Thermally Induced Desiccation of Geosynthetic Clay Liners in Landfill Basal Liner Applications

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ABSTRACT:

High temperatures may be encountered at the base of a landfill due to exothermic decomposition occurring in the overlying waste mass or hydration of ash. The corresponding thermal gradients create a risk of outward moisture movement and desiccation of the mineral component of composite lining system. This paper examines the potential effects of this thermally driven moisture movement on the long-term performance of geosynthetic clay liners in landfill basal liner applications. The results of large-scale laboratory experiments conducted in an effort to assess the behaviour of GCLs subjected to thermal gradients in landfill basal liner applications are discussed. In conjunction with this experimental program, a series of numerical models have been used to evaluate the pertinent thermal, hydraulic and mechanical properties of the soil and geosynthetic components of a composite liner system. The combination of insights gained through these programs allows a better understanding of the underlying mechanisms of moisture redistribution and desiccation behaviour. An analysis of the key results obtained through this investigation is presented. The discussion focuses on potential areas of concern with regards to thermally induced desiccation of geosynthetic clay liners. It is recommended that the potential for desiccation be addressed at the design stage of landfill construction, with numerical modeling used to identify potential risks. The avoidance of GCL placement over dry subsoils and the importance of managing heat generation within the landfill are stressed.

INTRODUCTION

Engineered lining systems for municipal solid waste landfill facilities are designed with the goal of minimizing outward contaminant migration, thus ensuring environmental protection. Increasingly, geosynthetic materials such as geomembranes and geosynthetic clay liners (GCLs) have been incorporated into the design of landfill basal liners, with a majority of jurisdictions now utilizing composite liners comprised of geosynthetics as the primary means of contaminant containment (Koerner & Koerner, 1999). Such products have been shown to be effective at reducing outward advective flow from the landfill, resulting in decreased contaminant loading on the surrounding environment (e.g. Rowe *et al*., 2004). However, due to the relatively short period of time during which geosynthetics have been incorporated into landfill designs, questions regarding certain aspects of their long-term performance remain unanswered. One such aspect is the performance of GCLs under the elevated temperatures that may arise at the landfill base as a result of exothermic decomposition of organic matter within the waste mass or hydration of incinerator ash.

Municipal solid waste is a highly heterogeneous material, the properties of which vary regionally and temporally based on the makeup of the generating population. However, studies have indicated that organic matter consistently makes up a significant portion of the total waste, typically 50-70% of the dry unit weight (USEPA, 2003). The biological degradation of this organic matter, both aerobic and anaerobic, involves exothermic reactions that lead to heat generation within the waste mass. These reactions are accelerated under conditions of high waste water content, which can occur due to mounding of leachate following failure of the primary leachate collection system or due to the purposeful addition of moisture to accelerate the stabilization of organic matter within the waste (Rowe, 1998). Temperatures at the base of landfills in the range of 20-60 °C have been reported (Barone *et al*., 2000; Koerner, 2001; Yoshida and Rowe, 2003). Hydration of incinerator ash can also generate high temperatures (Rowe *et al*., 2004)

Elevated temperatures at the landfill base have many potential consequences for the performance of the lining system, including increased leachate collection system clogging rates (Rowe *et al*., 1997), accelerated ageing of geosynthetic components (Hsuan and Koerner, 1998; Rowe, 1998; Sangam and Rowe, 2002) and increased diffusive and advective transport of contaminants (Barone *et al.*, 2000). In addition, the temperature gradients that result when the liner is heated from the overlying waste mass have the potential to induce a net movement of moisture away from the liner, with a resulting potential for desiccation cracking of mineral liner components. This last point is the focus of this paper.

A schematic of the conditions existing at the base of a landfill is shown in Figure 1. Initially, water within the underlying subsoil will move downward to achieve hydrostatic equilibrium with the groundwater table due to the effects of the overburden stress and gravity. Water will also generally flow from the subsoil into the GCL (the extent of which will depend on the as-placed water content). When the upper surface is heated by waste decomposition, heat flows downwards towards the cooler groundwater table. The temperature gradient thus established enhances the drainage of water by inducing downward vapour diffusion due to the dependence of vapour density on temperature. As it flows downwards, the water vapour cools, resulting in condensation. It may be assumed that the geomembrane, which comprises the upper boundary of the system, is practically impermeable to water, and thus the downward vapour flux must be balanced by the upward flux of liquid water under matric potential (suction) gradients. Especially when unsaturated hydraulic conductivity is low, this process has the potential to generate high matric potentials in the upper portion of the subsoil and GCL. These matric potentials and resulting low water contents may lead to shrinkage of the bentonite core of the GCL, with a corresponding risk of desiccation cracking. Where the overburden stress and tensile strength of the GCL are not sufficient to prevent cracking of the GCL, the potential for increased transport of contaminants, especially following the failure of the primary geomembrane liner, exists.

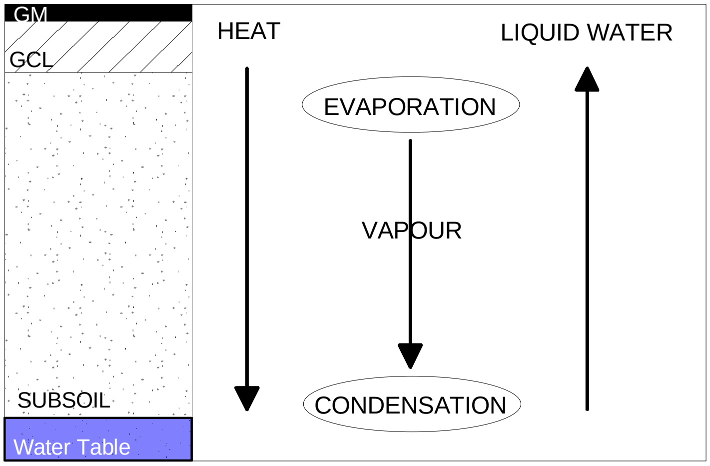

Figure 1 – Thermally induced moisture transport processes within and beneath a landfill composite liner

Investigations into thermally induced moisture movement have been conducted both experimentally and numerically in recent years. Gotthiel and Brauns (1994) and Philip et al. (2002) have conducted experimental investigations into the potential for desiccation due to thermal gradients with applicability to compacted clay liners. In addition, the numerical modeling of desiccation processes has advanced considerably, and several numerical models currently exist, each with varying applicability and limitations (e.g. Döll, 1997; Thomas and Missoum, 1999; Zhou and Rowe, 2003). Investigations into the susceptibility of geosynthetic clay liners to desiccation have also been undertaken (e.g. Lin and Benson, 2000; Sporer and

Gartung, 2002; Sivakumar Babu et al., 2002), although these studies focus on performance under the very different conditions occurring in landfill final cover applications. At present, a comprehensive investigation into the effects of thermal desiccation on composite landfill basal liners containing geosynthetic clay liners has not been undertaken.

The authors have previously reported the results of small and large-scale laboratory experiments conducted in an effort to assess the behaviour of GCLs subjected to thermal gradients in landfill basal liner applications (Southen and Rowe, 2002; Southen and Rowe, 2004). In conjunction with this experimental program, a series of numerical models have been used to evaluate the pertinent thermal, hydraulic and mechanical properties of the soil and geosynthetic components of a composite liner system. The goal of the research program is to use the combined insights gained through these investigations to achieve a better understanding of the underlying mechanisms of moisture redistribution and desiccation behaviour. This paper presents an overview of the key results obtained through this investigation. The discussion focuses on potential areas of concern with regards to thermally induced desiccation of geosynthetic clay liners and the means by which such concerns can be mitigated in the design of landfill lining systems.

LARGE SCALE LABORATORY TESTING

A brief description of the goals and methods employed in a large-scale experimental investigation into the desiccation behaviour of GCLs previously reported by the authors (Southen and Rowe, 2002) will be presented, followed by sample results and a synopsis of key findings from the study. The goal of these tests was to identify reasonable worst-case conditions that might give rise to desiccation in order to obtain data regarding spatial and temporal distributions of temperature and water content that could subsequently be used to check numerical models. To achieve this, the tests were conducted at as large a scale as was feasible, used materials representative of those used in practice and maintained flexibility and control over factors such as the applied overburden pressure, temperature gradient and initial soil conditions. The tests utilized columns 1m in height and 300 mm 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 by Southen and Rowe (2002).

An example of the results obtained from one of the large-scale tests is shown in Figure 2. This test utilized a GCL (Bentofix NS) comprised of a granular sodium bentonite core sandwiched between a slit-film polypropylene woven carrier geotextile and a polypropylene virgin staple fibre nonwoven cover geotextile. The GCL was reinforced by needlepunching and had thermally treated needlepunched fibres (thermal locking). The silty sand subsoil had an average initial volumetric water content (θ) of 0.073 and an initial dry density of 1.75 g/cm^3, while the GCL was placed with an initial volumetric water content of 0.713 (degree of saturation, S_r = 96 %). A 50 kPa overburden stress was applied. From Figure 2, it may be seen that the application of a temperature gradient of ~27 °C/m for 232 days resulted in significant movement of moisture away from the upper boundary. Water content in the upper portion of the subsoil had reduced to near residual values, while the GCL experienced a decrease in volumetric water content to 0.09 (S_r = 14 %).

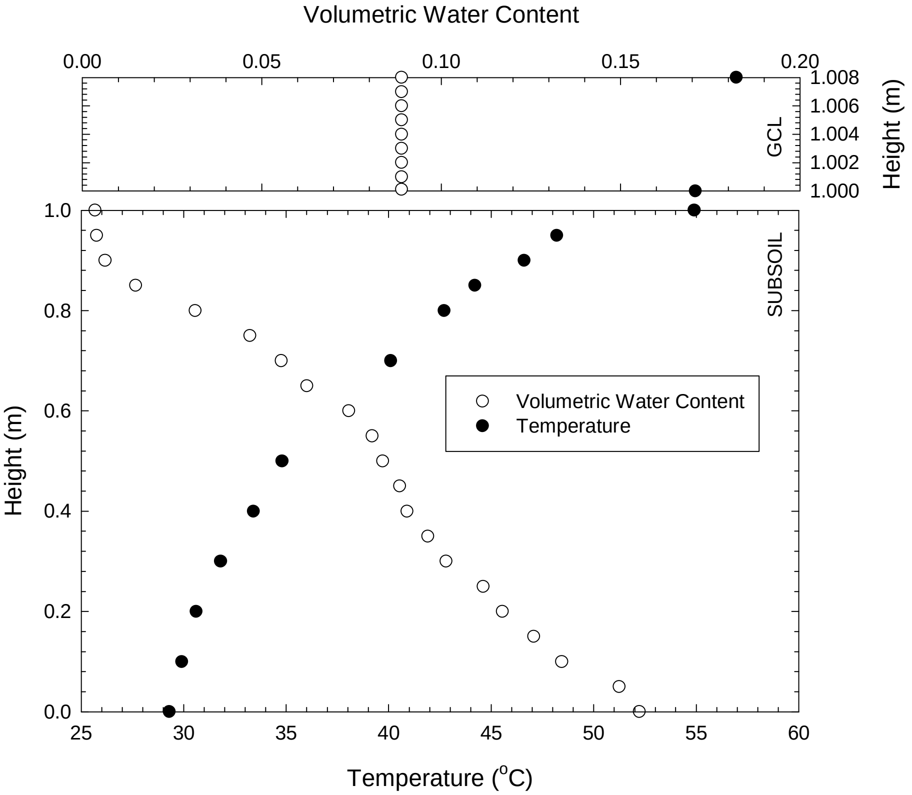

Figure 2 – Experimental results for typical large-scale laboratory test
($\theta_{initsubsoil}$ = 0.073, $\theta_{initGCL}$ = 0.713, σ_v = 50 kPa)

Significant desiccation cracking was noted through the entire thickness of the GCL, which had decreased in thickness from an as-placed value of 8.0 mm to an average of 6.1 mm. Based on this and other similar tests, it is clear that under certain unfavorable simulated landfill conditions, desiccation of the bentonite within a GCL is possible. Key findings from the experimental investigation included:

- The initial water content of the subsoil and the applied temperature gradient are critical factors affecting the potential desiccation of an overlying GCL.
- The GCL type played a secondary role, with one of the products being somewhat less prone to cracking than the other.
- Post-test hydraulic conductivity testing indicated self-healing ability and no permanent increase in hydraulic conductivity of the GCL, although the effects of chemical interaction with leachate or groundwater permeant were not studied. The applied overburden stress may impact the self-healing ability of the GCL, but it did not play a role in whether desiccation occurred under the conditions studied.

NUMERICAL MODELING

To more thoroughly investigate the thermally induced desiccation behaviour of a GCL, a program of numerical modeling was undertaken. Two different models (Döll, 1997 and Zhou and Rowe, 2003) were used to evaluate the relative importance of various material parameters and boundary conditions on the prediction of desiccation. The Döll model uses a finite difference approach to solve a system of coupled differential equations describing the transport of heat and moisture in an unsaturated rigid medium. The more rigorous model of Zhou and Rowe uses a finite element approach, which allows consideration of a deformable medium and the effects of stress. A full description of the governing equations and the numerical methods employed is not given here, but may be found in the referenced papers.

The modeling program adopted involved first the estimation of representative input parameters describing the pertinent thermal, mechanical and hydraulic properties of the materials. Parameters were chosen based on laboratory testing of the materials used in the large-scale tests or, where the time or expense necessary to obtain such data was prohibitive, from a review of pertinent literature. Using these parameters as a baseline, parametric investigations were undertaken to assess the relative importance of some key parameters such as the unsaturated hydraulic conductivity function of the subsoil and GCL, thermal conductivity and parameters describing the nonisothermal vapour transport. Based on the parametric studies, parameters giving the best fit to experimental data were identified. The parameters used to model one set of data are given in Table 1. A full description of the modeling program is in preparation, but a typical result is shown in Figure 3.

Table 1 – Input Parameters for Numerical Modeling

	Döll Model Parameters							
Material	n_p	θ_s	θ_r	α **(1/m)**	n	K_{sat} **(m/s)**	l	F_v
Silty Sand	0.35	0.35	0.005	.01	2.1	8×10^{-7}	0.5	2.5
GCL	0.74	0.75	0.05	0.0002	1.45	5×10^{-11}	-6.0	2.5
	Zhou and Rowe Model Parameters							
	a	b	c	d	a'	b'	c'	d'
Silty Sand	0.595	-0.006	-0.0003	1.0×10^{-5}	1.0	0.986	0	3.0×10^{-5}
GCL	8.0	-0.52	-0.306	0.0253	1	0.97	-1.55×10^{-6}	1.5×10^{-7}
	A	B	S_{lu}	α_k	B_k	γ_{dry}	γ_{sat}	u
Silty Sand	5.0×10^{-7}	1.0×10^{-12}	0	-2.5	4.0	0.256	2.804	0.35
GCL	5.0×10^{-11}	3.0×10^{-12}	-1.0	0.001	4.0	0.30	1.30	0.35

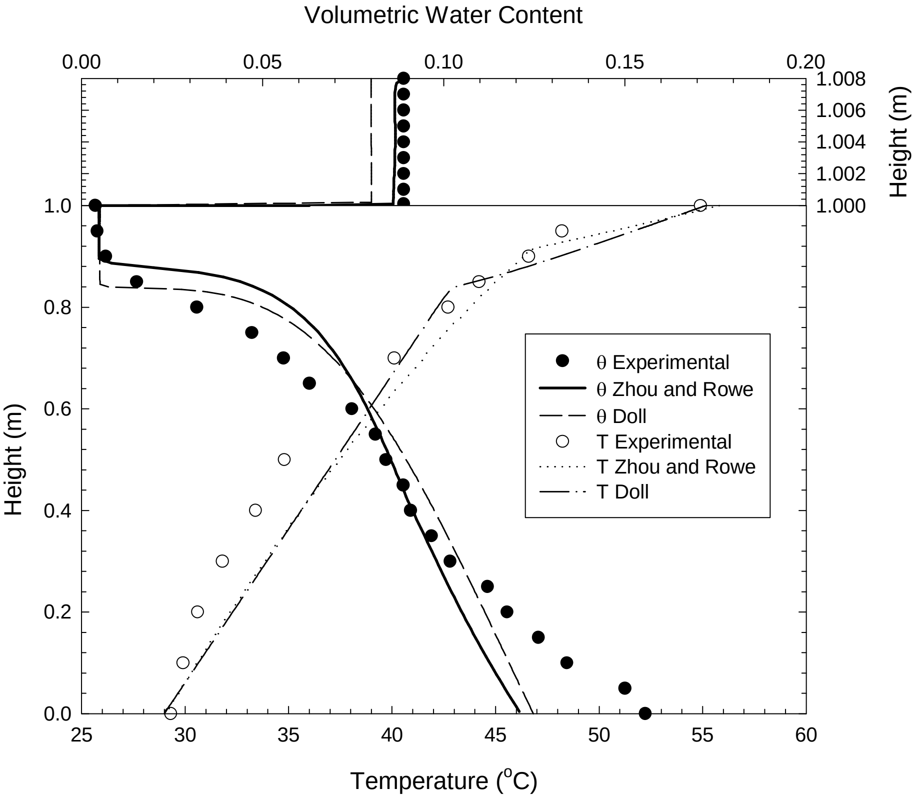

Figure 3 – Numerical Model Predictions

Figure 3 suggests that both models are able to predict the distribution of water content and temperature with reasonable accuracy. The dependence of hydraulic conductivity on suction and the weighting factor F_v for the nonisothermal vapour transport in the Döll model were found to have the most significant effects on the predicted water content distribution, while the parameters describing the thermal conductivity were found to have the most significant effect on the temperature distribution. The Zhou and Rowe model better captured the behaviour in the vicinity of the GCL, while both models tended to underpredict water content at the base. Although Figure 3 indicates that the Döll model compares favourably with the Zhou and Rowe model, some key limitations were identified through the course of the modeling program. The most important limitation was the assumption of a rigid media implicit in the Döll formulation. Although perhaps valid for simulation of a compacted clay liner for which the model was developed, this assumption is not valid for the prediction of GCL desiccation behaviour. As mentioned, the thickness and thus void ratio of the GCL was found to vary significantly during the large-scale tests. This has a significant effect on the volumetric water content and restricts the Döll model to more general investigations. Work is ongoing with the model of Zhou and Rowe to evaluate the ability to predict desiccation and resulting cracking of GCLs.

Based on the numerical modeling, some insights into the behaviour of the GCL-subsoil system under thermal gradients can be gained:

- Properties such as the unsaturated hydraulic conductivity and soil water characteristics of the subsoil play an important role in moisture redistribution throughout the system.
- The properties of the GCL have relatively little impact on the predicted behaviour of the subsoil, while the properties of the subsoil have a great influence on predicted GCL behaviour.
- Thermal conductivity and the thermal vapour diffusion coefficient used in the Döll model are difficult to obtain experimentally and may have a significant impact on predicted water content distribution.

RECOMMENDATIONS

Based on the results of the large-scale laboratory tests and the numerical modeling conducted to date, it may be said that under certain adverse conditions, there exists the potential for desiccation cracking of GCLs in landfill basal liner applications. Although GCLs which experience desiccation cracking may self-heal upon the introduction of liquid from above, it is desirable to avoid situations where desiccation is likely to occur in the design stage of landfill construction. In light of this, the following recommendations can be made:

- The placement of GCLs over dry subsoils should be avoided. The higher the initial water content of the subsoil, the lower was the potential for desiccation. GCLs placed on an adequately prepared foundation (i.e. in terms of water content) did not desiccate in tests conducted by the authors.
- Control should be exercised over temperature within the waste mass to avoid the development of high temperature gradients through the lining system. The maintenance of a functioning leachate collection system to control leachate mounding is thus important. Special care should be taken in the design of facilities utilizing leachate recirculation or moisture addition since such practices are likely to elevate temperatures within the waste mass, with a corresponding increased risk of desiccation in the underlying composite liner.

- Further testing of geosynthetic materials is necessary to better quantify their unsaturated hydraulic and mechanical properties. Data from such testing would be useful in refining available numerical models. In addition, further investigation into the self-healing ability of cracked GCLs when hydrated with leachate or groundwater permeants is necessary.
- Prior to construction of a landfill facility, it would be advantageous for numerical modeling to be carried out to assess the potential risks associated with thermally induced desiccation of composite liner components. Such modeling would incorporate site and material specific parameters where possible. The numerical model should be able to accommodate deformation of the GCL, since such deformation is likely under basal liner conditions and may have a significant impact on the desiccation behaviour of the GCL.

ACKNOWLEDGEMENTS

The research presented in this paper was funded by Terrafix Geosynthetics Inc., the Centre for Research in Earth and Space Technology (CRESTech) and the Natural Sciences and Engineering Research Council of Canada (NSERC). In addition, the value of discussions with Mr. K. von Maubeuge of Naue Fasertechnik and Mr. B. Herlin of Terrafix Geosynthetics Inc. is gratefully acknowledged.

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