MOISTURE MOVEMENT IN HIGHWAY PAVEMENT STRUCTURES COUPLED TO SOIL-ATMOSPHERIC FLUXES

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ABSTRACT
The performance of a highway pavement structure is influenced by the moisture conditions of the subgrade. Changes in the water content of the subgrade are related to dynamics of the soil-atmosphere fluxes through the highway structure. Preliminary modeling of moisture movement through a typical Saskatchewan highway pavement structure is undertaken using coupled heat and mass transfer modeling. The purpose of the modeling is to identify the influence that the base and sub-base have on causing progressive wetting of the subgrade as a result of climatic cycles of wetting and drying. This study is only a preliminary study in a long-term investigation into the impact of shoulder paving and side-slope steepness on moisture ingress below the pavement structure.

RÉSUMÉ
L'exécution d'une structure de trottoir de hihgway est influencée par les conditions d'humidité du subgrade. Les changements dans le contenu d'eau du subgrade sont relatés à la dynamique des flux de sol-atmosphère par la structure de route. Le modilage préliminaire de mouvement d'humidité par une structure de trottoir de hihgway de Saskatchewan typique est entrepris l'utilisation chaleur couplée et le transfert massif modelant. Le but de modelage sera obligé à identifier l'influence que la base et sub-base ont sur causant progressif se mouille du subgrade à la suite des cycles climatiques de se mouille et le séchage. Cette étude est seulement une etude preliminaire dans une étude à long terme examinant l'impact de paver d'épaule et la raideur de pente de côté sur l'entrée d'humidité au-dessous de la structure de trottoir.

1. INTRODUCTION

The performance of pavements over clay rich subgrades is strongly influenced by the water content of these soils. Increases in water content following construction can lead to a loss of strength, often aggravated by dynamic pore-pressures produced by traffic loading. It is not difficult, particularly in a semi-arid region, to construct a strong subgrade at low water contents. However, highway pavement structures are exposed to precipitation, such as snow and rain, which can cause progressive wetting of the sublayers especially in the subgrade layer.

Progressive wetting can occur as a result of cracks in the asphalt layer however water ingress can also occur from the unpaved shoulders and ditches adjacent to the pavement structure. Given the low hydraulic conductivity of the underlying clay subgrade the preferred pathway for water to escape from the highway structure would be by drainage through the base and sub-base towards the ditch. The hydraulic properties of the unsaturated base and sub-base are such that they allow ready infiltration under precipitation events but have limited capability for drainage or drying during extended evaporative cycles. This results in a net ingress of moisture during each cycle of wet and dry climatic conditions. In early spring conditions may also develop in which the base and sub-base below the asphalt surface thaw rapidly while the shoulder remains frozen and covered with snow. This may cause 'ponding' of water in unfrozen sections of the granular soil adjacent to the asphalt surface during spring melt.

The objective of this study is to simulate the coupled heat and moisture interactions between a typical highway pavement structure and the climate in order to obtain preliminary estimates of the long-term heat and moisture balances and fluxes within various elements of the highway pavement structure.

2. FLOW THROUGH UNSATURATED SOILS

Water migration near the ground surface can occur in the form of either liquid water or water vapour. The vapour pressure in the soil is a function of soil temperature and soil suction, therefore a system of equations is required to describe the flow of liquid water, water vapour and heat in the soil under transient conditions (Wilson et al, 1994).

2.1. Moisture Flow

Moisture flow through a porous medium can be described through equations developed by Richards (1931), Philip (1957a) and Lam (1983). The driving force for the flow of liquid water in both unsaturated and saturated porous mediums is a hydraulic head gradient. The flow of liquid water can therefore be described using Darcy's law, which is illustrated in Eq. 1.

$$q_1 = -k_w \frac{\partial h_w}{\partial y} \qquad [1]$$

where q_1 is the volumetric liquid water flux, k_w is the hydraulic conductivity, h_w is the hydraulic head (i.e $(u_w/p_wg)+y$), u_w is the pore-water pressure, y is the position, g is the acceleration due to gravity, and p_w is the density of liquid water.

Water vapour can be transported by either the diffusion of water molecules due to a gradient in the partial pressure of water vapour or the advection of water molecules in the vapour phase with the bulk pore-air flow caused by a gradient in the total air pressure. In an unsaturated soil system water vapour has the ability to flow between the liquid phase and the vapour phase across the air-water interface. This interphase liquid water flux must be accounted for to maintain a mass water balance. Fick's law is used to describe the flow of water vapour, which is illustrated in Eq. 2

$$q_v = -D_v \frac{\partial P_v}{\partial y} \qquad [2]$$

Where q_v is the water vapour flux, P_v is the partial pressure due to water vapour and D_v is the diffusion coefficient of the water vapour through soil (Bruch, 1993; Wilson et al, 1994 and Swanson 1995).

The combined transient flow of liquid water and water vapour in an unsaturated porous medium may result in a change in the volume of water. Combining Darcy's law and Fick's law and with the constitutive relationship for volume change results in the equation for one-dimensional transient moisture flow, shown in Equation 3.

$$\frac{\partial h}{\partial t} = C_w \frac{\partial}{\partial y}\left(k_w \frac{\partial h_w}{\partial y}\right) + C_v \frac{\partial}{\partial y}\left(D_v \frac{\partial P_v}{\partial y}\right) \qquad [3]$$

Where C_w is the modulus of volume change with respect to the liquid phase and C_v is the modulus of volume change with respect to the vapour phase. Equations 4 and 5 describe C_w and C_v respectively.

$$C_w = \frac{1}{\rho_w g m_2^w} \qquad [4]$$

$$C_v = \frac{1}{(\rho_w)^2 m_2^w}\left(\frac{P+P_v}{P}\right) \qquad [5]$$

Where m_2^w is the slope of the $(u_a - u_w)$ versus water volume curve when $(\sigma_y - u_a)$ is zero, $(P + P_v)P$ is a correction factor for vapour diffusion, P is the total atmospheric pressure, and P_v is the partial pressure in the soil due to water vapour (Wilson et al, 1994). Since vapour pressure is a function of temperature equation [3] must be coupled to an equation describing heat flow.

2.2. Heat Flow

There are three possible mechanisms that contribute to the heat transfer in a soil. These mechanisms include conduction, convection and latent heat transfer due to phase changes. The Fourier diffusion equation used to simulate the transfer of heat within a soil describes heat flow using conductive and latent heat transfers. The convective heat transfer mechanism is assumed to be negligible. Equation 6 shows the Fourier diffusion equation.

$$C_h \frac{\partial T}{\partial t} = \frac{\partial}{\partial y}\left(\lambda \frac{\partial T}{\partial t}\right) - L_v\left(\frac{P+P_v}{P}\right)\frac{\partial}{\partial y}\left(D_v \frac{\partial P_v}{\partial y}\right) \qquad [6]$$

where C_h is the volumetric specific heat, λ is the thermal conductivity and L_v is the latent heat of vaporization for water (Wilson et al., 1994).

2.3. Coupled Flow

In the moisture and heat flow governing equations it can be seen that there are three unknown parameters; pressure, temperature and vapour pressure. Therefore a third relationship is required to solve these governing equations (Joshi, 1993; Geoslope, 1991).

The coupling of moisture and heat flow can be accomplished through the soil vapour pressure term, Pv, which is common to both the heat and moisture flow governing equations. The vapour pressure within a soil is calculated on the basis of total suction in the liquid phase using the relationship developed by Edlefson and Anderson (1943), which is shown in Eq. 7.

$$P_v = P_{vs} h_r \qquad [7]$$

Where P_v is the partial pressure due to water vapour within the voids of the unsaturated soil, P_{vs} is the saturation vapour pressure of the soil water at the soil temperature, T, and relative humidity is defined as hr (Wilson et al, 1994; Swanson, 1995 and Bruch, 1993).

3. MODELLING CONDITIONS

Vadose/w is a finite element software product that analyzes flow from the environment, across the ground surface, through the unsaturated vadose zone and into the local groundwater regime. The key to modeling in the vadose zone is accurate predictions of the surface flux boundary. Vadose/w computes this surface flux boundary by coupling ground heat, mass and vapour flow with actual climate data. Both hydraulic and thermal properties are required to solve the finite element equations (Geoslope, 2004).

3.1 Hydraulic Properties

The hydraulic properties required are the functions of volumetric water content and hydraulic conductivity expressed in terms of negative pore water pressure (suction) for each of the highway pavement materials. The material gradation curves were used for preliminary estimates of the hydraulic properties for the base and sub-base layers. The asphalt hydraulic properties were based on cored samples collected from typical Saskatchewan roadways.

3.1.1 Soil Water Characteristic Curves

The soil water characteristic curves for the soils used in this simulation are shown in Figure 1. These curves for the base and sub-base were estimated from measured grain size curves using the method of Arya and Paris (1981) provided in Vadose/w (Geo-slope, 1991). The asphalt was assumed to have negligible amounts of water storage over the entire simulated suction range.

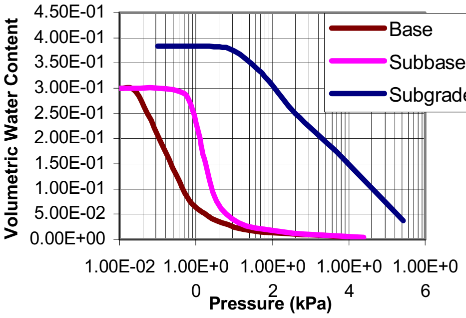


Figure 1. Soil Water Characteristic Curves

3.1.2 Hydraulic Conductivity

The unsaturated hydraulic conductivity of any soil can be obtained through direct measurement or can be estimated from the soil water characteristic curve (Geoslope, 1991; Swanson, 1995). The hydraulic conductivity functions for this preliminary simulation were estimated using the method proposed by Van Genuchten (1980) as contained in the Vadose/w software. The saturated hydraulic conductivity values for the base and sub-base were estimated from Hazen's equation (Holtz and Kovacs, 1981). The saturated hydraulic conductivity of the asphalt layer was measured in the laboratory. Asphalt has a very low saturated hydraulic conductivity of 7E-7 m/day. The hydraulic conductivity functions for the base, sub-base and subgrade materials are illustrated in Figure 2.

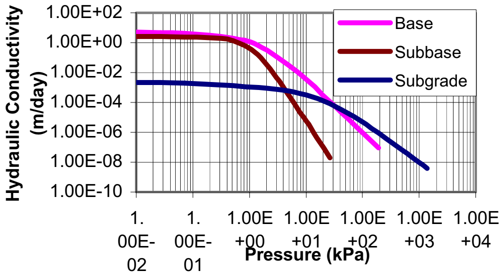


Figure 2. Hydraulic Conductivity Functions

3.2 Thermal Properties

The thermal properties required within Vadose/w include the thermal conductivity and the specific heat versus volumetric water content. The thermal properties are required to solve the conductive heat transfer component of the coupled finite element equations.

The heat capacity of a material is defined as the quantity of heat required to raise the temperature of the material by a unit degree (Geoslope, 1991). All thermal properties for this preliminary study estimated from the soil mineral specific heat and thermal conductivity along with the soil water characteristic curves using methods available within Vadose/w.

3.3 Geometry

Highway pavement designs in Saskatchewan are standardized by Saskatchewan's Department of Highways and Transportation. The highway design used for this study is similar to that of a typical flexible pavement system in Saskatchewan. This design consists of an asphalt surface layer underlain by a base layer, a sub-base layer and a subgrade layer. The surface geometry and layer thicknesses are illustrated in Figure 3. A 0.2 meter organic layer was used on the surface of the subgrade across the backslope and ditch surfaces. This organic layer is a clay/silt loam used to sustain the growth of vegetation.

3.4 Boundary Conditions

The boundary conditions required for the model include an initial boundary condition and transient boundary conditions. The initial boundary condition applied to the system includes an initial temperature of 6°C over the entire highway pavement system with a water table located at the base of the system with assumed initial hydrostatic pressures up to a maximum suction of approximately 10 kPa. This initial boundary condition represents a starting point for the transient solution.

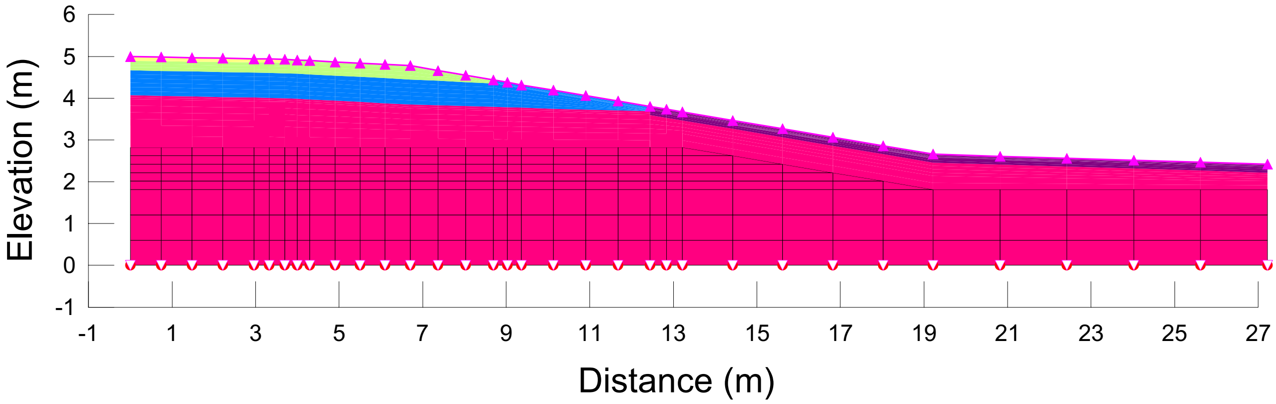


Figure 3. Geometry and Boundary Conditions of a Typical Saskatchewan Roadway Structure

The transient boundary conditions include a lower boundary condition and an upper boundary condition. The lower boundary condition applies a temperature of 4.5°C and a pressure of zero (head equal to 5m) along the base of the subgrade representing a long-term fixed water table condition. The upper boundary condition applied to the highway pavement system was a climate boundary. This climate boundary consists of data for a typical year in Saskatchewan. Saskatchewan has an annual precipitation of 350 mm including 260 mm of rainfall and 90 cm of snowfall. The average annual potential evaporation is much greater than precipitation and is about 450 mm. The amount of frost-free days in Saskatchewan varies with location. For example the Saskatoon area has about 111 frost-free days where Regina sees 123 frost-free days and the valley lands along the South Saskatchewan River ranges from 150 to 160 frost-free days. The asphalt and exposed base or sub-base shoulder is unvegetated while a vegetation boundary is applied across the ditch slopes. Figure 3 illustrates the boundary conditions applied to the highway pavement system.

The vegetative properties used within Vadose/w consist of a typical mix of grasses. The typical grass mix for Saskatchewan uses 5 grasses proportioned equally. This grass mix includes Brome Grass, Timothy, Crested Wheat Grass, Dahurian Wild Rye and Orchard Grass. The growing season for this mix is between May 15 and August 15. The maximum root depth of this grass mix ranges between 3 to 4 meters below the surface loam layer. The moisture limiting function indicates when the ability of the grass to draw water begins to shutdown and when it can no longer draw water. This function is illustrated in Figure 4.

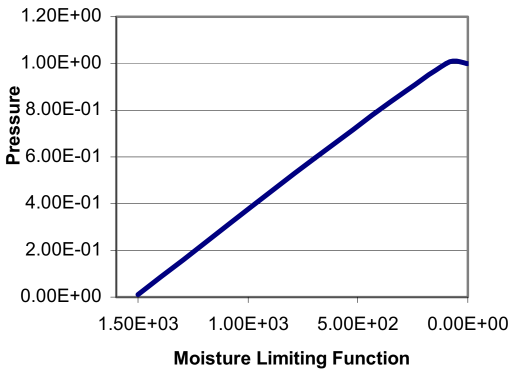
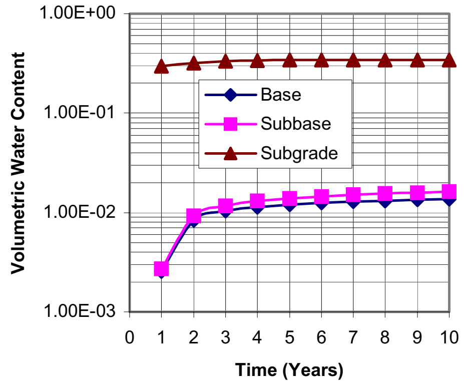


Figure 4. Plant Moisture Limiting Function for Typical Saskatchewan Grass Mix

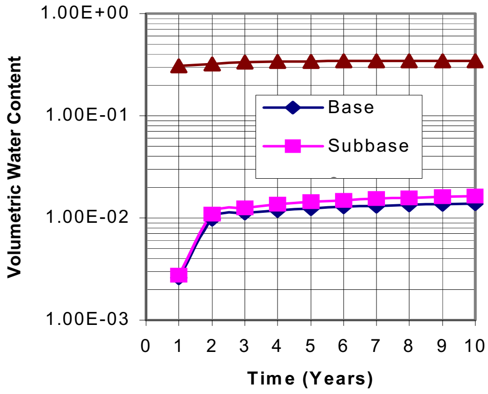
4. RESULTS-

The initial objective of the model was to establish a long-term moisture equilibrium condition in which the water fluctuations and water balance are the same over subsequent simulation years. The long-term equilibrium condition was reached after ten years of simulations using the 'typical' climatic data set.

The volumetric water content increases at different rates for the various sublayers in a highway pavement structure, as shown in Figure 5. After the first year of simulating climatic cycles of wetting and drying, the volumetric water contents within the base/sub-base and subgrade under the centerline of the highway structure were approximately 0.3% and 30%, respectively. The volumetric water contents at the edge of the shoulder were quite similar. After reaching long-term equilibrium conditions the water contents of the base/subbase and subgrade rose to approximately 1.5% and 34%, respectively below the centerline and the edge of the shoulder of the highway pavement structure. Figure 6 illustrates the moisture contours of the equilibrium year in the summer months.



(a)



(b)

Figure 5. Volumetric Water Contents at (a) the Edge of Shoulder and (b) the Centerline of Pavement Structure

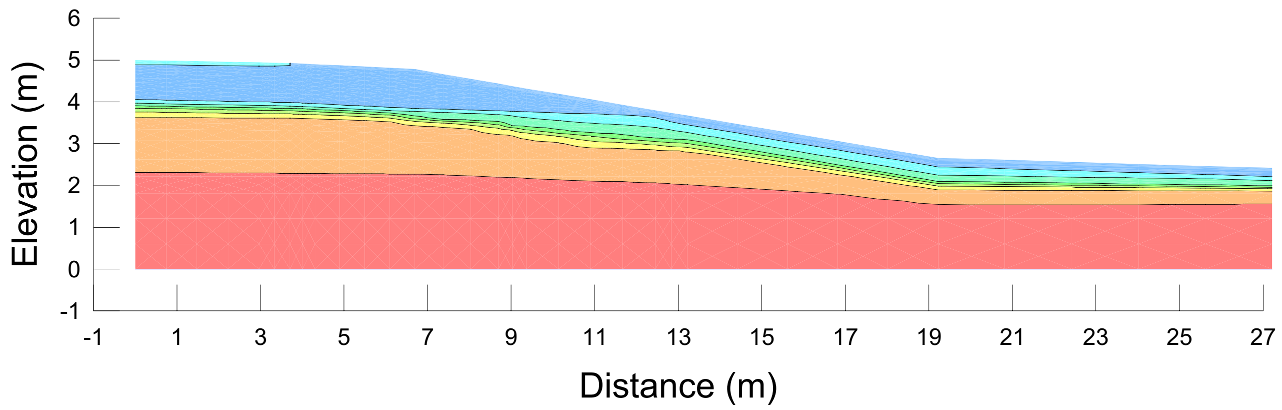


Figure 6. Moisture Contours for 'Equilibrium' Year in Summer Months

The water contents within the granular materials tend to move toward a 'residual' condition at which the suctions are quite low. The suction would be similar just above and below the interface between the base/sub-base and the subgrade, consequently, at these low suction values the water content in the subgrade can become quite elevated and approach saturation.

The annual cumulative boundary fluxes across the surface of the base and sub-base are shown in Figure 7. The liquid fluxes decrease rapidly while the vapour fluxes increase slightly as the pavement structure wets up. Large liquid fluxes into the base and sub-base occur within the first year after which the annual cumulative fluxes soon begin to stabilize at zero (annual balance of net vapour and liquid fluxes). The base and sub-base layers promote liquid influx, but do not provide sufficient outflux to keep the subgrade layer from wetting up. Majority of outflux for a highway pavement system occurs from the vegetated ditch and backslopes.

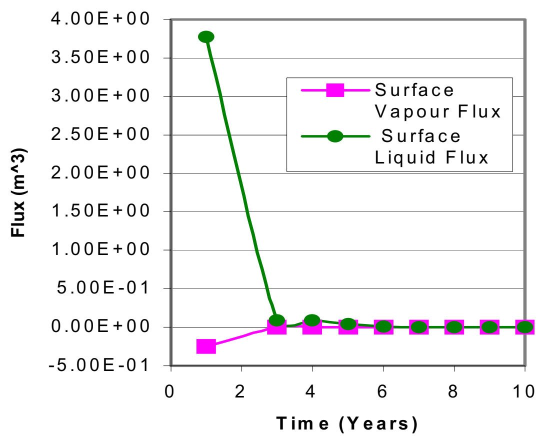


Figure 7. Cumulative Boundary Flux at the Base and Sub-base Surfaces

5. CONCLUSIONS & RECOMMENDATIONS

This study is preliminary in nature but provides some insights on the mechanisms responsible for progressive wetting of highway structures in semi-arid environments in Western Canada. Additional work is required to refine the simulations and carry out sensitivity studies; however, it appears that design decisions such as shoulder paving or flattening of vegetated backslopes are likely to alter the long-term water balance and distribution of moisture within pavement structures.

This initial model demonstrated that progressive wetting of the granular layers can occur as a result of the infiltration of liquid water into the shoulder without a mechanism to remove this water through evapotranspiration. The vegetated shoulders do provide a mechanism for removing excess water from below the pavement structure but the efficiency of this mechanism is restricted by the relatively low hydraulic conductivity of the subgrade, which limits the extent to which water can be drawn from below the pavement structure.

The base and sub-base layers affect the amount of moisture ingress seen in the subgrade layer of a highway pavement structure. Moisture moves quickly through the base and sub-base into the subgrade causing elevated moisture contents to be developed in the subgrade layer within the first five years of service.

This preliminary study precedes further work based on changes in geometry and material properties. The material properties of the asphalt and base layers will be modified after testing of sampled cores is completed to obtain a more accurate long-term moisture equilibrium condition. This modification will be compared to modifications of the long-term moisture conditions due to changes in the geometry of the highway structure. The geometric changes focus on paving the shoulder, adding a binder layer across the surface of the base layer for both an unpaved and paved shoulder condition, changing the backslope properties of the highway pavement structure and the influences of constructing a double lane highway pavement structure over a single lane highway pavement structure.

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