The Effect of Environment on the Pore Water Tension under Sealed Surfaces

Effet du milieu sur la tension de l'eau interstitielle sous des surfaces scellées

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SUMMARY

This paper considers the factors controlling the pore water tension in soils under sealed surfaces such as roads and buildings with particular reference to tropical conditions. For water-table depths down to 3 ft in sands and 20 ft in clays the pore water tension in road subgrades follows a normal hydrostatic gradient from the level of the water table. With deeper water tables, the pore water tension is affected by water made directly available as surface runoff at the edge of the covered area and evapotranspiration from vegetation. The paper considers the effects of climate, vegetation, and ground slope interacting with the soil permeability to influence the pore water tension in road subgrades in the tropics. Supporting data are given from measurements made in East and West Africa. Finally, the estimation of critical moisture conditions for design purposes is discussed and recommendations made.

SOMMAIRE

Cette étude considère les facteurs qui gouvernent la tension de l'eau interstitielle sous des surfaces scellées telles que routes et bâtiments. En particulier à propos des conditions tropicales. Quand la profondeur de la nappe phréatique ne dépasse pas 3 pieds dans les sables et 20 pieds dans les argiles, la tension de l'eau interstitielle dans le sous-sol d'une chaussée suit une pente normale hydrostatique normale à partir du niveau de la nappe. Quand la nappe est plus profonde, la tension de l'eau interstitielle est influencée par l'eau qui provient directement du ruissellement de surface à la limite de l'aire couverte et de l'évapo-transpiration de la végétation. L'étude considère l'action réciproque entre le climat, la végétation et la pente du terrain d'une part et la permeabilité du sol de l'autre et son influence sur la tension de l'eau interstitielle dans des sous-sols dans les régions tropicales. On présente des données corroborantes tirées des mesures faites dans l'Afrique de l'est et de l'ouest. Enfin, on discute, par rapport au calcul des chaussées, l'évaluation de l'état critique d'humidité et on fait des recommandations.

THE INFLUENCE OF ENVIRONMENT and soil properties on the pore water tension in road subgrades has received considerable attention at the Road Research Laboratory and other research centres during the last 20 years (Winterkorn, 1958). Initially, the work at the Laboratory was concerned with the influence of the water table in the climate of Great Britain. In drier climates, water tables are too deep to exert the dominant influence on the subgrade moisture and the research has been extended to include these conditions. This paper considers the effects of climate, vegetation, and ground slope, interacting with the soil permeability, to influence the pore water tension in road subgrades in tropical countries.

MOVEMENT OF MOISTURE IN SOIL

Movement of moisture in soil can take place in both the liquid and vapour phases, the moisture migration being caused by a gradient in the potential energy of the soil water. In the absence of high salt contents, which result in osmotic effects, the potential energy of the soil water is usually measured by the stress in the soil water, u, termed the pore water pressure or pore water tension depending on whether it is greater or less than the pore air pressure* (Schofield, 1935).

In road subgrades, longitudinal flow of moisture is largely confined to cases where the road is on a slope and free water enters a pervious pavement and moves longitudinally under the action of gravity. Otherwise, moisture movement is predominantly in a vertical plane transverse to the direction of the road, and results from a combination of both vertical and horizontal movements. The rate of movement of moisture $\partial\theta/\partial t$ is then given by the equation:

$$\frac{\partial \theta}{\partial t} = \frac{\partial k}{\partial z} - \left\{\frac{\partial}{\partial x} + \frac{\partial}{\partial z}\right\} \left\{k\left(\frac{\partial u}{\partial x} + \frac{\partial u}{\partial z}\right)\right\} \tag{1}$$

where k is the permeability of the soil and x is measured in the horizontal direction and z in the vertical direction.

Experimental data suggest that k is itself a function of the pore water tension (u), approximating to the form $k = a/u^n + b$. Factors a and b are constants for a given soil, and their ratio is numerically equal to the saturated permeability. The quantity n reflects the porosity of the soil varying from 1 for clays to 4 for loosely packed sands (Gardner, 1958).

ULTIMATE MOISTURE CONDITION BENEATH SEALED SURFACES

When a soil formation is covered by some form of road construction, movements of moisture then take place in the subgrade depending, in magnitude and direction, on whether the soil is wet or dry at the time of construction. A knowledge of the permeability of soil enables the moisture movement to be estimated for fixed boundary conditions from available solutions of Eq 1 (Gardner and Mayhugh, 1958). For example, with typical soils from Kenya initially at pF 4 it was estimated from measurements of permeability that a

*When the pore water tension is measured in a sample of soil free from external stress it is often termed the soil suction. The pF scale is a convenient form of measurement of the pore water tension and is defined as pF = $\log_{10}u$, where u is the tension expressed in centimetres of water.

wetting front could move approximately 3 in. during a period of a month into a heavy clay, about 3 ft into a friable red clay, and up to 9 ft in sands and loose pumice. Movement of a drying front was estimated to be somewhat slower.

The moisture movements result in the formation of a wet or dry zone in the road subgrade which has been found from experiment to be relatively independent of seasonal fluctuations. In wet weather the gradient in the pore water tension between the verge and subgrade is small when the permeability of the wet verge is high and, conversely, in dry weather the low permeability of the verge inhibits drying of the subgrade. Observations of moisture conditions under roads in Kenya have confirmed the existence of such relatively stable conditions (Williams and O'Reilly, 1963). In these circumstances the subgrade can be considered to have reached an ultimate moisture condition, since over an annual period the net change in subgrade moisture would be small. In Eq 1, therefore, $\partial\theta/\partial t$ can be considered zero.

VARIATION OF PORE WATER TENSION WITH DEPTH

Under conditions where the moisture movement is solely in the vertical direction, Eq 1, with $\partial\theta/\partial t = 0$, is integrated to give the ultimate distribution of pore water tension with depth. The distribution is of the form

$$z = \int_0^{u_z} \frac{du}{1 + q/k} \tag{2}$$

where q is the moisture flux.

If, after making due allowance for the difference in level, the pore water tension in soil decreases with depth, then the moisture flux is positive and evaporation is taking place from the soil. Conversely, if the adjusted pore water tension increases with depth then the moisture flux is positive and moisture is entering the soil from the surface.

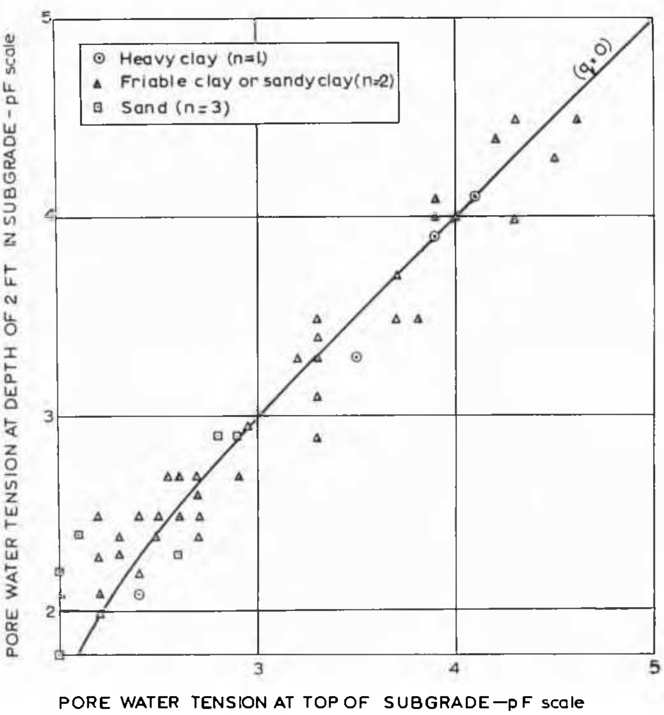

FIG. 1. Comparison of the pore water tension in soil at two different levels under the central part of bituminous-surfaced roads.

This form of analysis has been used to determine the inflow or outflow of moisture from the centre of roads away from edge effects. Samples of subgrade soil were taken from two levels beneath a number of roads in East Africa and Nigeria and the pore water tension was determined using null point methods. The road pavements varied between 4 and 18 in. in thickness and the base materials were mainly lateritic gravel or stone. All the roads had had a bituminous surfacing for at least 5 years.

The results (Fig. 1) show that there was approximately the same number of cases where the subgrade was wetting through the surfacing as where drying was occurring. Some of the sites with the lower values of pore water tension are thought to have been affected by fluctuating water tables but the readings from the other sites indicate that the net moisture flow was small. The bituminous surfacings on the roads were thin and in many cases a visual inspection suggested that they were not in good condition. It is reasonable to assume that on roads with bituminous surfacings of a thickness of 1 in. or more which are kept in good condition, the vertical moisture flux will be still further reduced to negligible proportions. In such circumstances Eq 2 reduces to

$$z = u + \text{constant}. \tag{3}$$

HORIZONTAL VARIATION OF PORE WATER TENSION

The moisture conditions in the soil under the verge at the side of a road is considerably influenced by the climatic conditions. The extremes in moisture conditions are: (*a*) following considerable rain, when drainage of water is taking place through the soil; (*b*) following a long period of dry weather, when the soil water tends to equilibrium with the atmospheric humidity. In the first case the pore water tension is close to zero and in the second is of the order of 2,000 lb/sq.in. Such extremes occur in tropical countries with pronounced wet and dry seasons.

The pore water tension in the soil beneath the central part of the pavement lies between the extreme conditions which occur in the verges during the year. Horizontal movement of moisture occurs to change the pore water tension under the centre of the pavement so that the amount of water leaving the subgrade during dry weather tends to be balanced by water entering the subgrade following rain. The pore water tension, u_0, which satisfies this requirement is given by

$$\sum_{\text{wet condition}}^{u_0} k \cdot du \cdot dt = \sum_{u_0}^{\text{dry condition}} k \cdot du \cdot dt. \tag{4}$$

The extent to which the horizontal flux changes the subgrade moisture condition is thus dependent on the interaction between the changing verge regime and the permeability characteristics of the soil. In any given environment, the change of permeability over the range of verge conditions will influence the trend to an ultimate moisture tension in the subgrade. Sands, which undergo a large change in permeability with moisture tension, will wet to lower pore water tensions than clays whose permeability is not so highly dependent on the moisture condition.

EFFECT OF VERGE SLOPE AND TREATMENT

Vegetation is known to have a considerable influence on soil moisture (Institution of Civil Engineers, 1948), and the effect of verge slope and treatment is being studied in a road experiment at Muguga, Kenya. The experiment is being carried out by the Road Research Laboratory in co-operation

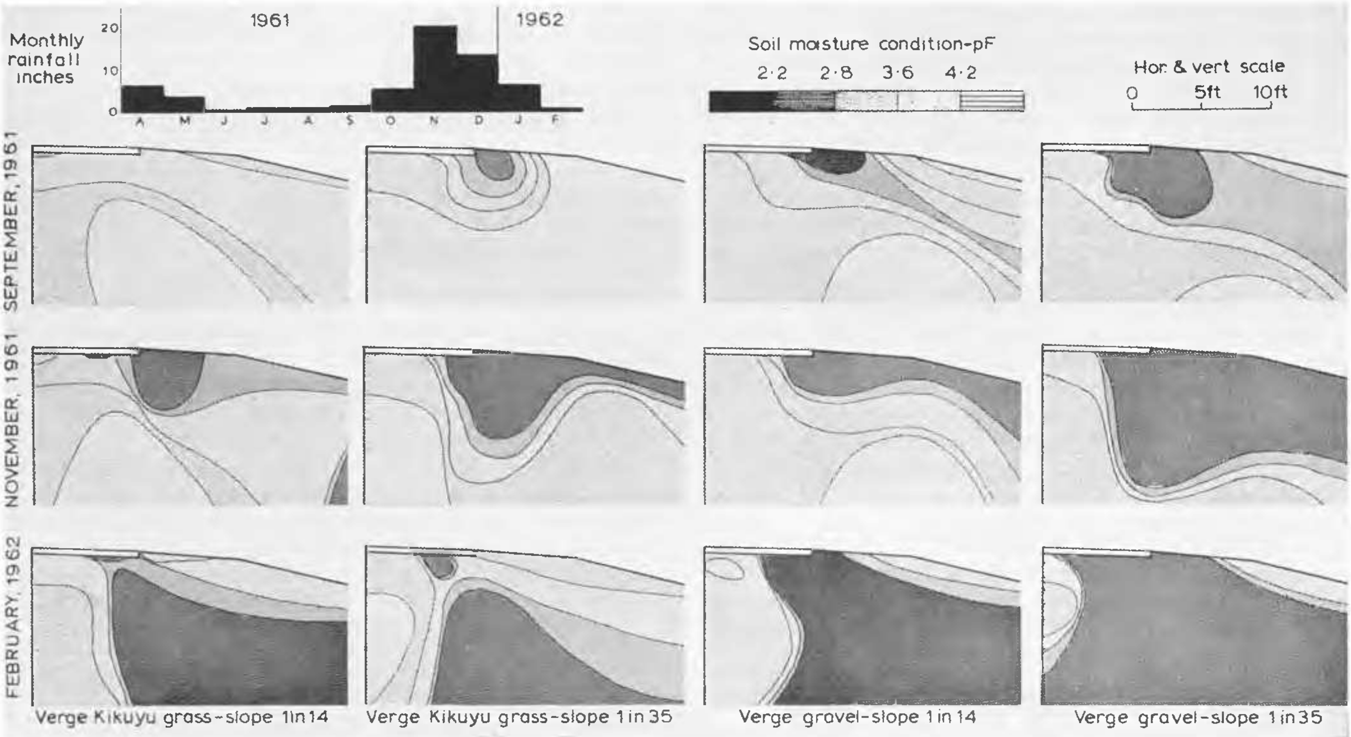

FIG. 2. Effect of verge treatment on moisture conditions at the edge of a road pavement, Muguga, Kenya.

with the East African Agricultural and Forestry Research Organization and the Ministry of Works, Kenya.

The road, 90 yards long, has been constructed with a 16-ft-wide, lime-stabilized gravel base and double surface dressing. The verge slopes are 1 in 35 and 1 in 14, the verge treatments being as follows: (*a*) deep-rooted Kikuyu grass (*Pennisetum clandestinum*); (*b*) a 2-in.-thick layer of gravel, unsealed; (*c*) a polythene membrane laid across the verge at the level of the road base.

Readings of grids of electrical moisture gauges and tensiometers installed under each section of road and verge to a depth of 10 ft commenced in April, 1961. The results to date, of which typical examples are given in Fig. 2, show that on the red friable clay at Muguga (permeability up to 5 by 10^{-2} cm/sec) the use of a steeper slope on the verge resulted in a considerable decrease in the rate of entry of water into the subgrade.

When the natural Kikuyu grass was replaced by gravel the infiltration of water was increased and during the dry weather the gravel effectively reduced loss of moisture by evaporation. The gravel treatment thus resulted in much wetter verge conditions than when grass was present and this should result ultimately in the subgrade also tending to be wetter adjacent to the gravel verge. Treatment with the polythene membrane indicated that the membrane tended to act as an extension of the road pavement.

A further example of verge condition affecting the subgrade was observed on the Nairobi-Mombasa road where a pervious stone shoulder was retaining rainfall and runoff from the road pavement. The soil was a heavy black clay with permeability of the order of 10^{-10} cm/sec. The measured pore water tension across the top of the subgrade (Fig. 3) was lower near the verge than under a nearby road on a similar soil type where there was no permeable stone shoulder.

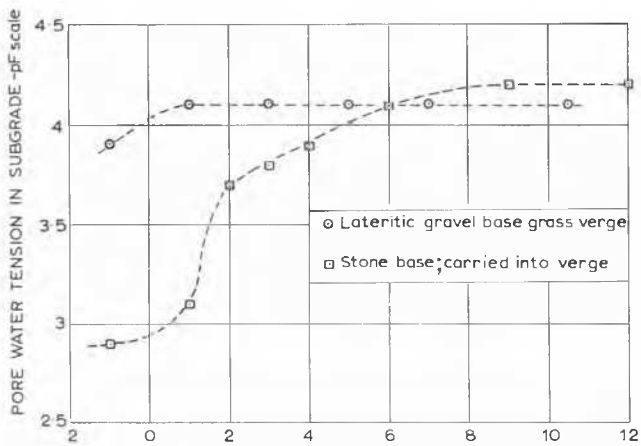

FIG. 3. Effect of base and verge construction on the pore water tension in road subgrades of heavy black clay, Kenya.

ESTIMATION OF THE ULTIMATE PORE WATER TENSION

The ultimate profile of stress in the pore water can be predicted for road subgrades where a persistent groundwater table exists close to the surface and at a known depth. In this case, $u = 0$ at the level of the water table, and the pore water tension in the soil above and below this level follows the normal hydrostatic gradient.

This procedure is satisfactory for depths of water table down to 3 ft in sands or 20 ft in heavy clays, but for deeper water tables the conditions at the edge of the pavement become the dominating influence on the pore water tension in the subgrade. The basis for calculating moisture conditions then becomes the balance between water available as surface runoff and that lost by evapotranspiration. A semi-empirical relation has been established relating climate, as assessed by the Thornthwaite moisture index, to the moisture condition under roads which have had a bituminous surfacing for at least 5 years and where any water-table levels were deeper than 12 ft below the surface (Russam and Coleman, 1961).

The relation using the Thornthwaite moisture index indicates that in very wet climates the subgrade moisture condition tends to about pF 2.8 in heavy clays and to pF 1.8 in sands. These pore water tensions correspond to the limiting depths where the water table is the major influence; hence, methods of estimating the ultimate pore water tension in road subgrades are available over a wide range of conditions. At present, in using the Thornthwaite relation, identification of texture is used to interpolate between sands and clays to allow for differences in the permeability characteristics of soils. A parameter obtained from the ratio of the permeability of the soil at two moisture conditions, e.g. pF 1 and pF 4, would be more definite. In these circumstances, where there is no shallow water table, measures to remove surface water rapidly away from the edges of sealed surfaces will reduce both the ultimate moisture content and the extent of seasonal variations under the surface.

ESTIMATION OF MOISTURE CONDITIONS FOR DESIGN PURPOSES

The moisture condition of the subgrade is an important consideration when designing structures such as roads and it is necessary to estimate the critical conditions affecting the design. Changes in moisture content, strength, and volume which are likely to occur during the lifetime of a road as the soil tends to its ultimate moisture condition can be determined by a laboratory test in which soil samples, simulating conditions at the time of construction, are placed on the appropriate suction plate or pressure membrane apparatus to attain the estimated pore water tension (Croney and Coleman, 1960).

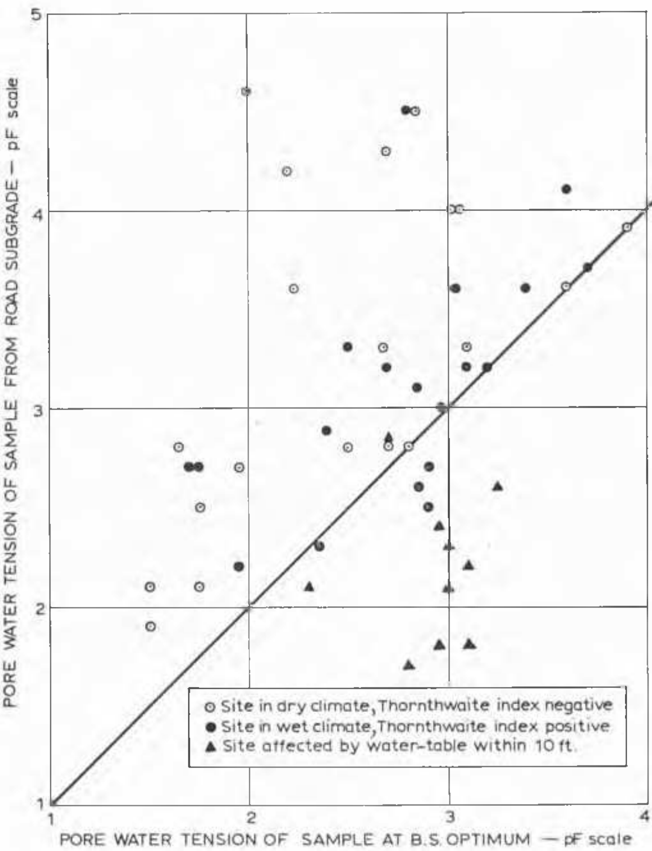

FIG. 4. Comparison of pore water tension in undisturbed samples from road subgrades with that in samples compacted at the optimum moisture content in the British Standard compaction test.

In tropical countries, such as Nigeria and East Africa, road construction is usually carried out between the wet seasons, and the subgrade is compacted approximately at the optimum moisture content to 95 to 100 per cent of the maximum dry density attained in the British Standard compaction test. The pore water tension of undisturbed samples of soil from beneath bituminous-surfaced roads in these countries and of samples of the same soil 24 hours after being remoulded to the optimum condition for the British Standard compaction test, are compared in Fig. 4.

Of the 48 sites investigated, 22 sites were in an area of moisture surplus, i.e. Thornthwaite moisture index positive. Only 13 sites were, however, found to have a pore water tension less than that at the optimum moisture condition, and of these sites, 9 were affected by water tables and 4 had stone bases which had been carried into the verges where runoff water was trapped.

The critical moisture conditions are usually taken as the lowest value of the pore water tension likely to occur during the lifetime of the road and the results indicate that in most instances this will occur immediately after construction of the pavement. Therefore, if the water table is deeper than the limits already mentioned, i.e. 3 ft for sands down to 20 ft for clays, and care is taken to prevent easy access of water to the subgrade from the verges, it is recommended that in tropical countries the critical conditions for road subgrades be taken as those pertaining at the optimum condition for the British Standard compaction test.

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