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Desiccation behaviour of composite landfill lining systems under thermal gradients

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ABSTRACT: The use of composite liners composed of geosynthetic materials such as geomembranes and geosynthetic clay liners has been shown to be effective at minimizing outward contaminant transport from municipal solid waste landfills. However, questions have been raised regarding the effect of thermal gradients caused by degradation processes within the waste mass on the long-term performance of the clay liner. This question is examined under simulated field conditions using medium scale laboratory experiments. The results of these simulation tests are presented in terms of the distribution of temperature and water content over time and the potential impacts on the performance of the geosynthetic clay liner. The results indicate that thermally induced desiccation is unlikely to adversely affect the performance of geosynthetic clay liners in landfill basal liner applications under the conditions examined.

1 INTRODUCTION

In many jurisdictions worldwide landfilling is used as either a primary or secondary means of municipal solid waste disposal. Modern landfills often have one or more engineered basal lining systems designed to minimize the transport of contaminants out of the landfill and thus protect groundwater resources. In recent years there has been increasing use of geomembranes and geosynthetic clay liners (GCLs) in landfill liner applications. A worldwide survey of landfill regulations indicates that a majority of jurisdictions employ a composite lining system containing some geosynthetic component as the primary means of contaminant (Koerner & Koerner 1999). Geosynthetic materials are often used due to their more reliable engineered properties, their relative ease of installation and typically lower cost.

Although municipal solid waste is an extremely heterogeneous material, studies have indicated that, on average, organic material makes up 50 to 70% of the dry unit weight (Barone et al. 2000). The biological decomposition of this organic matter over time generates heat within the waste mass due to the exothermic reactions involved. Anaerobic decomposition will continue within the waste mass for as long as organic matter is present, likely for decades. The heat generated by these reactions will elevate the temperature within the waste and at the base of the landfill. Temperatures of over 50°C have been reported at the landfill base (Barone et al. 2000).

Increased temperatures caused by exothermic waste degradation lead to the development of thermal gradients through the subsoil. Under such conditions, water vapor will diffuse from the warmer liner to the cooler groundwater table, a process that may be partially balanced by the upward flux of liquid water under matric potential gradients. The net effect of these processes is the drying of the uppermost portion of the subsoil. Several researchers have experimentally investigated the degree of desiccation induced by thermal gradients through soil (e.g. Holzlöhner 1990, Stoffregen et al. 1993, Gottheil & Brauns 1994). Much work has also been done on the modeling of such moisture movement and various numerical models exist (e.g. Döll 1997, Zhou et al. 1998; Thomas & Missoum 1999). Investigations have also been undertaken to examine the effects of desiccation on geosynthetic clay liners used in final cover applications (e.g. James et al. 1997, Melchior 1997, Lin and Benson 2000). However, the degree to which thermally induced desiccation is likely to affect the performance of geosynthetic clay liners in landfill basal lining applications is unknown at this time. The current project seeks to address this issue through a series of laboratory experiments and associated numerical modeling. This paper presents the results of testing and numerical modeling conducted in an effort to better ascertain the effects of desiccation on GCLs in such applications.

2 SIMULATION EXPERIMENTS

To examine the potential performance of geosynthetic clay liners under representative landfill conditions, a series of medium scale simulation experiments were conducted. These tests are meant to simulate as accurately as possible the conditions existing at the base of a landfill subjected to heating from waste decomposition. This section reports the experimental apparatus used and presents some experimental results.

2.1 *Experimental apparatus*

The apparatus was designed to simulate reasonable worst-case conditions occurring at the base of a landfill during the early stages of its life when heat produced by biological activity is considerable. A scale larger than normal laboratory column tests was selected in order to ensure one-dimensional conditions and to obtain a more representative distribution of material properties. The cell consists of a 1 m high, 600 mm interior diameter PVC pipe with 25 mm wall thickness. The cell is filled with a locally obtained sandy silt, representative of a suitable subgrade material for landfill construction. A composite liner consisting of a 1.5 mm thick HDPE geomembrane overlying a geosynthetic clay liner is placed above the subgrade material. The top and bottom boundaries of the test cell are sealed to prevent moisture movement. Although an actual landfill would have a water table as the bottom boundary, with moisture movement possible, the provision of a no-flow boundary in the test apparatus is conservative due to the limitation put on the amount of liquid water available for upward capillary movement. A pressure of approximately 80 kPa is applied to simulate waste overburden stress, and a thermal gradient is induced through the soil by heating the upper surface while leaving the lower boundary uninsulated. The walls of the pipe are heavily insulated to approximate one-dimensional thermal conditions. The apparatus is depicted in Figure 1a.

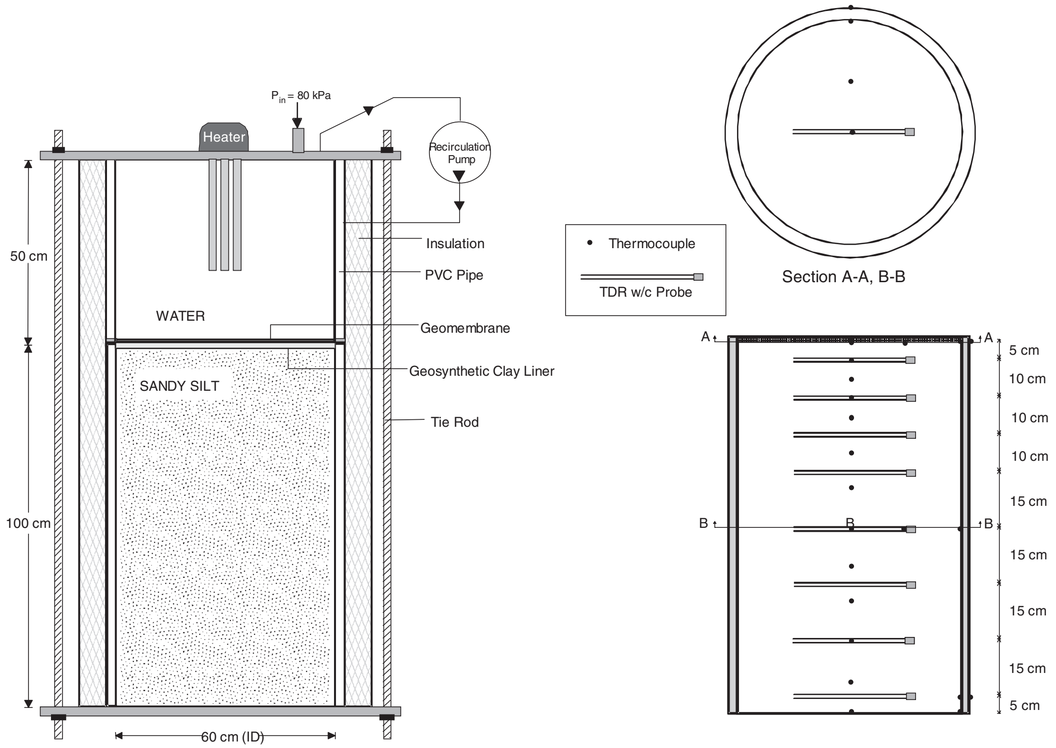
2.2 *Instrumentation*

Continuous monitoring of temperature and water content at various points within the subgrade soil is carried out. Thermocouples are placed along the central axis of the cell at various heights for temperature monitoring. In addition, thermocouples are placed at various distances from the central axis on horizontal planes at heights of 50 and 100 cm above the cell base to assess how effectively one-dimensional conditions are achieved. Eight TDR probes are used to establish the distribution of volumetric moisture content. The location of the instrumentation is depicted in Figure 1b.

2.3 *Experimental methodology*

The test cell was filled with a silty sand (SM). Prior to placement, the soil was mixed to a relatively uniform water content. Instrumentation was placed and gravimetric water content samples were taken as the cell was filled. In addition, a nuclear density gauge was used to determine the as-placed density of the soil in order to correlate gravimetric and volumetric water content data. A geosynthetic clay liner and geomembrane were then placed above the soil, and the test cell was sealed. The as-placed properties of the soil are summarized in Table 1. The properties of the needle-punched geosynthetic clay liner are presented in Table 2. The GCL was hydrated under zero applied stress conditions to a water content of approximately 80% prior to installation. This water content was adopted based on observations from a previous preliminary investigation. A small-scale laboratory test indicated a non-hydrated GCL overlying the soil in question at a water content of 12% under an applied load of 100 kPa would hydrate to a water content of 80%.

The cell was allowed to stand for a period of 42 days prior to the application of heat or pressure. This was due in part to problems with the pressure application system and in part to allow equilibrium conditions to be attained within the system. Following this period, a pressure of 80 kPa was applied and the heater was activated. Temperatures were automatically recorded at set 1-hour intervals using a datalogger, while TDR water content



(a) Schematic diagram (b) Test instrumentation

Figure 1. Medium scale simulation experiment test cell.

Table 1. Initial soil properties.

Property	Value	Notes
Water content	13.0%	Average as-placed value
Wet density (g/cm^3)	2.10	Average as-placed value
Dry density (g/cm^3)	1.86	Average as-placed value
Optimum water content	10.0%	From laboratory test
Maximum dry density (g/cm^3)	1.91	From laboratory test
Relative density	2.74	From laboratory test
Hydraulic conductivity (m/s)	2.5×10^{-7}	From laboratory test
Grain size distribution*		
Silt content	12%	
Sand content	80%	
Gravel content	8%	

* UCS classification system.

Table 2. Geosynthetic clay liner properties.

Layer	Material	Mass per unit area (g/m^2)
Cover geotextile	Polypropylene, nonwoven*	300
Bentonite layer	Sodium bentonite (powder)	4200
Carrier geotextile	Polypropylene, woven	200

* impregnated with 800 g/m^2 of bentonite.

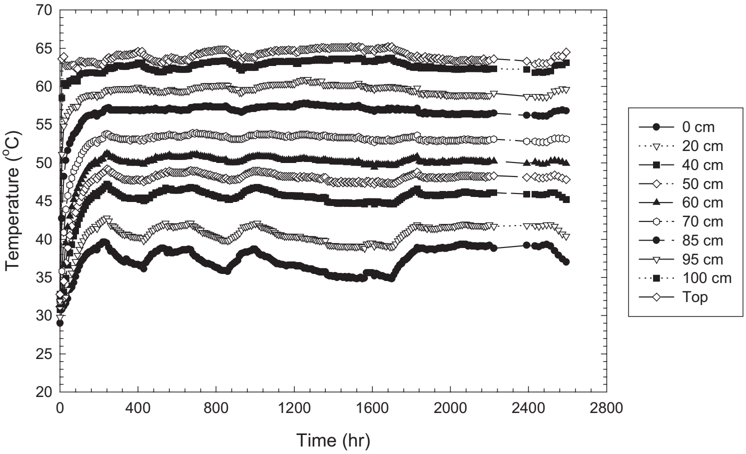


Figure 2. Temperature variation with time.

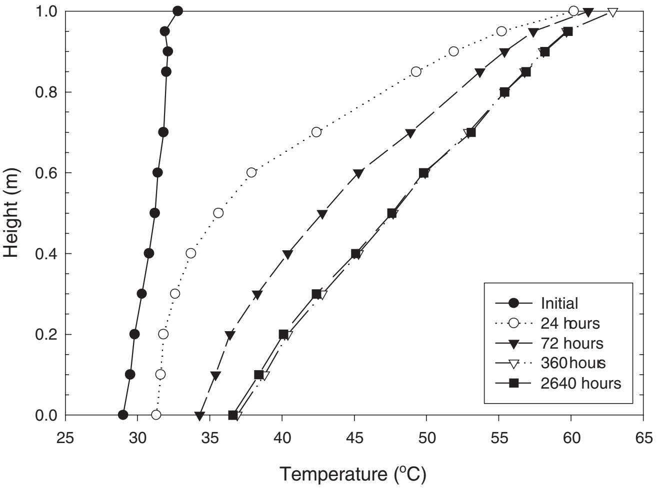


Figure 3. Temperature profiles.

measurements were taken periodically. The upper surface was raised to a temperature of approximately 65°C, creating a temperature gradient of approximately 30°C/m through the soil. The cell was monitored for a period of 110 days, at which time the heater was turned off, the pressure was removed and the cell was excavated.

2.4 *Experimental results*

Although a number of tests have been conducted in these medium scale test cells, only one set of results will be presented here in the interest of brevity. The results are presented in terms of temperature measurements, water contents and GCL properties.

2.4.1 *Temperatures*

Figure 2 depicts the temperatures at various heights within the cell with time. Figure 3 illustrates the observed temperature profiles at various times. Heat flow occurs rapidly through the system; temperatures in the uppermost

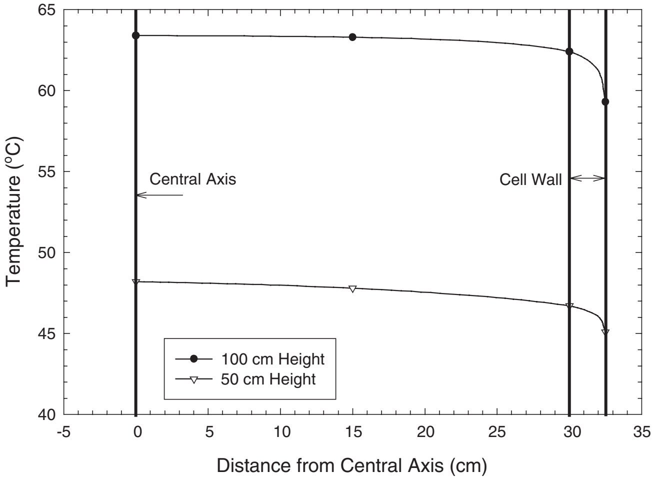


Figure 4. Horizontal distribution of temperature at 1200 hours.

portion of the soil stabilized within a few days from the start of heating. It can be seen that a stable thermal gradient is established through the entire soil column within 360 h (15 d) of the start of heating. Some fluctuation in temperature is noted over time due to changes in the ambient temperature of the laboratory in which the test cell was located.

In addition to the temperature profiles shown above, checks were made to assess the validity of the assumption of one-dimensional thermal conditions. At heights of 50 and 100 cm above the base, temperature measurements were taken at distances of 0, 15, 30 and 32.5 cm from the central axis. The results of these measurements are shown in Figure 4. As may be seen, the assumption of a one-dimensional thermal regime appears to be justified. The horizontal temperature gradient is approximately 3°C/m at a height of 100 cm and approximately 5°C/m at a height of 50 cm. This is in contrast to the vertical gradient of 30°C/m.

2.4.2 *Water contents*

As the test cell was filled, gravimetric water content samples were taken and nuclear density measurements were made. This allowed a reference water content profile to be established. These values were compared to those obtained in a similar manner during the excavation of the test cell following 110 days of heating. Figure 5 shows the distribution of water content with depth measured at the end of the test. Gravimetric water content samples were taken at the center of the test cell as well as at the edge and at intermediate points. Water contents given by the nuclear density gauge are shown as well. Despite some scatter, a clear trend of decreased water content towards the top of the cell and increased water content towards the bottom of the cell is noted. On average, a decrease of 5% was observed at the upper surface, while an increase of similar magnitude was observed at the bottom boundary. Samples taken from the edge of the test cell yielded generally higher water contents than those taken from central or intermediate locations. This is likely due to the slight horizontal temperature gradient mentioned in section 2.4.1. However, the similarity between central and intermediate water contents suggests that one-dimensional conditions prevail through the majority of the cross section. A trend of increasing water content with height is noted for the upper 10 cm of the cell, in contrast to decreasing water content with height through the majority of the cell. This can be explained in part by the higher initial water contents in this region, as well as by the likely uptake of water by the overlying GCL, as discussed further in the following section. No indications of subsoil desiccation were observed qualitatively. The TDR probes used to evaluate the temporal distribution of water content were found to give questionable readings and are thus not reported here.

2.4.3 *GCL water contents*

During excavation of the test cell, numerous water content samples were taken from the geosynthetic clay liner. As mentioned, the GCL was placed at an initial bulk water content of 80%. Following the test, samples of bentonite were taken from the GCL. Contour plots of water content from these samples are shown in Figure 6. It can be seen from these plots that the GCL has taken up water from the underlying soil. The average water

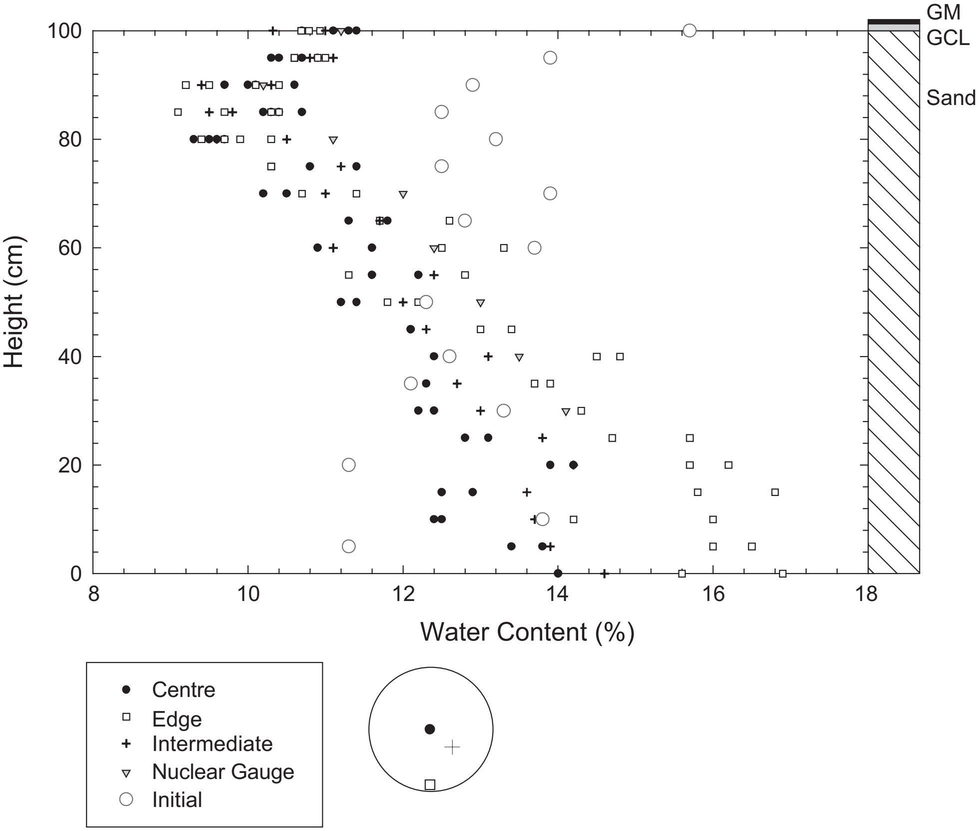


Figure 5. Water contents after 110 days of temperature gradient application.

content of the bentonite component of the GCL was 117%. Figure 6 suggests that some drying has occurred in the central area of the GCL, as water contents are approximately 5% lower than average in this region.

3 NUMERICAL MODELING

3.1 *SUMMIT numerical model*

The test cell was modeled using the numerical model SUMMIT (Döll 1996). SUMMIT solves a system of nonlinear equations for heat and mass transport using mesh-centered, fully implicit finite differences. 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. Further details of the model are provided by Döll (1996).

The test cell configuration was modeled as a two-layer system using 517 nodes. Pertinent material properties are summarized in Table 3. The initial conditions were input based on values measured during the filling of the cell. The top and bottom boundaries were modeled as impermeable with fixed temperatures based on measured values at these locations. The 42-day period prior to heating was modeled, followed by 110 days of applied heat.

3.2 *Numerical modeling results*

The results obtained from the numerical model are presented in Figure 7, along with the water contents measured at the end of the test. The model is seen to give a reasonable fit to the experimental data, capturing the general

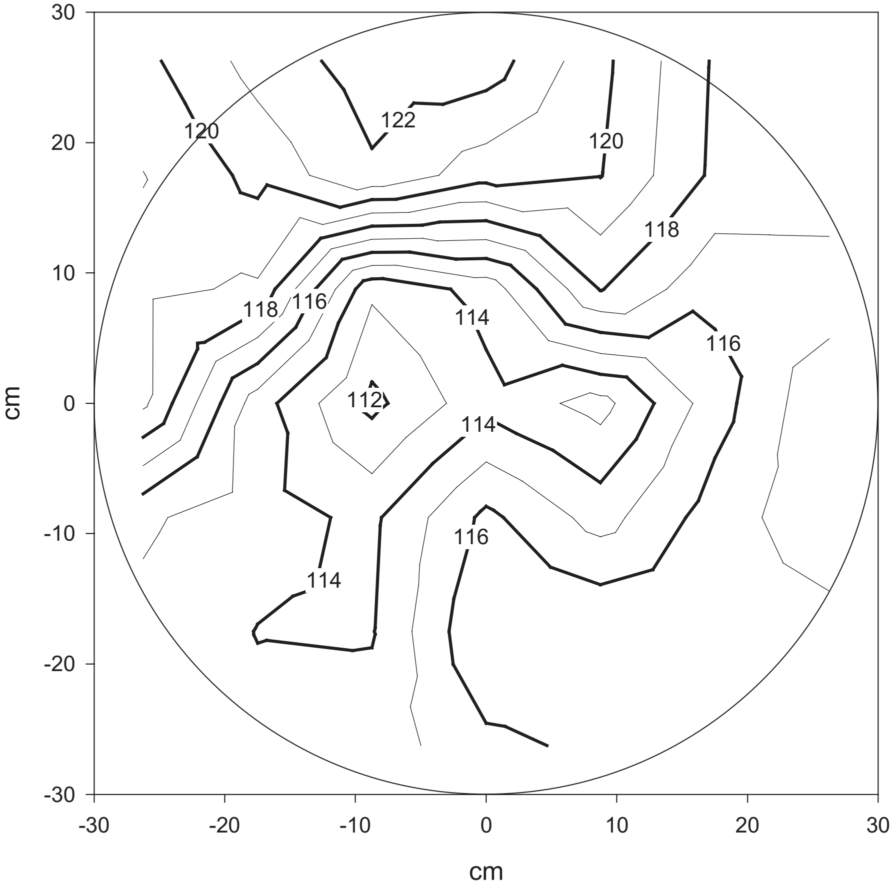


Figure 6. GCL water content distribution (from bentonite only).

Table 3. Soil properties for SUMMIT model.

Soil	Property	Value
Silty sand	Saturated hydraulic conductivity	2.33×10^{-2} m/d
	Saturated volumetric water content	0.333
	Residual volumetric water content	0.0
	α of Van Genuchten water content function	0.02
	n of Van Genuchten water content function	1.4
GCL	Saturated hydraulic conductivity	4.3×10^{-6} m/d
	Saturated volumetric water content	0.760
	Residual volumetric water content	0.100
	α of Van Genuchten water content function	0.00015
	n of Van Genuchten water content function	1.3

trend of drying near the top surface and wetting near the bottom surface. It may be seen that the majority of water content changes take place in the first 42 days, prior to the application of the thermal gradient. Thus, gravity-driven moisture movement appears to be most responsible for the observed changes in water content. Model results for the GCL indicated a rapid increase in volumetric water content from 57% initially to nearly saturated levels of 75.9%. Following this hydration, no water content changes were noted in the GCL layer

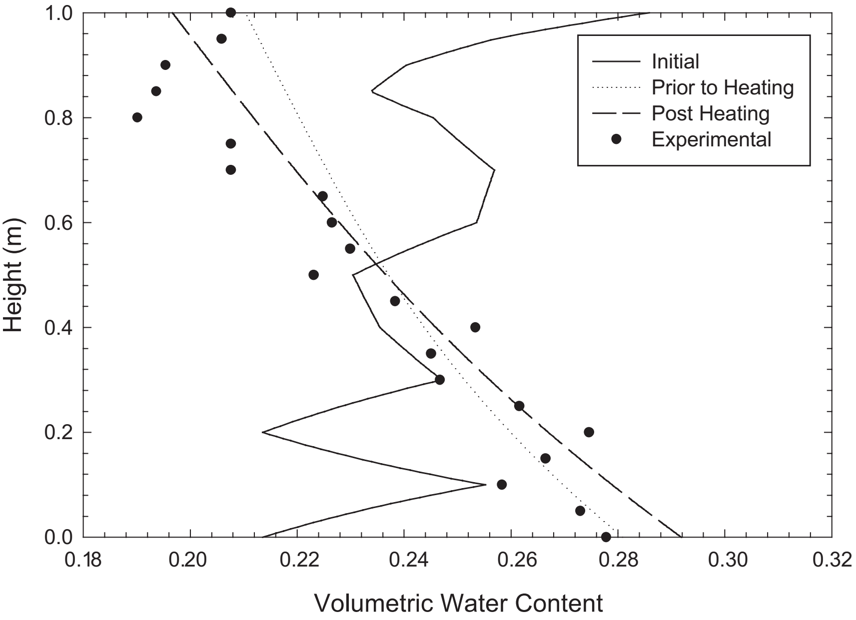


Figure 7. SUMMIT numerical model results

for the duration of the test, although matric potential increased slightly. As was the case for the subsoil, no qualitative indications of GCL desiccation were noted.

4 DISCUSSION

This paper has presented the results of a medium scale laboratory experiment and a numerical model investigating the desiccation behaviour of a composite landfill lining system under a thermal gradient. A 1 m high column of silty sand soil overlain by a composite liner comprised of a GCL and a geomembrane was exposed to a temperature gradient of 30°C/m for a period of 110 days. Results of temperature and water content monitoring have been presented and compared with values taken from the numerical model SUMMIT. Although a trend of reduced water content near the upper boundary and increased water content near the bottom boundary was noted, the level of this desiccation was not extreme. No qualitative evidence of desiccation was observed. No decrease in GCL water content was observed.

These results would suggest that, for the conditions under investigation, the risk of landfill temperature induced desiccation adversely affecting the performance of a composite liner system containing a GCL is negligible. It should be stressed that this study is not exhaustive, and that soil- and site-specific investigations should be made before conclusions are drawn for a specific site. This paper presents part of an ongoing study aimed at investigating fully the effects of temperature gradients on liner system performance. Further work is required to more fully address the issue of thermal desiccation in landfill applications, especially in the area of experimental data and numerical model development.

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