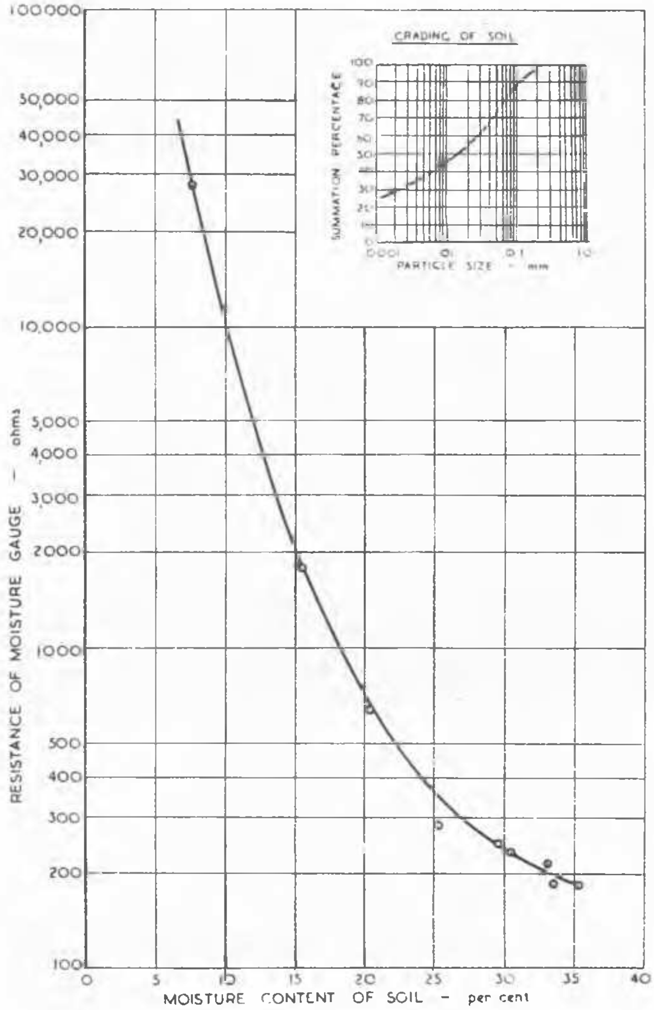
Where road subgrades are compacted under controlled moisture conditions the moisture content may be lower than that of the soil beneath or of the soil in the verges. Consequently, for the reasons discussed previously, there may be a slow transfer of moisture both from below and from the verges as a result of soil suction differences.

Unsaturated flow from the soil beneath the compacted subgrade - Where the soil beneath the compacted subgrade is in suction equilibrium with a water table, any change in the height of the water table will upset this equilibrium and will tend to change the soil moisture content under the compacted subgrade. The equilibrium moisture content beneath the



Stages in the manufacture of the latest type of gauge.

FIG.12




Moisture content - resistance characteristic of moisture gauge.

FIG.13

compacted subgrade can be estimated if the level of the water table is known, using the method described in the first part of this paper. Further, the changes in equilibrium moisture content associated with a rising and falling water table can be deduced.

Where conditions are such that the soil under a compacted subgrade will be excessively wet as a result of a high water table, a drainage system is installed to lower the water table. Further field experiments are necesary before a reliable method for determining the depth and spacing of drains to produce a given degree of water table lowering under the road can be established. However, drains laid in the verges at a depth of about 4 feet are generally considered adequate. The backfill in the drain trench should consist of graded filter material.

The use of a thin horizontal stratum of gravel beneath the compacted subgrade is sometimes recommended as a method of intercepting capillary moisture in fine-grained soils. Research into soil moisture suction indicates that the interposition of such a layer is unlikely to affect the equilibrium moisture distribution in the subgrade although it may delay upward moisture movements.

Moisture from the water table can be more effectively intercepted by the use of a horizontal impermeable membrane located beneath the compacted subgrade. Bituminized hessian has been used for this purpose.

Unsaturated flow from the verge - As a result of heavy rainfall or prolonged drought the moisture content in the verge may be greater or less than that of the soil at the same level under the road. The resulting suction differences may cause slow subgrade regression, and differential volume changes in the case of clay subgrades. In this connection it may be mentioned that the proloned drought during the summer and autumn of 1947 caused severe cracking on a number of British roads on clay subgrades.

Moisture changes in the subgrade can be delayed and possibly eliminated by providing an impermeable surface for the verge.

Horizontal suction movements from the verge into the subgrade can be dealt with in a similar manner to the vertical movements from the regression arising from water table suction movements.

4) Unsaturated flow resulting from vapour movements associated with temperature gradients

Since in Great Britain it is usually impracticable, as a result of climatic conditions, to maintain cohesive soils at moisture contents lower than the plastic limit, seasonal moisture fluctuations due to vapour movements are not in general likely to be of great importance. In the winter months however there is a downward increase in temperature of approximately 0.5°C. per foot over a depth of several feet; this may be sufficient to cause the moisture content of any dry cohesive soil used in summer road construction to increase to the plastic limit during the ensuing winter.

The use of completely impermeable blanket layers similar to those discussed in the previous section will prevent vapour movements. Such layers have been used in hot dry climates where road and aerodrome failures attributed to vapour movements have occurred.

FURTHER RESEARCH RELATING TO SOIL MOISTURE MOVEMENTS UNDER ROADS

Further research is necessary in connection with a number of aspects of soil moisture before the problem of subgrade regression can be fully understood. A long term study of moisture and temperature changes under experimental roads is considered of particular importance. Such a study necessitates the use of a continuous method for measuring soil moisture contents at various depths. An electrical moisture meter is at present being designed at the Road Research Laboratory for this purpose.

The resistance between the electrodes of a small moisture gauge is measured by an alternating current bridge when the gauge is in moisture equilibrium with the soil under investigation. The moisture gauge itself, stages in the construction of which are shown in Fig. 12, consists of a small cylindrical rod of plaster of paris (7 mm in diameter and 5 cm long) containing concentric electrodes.

This type of gauge is found to be sensitive over a wide range of moisture contents. Fig. 13 shows the calibration curve in a silty clay soil at 20°C. At low moisture contents temperature has an effect on the calibration and corrections for temperature must be applied.

To minimise the work involved in calibration, the gauges are moulded to accurate dimensions.

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## VIIIe6 A STUDY OF SUBGRADE CONDITIONS ON A RAILROAD IN THE WESTERN UNITED STATES

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SUMMARY

This paper described various subgrade conditions which were observed during a field investigation of railroad roadbeds. The subgrade soils are classified and drainage facilities are described. A tentative explanation of the mechanics of soft spot formation is presented.

INTRODUCTION

For some time the major railroads of the United States have been interested in the origin, nature, and correction of subgrade instability. This problem became particularly acute during the war years when the railroads were operating at capacity and were forced to perform roadbed maintenance with a minimum amount of labor. Unstable roadbeds resulted in the loss of thousands of dollars by necessitating "slow orders", abnormal resurfacing operations and extra maintenance. Various railroads attempted to find cures for their instability problems. One of the most promising of these was pressure cement grouting. However, little work was done to establish the actual cause of the loss of subgrade support.

Qualitative observations have established that free water, medium to highly plastic subgrade soils, and heavy traffic all contribute to the development of "soft spots". In this respect the problem is similar to the "pumping" problem on concrete pavements encountered by our state highway departments. The question as to whether unstable track is primarily the result of poor subgrade drainage has long been a subject for discussion. In few cases have investigators been able to determine any benefits from subgrade drainage lasting more than a year or two. Furthermore, the relative importance of surface and subgrade drainage has never been satisfactorily established.
Neither has sufficient information been collected to determine the amount or thickness of plastic clay required to start the development of soft spots.

To study these problems the Association of American Railroads and the Engineering Experiment Station of the University of Illinois entered into a cooperative agreement for investigation being carried on under the direction of Mr. G.M. Magee, Research Engineer of the A.A.R. and Dr. R.B. Peck, Research Professor of Soil Mechanics of the University.

During the summer of 1946 it was observed that a portion of the Denver & Rio Grande Western Railroad about 40 miles south of Denver, Colorado lay in an area which was especially suited to the type of investigation which was desirable. Within a distance of several hundred