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ROAD PAVEMENTS ON EXPANSIVE CLAYS

ABSTRACT

This paper briefly outlines the world-wide problems that can result from the construction of road pavements on expansive clay subgrades. Initially the basic concept of clay soil heave is discussed, including the effects of site drainage and pavement loading. A seasonal heave prediction method for Australian conditions is also presented. A brief 'state of the art' on the major techniques most commonly used in an attempt to overcome these problems is presented as well as a list of references for more extensive information. These common techniques include lime stabilisation, prewetting, and the use of membranes to prevent moisture migration within the subgrade. The need for appropriate site drainage and edge treatments are emphasised and the paper concludes that from the point of view of expansive clay behaviour, road pavements are best constructed on initially wet subgrades.

Reference: Aust. Rd Res. 12(3), pp. 173-179.

INTRODUCTION

Clay soils change in volume in response to changes in their moisture contents: they increase in volume upon wetting and decrease in volume if dried out. Clay soils, therefore, change in volume with the seasons, the change being manifested in seasonal vertical and horizontal movements of the soil. The horizontal movements lead to fissures opening in the drier months of the year and closing during the wetter months, while vertical movements lead to cyclic changes in the soil surface level as indicated in *Fig. 1*.

The magnitude of these cyclic movements decreases with depth down to a level below which no seasonal moisture changes and hence no volume changes occur. This depth is called the depth of seasonal movement (*Fig. 1*) and generally varies from about 1 to 5 m, depending mainly on the climatic pattern prevailing at a particular site. The amount of seasonal movement can also vary greatly, depending on many factors that will be discussed later.

In those parts of the world where significant seasonal movements occur, notably the U.S., India, South Africa and Australia, substantial damage to road pavements and lightly-loaded structures is experienced. In an effort to overcome these cyclic soil movements and the high cost of remedial maintenance that result, road construction authorities and research establishments have been investigating various design and construction methods.

This paper presents a brief summary of these methods and presents the current 'state of the art' for the design, construction and performance of road pavements on expansive clay sites.

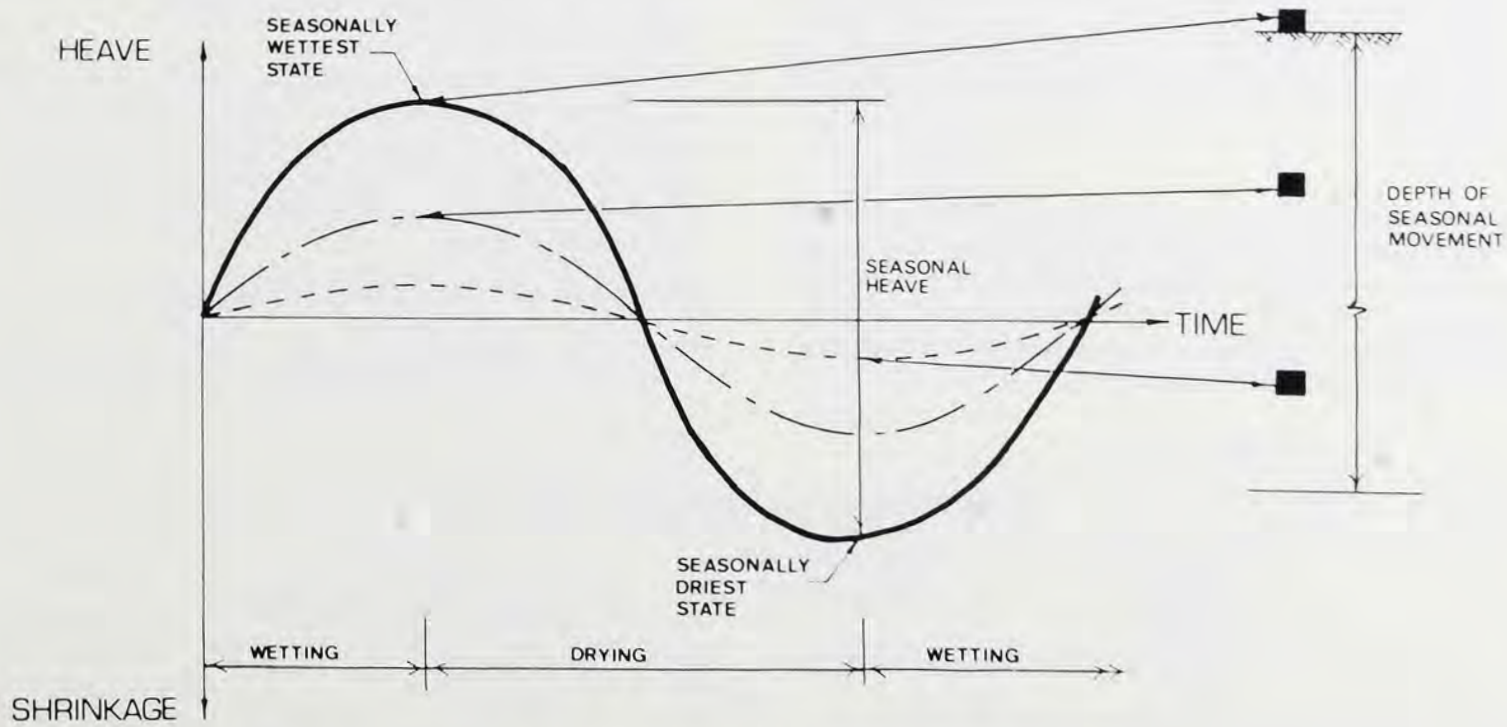


Fig. 1 — Seasonal, vertical clay soil movements

SEASONAL HEAVE OF EXPANSIVE CLAY SOILS

FACTORS AFFECTING SEASONAL HEAVE

The major factors affecting the magnitude of seasonal heave of clay soils in the open (i.e. outside the influence of ground covers and buildings) are as follows.

Type and Amount of Clay

The basic mineral, its surface chemistry and the fabric of a particular clay, together with the salt concentration of the soil water, generally determine the potential for heave. For engineering purposes the type of clay is most easily determined indirectly from linear shrinkage (LS) or plasticity index (w_p), and is often related empirically to potential heave (*Table I*). The clay content (c), can also be seen to affect the magnitude of heave.

Soil Profile

The thickness and location of potentially expansive clay layers in the soil profile considerably influence the seasonal heave. If the expansive clay is overlain by a layer of non-expansive topsoil, or overlies bedrock at a shallow depth, the swelling of the clay will be greatly reduced. The greatest seasonal heaves are, therefore, likely where potentially expansive clays exist from the surface to at least the depth of seasonal movement.

Site Drainage

When a site is sloping and well drained, rain falling on it will mostly run off, so the clay will not have a chance to wet up significantly and therefore little seasonal heave will occur. Alternatively, if a site is flat and water-logged during the wetter months of the year, significant wetting up of the clay will occur, leading to substantial heave. Improvement of site drainage can, therefore, dramatically reduce the magnitude of seasonal heave.

Climate

Generally, potentially expansive clays will only swell and shrink if the prevailing climatic conditions lead to significant seasonal wetting and drying. The greatest seasonal heaves will, therefore, occur under semi-arid climatic conditions where pronounced short wet and long dry periods lead to major moisture changes in the clay.

Loading

Comparatively small loading will significantly reduce clay soil swell. Damage due to underlying clay heave is usually restricted to lightly-loaded structures and road pavements. This factor becomes particularly important for road pavements when significant depths of fill are to be placed.

Location and Type of Vegetation

Trees and large shrubs draw moisture via their root systems and transpire this moisture after removing nutrients from it, to the atmosphere (*Fig. 2*). The removal of soil water from clay soils dries the clay (or increases the soil water suction) and causes shrinkage. This leads to localised settlements over the volume of clay from which the tree is drawing moisture.

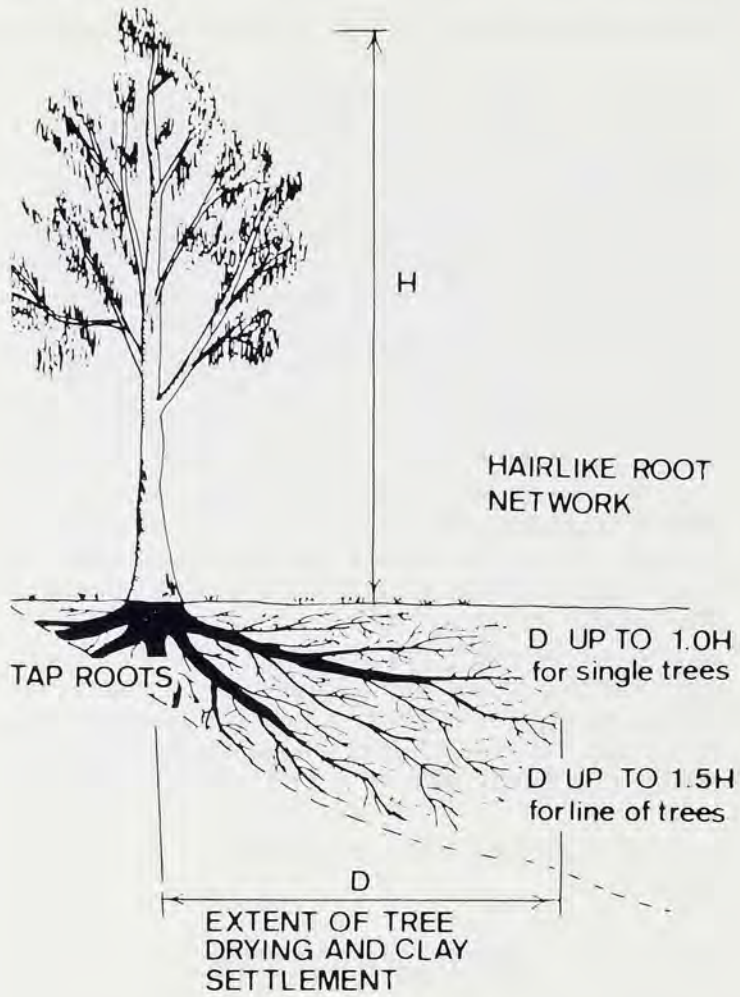


Fig. 2 — General tree root system

It is commonly accepted that a tree's root system can spread and cause clay drying up to its height laterally for single trees and up to one and a half times the tree height if planted in line or a group. The root systems of large shrubs can also dry clay soils up to their height laterally. Root systems tend to spread even further under paving and where shallow bedrock exists. Localised clay settlements over the zone of drying of a tree or shrub can lead to distortion of a road pavement.

SEASONAL HEAVE PREDICTION METHODS

Extensive monitoring of the seasonal heave of Australian clay soils by Holland (1981) highlights the

TABLE I

POTENTIAL CLAY VOLUME CHANGE

Potential Volume Change	*Arid to Semi-Arid Climatic Areas*		*Humid Climatic Areas*	
	LS (%)	*w_p (%)*	*LS (%)*	*w_p (%)*
Low	0 to 5	0 to 15	0 to 12	0 to 30
Moderate	5 to 12	15 to 30	12 to 18	30 to 50
High	> 12	> 30	> 18	> 50

major factors which determine the magnitude of heave at a particular undeveloped site.

Since the early 1950s researchers have attempted, with limited success, to develop reliable seasonal heave prediction methods. The prediction methods can be classified into the following groups:

(a) methods empirically relating heave, mainly to clay type;

(b) consolidometer methods; and

(c) mathematical moisture flow models.

These methods and their accuracy are discussed by Holland and Cameron (1981) and Holland (1981). The major conclusions of these two papers relating to these general heave prediction methods are as follows.

(1) The methods which attempt to empirically relate heave mainly to clay type are of little value.

(2) Consolidometer methods employing full sample saturation do not accurately model the real seasonal moisture conditions and tend to overestimate heave.

(3) The simple mathematical moisture flow model of Richards (1967) expressed in eqn (1) considers both soil profile and annual extremes of soil moisture. It is presently the most satisfactory method of heave prediction for design purposes.

$$SH = \frac{1}{3} \Sigma \text{ layers } \left(\frac{W_w - W_d}{100 + WdGs} \right) \Delta H \qquad (1)$$

where

w_d, w_w = seasonally driest and wettest moisture contents respectively, corresponding to total soil-water suctions p_d and p_w

G_s = soil specific gravity, and

SH = seasonal soil heave of the soil layers with individual thickness of ΔH.

MODIFICATION OF SEASONAL MOVEMENTS IN THE OPEN BY ROAD PAVEMENTS

When an impermeable surface cover or pavement is placed on an expansive clay, the pattern of seasonal soil moisture changes will alter, since surface evaporation from the clay will be terminated (*Fig. 3a*). If the site is very dry when a completely flexible cover is placed on it, edge wetting and heave of the underlying clay will lead initially to the development of an edge heave, or dishing distortion mode (*Fig. 3b*). Theoretically, with time the heave under the cover will slowly progress inwards (*Fig. 3c* and *d*, until ultimately a centre heave or mound distortion mode will form under the cover (*Fig. 3e*). There is much observational and research evidence, however, to suggest that many covers may never fully develop a centre heave distortion mode.

The soil surrounding and under the edges of the pavement will move up and down with the seasons, so leading to flexing of the edges over a distance commonly referred to as the edge distance, *e* (*Fig. 3e*). However, if the pavement is sufficiently rigid it will not flex and distress will not occur.

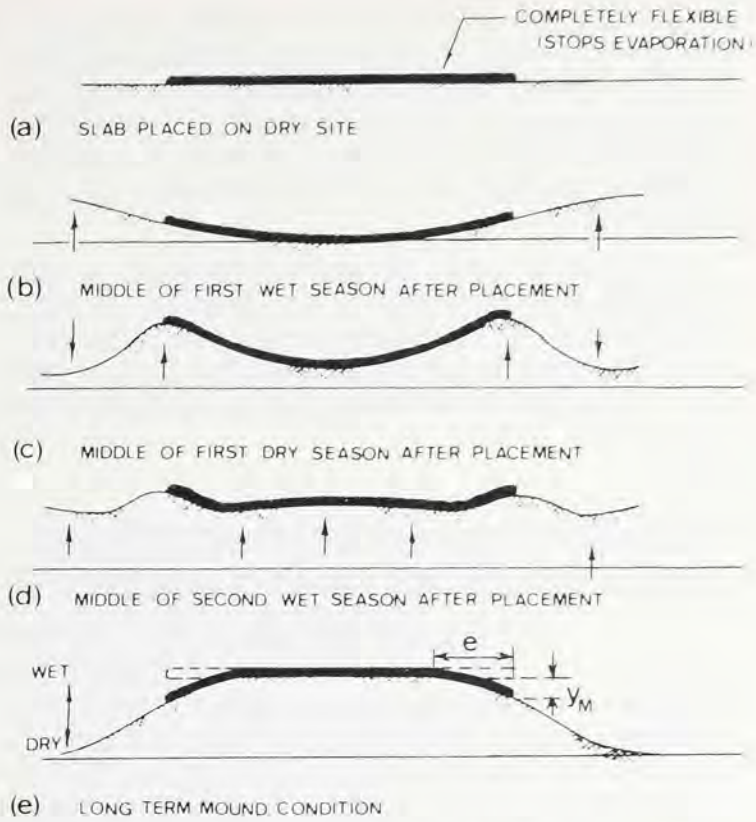


Fig. 3 — Formation of a mound under a flexible pavement

TABLE II

LIKELY RELATIONSHIP BETWEEN EDGE DISTANCE AND DIFFERENTIAL MOUND HEAVE

Differential Heave 'y_m' (mm)	*Edge Distance 'e' (m)*
0-20	0-0.5
10-40	0.5-1.0
20-50	1.0-1.5
30-60	1.5-2.0
50-90	2.0-2.5
70-120	2.5-3.0

If a pavement is placed on a wet site, a mound will effectively already exist, so only seasonal wetting and drying of the clay under the edges will need to be accommodated. Richards and Chan (1971) have suggested that if the soil is very wet when the cover is placed, moisture will move laterally from the centre and eventually form a long-term stable edge heave condition.

While the formation of a long-term mound after the initial development of an edge heave condition has been recorded by a number of researchers (Ward 1953; De Bruijn 1965 and 1973; Johnson and Desai 1975), the development of a stable long-term edge heave condition at an initially very wet site has not been reported.

The extensive monitoring of covers over expansive clays (Holland 1981) has revealed empirical relationships between seasonal heave, y_m and edge distance *e* (eqn (2) and *Table II*).

$$y_m = 0.70 \times SH \qquad (2)$$

EFFECT OF PAVEMENT STRENGTH

The degree of movement of a pavement or ground cover at a given site depends on the rigidity of the

pavement. A flexible pavement will follow the heave mound of the clay. Depending upon the strength and flexibility of the pavement, longitudinal cracking may or may not occur. However, in the long term cracking will usually occur due to the continual flexing of the pavement edge over a vertical distance (y_m) as shown in *Fig. 3e*.

Depending upon its relative stiffness, a rigid pavement should be able to withstand the formation of the critical central mound. Central tensile cracking and edge shear cracking are the two most common types of failure for an inadequately designed rigid pavement.

DESIGN AND CONSTRUCTION OF ROAD PAVEMENTS AT EXPANSIVE CLAY SITES

The main aim when designing or constructing a road pavement on expansive clay soil sites is to reduce the effective heave or movement of the soil beneath the pavement to a level that will not affect traffic efficiency and safety.

A potentially expansive clay subgrade will undergo a volume change as a direct result of a change in soil moisture content. Therefore attempts to minimise pavement heave have been concentrated on limiting soil moisture fluctuations, or reducing the potential for expansion of the clay subgrade.

Most of the techniques commonly available can be broadly classified into three categories:

(a) avoidance of problems,

(b) control of moisture, and

(c) exclusion of moisture.

AVOIDANCE OF PROBLEMS

This is perhaps the most obvious method of coping with the expansive clay problem. Unfortunately, it is rarely feasible to avoid expansive clay deposits as they are usually widespread.

A feasible solution in some instances (i.e. cut/fill situations) is to remove the potentially expansive stratum over at least the depth of seasonal movement, and replace it with a non-expansive material.

CONTROL OF MOISTURE

Prewetting

The object of prewetting is to allow dessicated expansive soils to swell and reach equilibrium prior to the placement of the pavement.

The three most common methods used for prewetting are:

(a) bored holes,

(b) sand drains or trenches, and

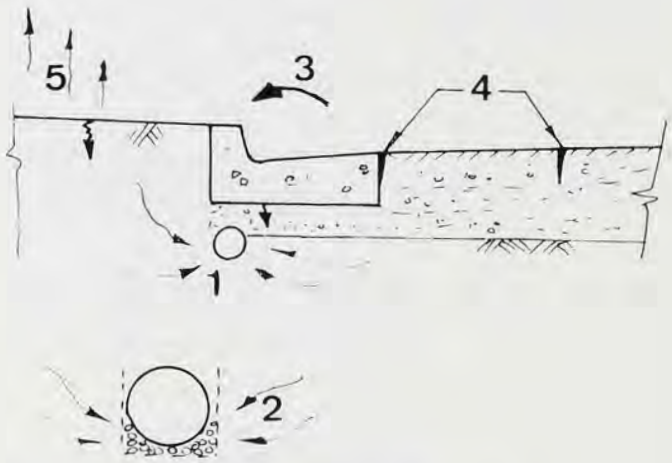
(c) open flooding.

Bored holes are usually placed on a grid of about 1.5 m and their depth depends on the predicted depth of seasonal movement. Sand drains or trenches are usually dug with a ditch-witch or the like, as a series of continuous parallel lines about 1.5 m apart. Open flooding is the most commonly used method of prewetting and is often used when the subgrade is 'boxed out'.

Any form of prewetting, particularly at initially dry sites, may need to be continued for many months in order to be effective. Once prewetting ceases, the subgrade must be sealed or covered to prevent drying out prior to pavement construction. Prewetting has had rather limited use due to its cost, the length of time involved, and the 'soft' and wet subgrade surface that it produces.

In rural areas of Australia it is difficult or often impossible to obtain sufficient quantities of water for prewetting. In the urban situation the sequence of construction dictates that drainage, including subgrade drainage beneath kerbing, is placed prior to the pavement. This usually limits the effectiveness of open flooding as a method of prewetting due to the action of the drains.

Prewetting using trenches or bored holes can also suffer due to the placement of road drainage. The prewetting in these situations can develop the required heave prior to pavement construction but unfortunately within a few months of completion the pavement will undergo edge drying settlement (*Fig. 4*).



1 AGRICULTURAL DRAINS DRY OUT SUBGRADE

2 STORMWATER DRAINS TEND TO DRY SUBGRADE AT EDGES.

3 EDGE DRYING SETTLEMENT CAUSES KERB ROTATION.

4 EDGE DRYING SETTLEMENT CAUSING LONGITUDINAL CRACKING.

5 POORLY MAINTAINED NATURE STRIP ALLOWS DRYING SETTLEMENT.

Fig. 4 — Edge drying settlement of pavements placed on initially wet sites

Chemical Stabilisation

Chemical stabilisation is carried out on expansive clay subgrades to alter the clay structure or clay-water combination to prevent or minimise swelling. A large range of chemicals or additives has been tried, with generally very limited success, in an attempt to reduce the swelling in clays (Ingles and Metcalf 1972). Lime continues to be the most widely used and effective additive for the stabilisation of expansive clays.

Vertically placed impermeable sheetings are usually used in conjunction with impermeable membranes placed over the subgrade. In areas where excessive temperature changes exist, condensation is likely to occur near the plastic cut-off, resulting in an increase in moisture. In most cases, the use of vertical moisture barriers only slows down the rate of water infiltration to the top of the subgrade as great depth installation is expensive.

Horizontal barriers can be used to reduce the level of seasonal movement at the edges of a road pavement. As the theoretical mound develops beneath a pavement (*Fig. 3*), or after prewetting of a subgrade, the formation will undergo edge flexing due to seasonal drying and wetting of the clay soil. The distance over which this seasonal movement occurs has already been defined as edge distance *e* (*Fig. 3e*).

Once mound equilibrium is reached beneath a pavement those areas beyond the edge distance remain virtually stable. Therefore there is a strong argument for placing wide, sealed shoulders or bicycle paths adjacent to pavements. These shoulders or pathways should be as wide as the expected edge distance (*Fig. 6*).

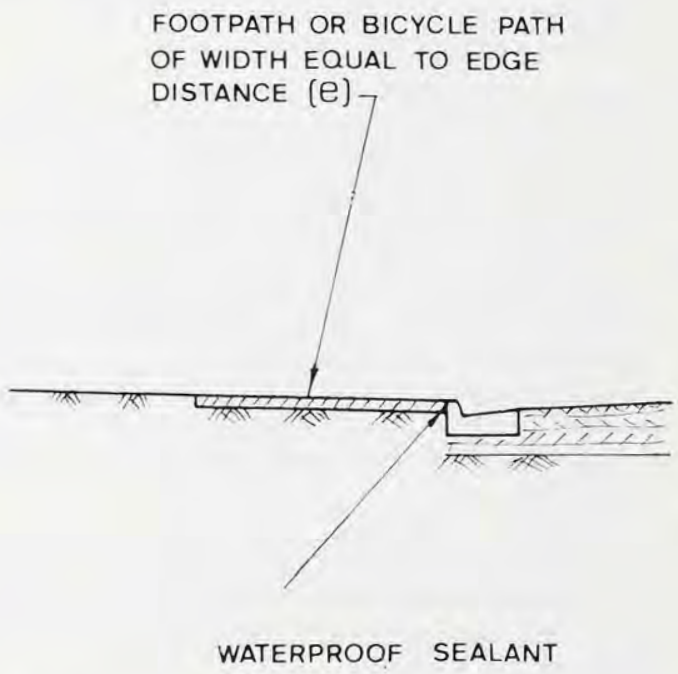


Fig. 6 — Construction of a trafficable surface barrier to reduce pavement flexing due to seasonal heave

Drainage

Provision of adequate drainage along road pavements would minimise the amount of moisture finding its way into the clay subgrade. A good drainage system should drain away water from rainfall and other sources as quickly as possible and allow as little moisture as possible to penetrate into the subgrade, thus preventing excessive moisture build up. Two systems are usually used, namely surface and sub-surface drains. Ideally, both systems should be employed in areas experiencing high rainfalls.

Surface Drainage

In order to remove surface runoff from road pavements and shoulders as quickly as possible, surface drainage facilities should be provided. Such drains are best suited to areas where they are more economical than other forms of moisture exclusion, i.e. rural roads with wide right-of-ways, and elevated formations. Drains should be of adequate size and ideally have an invert below the level of the pavement subgrade for effective drainage with the shoulders and verges having the maximum allowable grades.

Typically, on a poorly-drained urban road subjected to significant edge drying, during summer, longitudinal pavement cracking and kerb rotation will occur.

Sub-surface Drainage

The purpose of a sub-surface drain is to give pavements maximum practical protection from free water. The sub-surface system has a definite beneficial effect on the moisture distributions in the clay. By removing free water which penetrates cracks, it helps in maintaining a low range of moisture variations between summer and winter and thus inhibits large movement at the edge of the pavement.

In view of the enormous potential benefits of good drainage in cutting maintenance and replacement costs and in extending pavement life, the burden of proof should be to determine 'where drains are not needed', rather than 'where they are needed'.

Shoulder Paving

In roads where shoulders are provided they should receive as much attention as the road pavement during design. As mentioned earlier, they should have maximum allowable crossfall and ideally be as wide as the likely edge distance (commonly 1.5 to 3 m). The joint between the shoulder and pavement should be continuously sealed to prevent water penetration.

The shoulder area typically experiences the most significant movements but unfortunately is not repaired until substantial failure of the pavement develops. A well designed shoulder in good repair will greatly prolong the life of a pavement on expansive clay subgrades.

CONCLUSIONS

From the point of view of long-term performance, road pavements are best constructed on a seasonally wet site; however, some construction difficulties can often arise.

Proper attention to drainage and edge treatments to ensure that no excessive moisture build up, or seasonal variations occur, is probably the best method of designing or improving pavement on expansive clays.

Of the stabilisation procedures currently used in Australia, lime stabilisation by mechanical means is probably the most common. This is largely due to the excessive cost of using membranes or barriers and the ineffectiveness of lime slurry, chemical or mechanical stabilisation. Prewetting has been used but it can create construction and performance difficulties.

There is a definite need for research aimed at developing a reliable and practical method of determining the subgrade moisture content at which paving may be constructed so that future significant underlying clay moisture changes do not lead to excessive pavement distortion.

REFERENCES

de BRUIJN, C.M.A. (1965). Annual redistribution of soil moisture suction and soil moisture density beneath two different surface covers and the associated heaves at the Onderstpoort test site near Pretoria. Moisture equilibria and moisture changes in soils beneath covered areas. (Butterworth: Sydney), pp. 112-34.

—— (1973). Moisture redistribution and soil movements in Vereeniging (Transvaal). Proc. 3rd Int. Conf. on Soil Mech. and Found. Eng., Moscow, Vol. 2, pp. 37 to 44.

HOLLAND, J.E. (1981). *The Design, Performance and Report of Housing Foundations.* (Swinburne College Press: Melbourne.) pp. 6-12.

—— and CAMERON, D.A. (1981). Seasonal heave of clay soils. *Civ. Eng. Trans. Inst. Eng. Aust.* CE 23 (1), January, pp. 55-67.

INGLES, O.G. and METCALF, J.B. (1972). *Soil Stabilisation Principles and Practices.* (Butterworths: Melbourne.)

JOHNSON, L.D. and DESAI, C.S. (1975). A numerical procedure for predicting heave. Proc. 2nd Aust. N.Z. Conf. on Geomechanics, Brisbane, Australia, July, pp. 269-73.

RICHARDS, B.G. (1967). Moisture flow and equilibria in unsaturated soils for shallow foundations. Permeability and capillary of soils. ASTM Special Tech. Pub. STP 417, pp. 4-34.

—— and CHAN, C.Y. (1971). Theoretical analysis of subgrade moisture under Australian environmental conditions and their practical implications. *Aust. Rd Res.* 4(6), pp. 32-49.

RICHARDS, B.G. and GORDON, R. (1972). Prediction and observation of the performance of a flexible pavement on an expansive clay subgrade. Proc. 3rd Int. Conf. on Structural Design of Asphalt Pavements, London, Vol. 1, pp. 133-43.

SNETHEN, D.R. (Ed.) (1975). A review of engineering experiences with expansive soils in highway subgrades. Fed. Highw. Admin., Washington, D.C. Interim Report, June.

WARD, W.H. (1953). Soil movement and weather. Proc. 3rd Int. Conf. on Soil Mech. and Found. Eng., Switzerland, pp. 447-82.

WISE, J.R. and HUDSON, W.R. (1971). An examination of expansive clay problems in Texas. Texas Highway Dept, Research Report 118-5.

J.E. HOLLAND, B.E., Ph.D.

John Holland is a Principal Lecturer in the Civil Engineering Department of Swinburne Institute of Technology. In 1973 a major research study was commenced under the direction of Dr Holland into the behaviour of expansive clay soils. In 1978 this study was widened to include the cement and lime stabilisation of soil subgrades and in 1979 concrete road pavements were also included. Throughout this major project Dr Holland has been the author of a total of 39 published papers to date. In addition, following the research undertaken at Swinburne some nine postgraduate students have been awarded higher degrees. In conjunction with research activities at Swinburne, Dr Holland was awarded the C.C.A.A. Award of Excellence in 1980. Dr Holland was an invited discussion leader at the 3rd International Conference on Expansive Soils in Denver U.S.A. (1980). Recognised throughout the world, Dr Holland has been approached by leading U.S. Consultants and in mid-1982 was awarded a Fellowship by the Natal Building Society of South Africa. More recently, a delegation from the Peoples Republic of China visited Swinburne where they attended a Seminar given by Dr Holland.

J. RICHARDS, B.E.

Jon Richards graduated from Swinburne in 1979 with a degree with distinction. Since that time he has been employed at Swinburne as a Research Engineer working mainly in the area of expansive clays. To date Jon Richards has been the joint author of five published papers including a paper to the 7th International Conference in Concrete and Structures in Singapore 1982. In 1981 Jon Richards travelled to Dallas, U.S., where he worked closely with an engineering grouting company engaged in relevelling of road pavements and foundations using the slab jacking technique. In conjunction with research and consulting activities at Swinburne Jon is currently writing a thesis on foundation repair.

Lime treatment of an expansive clay subgrade has been carried out using the following methods.

(a) Mix-in place. This is the cheapest of the available methods but does not stabilise to any considerable depth. The primary use of this method appears to be for establishing a working base during construction or to marginally increase subgrade strength.

Various quantities of lime have been used by the different road construction authorities but a mix of 2 to 5 per cent by weight has proved to be the most economical (Snethen 1975; Wise and Hudson 1971).

(b) Drill hole. A grid of holes at about 1.5 to 1.8 m centres, ranging in depth from 0.8 to 6 m are filled with a lime slurry or lime slurry and sand mixture. The expected result is for the hydrated lime to diffuse more rapidly into the subgrade initiating the soil-lime reaction. Unless a network of fissures exist then the diffusion process may take several months to affect a sufficient volume of soil. The amount of lime required for this process is generally not more than 100 g/L. Too much lime will inhibit total lime-water migration.

(c) Deep plough. This technique is used when it is required to stabilise a substantial depth of soil (from 0.3 to 0.9 m) (Richards and Gordon 1972). This is probably the most useful of all the lime stabilisation methods when used for the control of expansive clays.

(d) Pressure injection. This technique relies on the pressure injection of a lime slurry into the expansive subgrade. Basically, the method is to pump lime under high pressure through hollow injection rods into the subgrade to depths of up to 3 m. The injection rods are placed on about a 1.5 m grid and generally up to 2 m deep. Injection pressures in most cases are in the range of 350 kPa to 1400 kPa. The normal lime-water slurry ratio is 0.3 kg to 0.4 kg of lime to each litre of water. A wetting agent is also used to help the lime flow as a solution.

Lime stabilisation processes are more effective when carried out during the drier months when the clay is fissured. When the clay is wet it will effectively seal itself off from slurry migration and the two slurry methods are of doubtful effectiveness. In dry fissured clays, the use of the pressure injection slurry method may result in large volumes of slurry passing through these fissures to stabilise soil well outside the desired area.

After lime stabilisation care must be taken to ensure water infiltration into subgrades does not 'wash out' the lime.

Mechanical Stabilisation

Mechanical stabilisation is used to limit the heave of expansive soils under paving by altering the moisture condition of the subgrade by compaction. In order to obtain this ideal subgrade moisture condition, it is necessary to establish the long-term moisture content or total soil water suction which will develop under the paving or cover at the site in question. A reliable method of determining this moisture condition is not presently available.

If the soil is significantly below this long-term moisture content, or if the prevailing climate is such that the surface will dry out rapidly, then water must be added. Distribution of water through the subgrade can be difficult and generally requires the use of heavy disc harrows followed by heavy duty cultivators and rotary speed mixers.

EXCLUSION OF MOISTURE

If a subgrade experiences no change in moisture content or suction then it will not change volume. The aim, then, of these methods is to effectively 'lock in' the soil moisture regime beneath the pavement by preventing moisture migration.

Membranes

The types of membranes currently being used and their application to specific areas is self evident.

(a) Asphalt membranes. In cases such as arid regions where surface moisture, either runoff or from hydrogensis, is the source of infiltration, asphaltic membranes, or full depth asphalt pavements are effective. However, this form of treatment may be expensive because of the rising cost of asphalt. The full depth asphalt is laid directly on the swelling clay subgrade with asphalt-line verges and backslopes. The asphalt membrane is also placed on the swelling subgrade and the road pavement bases and courses are placed directly over it.

(b) Plastic membranes. Currently some research is being undertaken into the performance of plastic membranes as a form of moisture exclusion. There is some considerable doubt about the long-term durability of many plastic membranes.

(c) A polythene plastic sheeting placed vertically along the edges of the pavement can be used to act as a vertical barrier against moisture infiltration. In rural roads where impermeable shoulders are provided the barrier may be placed along the edge of the shoulders. For urban roads the barriers should be just inside of the edge of the pavement.

(d) In the case of urban roads the cost of placement of vertical polythene or asphaltic barriers could be reduced if they were placed in the side of service trenches which commonly exist near the kerb line (see *Fig. 5*).

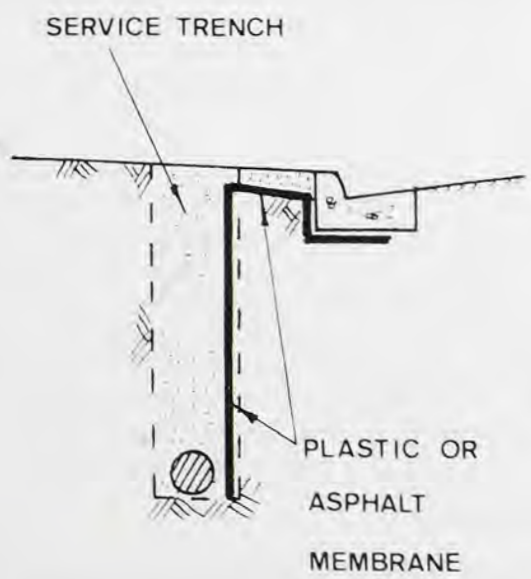


Fig. 5 — The economical use of vertical barriers to prevent edge drying settlement