THE PREDICTION OF THERMALLY-INDUCED DESICCATION IN GEOSYNTHETIC CLAY LINERS USED IN LANDFILL BASAL LINER APPLICATIONS

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ABSTRACT: Studies have shown landfill barrier systems incorporating composite liners comprised of geosynthetic materials such as geomembranes and geosynthetic clay liners to be effective in reducing outward advective flow from the landfill, resulting in decreased contaminant loading on the surrounding environment. However, questions regarding their long-term performance are sometimes raised, especially with consideration to the potentially high temperatures basal temperatures resulting from exothermic decomposition occurring in the overlying waste mass. The thermal gradients that may be generated by such heating create a risk of outward moisture movement and desiccation of the lining system, with potential effects on the long-term performance of the geosynthetic clay liners component. The authors have previously reported experimental work addressing this issue. This paper addresses the second phase of the study – the prediction of desiccation. A numerical model is being used to investigate the influence of various conditions on the desiccation behaviour of geosynthetic clay liners. The results of a series of numerical simulations using a variety of input parameters to represent the pertinent thermal, hydraulic and mechanical properties of the soil and geosynthetic components of a composite liner system are presented. The distribution of temperature and water content over time when subjected to a range of initial and boundary conditions is examined and compared with the results of laboratory tests. The implications of these results on the design of composite basal liners containing geosynthetic clay liners are discussed .

1 INTRODUCTION

Composite liners comprised of geosynthetic materials such as geomembranes and geosynthetic clay liners are increasingly being used in landfill basal liner applications due to their effectiveness in reducing outward advective flow. Due to the relatively short period of time during which geosynthetics have been incorporated in landfill designs, questions regarding their long-term performance are sometimes raised. This is especially true when consideration is given to the potentially high temperatures that may be encountered at the base of a landfill due to exothermic decomposition occurring in the overlying waste mass.

Organic material typically accounts for 50-70% of the dry unit weight of municipal solid waste (Barone et al., 2000). The biological decomposition of organic matter is an exothermic process that results in significant heat generation. Under certain conditions, the heat generated by these reactions may raise the temperature at the landfill base to in excess of 50 °C. The thermal gradients thus created cause water vapour to diffuse from areas of higher temperature to areas of lower temperature, while liquid water will flow in the opposite direction under matric potential gradients. The net effect of these and other mechanisms may be a net flux of water away from the top of the composite lining system, creating the potential for desiccation of the mineral component of GCLs.

Numerical models have been developed by Döll (1996), Thomas and Missoum (1999) and Zhou and Rowe (2003) to describe the thermal desiccation behaviour of soils. Some experimental investigations into the desiccation behaviour of GCLs in landfill cover applications (e.g. Sporer and Gartung, 2002) have been performed, however little investigation has been done into the thermal desiccation behaviour of these materials in landfill basal liner applications.

The authors have previously reported experimental work addressing this issue. The current paper addresses the extension of this experimental work to the prediction of desiccation. The numerical model developed by Döll (1996) is being used to investigate the influence of various conditions on the desiccation behaviour of GCLs. The results of a series of numerical simulations using a variety of input parameters to represent the pertinent thermal, hydraulic and mechanical properties of the soil and geosynthetic components of a composite liner system are presented. The distribution of temperature and water content over time when subjected to a range of initial and boundary conditions is examined and compared with the results of laboratory tests. The implications of these results on the design of composite basal liners containing geosynthetic clay liners are discussed.

2 INVESTIGATIVE PROGRAM

The design of an experimental program involving medium-scale laboratory tests has been previously reported by the authors (Southen and Rowe, 2002; Southen et al., 2002). These tests form the basis of the investigative program that is currently being extended into numerical modelling. The numerical model developed by Döll (1996) is used in this report in an effort to simulate the results obtained experimentally. This section presents a brief description of the laboratory experiments, followed by a description of the numerical model. Finally, the procedure followed in numerically modelling the experimental results is presented.

2.1 *Laboratory Experiments*

To investigate the desiccation behaviour of GCLs, a series of medium-scale laboratory tests were performed. The goal of these tests was to simulate reasonable worst-case landfill conditions as accurately as possible. The tests utilized columns 1m in height and 30cm in diameter. These columns were filled with a silty sand soil representative of a suitable subsoil for landfill construction. On top of this soil was placed a composite liner comprised of a GCL and a HDPE geomembrane. The top and bottom of the column were sealed and heat and pressure were applied to the upper surface, while the lower surface was not heated. Insulation was provided around the exterior of the column to ensure that the thermal gradient developed through the system was one-dimensional. Further details and results of these experiments are reported elsewhere (Southen and Rowe, 2002; Southen et al., 2002; Southen and Rowe, 2004).

2.2 *SUMMIT Numerical Model*

The numerical model SUMMIT is used in the present study to investigate the behaviour of composite liners comprised of geosynthetics subjected to thermal gradients. This model was developed by Döll (1996) specifically for the simulation of desiccation of mineral liners in landfills with heat generation. SUMMIT solves a system of nonlinear equations for heat and mass transport using mesh-centered, fully implicit finite differences. Two partial differential equations are solved, one an extension of the Richards equation for the transport of water in liquid and vapour form and one for the transport of heat. The equations are discretized using in their mixed forms and solved using simple time stepping (Picard iteration). Unknown moisture and heat contents are related to the dependent variables matric potential and temperature using a Taylor expansion. The formulation of the equations is based on the work of Philip and de Vries (1957) and Milly (1984). Further details of the model are provided by Döll (1996).

The SUMMIT model uses the water retention and unsaturated hydraulic conductivity functions of van Genuchten (1980). The equation for the water retention function (soil-water characteristic curve) is given as Equation 1, while the equation for the unsaturated hydraulic conductivity function is given in Equation 2.

$$\theta_l(\psi,T_0)=\theta r+\frac{\theta s-\theta r}{\left(1+|\alpha\psi|^n\right)^m} \tag{1}$$

where,
θ_l = volumetric liquid water content
ψ = matric potential (cm)
θ_r = residual water content (m^3/m^3)
θ_s = saturated water content (m^3/m^3)
α = van Genuchten parameter (1/cm)
n,m = van Genuchten parameters (-); m = 1-1/n

$$K_u(S,T_0)=K_{sat}S^l\left[1-\left(1-S^{1/m}\right)^m\right]^2 \tag{2}$$

where,
$S = (\theta_l - \theta_r) / (\theta_s - \theta_r)$
K_{sat} = saturated hydraulic conductivity (m/s)
l = van Genuchten-Mualem parameter (-)

In addition to these parameters, SUMMIT also requires the user to specify the porosity, n_p, the volumetric fractions of quartz, other minerals and organic matter (f_Q, f_{AM}, f_{OM}) and the thermal vapour diffusion enhancement factor, F_v. Initial temperature and matric potential must be specified, as well as moisture flow and heat flow boundary conditions.

2.3 *Modelling Procedure*

Parameters for the soil-water characteristic curve (α, n, θ_s, θ_r) were obtained through a series of laboratory tests using pressure plate and membrane extractors previously reported by Southen and Rowe (2004). Porosity and initial temperature and matric potential were based on values measured during the course of the experimental set-up. The saturated hydraulic conductivity was determined from laboratory tests. The parameters a and n for the unsaturated hydraulic conductivity function were taken as the same as those used for the water characteristic curve, as discussed by van Genuchten (1980). The remaining parameters were varied to obtain a good fit with the experimental data for one test. The parameters obtained from this study were then used to predict the behaviour of two subsequent tests. The results of this investigation are discussed in the following section.

3 RESULTS

3.1 *Parametric Study for Test 1*

A laboratory experiment was conducted on a 1m high column of silty sand overlain by a composite liner comprised of a GCL and a geomembrane. A summary of the material properties and pertinent test details for Test 1 is presented in Table 1. The parameters used for modelling the experiment are given in Table 2.

Table 1 Material properties and test details for Test 1

Subsoil Type	Silty sand
Initial w/c	0.045 (by weight)
Initial dry density	1.77 g/cm^3
GCL Type	Woven PP carrier GT (105 g/m^2) Nonwoven PP cover GT (200 g/m^2) Granular sodium bentonite (4340 g/m^2)
Initial GCL w/c	1.10 (by weight)
Test duration	90 d
Temperature gradient	26 °C/m
Surcharge	~5 kPa

Table 2 Model parameters

Silty Sand		GCL	
n_p	0.35	n_p	0.86
θ_{init}	0.080	θ_{init}	0.68
ψ_{init}	-449 cm	ψ_{init}	-11203 cm
θ_s	0.35	θ_s	0.85
θ_r	0.005	θ_r	0.05
α	0.0112	α	0.0003
n	1.93	n	1.5
l	varies	l	varies
K_{sat}	8.0 x 10^{-7} m/s	K_{sat}	5.0 x 10^{-11} m/s
F_v	varies	F_v	varies

The volumetric water contents measured at the end of the laboratory experiment are plotted in Figure 1. A series of numerical simulations were performed with variable values of l and F_v. The best results were obtained using l_{ss} = 1.0, l_{gcl} = -6.0, $F_{v\ ss}$ = $F_{v\ gcl}$ = 1.5. The geosynthetic clay liner was modelled as an 8 mm thick layer using 40 nodes. 100 nodes used in the upper 5 cm of the silty sand and 190 nodes used for the remaining 95 cm. Nodes were evenly spaced in each region. The volumetric water contents predicted using these parameters are shown in Figure 1. It can be seen that good agreement between the experimental data and the numerical results has been obtained for both the sandy silt and GCL layers.

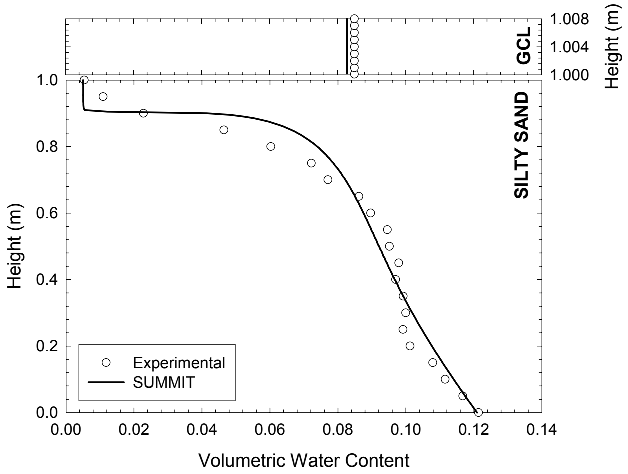

Figure 1 Test 1 volumetric water content

Figure 2 shows a comparison between the experimental and model temperatures. The fit is reasonable, although not as good as that for volumetric water content.

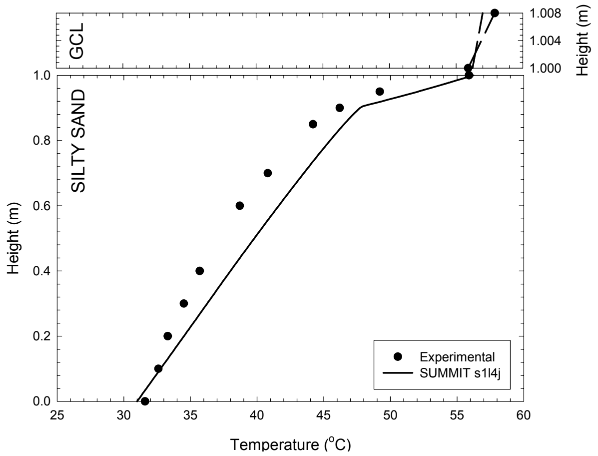

Figure 2 Test 1 temperature

3.2 *Predictions for Test 2*

Based on the good agreement between experimental and model volumetric water contents and temperatures, the model parameters shown in Table 2 were adopted for the modelling of two additional laboratory. The geometry of these tests is identical to that of Test 1, although some initial and boundary conditions are different. The most notable variation between Test 1 and Test 2 is the application of a 50 kPa surcharge to Test 2 to simulate waste overburden stress. The material properties and test details for Test 2 are presented in Table 3. Due to the slightly different initial conditions, minor modifications to the model parameters n_p and θ_s were required.

Table 3 Material properties and test details for Test 2

Subsoil Type	Silty sand
Initial w/c	0.041 (by weight)
Initial dry density	1.77 g/cm^3
Initial GCL w/c	1.05 (by weight)
Test duration	225 d
Temperature gradient	29.5 °C/m
Surcharge	50 kPa

The volumetric water contents obtained with SUMMIT are compared with experimental data in Figure 3. Reasonable agreement is noted for water contents in both the GCL and the underlying subsoil. The predicted and measured temperatures are shown in Figure 4. Again, good agreement is noted.

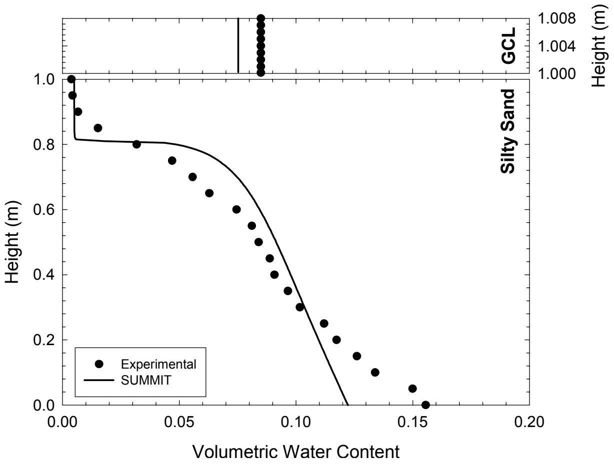

Figure 3 Test 2 volumetric water content

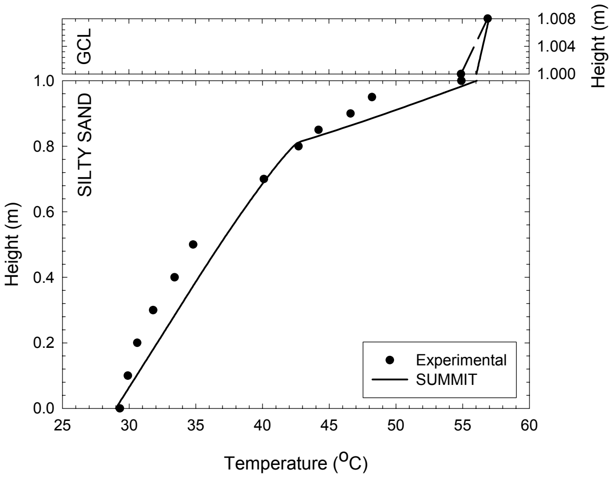

Figure 4 Test 2 temperature

3.3 *Predictions for Test 3*

As was the case for Test 2, SUMMIT was used to predict the behaviour of Test 3 using parameters obtained by fitting the numerical prediction to the results of Test 1. The material properties and test details for Test 3 are given in Table 4.

Table 4 Material properties and test details for Test 3

Subsoil Type	Silty sand
Initial w/c	0.125 (by weight)
Initial dry density	1.84 g/cm^3
Initial GCL w/c	0.80 (by weight)
Test duration	76 d
Temperature gradient	25 °C/m
Surcharge	95 kPa

Again, slight adjustments were made to the model parameters due to variations in initial water content and density. The subsoil in Test 3 was placed at a significantly higher initial water content and dry density than the other two tests and was subjected to a higher surcharge loading. The volumetric water contents obtained with SUMMIT are compared to the experimental data in Figure 5. The final water contents in both the soil and GCL are much higher than in previous tests, due to the difference in initial conditions. Reasonable agreement is noted for this case, although the predicted GCL water contents do not agree with the experimental values as well as in previous tests.

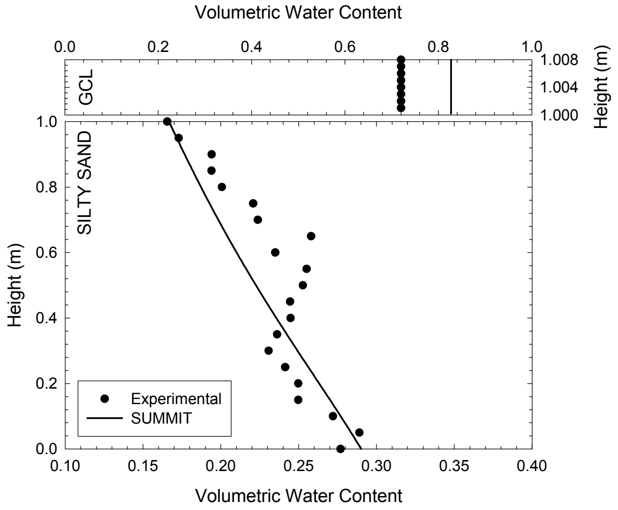

Figure 5 Test 3 volumetric water contents

The temperature within the system was also modelled using SUMMIT. The results are compared with the measured temperatures in Figure 6, and good agreement is noted.

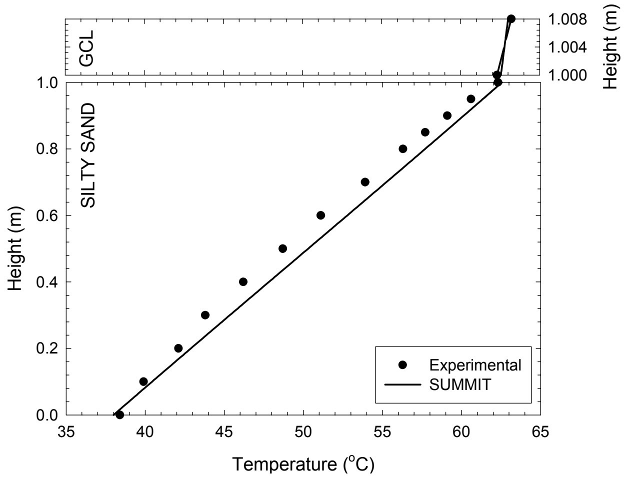

Figure 6 Test 3 temperature

4 DISCUSSION

This paper has reported the results of an investigation into the behaviour of composite liner systems containing geosynthetics when subjected to thermal gradients. The numerical model SUMMIT was used to obtain volumetric water content and temperature profiles which were compared with experimental results. Good agreement was observed for simulations using a range of initial and boundary conditions.

Based on this work, it appears that the numerical model is suitable for predicting desiccation behaviour under these conditions. The authors are currently continuing this work using the more detailed model of Zhou and Rowe (2003), which is capable of evaluating the stress state within the soil and thus better able to evaluate the risk of desiccation. Based on the good agreement demonstrated between predicted and experimental results, the study will be expanded to predict desiccation behaviour in typical field applications.

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