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Thermally-induced moisture movement beneath geosynthetic clay liners

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ABSTRACT: Composite liners comprised of geomembranes and geosynthetic clay liners can be an effective means of minimizing fluid flow and associated groundwater contamination from municipal solid waste landfills. Questions have been raised, however, regarding the long-term performance of such systems under conditions of elevated temperature, which may occur at the landfill base due to exothermic waste degradation processes. Thermal gradients produced by this degradation create the risk of desiccation within the uppermost portion of the subsoil and the geosynthetic clay liner itself, and the effects of such desiccation on the performance of the composite liner are of interest. To investigate this issue, medium scale laboratory experiments were developed to simulate field conditions. The design goals and methods are discussed. Results from a preliminary investigation are presented in terms of temperature and water content distribution. The course of future experimental work in this area is discussed.

1 INTRODUCTION

The use of landfilling is a prevalent means of municipal solid waste disposal currently practiced in many jurisdictions worldwide. Modern landfills are typically designed to reduce environmental impacts to acceptable levels and often incorporate one or more engineered basal lining systems to minimize outward contaminant transport. Geomembranes and geosynthetic clay liners (GCLs) are frequently used as integral components of such basal lining systems. The majority of jurisdictions employ composite geosynthetic lining systems to contain contaminants (Koerner & Koerner 1999).

Municipal solid waste is an extremely heterogeneous material, and its properties may vary significantly from region to region depending on local tendencies and cultural differences. However, studies have shown that organic matter makes up a significant portion of municipal solid waste, typically 50-70% of the dry unit weight (Barone et al. 2000). The aerobic and anaerobic biological decomposition of this organic matter involves exothermic reactions that lead to heat generation and consequently increased temperatures within the waste mass. Decomposition is likely to continue for as long as organic matter is present within the waste, resulting in elevated temperatures persisting likely for decades. Increased waste water content, due either to leachate mounding following the failure of the primary leachate collection system or to purposeful introduction of moisture to accelerate waste stabilization, have been shown to amplify the level of temperature increase (Rowe 1998). Temperatures of 20-60°C have been reported at the landfill base (Barone et al. 2000).

The effects of increased basal temperatures are many, and may include increased leachate collection system clogging rates (Rowe et al. 1997), increased diffusive and advective contaminant transport (Barone et al. 2000), more rapid ageing of geosynthetic components (Rowe 1998, Sangam 2001) and the potential for desiccation of mineral layers. This last effect arises due to the development of thermal gradients between the warmer liner and cooler groundwater table. Under these conditions, water vapour will diffuse from areas of high temperature to areas of low temperature, while liquid water will flow in the opposite direction under matric potential gradients. These processes could result in a net flux of water away from the liner, resulting in drying of the uppermost portion of the subsoil. This process is exacerbated by the presence of an overlying geomembrane, which prevents the infiltration of moisture from above.

The topic of thermally-induced desiccation has received some recent scrutiny. Experimental investigations of soil desiccation due to thermal gradients with applicability to compacted clay liners have been conducted by Holzlöhner (1990), Stoffregen et al. (1993) and Gotthiel & Brauns (1994). In addition, the numerical modeling of desiccation processes has advanced considerably, and numerous numerical models currently exist, each with varying applicability and limitations (e.g. Döll 1997, Zhou et al. 1998, Thomas and Missoum 1999). Investigations into the susceptibility of geosynthetic clay liners to desiccation have also been undertaken (e.g. James et al. 1997, Melchior 1997, Lin and Benson 2000), 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 current project seeks to address this issue. This paper presents a description of the goals of an experimental testing program and the methods used to assess the effects of desiccation on GCLs in such applications.

2 EXPERIMENTAL PROGRAM

Heat generated by waste decomposition leads to the development of temperature gradients through the basal liner and subsoil which have the potential to cause desiccation. Although this issue as it pertains to compacted clay liners has been examined in some detail by many researchers, an assessment of the potential impacts of thermally-induced moisture movement on geosynthetic clay liners has not yet been undertaken. This section provides a description of the objectives and methods of an experimental investigation into this issue.

2.1 *Experimental Goals*

To examine the issue of desiccation effects on geosynthetic clay liners, data from laboratory or field sources is required. This data can subsequently be used to gain a clearer understanding of the key processes affecting desiccation and as a means of verifying numerical models. The primary goal of the experimental program described below is thus to assess the effects of heat generation on the spatial and temporal distribution of moisture and temperature within and beneath a GCL. Although field data from an operating landfill would be ideal, the time and instrumentation required to obtain such data is prohibitive. The use of laboratory testing is thus required. The objective of such testing is to simulate as accurately as possible the conditions occurring at the base of a landfill. Such a simulation should attempt to replicate reasonable worst-case conditions to conservatively assess the performance of a GCL under conditions most conducive to desiccation. The materials used, such as the GCL, geomembrane and subsoil, should therefore be representative of those used in practice. Due to the large areal extent of modern landfills, one-dimensional conditions may be assumed to prevail over the bulk of the area under consideration. It is desirable that experiments be conducted at as large a scale as possible in order to ensure one-dimensional conditions and to more fully capture the spatial variability of monitored variables. As well, the flexibility afforded by the laboratory setting should be maximized, and control maintained over factors such as the applied temperature gradient, initial soil conditions, etc.

2.2 *Experimental Apparatus*

To achieve the objectives set out in Section 2.1, a medium scale test cell was developed. A schematic diagram of the cell is presented in Figure 1. The cell is a large soil column contained within a section of PVC pipe. The cell is 100 cm in height, with an internal diameter of 60 cm and a wall thickness of 2.5 cm. PVC was chosen as the test cell material due to its relatively low thermal conductivity and availability. The cell is bolted to a 2.5 cm PVC plate at the bottom boundary. This prevents water flow out of the system, a boundary condition deemed conservative, as it does not allow additional water input into the system. Actual field conditions would likely include an underlying water table from which additional moisture could be provided, reducing the degree of desiccation.

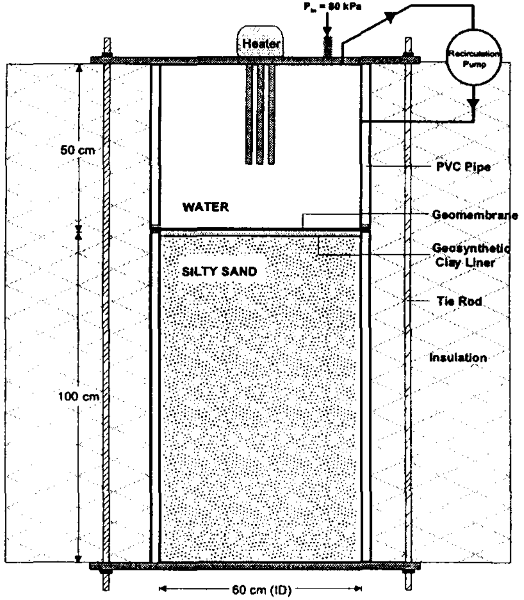

Figure 1. Schematic diagram of medium scale test cell.

The test cell was filled with a locally obtained silty sand soil. The pertinent geotechnical properties of this soil are given in Table 1. This soil was chosen as being representative of a suitable subsoil for use as an attenuation layer beneath a composite lining system. Guidelines for landfill design such as those used in Ontario, Canada and in Europe typically specify the inclusion of a natural or engineered attenuation layer. The generic designs presented under Ontario landfill regulations specify that this layer must be relatively homogeneous, have a hydraulic conductivity less than or equal to 1×10^{-7} m/s and be from 1 to 3 m thick, depending on the level of engineering utilized in the lining and leachate collection systems (MoE 1998). The hydraulic conductivity of the soil used in this case exceeds that specified; results obtained will thus likely be conservative.

Table 1. Silty sand soil properties.

Property	Value	Notes
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
Grain size distribution		UCS classification
Silt content	12%	
Sand content	80%	
Gravel content	8%	
Hydraulic conductivity (m/s)	2.5×10^{-7}	From laboratory test

Above the subsoil, a composite liner comprised of a GCL and overlying geomembrane was placed. The properties of the GCL are given in Table 2. GCLs of this type are currently in use in landfill basal liner applications. A 1.5 mm thick HDPE geomembrane was used. This geomembrane was placed between the top and bottom portions of the test cell to seal the system above the geosynthetic clay liner.

Table 2. Geosynthetic clay liner properties.

Property	Value
Bentonite mass per unit area	4340 g/m^2
Cover (upper) geotextile type	Polypropylene woven
Cover (upper) geotextile mass per unit area	105 g/m^2
Carrier (lower) geotextile type	Polypropylene nonwoven
Carrier (lower) geotextile mass per unit area	200 g/m^2
Construction	Needlepunched
Nominal permeability	5×10^{-11} m/s maximum

A temperature gradient was induced through the system by heating the upper boundary. An additional 50 cm high section of PVC pipe was installed above the geomembrane and filled with water. A 6 kW immersion heater was used to heat the water, while a pump was used to circulate the heated water to ensure an even temperature distribution at the top boundary. The walls of the cell were insulated with 45 cm thick fiberglass insulation in an effort to approximate one-dimensional thermal conditions.

A pressure of 80 kPa was applied to the water using an air line. This pressure was meant to simulate the effect of waste overburden stress, as well as to ensure intimate contact between the components of the composite liner and the underlying subsoil. A pressure of 80 kPa is equivalent to 10 m of waste thickness, assuming waste bulk unit weight of 8 kN/m^3. The entire test cell was constrained by tie rods to ensure that leakage did not occur.

2.3 *Instrumentation and Monitoring*

The primary objective of the instrumentation and monitoring plan was to obtain an accurate assessment of the spatial and temporal distribution of water content and temperature. The test cell was instrumented with a number of thermocouples for temperature measurement and TDR probes for volumetric water content assessment. The location of instrumentation is illustrated in Figure 2.

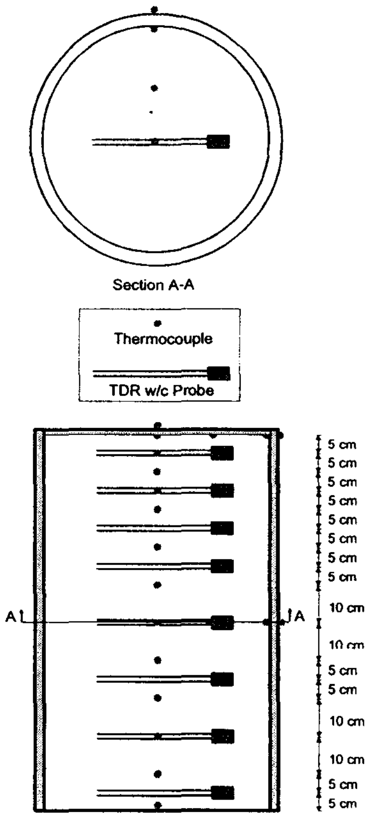

Figure 2. Test cell instrumentation

Thermocouples were placed at various heights along the central axis of the cell to monitor the variation of temperature. Additional thermocouples were placed at various distances from the axis on horizontal planes to assess the validity of the assumption of one-dimensional temperature conditions. TDR probes were installed horizontally at various heights to assess changes in volumetric water content. The thermocouples and TDR probes were monitored regularly during the duration of the test to examine temporal variation. In addition, soil samples were taken at various heights during the filling and post-test excavation of the cell for gravimetric water content testing. A nuclear density meter was used during filling and excavating to assess soil density.

2.4 *Experimental Methodology*

Prior to placement, the silty sand was mixed to a relatively uniform water content. The soil was then placed in the test cell in lifts and compacted to a bulk density of approximately 2.1 g/cm^3. The target gravimetric water content was 12%, which corresponds to a volumetric water content of 22.5% at a bulk density of 2.1 g/cm^3. Based on soil-water characteristic curve testing, the silty sand in question would achieve this water content at a matric potential (suction) of −10 kPa. In a field situation, this matric potential would occur at a height of 1 m above the water table, assuming static equilibrium conditions. Following placement, the system was allowed to equilibrate under isothermal conditions. Although measurements were not made during this phase of testing, the literature suggests that the system will reach gravitational equilibrium during this period, leading to a matric potential gradient of −10 kPa/m. Thus, prior to application of heat, the system is representative of the conditions existing beneath a landfill whose base lies 1.5 m above the water table, with matric potential varying linearly from −15 kPa at the top to −5 kPa at the bottom.

The GCL was hydrated under zero stress conditions to a water content of approximately 80% prior to placement. Small-scale investigations were conducted prior to the medium scale tests to assess the degree of water uptake an initially unhydrated GCL would experience when placed over a partially saturated soil under stress. The GCL in question was placed over the silty sand used at a water content of 12%, and a stress of 100 kPa was applied. The results of this test suggested that under these conditions the GCL would take up water from the underlying soil until it reached a water content of 80%.

Once the soil was placed and compacted and the GCL was installed, the cell was sealed and a pressure of 80 kPa was applied. The heater was activated and the temperature at the upper boundary was increased to approximately 60 °C. The temperature at the bottom boundary remained at room temperature, which was approximately 30 °C. Thus, a 30 °C/m thermal gradient was induced through the soil. This gradient is representative of that which would develop through a 1.5 m thick attenuation layer for a landfill base temperature of 60 °C and a groundwater temperature of 15 °C. 60 °C was chosen for the top temperature as a reasonable worst-case condition based on observed basal temperatures, as discussed in Section 1. The thermal gradient was maintained until observations indicated that steady state conditions had been achieved, at which time heating was terminated and the test cell was excavated.

3 EXPERIMENTAL RESULTS

The experimental program described in Section 2 was used to evaluate the performance of a GCL under representative field conditions. The results of two duplicate tests are presented here. Each used the same soil and GCL (refer to Tables 1 and 2). Test 1 was run for a period of 112 days, while Test 2 was run for 76 days. Figure 3 presents the spatial variation of temperature at various times for the two tests. A stable thermal gradient was established within a few days for each test, with little further variation. Overall temperatures were somewhat higher for the second test, due to an increase in the ambient air temperature. The thermal gradient was thus slightly lower for Test 2 at approximately 25 °C/m than for Test 1 at 30 °C/m.

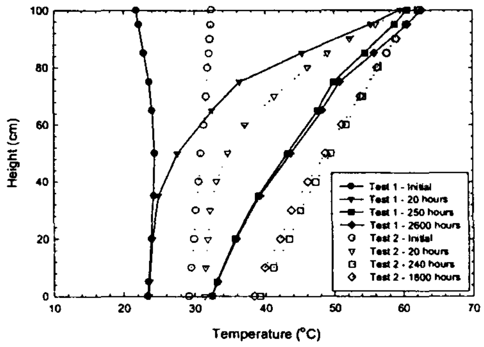

Figure 3. Temperature variation for Tests 1 and 2.

The gravimetric water contents measured during filling and excavation are presented in Figure 4. Despite the scatter, a clear trend of drying of the upper portions of the soil and wetting of the lower portions can be noted. The magnitude of this drying is not severe, however. The water contents at the top and bottom boundaries differ from the average initial value by approximately

4 %. No visual indications of desiccation were observed. The GCL water content was found to have increased to an average value of 90%.

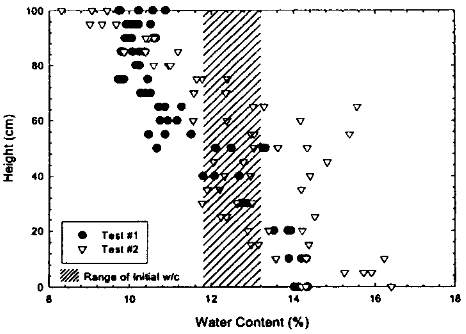

Figure 4. Final water contents for Tests 1 and 2.

4 DISCUSSION AND FUTURE WORK

The design and operation of medium scale laboratory test cells used to investigate the effects of thermally-induced moisture movement on geosynthetic clay liners has been presented. Results from preliminary tests using this cell have indicated that for the conditions examined no signs of desiccation were noted and there was no decrease in GCL water content, and thus GCL performance is unlikely to be impaired by desiccation under these conditions. It must be stressed that these tests are by no means exhaustive and that further testing is necessary to better quantify this phenomenon.

Work is currently under way to assess the effects of varying subsoil type and initial water content, and different GCLs are being used. The results of this testing are being used to assess the importance of various parameters on thermal desiccation behaviour, as well as to verify numerical model predictions. It is hoped that this research will provide a better understanding of the processes involved in thermally-induced desiccation and the implications for landfill liner designs incorporating geosynthetic clay liners.

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