



Modelling of thermally induced desiccation of geosynthetic clay liners

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Abstract

Composite basal liners for municipal solid waste landfills may be comprised of geosynthetic materials such as geomembranes and geosynthetic clay liners. Exothermic degradation of organic matter or hydration of incinerator ash within the landfill generates heat within the waste mass. This creates thermal gradients through the composite liner, which have the potential to induce a net movement of moisture away from the warmer liner. The result is a potential for desiccation that may impair the long-term performance of the GCL. This paper presents the results of an investigation into the potential for desiccation of GCLs under thermal gradients using the numerical model SUMMIT. The results from a series of large-scale laboratory experiments are compared with predictions made using the numerical model in terms of volumetric water content and temperature distributions. The influence of key thermal and hydraulic parameters is discussed, as well as the ability of the model to predict situations where cracking is likely. Key limitations of the model, especially the assumption of a rigid media, are identified and discussed within the context of GCL desiccation behaviour. It is concluded that although the SUMMIT model may be suitable for general investigations of thermally induced moisture movement, a more comprehensive model is required to extend the investigation to the case of GCLs as part of a composite lining system.

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1. Introduction

Composite liners comprised of geosynthetic materials such as geomembranes and geosynthetic clay liners (GCLs) are often used in landfill basal liner applications due to their effectiveness in reducing outward advective flow. In these applications, the GCL serves as both a diffusive barrier to contaminant migration and an advective barrier to the flow of leachate through defects or holes in the overlying geomembrane (Rowe et al., 2004). When holes develop in the geomembrane with time (e.g. due to stress cracking as the geomembrane ages), the GCL serves as the primary barrier to leachate flow. This requirement leads to questions regarding the long-term performance of GCLs, especially in light of the potential for high temperatures at the landfill base.

The degradation of organic matter within the waste mass is an exothermic process that may result in significant heat generation. Under certain conditions, the heat generated by this process may raise the temperature within the waste mass to 70 °C, with corresponding temperatures in the vicinity of the landfill base in excess of 50 °C (Koerner, 2001; Yoshida and Rowe, 2003). These elevated temperatures are likely to persist as long as organic matter remains in the waste, likely for decades. In contrast, the temperature of groundwater in underlying aquifers is typically 5–20 °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 flux of water away from the top of the composite lining system, creating the potential for desiccation of the mineral component of GCLs.

There is a limited data regarding the desiccation potential of GCLs under thermal gradients. Numerical models have been developed by Döll (1996, 1997), 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.

This paper seeks to apply the numerical model SUMMIT of Döll (1996, 1997) to evaluate the authors' experimental data and assess 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 and hydraulic 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 performance of the Döll model in predicting thermal desiccation behaviour is evaluated, with specific focus on the limitations of the model with regard to GCLs. The potential advantages of the more rigorous model developed by Zhou and Rowe (2003) are identified and discussed.

2. Numerical model

2.1. Numerical methods

The numerical model of Döll (1996, 1997) adopts a mechanistic approach to assessing the one-dimensional coupled transport of liquid water, water vapour and heat in a rigid unsaturated porous medium under non-isothermal conditions, following the approach developed by Philip and de Vries (1957) and extended by Milly (1984). Coupled differential equations describing the transport of water in vapour and liquid forms, as well as the transport of heat, are formulated as shown in Eqs. (1) and (2).

$$\frac{\partial \theta(\psi, T)}{\partial t} = \frac{\partial}{\partial z} \left\{ [K_u(\psi, T) + D_{\psi v}(\psi, T)] \frac{\partial \psi}{\partial z} + D_{Tv}(\psi, T) \frac{\partial T}{\partial z} + K_u(\psi, T) \right\}, \quad (1)$$

where ψ is the matric potential (m), T the temperature ($^{\circ}\text{C}$), K_u the unsaturated hydraulic conductivity (m/s), z the vertical coordinate (positive upward) (m), $D_{\psi v}$ the isothermal vapour diffusion coefficient (m/s), D_{Tv} the nonisothermal vapour diffusion coefficient [$\text{m}^2/(\text{s}^{\circ}\text{C})$].

$$\begin{aligned} \frac{\partial Q(\psi, T)}{\partial t} = \frac{\partial}{\partial z} \left(\left\{ L(T) \rho_l D_{\psi v}(\psi, T) + c_l \rho_l (T - T_0) [K_u(\psi, T) + D_{\psi v}(\psi, T)] \right\} \frac{\partial \psi}{\partial z} \right) \\ + \frac{\partial}{\partial z} \left\{ [\lambda + c_l \rho_l (T - T_0) D_{Tv}(\psi, T)] \frac{\partial T}{\partial z} + c_l \rho_l (T - T_0) K_u(\psi, T) \right\}, \end{aligned} \quad (2)$$

where Q is the volumetric heat content (J/m^3), T_0 the reference temperature ($^{\circ}\text{C}$), λ the effective thermal conductivity (including transport of latent heat of evaporation by temperature gradients) [$\text{W}/(\text{m}^{\circ}\text{C})$], c_l the specific heat of liquid water [$\text{J}/(\text{kg}^{\circ}\text{C})$], ρ_l the density of liquid water (kg/m^3).

These equations are solved numerically in their one-dimensional forms by an implicit finite-difference method. The numerical solution uses simple Picard iteration, with the moisture transport equation solved first in each iteration. Eqs. (1) and (2) are discretized directly in their mixed form, which is implicitly mass-conservative, based on the recommendation of Celia et al. (1990). Mesh-centred finite differences are used to approximate the space coordinate. Further details of the numerical method, including verification of the code, may be found in Döll (1996).

2.2. Parameter functions

To solve the heat and moisture transport equations given above, six soil-specific parameters are required: the soil water characteristic curve, the unsaturated hydraulic conductivity function, isothermal vapour diffusion coefficient, nonisothermal vapour diffusion coefficient, volumetric heat content and effective thermal conductivity. The Döll model uses the van Genuchten–Mualem functions (van Genuchten, 1980) to represent the soil water characteristic curve and the unsaturated

hydraulic conductivity function. The expression for the soil water characteristic curve is

$$\theta_l(\psi, T_0) = \theta_r + \frac{\theta_s - \theta_r}{(1 - |\alpha\psi|^n)^m}, \quad \theta_r \leq \theta_l \leq \theta_s, \quad (3)$$

where θ_l is the volumetric liquid water content (m^3/m^3), θ_r the residual water content (m^3/m^3), θ_s the saturated water content (m^3/m^3), α the van Genuchten–Mualem fitting parameter ($1/\text{m}$), n the van Genuchten–Mualem fitting parameter (dimensionless) and m the van Genuchten–Mualem fitting parameter (dimensionless) ($= 1 - 1/n$).

Based on the soil water characteristic curve, a function describing the unsaturated hydraulic conductivity of a material may be constructed based on the model of Mualem (1976):

$$K_u(\psi, T_0) = K_{\text{sat}} \frac{[(1 + |\alpha\psi|^n)^m - |\alpha\psi|^{n-1}]^2}{(1 + |\alpha\psi|^n)^{m(l+2)}}, \quad (4)$$

where K_{sat} is the saturated hydraulic conductivity (m/s) and l the exponent in van Genuchten–Mualem model (dimensionless).

The soil water characteristic curve and unsaturated hydraulic conductivity function are calculated at a temperature T different from the reference temperature T_0 as

$$\theta_l(\psi, T) = \theta_l(\psi e^{-\gamma(T-T_0)}, T_0) \quad (5)$$

and

$$K_u(\psi, T) = K_u(\psi e^{-\gamma(T-T_0)}, T_0) e^{\kappa(T-T_0)}, \quad (6)$$

where γ is the temperature coefficient of soil water characteristic curve ($1/^\circ\text{C}$) and κ the temperature coefficient of hydraulic conductivity function ($1/^\circ\text{C}$).

If the temperature dependence of the soil water characteristic curve is due only to the temperature dependence of the surface tension of water, then $\gamma \approx -0.0021/^\circ\text{C}$. Likewise, if the temperature dependence of the hydraulic conductivity function is due solely to the variation of water viscosity with temperature, then $\kappa \approx 0.021/^\circ\text{C}$. A review of the literature by Döll (1996) indicates that reported values for γ are typically larger than the theoretical value, while measured values for κ tend to be very similar to the theoretical value.

Philip and de Vries (1957) postulate that vapour diffusion occurs at an accelerated rate under nonisothermal conditions since local temperature gradients within air-filled pores are larger than the bulk temperature gradient. As well, water vapour may diffuse across adsorbed water bridges between soil particles, which decreases the importance of tortuosity and the proportion of air-filled void space. Döll (1997) indicates that even when these factors are taken into account, calculated nonisothermal vapour diffusion coefficients are lower than those measured experimentally. The source of this discrepancy is unknown, but it is accounted for in the Döll model by applying a correction factor, F_v , which typically ranges between 1 and 5.

The heat capacity of an unsaturated soil is approximated in the Döll model as the sum of the volumetric heat capacities of the constituents quartz, other minerals, organic matter, water and air, weighted by their volumetric fractions. The effect of temperature on heat capacity is neglected in the model. The thermal conductivity is predicted using the de Vries (1963) model, which uses a weighted arithmetic mean of the thermal conductivities of individual soil components weighted based on their volumetric fraction and the ratio between the thermal gradient across the particle and the thermal gradient in the continuous phase. The continuous phase is assumed to be water above a specified volumetric water content (typically 0.10 for fine-grained soils and 0.05 for coarse-grained soils) and air below it.

3. Modelling of GCL desiccation

The model of Döll was developed as a tool to investigate the potential for desiccation of compacted clay liners in landfill basal liner applications with heat generation. The present study seeks to examine the performance of this model when applied to a composite liner containing a geosynthetic clay liner. The authors have previously reported the results of a program of large-scale laboratory investigations into the thermal desiccation behaviour of GCLs (Southen and Rowe, 2004b). A brief synopsis of these tests and the materials used will be presented, followed by the results of a parametric investigation using the Döll model.

3.1. Laboratory testing

To investigate the desiccation behaviour of GCLs, a series of large-scale laboratory tests were performed. The goal of these tests was to simulate reasonable worst-case landfill conditions. The tests utilized columns 1 m in height and 30 cm 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 HDPE geomembrane and GCL. 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.

Two subsoil materials (S1 and S2) and two GCL products (G1 and G2) were used in the large-scale testing program. The soils were silty sands with 12–19% silt content, optimum water content of 10–12%, and maximum dry density of 1.91–1.95 g/cm³. The first GCL, G1 (Bentofix NS), was comprised of a 4240 g/m² granular sodium bentonite core sandwiched between a 105 g/m² slit-film polypropylene woven carrier geotextile and a 200 g/m² polypropylene virgin staple fibre nonwoven cover geotextile. The GCL was reinforced by needlepunching and had thermally treated needlepunched fibres (thermal locking). The second GCL, G2 (Bentofix BFG 5000), differs from the first in that the core contains 5000 g/m² of powdered sodium bentonite and the cover nonwoven geotextile is impregnated with

800 g/m² of bentonite. The carrier geotextile is a 200 g/m² polypropylene slit-film woven, while the cover geotextile is a 300 g/m² polypropylene nonwoven.

A full description of the experimental procedure and results may be found in Southen and Rowe (2004b). Table 1 presents pertinent data regarding four tests that are modelled in the current study. Of note is the variation in initial subsoil water content between the tests, as this was found to be a significant factor affecting the desiccation behaviour of the GCL. The type of GCL played a minor role, while the applied overburden stress was not found to significantly impact the results. Other parameters, such as the applied temperature gradient, initial soil dry density and initial GCL water content were held relatively constant between tests.

Measurements taken at the end of the tests indicate that, for the conditions analysed, the potential for desiccation of a GCL in a composite liner subjected to a thermal gradient does exist. The tests with relatively low initial subsoil water content (G1-S1-L1 and 2, G2-S2-L2) gave final GCL volumetric water contents between 0.09 and 0.23. Observations of the GCLs following these tests indicated that significant desiccation cracking had occurred. However the GCL in the test with a higher initial subsoil water content (G2-S2-L1) experienced no desiccation even though all other factors were essentially the same, clearly demonstrating that the initial water content of the subsoil is a key factor influencing the potential for desiccation of the GCL.

3.2. Parameterization and modelling procedure

In order to model the experimental results, it was necessary to have values for the parameters in Eqs. (3) and (4). Soil water characteristic curves were developed for the subsoils and the GCLs based on the results of a series of laboratory tests using pressure-plate and pressure-membrane extractors. The GCL tests were conducted using intact, 50 mm diameter GCL samples under applied loads of 3 and 100 kPa (Southen and Rowe, 2004a). The van Genuchten–Mualem parameters (α , n , θ_s , θ_r) were selected based on curves fitted to the experimental data. The saturated hydraulic conductivity (Table 2) was based on variable-head permeability testing for the subsoils and manufacturers' specifications for the GCLs. The parameters α and n for the unsaturated hydraulic conductivity function (Eq. (4)) were taken to be the same as those used for the water characteristic curve, as discussed by van Genuchten

Table 1
Test details

Test	Test duration (d)	Initial subsoil volumetric water content	Initial subsoil dry density (g/cm ³)	Initial GCL volumetric water content	Applied pressure (kPa)	Applied temperature gradient (°C/m)	Final GCL vol. water content (%)	Final subsoil vol. water content
G1-S1-L1	90	0.08	1.76	0.72	15	25	0.11	0.005–0.12
G1-S1-L2	232	0.07	1.75	0.71	50	27	0.09	0.004–0.16
G2-S2-L1	109	0.24	1.85	0.56	80	25.5	0.68	0.21–0.29
G2-S2-L2	233	0.11	1.79	0.46	70	24.8	0.23	0.005–0.29

Table 2
Parameters used in modelling

Material	n_p	θ_s	θ_r	α (1/m)	n	K_{sat} (m/s)	l	F_v
Silty Sand 1	0.32–0.35	0.32–0.35	0.005	0.01	2.1	8×10^{-7}	varies	varies
Silty Sand 2	0.32–0.35	0.32–0.35	0.005	0.012	2.2	2.5×10^{-7}	varies	varies
GCL 1	0.74–0.75	0.74–0.75	0.05	0.0002	1.45	5×10^{-11}	–6.0	varies
GCL 2	0.72–0.78	0.72–0.78	0.08	0.00006	1.55	5×10^{-11}	–6.0	varies

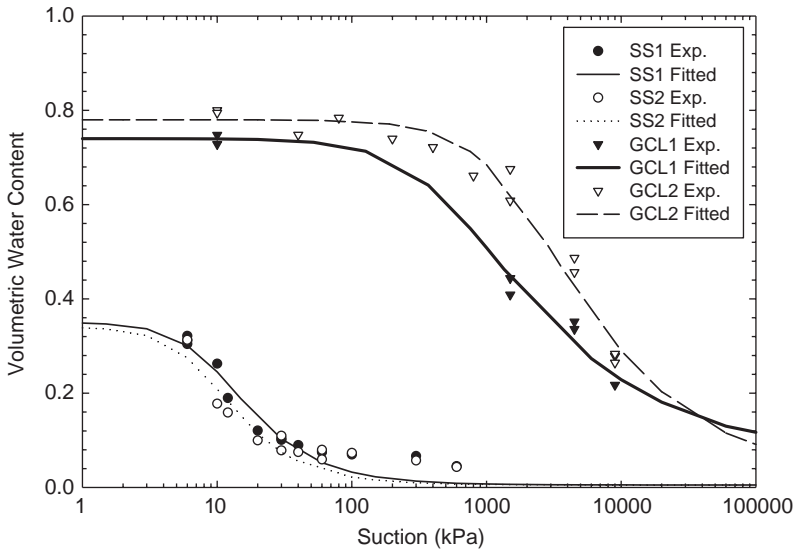


Fig. 1. Soil water characteristic curves for soil and GCL materials.

(1980). A summary of the parameters used is found in Table 2. Experimental and fitted soil water characteristic curves for the materials are shown in Fig. 1.

Due to the difficulty of laboratory testing, values for l of the water retention function (Eq. (4)) and the nonisothermal vapour diffusion correction factor, F_v , were not experimentally obtained. A value of l of 0.5 is suggested by Mualem (1976) when unsaturated hydraulic conductivity is predicted based on measured soil water characteristic curves rather than fitted to experimental data. However, for fine-grained soils, Döll (1997) reports values of l as low as -7 . Values of F_v are highly soil-dependent, with a literature review performed by Döll (1996) indicating values ranging between 1 and 5. These parameters were thus varied to obtain a good fit with the large-scale experimental data obtained from one test with each GCL–subsoil combination. The parameters obtained from this study were then used to predict the behaviour of subsequent tests. A similar approach was used for the temperature coefficients of Eqs. (5) and (6).

The GCL was modelled as a continuous layer, 8 mm thick, using 40 nodes. The GCL was modelled as a whole, rather than as three separate soil and geosynthetic layers, since the pressure membrane tests gave parameters representative of the entire GCL “system”. The 1.0 m thick subsoil was discretized using 100 nodes in the upper 5 cm and 190 nodes in the lower 95 cm. The upper boundary adopted a constant temperature and zero moisture flux (due to the presence of the overlying geomembrane) condition, and a prescribed overburden pressure. The lower boundary adopted constant temperature, zero moisture flux and zero displacement conditions.

3.3. Results

Two tests, one for each GCL–subsoil combination, were used for a parametric investigation. The experimental parameters given in Table 2 were used as a baseline, while values of l_{ss} between -1.0 and 0.5 and F_v between 1 and 3 were modelled to obtain the best fit to the test results. Other variables, such as l_{GCL} (Eq. (4)), γ (Eq. (5)) and κ (Eq. (6)), were found to have only minor effects on the results of the simulation. Standard values of $l_{GCL} = -6.0$, $\gamma = -0.002$ 1/K and $\kappa = 0.02$ 1/K were thus adopted for these parameters. The measured and fitted volumetric water contents at the termination of test G1-S1-L2 are shown in Fig. 2. The upper portion of the figure depicts the behaviour within the GCL at an exaggerated scale, while the lower portion depicts the behaviour within the silty sand subsoil. For this test, the GCL and upper portion of the subsoil exhibited significantly decreased water contents; desiccation cracking was observed in the GCL.

It may be seen from Fig. 2 that, with l_{ss} constant, an increase in the vapour diffusion correction factor, F_v , results in enhanced vapour diffusion and thus more transport of moisture downward (same line types in Fig. 2). Water contents in the GCL and upper portion of the subsoil are thus decreased, while the water content in the lower portion of the subsoil is increased. A similar trend is noted for increasing values of l_{ss} , with constant F_v (same symbol types in Fig. 2). At a given degree of saturation, an increase in l_{ss} corresponds to a decrease in the unsaturated hydraulic conductivity of the soil. Because of this, liquid water moves upward more slowly and cannot balance the downward vapour flux to the same degree, resulting in decreased water contents in the upper portion of the subsoil for the models with higher values of l_{ss} . The best fit to the experimental data was achieved using $F_v = 2.5$ and $l_{ss} = 0.5$.

The temperatures predicted using SUMMIT are compared with data measured at the end of the test in Fig. 3. Changes in temperature gradient are highly dependent on the water content of the subsoil, due to the effect of water content on thermal conductivity. Thus the change in gradient occurring approximately 20 cm from the surface is due largely to the sharp change in water content at this location as shown in Fig. 3. It appears that the Döll model under predicts the thermal conductivity in the wet subsoil and over predicts the thermal conductivity in the dry upper portion of the subsoil and in the GCL.

The variation of water content with time predicted by the SUMMIT model for test G1-S1-L2 is given in Fig. 4. The water content at the top of the subsoil decreases

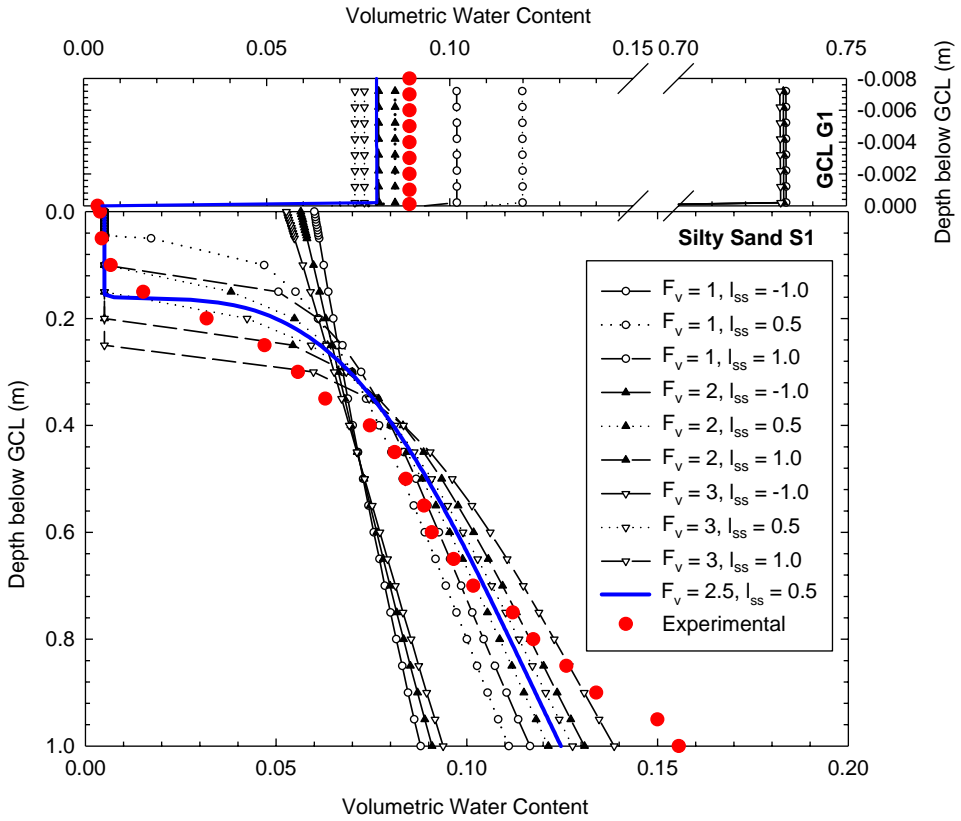


Fig. 2. Measured and predicted volumetric water contents for test G1-S1-L2.

rapidly from its initial value, reaching a residual value of 0.005 within 30 days following the start of heating. At other locations, the change in water content was less rapid, although by 200 days after the start of heating, equilibrium had been reached within the system. This is in contrast to the simulations of Döll (1996, 1997), where the time to equilibrium for simulated field conditions involving compacted clay liners was as much as 50 years. The most likely explanation for the rapid stabilization of water contents in the current study is the relative thinness of the GCL. The unsaturated hydraulic conductivity of this layer is comparable to that of the compacted clay liners simulated by Döll, but the thickness is two orders of magnitude less. Thus, although water and vapour moves slowly in this layer, the distance is small and thus equilibrium is rapidly achieved. The more rapid movement of moisture observed implies that elevated landfill temperatures need only occur for a short period of time for there to be a risk of desiccation.

The same procedure of varying F_v and l_{ss} was followed for test G2-S2-L2. The best fit for this combination was obtained using $F_v = 2.0$ and $l_{ss} = 0.5$. Temperature and volumetric water content estimated by the model are compared with experimental

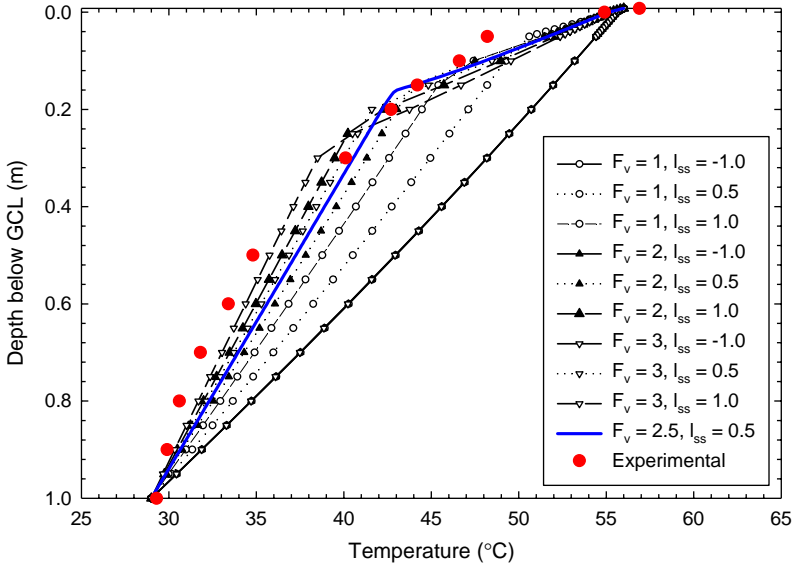


Fig. 3. Measured and predicted temperatures for test G1-S1-L2.

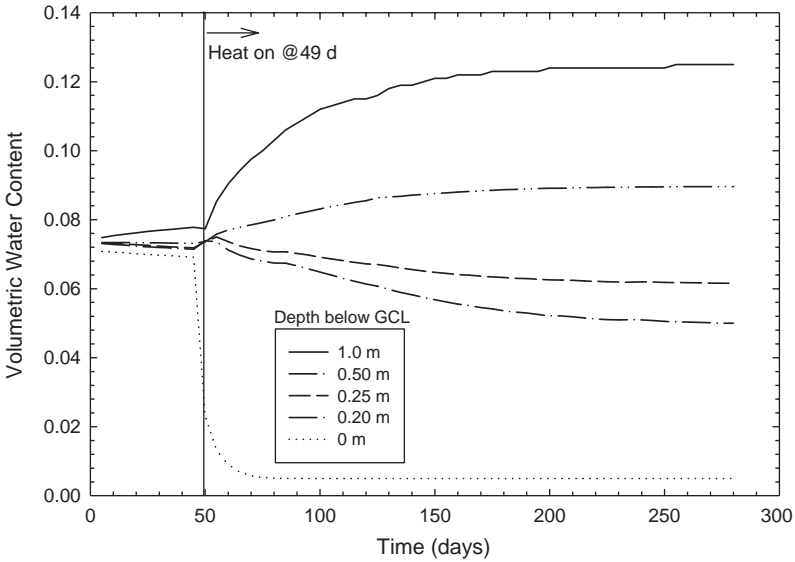


Fig. 4. Variation of volumetric water content with time for test G1-S1-L2.

data in Fig. 5. Reasonable agreement between measured and fitted data within the subsoil is achieved, although the fit is not as good as was the case for G1-S1-L2. The SUMMIT model underpredicts the GCL water content by approximately 50%.

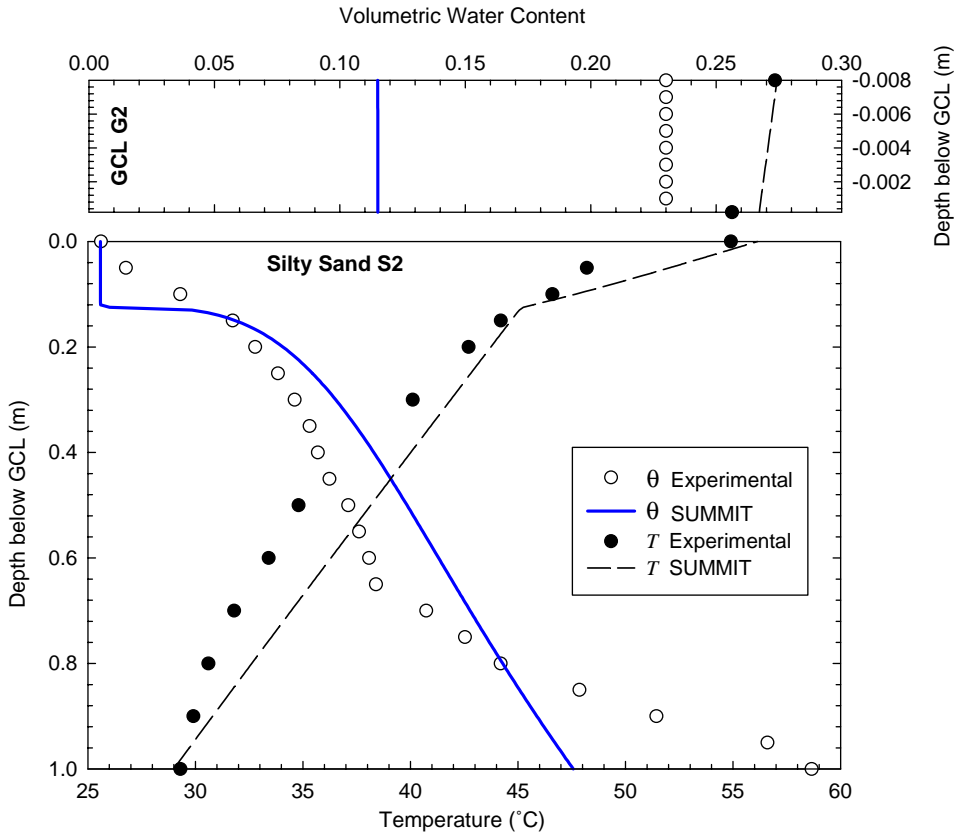


Fig. 5. Measured and fitted volumetric water content and temperature for test G2-S2-L2.

The results from these two tests were used as a basis for the predictive modelling of two additional tests. The best-fit parameters from test G1-S1-L2 were used to model test G1-S1-L1, and similarly the best-fit parameters from test G2-S2-L2 were used to model G2-S2-L1. Slight modifications were made due to variations in initial density of the soil and GCL materials. Thus, for test G1-S1-L1, the parameters listed in Table 2 were used with $F_v = 2.5$ and $l_{ss} = 0.5$. A plot of the predicted temperature and volumetric water content as well as the experimental data obtained at the end of the test are shown in Fig. 6. A good fit is obtained for the water content within the soil, but the predicted GCL volumetric water content is approximately 20% lower than the measured value. Reasonable agreement between measured and predicted temperature is achieved, although again the effect of water content on thermal conductivity appears to be underestimated by SUMMIT. Fig. 7 shows the predicted and experimental temperature and volumetric water content for test G2-S2-L1. In this case, the water content of the GCL is overpredicted by only 6%, although again the thermal gradient predicted in the upper portion of the system is lower than that observed experimentally.

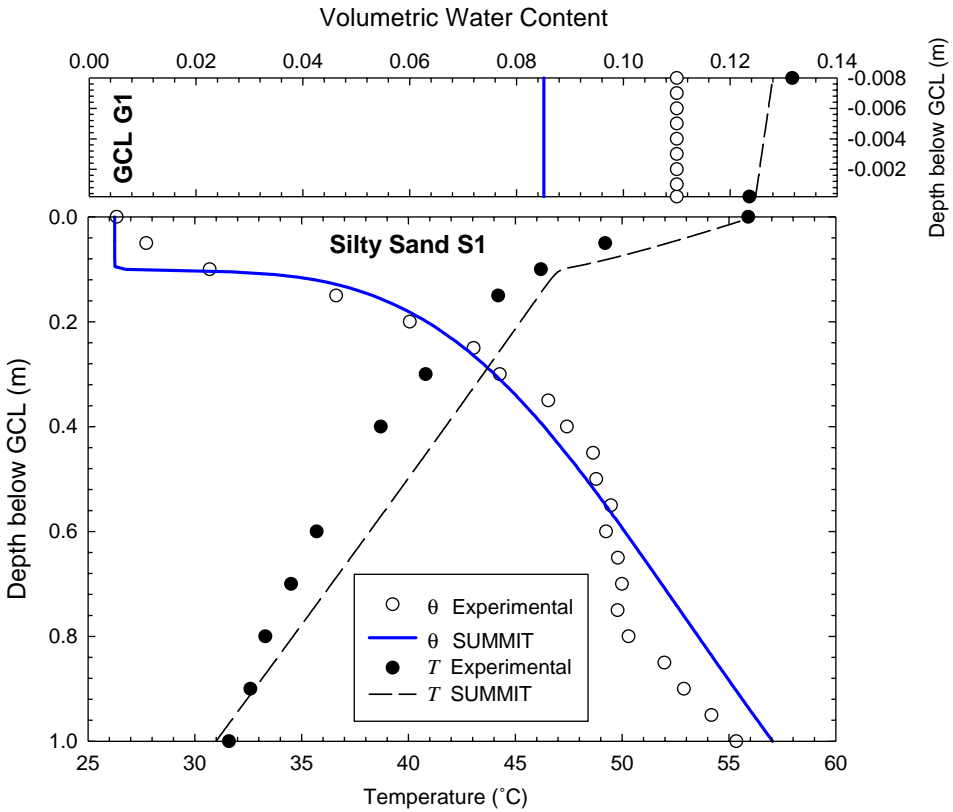


Fig. 6. Measured and predicted volumetric water content and temperature for test G1-S1-L1.

4. Discussion

4.1. Fit with experimental data

The results of a numerical investigation using the model SUMMIT, presented in Figs. 2–6 indicate that a reasonable approximation of experimental results can be made. The prediction of volumetric water content was generally good in the subsoil, while predictions of temperature were less accurate. This latter issue is most likely due to limitations regarding the calculation of thermal conductivity for an unsaturated soil. The SUMMIT model uses the method of de Vries (1963) to determine a weighted average of the thermal conductivities of the various soil components. Observing the relationship between predicted and experimental results for the tests in the current study, it appears that the de Vries model over predicts thermal conductivity in the upper portion of the test cell (including the GCL) and under predicts thermal conductivity in the lower portion of the cell. The over prediction of thermal conductivity by the de Vries model for relatively dry soils with aggregate size

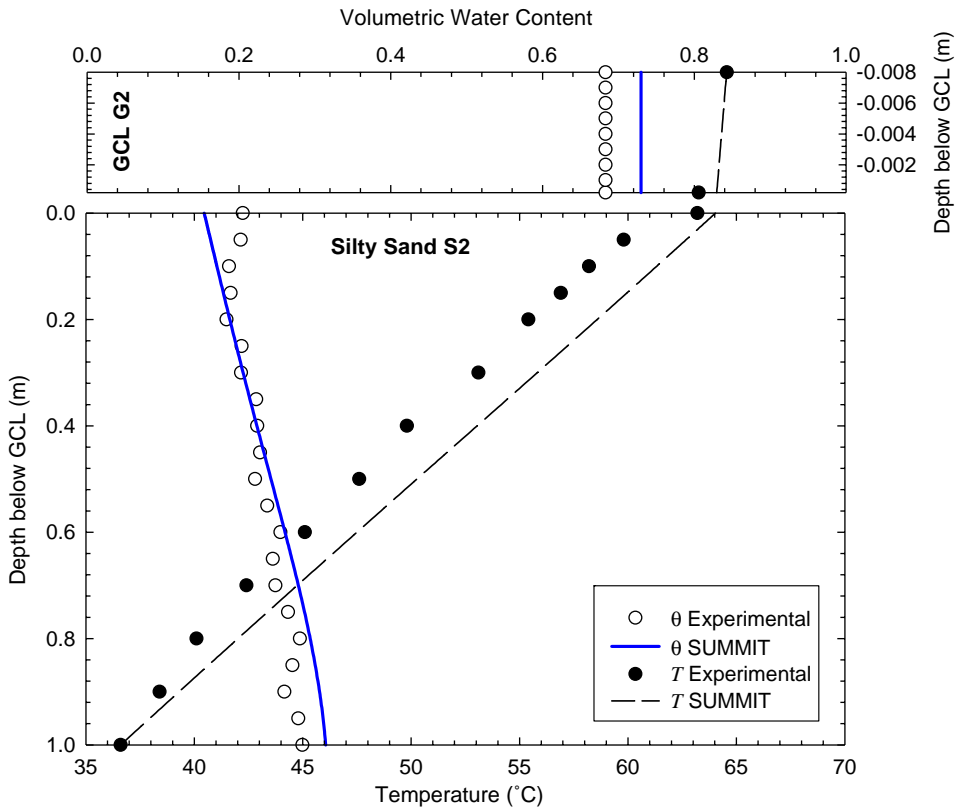


Fig. 7. Measured and predicted volumetric water content and temperature for test G2-S2-L1.

>0.2 mm (which is the case for the silty sands under consideration) has been noted by Hadas (1977) and can be explained by the inability of the model to account for a limited number of soil grain contact points. The under prediction of thermal conductivity in the lower portions of the subsoil is likely related to the under predicted water contents in this region. Although suggestions for improving the method of de Vries for calculating thermal conductivity have been proposed, Döll (1996) notes that none are capable of consistently improving predictions in the general case.

Within the GCL, predicted volumetric water contents and temperatures are relatively less accurate. The water content is consistently underpredicted, although the degree of the disparity varies from test to test. Further discussion of this behaviour is given in Section 4.3. The thermal gradient is consistently underpredicted. This may be due to the presence of the geotextiles, which have thermal conductivity lower than the mineral materials assumed in the model to make up the solid component of the GCL. As a comparison, the thermal conductivity of polypropylene is typically 0.12 W/(mK), while the GCL was modelled as being

comprised of “other minerals” with thermal conductivity of 2.0 W/(m K). An additional run with the GCL comprised of “organic matter” with thermal conductivity of 0.25 W/(m K) improved the prediction of temperature within the GCL somewhat, but had no discernable effect on the predicted water contents in the GCL or the underlying subsoil.

It should also be noted that the properties of the GCL had minimal influence on the distribution of water content within the underlying subsoil. Additional simulations were run with varying GCL properties, and one test run without the GCL present. The only effect was a shifting of the predicted volumetric water content curve to the left, i.e. a decrease in overall water content caused by the elimination of water from the overlying GCL. Thus, while the properties assumed for the silty sand had significant impact on the predicted behaviour of the GCL, the reverse was not found to be the case.

4.2. Prediction of cracking

Since the model SUMMIT assumes a rigid media, no estimates of stress within the GCL or subsoil are made. Döll (1997) recommends that the method of Holzlöhner (1992) be used to evaluate the likelihood of desiccation cracking. Holzlöhner suggests that cracking occurs when the total horizontal stress reaches zero, i.e.:

$$-\chi\psi\rho_1g = \sigma_{sh} = K_0\sigma_{sv} = K_0(\sigma_{tv} - \chi\psi\rho_1g), \tag{7}$$

where χ is the water saturated fraction of a plane in the soil, ψ the matric potential (m), ρ_1 the density of water (kg/m³), g the gravitational acceleration (m/s²) and σ_{sh} the horizontal granulate stress, K_0 the coefficient of lateral earth pressure at rest (= σ_{sh}/σ_{sv}), σ_{tv} the total vertical stress (N/m²).

Thus cracking occurs if

$$-\psi \geq \frac{K_0\sigma_{tv}}{\chi\rho_1g(1 - K_0)}. \tag{8}$$

Döll (1997) recommends that K_0 should be set to 0.33 and χ set to 1 for a conservative estimate. Table 3 summarizes the final matric potential within the GCL estimated by SUMMIT in relation to the applied overburden stress and the corresponding prediction of cracking. It may be seen that the model agrees with the

Table 3
Cracking predictions

Test	Overburden stress applied (N/m ²)	SUMMIT predicted matric potential (m)	Cracking limit (Eq. (8)) (m)	Cracking expected?	Cracking observed?
G1-S1-L1	15000	-4.9 × 10 ⁴	0.75	Yes	Yes
G1-S1-L2	50000	-3.6 × 10 ⁴	2.55	Yes	Yes
G2-S2-L1	80000	-3.6 × 10 ⁴	4.08	Yes	Yes
G2-S2-L2	70000	-1.2	3.57	No	No

experimental observations of cracking occurrence. It would be beneficial to have more data between the extremes of GCL water content in the current study to more accurately verify the ability of the SUMMIT model to predict the onset of cracking. It should be stressed that Eq. (8) is only an estimate of the cracking limit and does not take into account factors such as the effect of temperature on deformation or the tensile strength of soil.

4.3. Limitations of SUMMIT model

Although the SUMMIT model has been shown to be capable of predicting trends of thermally induced moisture movement and associated desiccation with reasonable accuracy, there exist limitations to its ability to fully investigate the desiccation behaviour of composite liner systems containing GCLs. Some of the key limitations include:

- *Difficulty in obtaining model parameters:* Parameters such as the thermal vapour enhancement factor, F_v , and the exponent l of the van Genuchten–Mualem unsaturated hydraulic conductivity function require time consuming, soil-specific testing to obtain reliable results. The dependence of these properties on the materials and conditions being simulated make the use of general reported values problematic. Thus, in the absence of experimentally obtained parameters, a parametric investigation must be undertaken to credibly assess the degree of moisture movement expected.
- *Difficulty in predicting thermal conductivity:* As discussed above, the SUMMIT model tends to under predict thermal conductivity in relatively wet areas and over predict thermal conductivity in relatively dry areas for the materials and conditions studied.
- *Assumption of a rigid media:* This last point is the most severe limitation when considering the extension of the SUMMIT model to composite liners incorporating geosynthetic clay liners. GCLs are quite thin (~ 10 mm) and the bentonite core is both highly compressible and susceptible to swelling behaviour. When subjected to stresses and temperatures such as those examined in the current study, it is thus unlikely that the assumption of a rigid media will be valid for a GCL.

Table 4 presents the bulk GCL void ratios calculated before and after the large-scale testing. Under the test conditions examined, the GCL void ratio decreased by as

Table 4
Bulk GCL void ratios

Test	Pre-test bulk GCL void ratio	Post-test bulk GCL void ratio
G1-S1-L1	2.75	1.80
G1-S1-L2	2.62	1.76
G2-S2-L1	2.88	0.99
G2-S2-L2	2.35	2.89

much as a factor of 2.8, while for one test the void ratio increased. This change in void ratio clearly has an effect on the ability of the SUMMIT model to predict water content. Referring to Fig. 5, the predicted volumetric water content is only half of the experimentally obtained volumetric water content for test G2-S2-L2. The gravimetric water content calculated from the SUMMIT output (based on a constant void ratio) is 0.20, which compares more favourably with the experimental average of 0.18. The reduction in GCL void ratio is not accounted for by SUMMIT and thus the predicted volumetric water contents in the GCL are not reliable. Neglecting deformation of the media further limits the accuracy of the model since effects such as heat flow due to mass flow, stress effects on the soil water characteristic curve and the heat sink due to thermal expansion are not taken into account.

5. Conclusions

The model SUMMIT has been used to numerically investigate the potential for thermally induced desiccation cracking of GCLs under simulated landfill basal liner conditions. Based on this investigation and comparison with experimental results, the following may be concluded:

- The SUMMIT model gives reasonable estimates of volumetric water content within the subsoil layer underlying a composite liner. Variations of water content throughout the soil column were in good agreement with experimental results.
- Predictions of temperature are less accurate, but still in reasonable agreement with experimental results.
- The SUMMIT model performs poorly when predicting volumetric water content and temperature within the GCL component. Volumetric water contents were typically underestimated by as much as a factor of 2, while the temperature gradient through the GCL was consistently under predicted.
- Predictions of cracking based on matric potentials computed by SUMMIT were in agreement with experimental observations, although the extremes of the test results make a definitive statement on the reliability of this method impossible.
- The poor performance when predicting GCL volumetric water content is attributed to limitations of the numerical model, the most significant of which is the assumption of a rigid media. The high compressibility and swelling capacity of a GCL calls into question the suitability of the SUMMIT model for the task of predicting desiccation in composite lining systems.

It may be concluded that while the SUMMIT model is useful for making a general investigation into thermally induced moisture movement, a more complete model is necessary for extension of the investigation into cases involving composite liners containing GCLs. In light of this, a mass-conservative finite element model developed by Zhou and Rowe (2003) is seen as a key advancement in the ability to predict desiccation in GCLs. This model uses fully coupled governing equations

which incorporate the flow of heat, moisture and air; a non-linear constitutive relationship; the dependence of void ratio and volumetric water content on stress, capillary pressure and temperature; and the effect of deformation. By including all of these elements, the Zhou and Rowe model allows a more detailed investigation of desiccation behaviour that is not possible within the framework of the SUMMIT model and warrants further investigation.

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References

- Celia, M.A., Bouloutas, E.T., Zarba, R.L., 1990. A general mass-conservative numerical solution for the unsaturated flow equation. *Water Resources Research* 26 (7), 1483–1496.
- de Vries, D.A., 1963. Thermal properties of soils. In: van Wijk, W.R. (Ed.), *Physics of Plant Environment*. Wiley, New York, pp. 210–235.
- Döll, P., 1996. Modeling of moisture movement under the influence of temperature gradients: desiccation of mineral liners below landfills. Ph.D. Thesis, Technical University of Berlin, Germany.
- Döll, P., 1997. Desiccation of mineral liners below landfills with heat generation. *Journal of Geotechnical and Geoenvironmental Engineering* 123, 1001–1009.
- Hadas, A., 1977. Heat transfer in dry aggregated soil: 1. Heat conduction. *Soil Science Society of America Journal* 41 (6), 1055–1059.
- Holzlohner, U., 1992. Austrocknung und Rißbildung in mineralischen Schichten der Deponiebasisabdichtung (Desiccation and cracking in mineral layers of the landfill base liner). *Wasser und Boden*, vol. 5, Hamburg, Germany, pp. 289–293.
- Koerner, G., 2001. In situ temperature monitoring of geosynthetics used in a landfill. *Geotechnical Fabrics Report*, May 2001, pp. 12–13.
- Milly, P.C.D., 1984. A simulation analysis of thermal effects on evaporation from soil. *Water Resources Research* 20 (8), 1087–1098.
- Mualem, Y., 1976. A new model for predicting the hydraulic conductivity of unsaturated porous media. *Water Resources Research* 12 (3), 513–522.
- Philip, J.R., de Vries, D.A., 1957. Moisture movement in porous materials under temperature gradients. *AGU Transactions* 38 (2), 222–232.
- Rowe, R.K., Quigley, R.M., Brachman, R.W.I., Booker, J.R., 2004. *Barrier Systems for Waste Disposal Facilities*. Taylor & Francis Books Ltd (E & FN Spon), London, 587pp.
- Southen, J.M., Rowe, R.K., 2004a. Investigation of the behavior of geosynthetic clay liners subjected to thermal gradients in basal liner applications. *Journal of ASTM International* 1 (2) ID JAI11470, Online; Available: www.astm.org; 13pp.
- Southen, J.M., Rowe, R.K., 2004b. Laboratory investigation of GCL desiccation in a composite liner subjected to thermal gradients. *Research Report*, GeoEngineering Centre at Queen's-RMC, Department of Civil Engineering, Queen's University.
- Sporer, H., Gartung, E., 2002. Laboratory tests on desiccation of geosynthetic clay liners. *Proceedings of the International Symposium on Clay Geosynthetic Barriers*, Nuremberg, Germany, pp. 331–338.

- Thomas, H.R., Missoum, H., 1999. Three-dimensional coupled heat, moisture and air transfer in a deformable unsaturated soil. *International Journal for Numerical Methods in Engineering* 44 (7), 919–943.
- van Genuchten, M.T., 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Science Society of America Journal* 44 (5), 892–898.
- Yoshida, H., Rowe, R.K., 2003. Consideration of landfill liner temperature. *Proceedings of Eighth International Waste Management and Landfill Symposium*, S. Margherita di Pula, Cagliari, Sardinia, Italy, October, CD-ROM, 9pp.
- Zhou, Y., Rowe, R.K., 2003. Development of a technique for modelling clay liner desiccation. *International Journal for Numerical and Analytical Methods in Geomechanics* 27 (6), 473–493.