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RESPONSE OF THIN SEAL COATED ROAD PAVEMENT TO THE SWELLING AND SHRINKAGE OF REACTIVE CLAY SUBGRADES

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An analysis procedure is developed to carry out useful, relevant parametric studies on the interaction between thin seal coated road pavement and an underlying reactive clay subgrade. The procedure uses a thermal analogy for moisture diffusion and volume change in combination with a simplified description of swell and shrinkage characteristics such that an available thermo-mechanical stress analysis programs can be used directly for analysis of swelling and shrinking soils. The paper outlines the development of the procedure and applies it to analyze a typical pavement on reactive soil. The results highlight the critical factors that affect pavement response.

Key Words: *reactive clays, expansive soils, swelling, shrinkage, low cost pavements, thermal analogy, unsaturated flow*

1. INTRODUCTION

A typical low cost road pavement consists of a relatively thin granular layer surfaced by a thin layer of bitumen and cover stone as a seal coat. Such pavement when constructed over a reactive clay subgrade, undergoes distress and deterioration when the subgrade: (1) wets up and swells due to infiltration of rain water or (2) dries out and shrinks due to the evaporation of existing moisture from the edge of pavement. These phenomena like in **Figure 1**, have been commonly observed in arid and semi-arid areas of the world where reactive clays of high swelling and shrinking potential are widely spread, and have resulted millions of dollars in annual cost of extra maintenance and replacement of pavement.

In this paper the complex mechanical behavior of reactive clay subgrade during wetting up and swelling as well as drying out and shrinking is described by using the conceptual models of volume change and the associated stress development. Later these theoretical models are applied in the numerical analysis where a typical situation shown in **Figure 1** is analyzed to study the response behavior of overlying thin seal coated road pavement subjected to the subgrade volume change. Study on the analysis results shows that different parameters such as subgrade swell and shrinkage parameters, edge restraint of both pavement and subgrade, etc. play critical role in the subgrade swell and shrinkage processes and consequent pavement response.

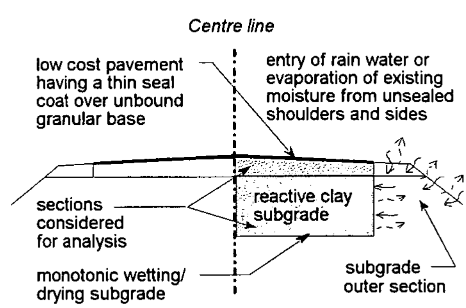


Fig. 1 Typical situation analyzed

2. VOLUME CHANGE OF REACTIVE CLAYS

For analyses of swelling and swell pressure development as reactive clays are wetted up or shrinking and shrinkage stress development as these clays are dried out beneath lightly loaded structures like a pavement, the moisture condition of the soil must be described in a manner that relates to the potential gradients drawing water into or out of the soil and to the degree of swell or shrink as the soil wets up or dries out. In this work, as suggested by Richards[1], total suction (h) is used to describe the moisture condition of the soil. (This total suction is the sum of matrix suction due to capillary action of soil structure, and osmotic suction due to presence of solute in soil.)

The present analysis uses log suction as the independent variable. This is done because the response of soil is more linearly related to log suction than suction. If volumetric moisture content is linearly related to log suction (in a similar manner to the traditional e-log p compression curves for soil) then it can be argued that it is valid to describe the diffusion of water through the soil in terms of log suction rather than in terms of volumetric moisture content as is done in conventional moisture diffusion analyses[2].

(1) Swell and Swell Suppression

When an unsaturated clay wets up it tends to swell. If this swell is suppressed by applied stresses or by confining boundaries then the swell pressures are developed within the soil. For analysis of such swell and swell pressure development it is necessary to define the initial and final moisture suctions, the degree of swell with decrease in suction and the degree to which this swell is suppressed by applied stress. Meanwhile, the present approach does not consider coupling between applied stress and suction as it is assumed that under a lightly loaded structure the effect of applied stress on suction is relatively small and that such small effect can be eliminated by measuring the swell parameters in tests which simulate field conditions as closely as possible.

Different parameters are used to describe swell and swell suppression. As suggested by Wallace and Sapkota[2], the writers prefer those measured in laterally confined swell in an oedometer because the tests are relatively easy to perform and because most useful data is in this form. They adopted two parameters: a free swell parameter γ_h relating increase in vertical swell strain in the oedometer (ε_{vsw}) to decrease in log suction (log h) under a light load of about 7 kPa and a swell suppression parameter γ_σ relating decrease in vertical swell strain in the oedometer to increase in log of applied total stress (log σ). This results, for one dimensional swell

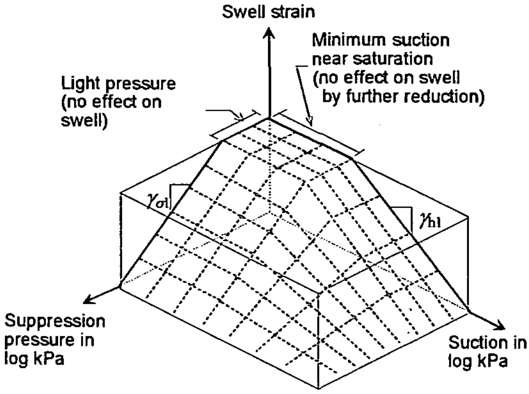


Fig. 2 Swell and swell suppression in 3-dimensions

in an oedometer:

$$\varepsilon_{vsw} = \gamma_h \,\Delta\log h + \gamma_\sigma \,\Delta\log \sigma \qquad (1)$$

Figure 2 illustrates a 3-dimensional representation of this relationship.

The two soil parameters γ_h and γ_σ could be estimated from typical laboratory oedometer swell tests which reproduces the field stress and suction conditions as closely as possible. For lateral pressure studies it is also important that the oedometer be strain gauged to monitor lateral pressure development.

Table 1 presents the characteristic values of the soil parameters γ_h and γ_σ considered for the present parametric study. These values were derived by Wallace and Sapkota[3]. They estimated γ_h by back-analysis of ground heave predictions using the Australian house foundations code-AS2870[4], and γ_σ by using two of the more comprehensive and authoritative correlations between index properties and lateral swell pressures[5), 6]. These correlations are based on laboratory oedometer testing of compacted and of "undisturbed" natural clay specimens.

(2) Shrinkage and Shrinkage Compression

When an unsaturated clay dries out it tends to reduce its volume. If this shrinkage is restrained, soil develops shrinkage stress. This general concept together with the remaining hypothesis of swell and swell suppression is used to develop the conceptual model of shrinkage and compression. Like in the description of swell, two soil parameters: λ_h and λ_σ are used to describe the shrinkage compression behavior. λ_h relates the increase in vertical shrinkage under light load of about 7 kPa due to increase in log suction. And λ_σ relates the decrease in vertical strain under an applied stress due to increase in log suction.

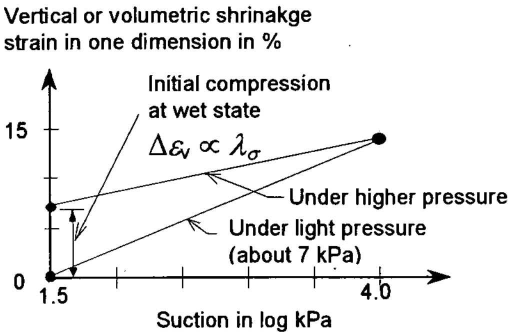


Fig. 3 Shrinkage compression under different applied stresses

Table 1 Characteristic values of swell and shrinkage parameters

Type of soil		Values of swell and shrinkage parameters			
Degree of reactivity	Typical liquid limit	'γ_h'	'γ_σ'	λ_h	λ_σ
Medium	50	0.035	0.040	0.04	0.01
High	70	0.050	0.065	0.06	0.02
Extremely high	90	0.070	0.080		

This results for one dimensional shrinkage compression,

$$\varepsilon_{vsh} = \lambda_h \,\Delta\log h + \lambda_\sigma \,\Delta\log \sigma \tag{2}$$

Figure 3 illustrates the conceptual description of shrinkage compression. The underlying assumption indicated in the figure is that at a certain higher value of suction close to shrinkage limit (for example 4 kPa considered in the figure and in this study) the curves of shrinkage compression under light applied stress and under higher applied stress converge together. This means, when the soil is close to shrinkage limit, an increase in stress does not result shrinkage compression. Similar concept was applied in the swell model **(Figure 2)** where swell strain curves under different applied stresses converged together at higher suction. In both swell and shrinkage models, a 1.5 kPa suction accounts for osmotic effect of soil and further reduction has no effect on swelling and shrinkage.

The magnitude of free shrinkage parameters: λ_h can be estimated from the load free three dimensional shrinkage test, and λ_σ from the suction controlled oedometer compression test under applied stress. Very limited published data is available on the laboratory shrinkage compression tests under controlled suction environment. However, for the purpose of parametric study, result of measurements made by Richards et al.[7] is analyzed to obtain typical range of magnitude of these parameters to be considered for a parametric study. It is presented in **Table 1** together with swell parameters.

3. UNSATURATED MOISTURE FLOW IN SUBGRADE

In an unsaturated flow, as the permeability usually known as hydraulic conductivity 'K' varies with the degree of wetness, it is preferred to normalize hydraulic conductivity with wetness. This produces a variable called moisture diffusivity 'D' in function of volumetric water content 'θ' as

$$D(\theta) = \frac{K(\theta)}{C(\theta)} \tag{3}$$

where $C(\theta)$ is the specific water capacity of soil.

As discussed earlier, the flow of moisture is governed by the suction potential 'h', the writers prefer the moisture diffusivity to be described as the function of h for which available relations for example Gardner's empirical relation[8]

$$h = A \cdot \theta^{-B} \tag{4}$$

where A and B is a constant, may be used.

Application of above concept using log suction as the independent flow variable produces the relation of moisture diffusivity in terms of log suction as depicted in Equation (5). The first writer[9] conducted typical analyses of monotonic wetting of an unsaturated homogenous expansive clay subgrade under horizontal one dimensional flow using a constant, linear and non-linear variation of diffusivity with log of total suction; and found that with the use of non-linear log suction dependent diffusivity

$$D(\log h) = A + B(\log h)^n \tag{5}$$

where n is a constant, a sharper shape of wetting front as commonly observed in the field, can be obtained. Such form of description of wetting is useful as it can be conveniently applied in the numerical analysis.

The relationship of Equation (5) describing diffusion of log suction is assumed to be equally applicable to both wetting and drying processes in a subgrade. Because the flow considered is monotonic with continuously wetting for subgrade swell analysis and continuous drying for shrinkage analysis, and that the hysteresis effect due to change in flow path is not included.

4. STIFFNESS PARAMETERS FOR SWELL AND SHRINKAGE

(1) Modulus of Swell Suppression

For monotonic swelling, the relevant modulus is that describing the degree to which applied stress suppresses swell. This is quite different and typically less than one-tenth that describing the deformation of the clay under an externally applied load [10].

The constant value of γ_σ in Equation 1 infers that the constrained swell suppression modulus varies linearly with log of applied stress. For analysis of any swell situation it is necessary to describe how the swell suppression moduli vary with the complete three dimensional stress system. This is an extremely complex undertaking which has been subject to some promising theoretical speculation and has been demonstrated by sophisticated description of the observed laboratory swell characteristics of a few particular soil specimens[1]. In the present work a much simpler conceptual model is used. It is assumed that:

$$E_s = B\left(\frac{\sigma_1 + \sigma_2 + \sigma_3}{3}\right) \quad (6)$$

where E_s is the swell suppression modulus, σ_1, σ_2, and σ_3 are the principal normal stresses and B is a constant.

A simple model described by Wallace and Lytton[11] and applied by Wallace and Sapkota[10], is used to estimate B values from corresponding values of γ_h and γ_σ. The model assumes swelling clay as an isotropic, incremental linear elastic material whose Poisson's ratio remains constant during the wetting up and swelling processes. The detailed discussions are available in these references, in brief the B values are estimated iteratively. First at a suction value, E_s and β are estimated by using Equation 7 for two quarter points values of σ_1 between the light pressure as 7 kPa and the expected overburden pressure in the field. (Equation 7 is derived from the oedometer boundary condition). Then taking average of these two quarter point β values as B for that pressure level at that suction value, actual value of B is calculated iteratively. During the iterative process lateral stresses σ_2, σ_3 are computed by using lateral swell pressure equation described in these references.

$$E_s = \beta\,\sigma_1 \quad (7)$$

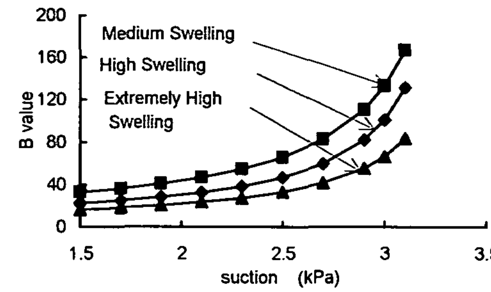


Fig. 4 Order of B values for soils in **Table 1**

$$\text{where} \quad \beta = \frac{2.3\,(1+\nu)(1-2\nu)}{\gamma_\sigma(1-\nu)}$$

and σ_1 is the applied stress, and ν is Poisson's ratio which is assumed to remain constant during the swelling process.

Figure 4 shows values obtained in this manner for the three soils in **Table 1** wetting up from 3.5 kPa to various final log suction levels under a vertical stress of 15 kPa. Actual measurements of lateral pressures in oedometer swell tests suggest that the order of magnitude of B is 1.5 to 1.75 times that suggested in **Figure 2**[9]. This is thought to be adequate for the present objective of parametric studies but it is obviously an important topic for further study using full scale field and laboratory measurements.

(2) Shrinkage Compression Modulus

As depicted from **Figure 3**, the modulus of shrinkage compression of soil due to applied stress varies linearly with log of total suction. Using the concept of one dimension compression in an oedometer compression test, the modulus of shrinkage compression can be described by

$$E_{sh} = \beta_c\,\sigma_1 \quad (8)$$

$$\text{where} \quad \beta_c = \frac{2.3\,(1+\nu)(1-2\nu)}{\lambda_\sigma(1-\nu)}$$

and σ_1 is applied stress. ν is Poisson's ratio assumed to remain constant during the shrinkage process.

Above relationships produce a uniaxial stress dependent shrinkage compression modulus. The description of shrinkage compression modulus in a three dimensional state is desirable and has formed a part of ongoing research, in this paper this uniaxial model is used for the numerical work.

β_c is estimated by using Equation 8. As indicated in **Figure 3**, the shrinkage compression due to an applied stress (difference in strain under two

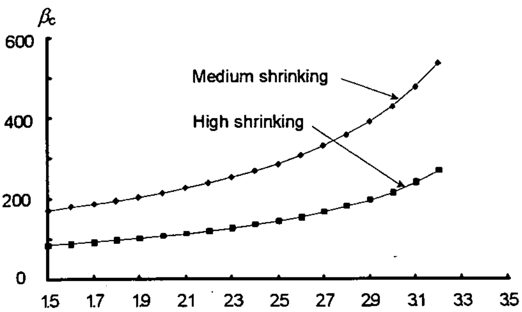


Fig. 5 Magnitude of β_c for soils in **Table 1**

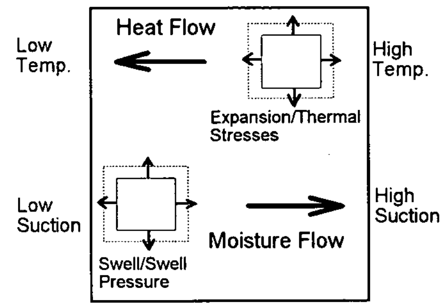


Fig. 6 Concept of thermal analogy

pressures) decreases linearly with the increase in log suction. So the values of λ_σ is decreased linearly with log suction taking the values presented in **Table 1** as initial values at wet state (at 1.5 kPa) and zero at the point of convergence (at 4.0 kPa). The variation of β_c for these soils is presented in **Figure 5**.

(3) Poisson's Ratio for Swell and Shrinkage

Both the swelling and shrinkage of a reactive clays effectively undergoes drained condition because these phenomena and respective wetting and drying processes occur side by side with the same rate as of movement of moisture. This indicates that the Poisson's ratio should not be 0.5 as in an undrained situation. Survey of literature on Poisson's ratio for swell and shrinkage by Wallace and Lytton[11)] shows that the order of magnitude of Poisson's ratio for reactive clays generally lie between 0.2 to 0.35. A value of 0.3 is selected for the present study.

5. THERMAL ANALOGY

Figure 6 illustrates the concept of thermal analogy. The thermal analogy concept was initially applied by Wallace and Lytton[12)] in the analysis of cracked block of expansive clay soils. Later Wallace and Sapkota[3)] used it in a typical analysis of response of pavement to subgrade volume increase. To apply this analogy, a set of thermal parameters summarized in **Table 2**, are required to be defined to simulate the analysis of unsaturated flow and swelling to thermo-mechanical analysis.

For parametric analysis typical range of values are estimated by considering observed field behavior of soil profile and conducting dimensional analysis. For example, Wallace and Sapkota[3)] indicated that if a 1.2 m width of an initially uniformly dry outer section of road subgrade wets up to 90 % of its final saturation at a period of about 2 months under a monotonic wetting process, then the magnitude of equivalent thermal diffusivity comes to an order of about 0.012 m^2/day. The specific heat of a typical expansive clay, is of the order of 576,000 kJ/t·°C.

Using above values of thermal parameters together with the mass density of expansive clay as 1.7 t/m^3, the non-linear thermal conductivity 'K' can be obtained as:

$$K = 1096 + 696\,T^{2.5} \tag{9}$$

where T is equivalent temperature in degree Centigrade. This relationship is in the form described by Equation (5) and is used to describe moisture flow during both wetting and drying processes. Note that the moisture potential is considered in terms of log kPa and, in thermo-mechanical analogy, changes of moisture potential in log suction are the same as the thermal potential in degrees Centigrade. To simplify the correlations and give the same sense for temperature and log suction changes $T = C - \log h$, where C is the value of log suction above which there is no swell suppression under applied load. ($C = 4.0$ for the present analysis).

The magnitude of other thermal parameter, the coefficients of thermal expansion and contraction can be set equal to linear free swell and shrinkage strains respectively per unit change in log suction.

Table 2 Parameters involved in the thermal analogy

Variables	Unsaturated flow	Heat diffusion in media
Conductivity	rate of moisture flow through a unit area under a unit gradient of suction potential	flow of heat through a unit area under a unit gradient of temperature
Specific water/heat capacity	specific water capacity determines the volume of water retained in a unit total volume of soil under a unit suction potential	specific heat capacity is the energy required to change a unit mass to a unit degree rise in temperature
Mass density	total mass contained in a unit volume of soil-water, with the unit as t/m^3	total mass contained in a unit volume of heat flow media, with the unit as t/m^3
Diffusivity	hydraulic diffusivity in an unsaturated soil media relates variation of hydraulic conductivity with change in water capacity	thermal diffusivity is a function of heat conductivity, specific heat and mass density
Coefficient of expansion/ contraction	in this reactive clay study the coefficient of expansion/shrinkage is considered volume increase/decrease per unit change in suction potential	in thermal analysis, the coefficient expansion/contraction is considered as increase/decrease in volume per unit change in temperature.

6. NUMERICAL ANALYSIS

Numerical analysis can be carried out with any available finite element/finite difference software which has program for solving thermo-mechanical analysis. In the present analysis, the writers used micro-computer program FLAC - *F*ast *L*agrangian *A*nalysis of *C*ontinua[12]. FLAC provides a thermo-mechanical option which simulates the transient flow of heat in materials and the resultant development of thermally induced stresses.

The detailed description of analysis procedure is beyond the scope of the present paper. It generally follows the procedure outlined by Wallace and Lytton[13] and is discussed in detail by Sapkota et al.[14]. The analysis steps through time as the thermal option in FLAC wets up or dries out the subgrade, pausing at time intervals to reanalyze the stresses and displacements with new value of stiffness and strength using the mechanical option in FLAC. Thus FLAC is ideally suited for such operation because it has an internal language, FISH, which enables variables such as temperature and stresses to be accessed at any thermal or mechanical step and material properties modified accordingly.

The mechanical behavior of soil is analyzed by assuming that the soil response can be modeled by an incremental linear elastic-plastic model in which plastic failure criterion is the Mohr-Coulomb shear strength law. At each interval of moisture flow and mechanical analysis the soil strength and stiffness are adjusted with new values of the soil moisture suction and stresses at that time for example, using Equation 6 and **Figure 4** for swell analysis, and Equation 8 and **Figure 5** for shrinkage analysis.

(1) Typical Pavement/Subgrade Situation

Figure 7 illustrates a typical situation. Analysis considers initial uniform dryness having total suction of 3.2 kPa for swell analysis. The analysis begins when the right edge suddenly wets up due to intense rainfall and maintains a continuous supply of water at a suction of 1.5 kPa. For shrinkage analysis, the initial moisture condition of subgrade belongs to the wetness reached at the end of two months modeled wetting in the swell analysis. And analysis begins with the continuous drying of the right edge.

For both swell and shrinkage analyses, the subgrade section is considered as an intact soil mass without any major cracks and fissures. In case of swell, such cracks tend to relieve swell pressure during initial crack closure. The effect of minor cracks and fissures would be directly included in the swell and shrinkage parameters measured in swell and shrinkage tests respectively of undisturbed specimens.

Figure 7 also shows the dimensions of the pavement and subgrade sections together with the grids of finite difference and the displacement boundary conditions of the section. Regarding flow boundary, all the three edges of subgrade section are considered as no flow boundary except the vertical right edge through which moisture enters. The analysis followed a plane strain analysis in which strain along the road length is considered zero.

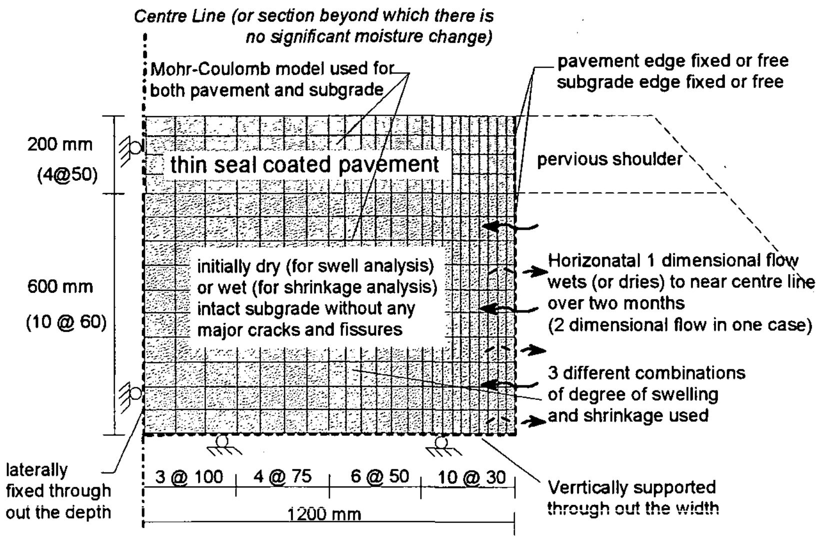


Fig.7 Features of typical pavement/subgrade situation considered

(2) Material Properties

The following properties are used for the present analysis with both the clay subgrade and unbound gravel pavement modeled as linear elasto-plastic, Mohr-Coulomb materials.

a) Subgrade Properties

Constant properties for both swell and shrinkage analyses are: Poisson's ratio $\nu = 0.3$, mass density = 1.7 t/m^3, friction angle $\phi = 20°$, and dilation angle $\psi = 0°$; and variable properties are:

swell analysis: the initial values representing stiff clay at unwetted state under drained condition with Young's modulus = 5 MPa, cohesion = 60 kPa and tensile strength = 2 x cohesion = 120 kPa.

shrinkage analysis: initial values of Young's modulus, cohesion and tension of subgrade elements depended on the value of log total suction of these elements. The suction values belong to the two months wetting carried out in the swell analysis. With these suction values, the program computed initial stiffness of these elements by applying Equation 8 with appropriate β_c from **Figure 5**.

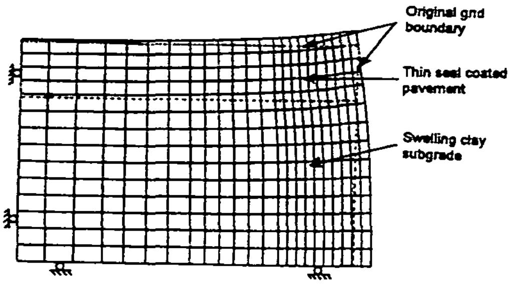
For both swell and shrinkage analyses the strength parameters: cohesion and tensile strength are varied linearly with log suction. The minimum value of cohesion at wet saturated state is taken as 5.0 kPa and tensile strength considered as twice the cohesion.

For swell analysis of subgrade three sets of combination of magnitude of swell parameters as: γ_h = 0.035 and 0.07, and γ_σ = 0.04 and 0.08 are used to cover wide range of reactive clays from medium to extremely high degree of swell and swell suppression. And for shrinkage analysis, two sets of combination of magnitude of shrinkage parameters as: λ_h = 0.04 and 0.06, and λ_σ = 0.01 and 0.06 are used to study the effect of medium to high shrinking clays. Regarding flow variables, the thermal properties discussed in the earlier section on thermal analogy, are used together with the temperature dependent thermal conductivity described by Equation 9.

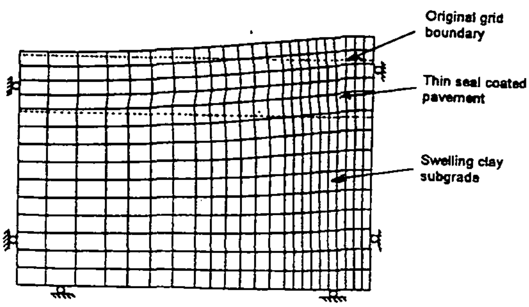
b) Pavement Properties

Young's modulus E = 5 MPa, Poisson's ratio ν = 0.3, mass density = 2.2 t/m^3, cohesion = 10 kPa friction angle ϕ = 40°, dilation angle ψ = 0°, and tensile strength = 10 kPa. This pavement modulus seems low when compared with the resilient moduli used for pavement design but it is describing different loading condition in which tensile forces are causing critical, low tensile stresses in the pavement. The first author[9)] had conducted measurements on tensile strength of seal coat surfaced pavement by using a *prototype model of seal coated crushed rock base*. The results of initial test showed a typical magnitude of about 5.5 kPa which confirms that the preceding value of tensile strength is of the right order of the magnitude but about twice the measured value.

Regarding the treatment of interface existing between pavement and subgrade, the analysis did not apply interface elements in swell analysis because of difficulty in accessing interface properties. However, without an interface subgrade shrinkage resulted vertical stretching of pavement elements leading to the unwanted increase in the thickness of pavement. This was because of lower modulus of pavement material. Therefore, an interface was applied with the interface bond strength same as the strength of stiff clay. (Trial analysis with increasing the modulus

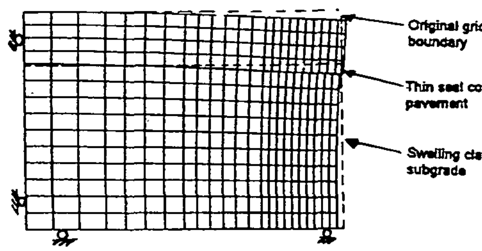


(a) with free lateral displacement boundary for both pavement and subgrade



(b) lateral fixity for both pavement and subgrade

Fig. 8 Pavement distortion after wetting for a period of two months (Broken lines show the original section)



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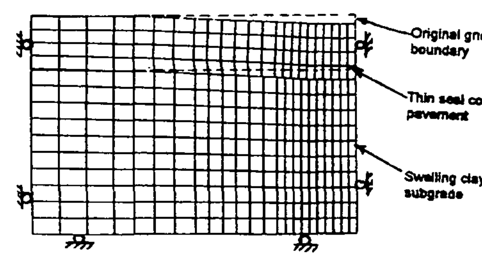

(b) lateral fixity for both pavement and subgrade

Fig. 9 Pavement distortion after drying for a period of two months (Broken lines show the original section)

showed an early tensile failure of pavement elements, and the increase in tensile strength was not possible because the applied value is already in the upper range.) The effect of presence of this interface is discussed in the succeeding section. (Note that the swell analysis results did not show any adverse nature without interface element.)

(3) Typical Results

a) Effect of Subgrade Swelling

Figures 8 (a) and (b) illustrate how a pavement undergoes distortion when the underlying swelling clay subgrade deforms with increasing volume due to continuous monotonic wetting for a period of two months. Figures also illustrate the critical role of lateral fixity in the magnitude and shape of surface heave, and pattern of lateral stressing of pavement. Results showed that with extremely high swelling clay subgrade (γ_h = 0.07 and γ_σ = 0.08), the pavement surface heave reaches to a value of 56 mm for free right edge and 84 mm for fixed right edge for both pavement and subgrade. For the same wetting period, with medium swelling clay subgrade (γ_h = 0.035 and γ_σ = 0.04) the surface heave reduces to 27 mm for free and 29 mm for the fixed lateral displacement boundaries. These values of computed surface heave fall within the range of reported field observation, thus reveal that the analysis procedure gives reliable result.

b) Effect of Subgrade Shrinkage

Figures 9 (a) and (b) illustrate the response of pavement against the shrinkage of underlying reactive clay subgrade due to continuous monotonic drying for a period of two months. Results showed that with high shrinking clay subgrade (λ_h = 0.06 and λ_σ = 0.02), the pavement edge subsides to a value of 40 mm for free right edge and 34 mm for fixed right edge for both pavement and subgrade. For the same wetting period, with medium clay subgrade (λ_h = 0.04 and λ_σ = 0.01) the surface subsidence reduces to 27 mm for free and 23 mm for the fixed right edge.

Note that during the analysis some difficulties on transmission of subgrade effects to the pavement were observed at the latter stage of drying due to separation of interface provided between subgrade and pavement. Such separation was attributed to the improper magnitude of interface stiffness and strength as well as the limitation of the computer program in dealing interface elements. Solution to this problem has become part of an ongoing research.

(4) Parametric Study

Study of the analysis results showed that the following parameters play critical role in the subgrade swell and shrinkage processes and consequent pavement response.

Lateral Fixity: Results of both the swell and shrinkage analyses for example, **Figures 8** and **9** demonstrated that the choice of lateral fixity of the outer edge of subgrade and shoulder critically effects the degree of edge heave and subsidence. In practice the free subgrade condition could result from existing crack in the subgrade or narrow width of outer shoulder with steep verge, and the fixed right edge results from retaining walls on the sides or a relatively wide compacted shoulder.

The behavior of a constrained pavement under subgrade swell is similar to a cantilever over hang with tension on the upper surface. This suggests that there may be merit to introduce a flexible water proof joint in the outer edge of pavement by using unbound gravel shoulder material separated from the pavement by an inclined spray seal surface. Such a detail has already been used in Western Queensland in Australia, to control the lateral penetration of water from the shoulder into the pavement and sub-base[2)].

Period of Wetting: Both surface heave and subsidence increase progressively, and extend inwards across the pavement as time progresses. Detailed results showed that both the vertical and lateral stresses developed in the subgrade during swelling were high in the initial stages and decrease gradually as the wetting progresses. This is attributed to the higher degree of constraint offered by stiffer, drier surrounding material early in the process. This behavior was opposite in the shrinkage analysis as at earlier stage soil was wet and soft, and resulted substantial initial straining with lower stress development.

Magnitude of Swell and Shrinkage Parameters: With a free outer edge for lateral displacement and with γ_σ = 0.04, an increase in free swell parameter γ_h from 0.035 to 0.07 resulted a rise in edge heave from 29 mm to 65 mm. Without changing the γ_h increase in swell suppression parameter γ_σ did not result any change. This is attributed to the low overburden pressure. Similarly with the shrinkage analysis, an increase in free shrinkage parameter λ_h from 0.04 to 0.06 resulted a rise in edge subsidence from 27 mm inward compared to about 40 mm. While the effect of change in value of λ_σ was negligible.

Pattern of Subgrade Moisture Flow: Some analyses were carried with the subgrade wetting and drying from the base of pervious shoulder resulting in two dimensional moisture flow. The magnitude of edge heave as well as subsidence were found to be almost equal to that under one dimensional horizontal moisture flow.

Pavement Properties: The effect of variation of pavement material properties has not been studied in detail but the result obtained to date show that the tensile strength of the pavement material is critical. Therefore a detailed laboratory evaluation of tensile strength of the seal coated unbound crushed rock pavement is desired. Such tests should produce the key parameters necessary to include for studying the effect of different pavements on patterns of heave, subsidence and associated cracking.

(5) Verification of Procedure

The analysis procedure has been verified by comparing results obtained from the FLAC analysis of typical situations with the available closed form solutions. The detailed discussion on the verification of analysis procedure is beyond the scope of this paper. It generally follows the methods outlined by Richards[1)] and is discussed in detail by Sapkota[9)]. The verifications of thermal analogy were carried out individually for moisture flow, and for volume change due to swell and shrinkage or swell pressure and shrinkage stress development under confinement. Validations of mechanical analyses of stresses and displacement conducted by the program under elastic as well as Mohr-Coulomb plasticity model were also carried out. Overall, the present analysis procedure using the thermo-mechanical option of the program, furnished promising results by presenting analysis results in close agreement with that obtained from the closed form solutions.

7. CONCLUSION

The work has illustrated the complex nature of swelling and shrinkage of reactive clay subgrades and its effect on overlying pavement. With the application of simplified description of swelling and shrinkage, the work could highlight critical parameters required to be considered in an analysis, and could identify some important distinctions such as the difference between elastic modulus under load and swell suppression and shrinkage compression moduli. The range of values of critical parameters has been determined for parametric studies while the work strongly recommends laboratory tests to obtain the values of these parameters for field analyses.

The thermal analogy which is used in this paper, produces a simplified, accessible numerical analysis procedure to analyze a typical situation of road pavement over reactive clay subgrade. It has demonstrated how the use of a readily available thermo-mechanical analysis program can develop an insight into the response of overlying pavement subjected to the swelling and shrinkage of a range of reactive clay subgrades. The study on the analysis results showed that some factors such as lateral fixity, wetting and drying periods, and magnitude of swell and shrinkage parameters significantly affect the pavement response.

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反応性路床土の膨張・収縮に対する薄層シールコート舗装の応答

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薄層シールコート舗装とその下層にある反応性路床土との間の相互作用の有効かつ適切な研究を行うための解析方法が開発された．この手法は，水分拡散と体積変化の熱類推法における，膨張・収縮特性を簡易化することによって，熱力学的応用解析プログラムを膨張・収縮土の解析に直接使用することができるようにしている．

この論文は，この手法の開発と，典型的な反応土上の舗装の解析への応用について概説したものである．その結果，舗装の応答に影響を与える要因が明らかになった．