Laboratory Investigation of Geosynthetic Clay Liner Desiccation in a Composite Liner Subjected to Thermal Gradients

Jonathan M. Southen¹ and R. Kerry Rowe, F.ASCE²

Abstract: Geosynthetic materials such as geomembranes and geosynthetic clay liners (GCLs) are frequently used in composite liners for municipal solid waste landfills. Heat generated within such facilities due to decomposition of organic material within the waste creates thermal gradients that have the potential to cause desiccation of the mineral component of GCLs, with potential impacts on long-term performance. This paper presents the results of an experimental investigation into the potential for moisture redistribution in and around GCLs forming part of a composite liner system when subjected to thermal gradients. Large-scale laboratory testing was performed using two different subsoils and GCL materials, with emphasis placed on the spatial and temporal variation of temperature and water content within and beneath the GCLs. The influence of key initial and boundary conditions such as the applied temperature gradient, initial GCL and subsoil water content, and the type of GCL is discussed, as well as the implications of the findings for long-term GCL performance. Recommendations are made regarding aspects of the design and operation of landfill facilities likely to reduce the potential for desiccation.

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CE Database subject headings: Clay liners; Geosynthetics; Desiccation; Thermal gradient; Landfills; Laboratory tests.

Introduction

Geomembranes and geosynthetic clay liners (GCLs) are frequently used as integral components of modern municipal solid waste (MSW) landfill lining systems (Koerner and Koerner 1999). Although MSW is heterogeneous and its properties may vary from region to region depending on local custom, studies have shown that organic matter makes up a significant portion of municipal solid waste, typically 50–70% of the dry unit weight (USEPA 2003). 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 wastewater 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 (e.g., a bioreactor landfill), has 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; Koerner 2001; Yoshida and Rowe 2003).

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 (Hsuan and Koerner 1998; Rowe 1998; Sangam and Rowe 2002), 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. A schematic of the conditions existing at the base of a landfill is shown in Fig. 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, depending on the as-placed water contents of the materials. When the temperature of the upper surface is increased by waste decomposition, heat flows downwards toward the cooler groundwater table. The temperature gradient thus established enhances the downward flux of moisture by inducing downward vapor diffusion due to the dependence of vapor density on temperature. It may be assumed that the geomembrane, which comprises the upper boundary of the system, is practically impermeable to water, and thus the downward vapor 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.

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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 Gotthiel and Brauns (1994) and Philip et al. (2002). 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; Sivakumar Babu et al. 2002; Sporer and Gartung 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 objective of this paper is to experimentally investigate the potential for moisture redistribution in and around geosynthetic clay liners forming part of a composite liner system when subjected to thermal gradients. Particular attention will be focused on the effects of a heat source above a geomembrane on the spatial and temporal distribution of moisture and temperature within and beneath a GCL. This testing is directed at identifying reasonable worst-case conditions that might give rise to desiccation with the objective of providing data that can subsequently be used to check numerical models and hence develop design recommendations that will minimize the risk of desiccation. To achieve these goals, the experimental program:

1. Involved tests conducted at as large a scale as is feasible;
2. Used materials, such as the geomembrane, GCL, and subsoil, that are representative of those used in practice; and
3. Provided the maximum flexibility afforded by the laboratory setting to maintain control over factors such as the applied temperature gradient and initial soil conditions.

Testing Program

Apparatus

Two test cells were developed involving a soil column contained within a section of poly(vinyl chloride) (PVC) pipe (Fig. 2). The cells were 1.0 m high, with an internal diameter of 600 mm and a wall thickness of 25 mm. The PVC was chosen as the test cell material due to its relatively low thermal conductivity and availability. The cell was filled (from bottom up) with a locally obtained silty sand soil (see the following section for details) representative of a suitable subgrade for landfill construction and a composite liner consisting of a GCL overlain by a geomembrane. The design allowed the recirculation and pressurization of water within a reservoir above the geomembrane (Fig. 2). The water was pressurized to simulate the waste overburden stress that would occur at a landfill. The cell was bolted to 25 mm PVC plates at the top and bottom boundary; these plates were connected using a system of steel bars and tie rods, which allowed the cell to remain sealed under the applied pressure.

The test cells were instrumented to allow continuous monitoring of temperature and water content at various points within the subgrade soil. Thermocouples [Type “T”, Thermo Electric (Canada) Ltd., Brampton, Ontario] were placed along the axis of the cell at various heights (Fig. 2). Additional thermocouples were 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 were achieved. Eight single-diode time domain reflectometry (TDR) probes (30 cm SDP, ESI Environmental Sensors Inc., Victoria, B.C.) were installed at consistent vertical spacing to investigate the distribution of volumetric moisture content as the test progressed (Fig. 2). The cell was insulated using multiple layers of Reflectix® bubble foil insulation (total thickness ~100 mm) around its circumference to provide, as far as possible, one-dimensional conditions.

Material Properties

Tests were conducted using two different subsoil materials and two different geosynthetic clay liners. The subsoils were both silty sand materials, with nominal properties as indicated in Table 1. The properties of the two GCLs studied are given in Table 2. The first GCL was comprised of a granular sodium bentonite core sandwiched between a slit-film polypropylene woven carrier geotextile and a polypropylene virgin staple fiber nonwoven cover geotextile. The GCL was reinforced by needlepunching and had thermally treated needlepunched fibers (thermal locking). The second GCL differs from the first in that the core is a powdered sodium bentonite and the cover nonwoven geotextile is impregnated with 800 g/m² of bentonite.

Test Descriptions

Eight tests were conducted using the procedure described below. First, the test cell was filled by compacting the soil in 5 cm lifts using a tamping plate, with the total energy applied to each lift being equivalent to that used in a standard compaction test (ASTM D6968). Water content samples were taken following the compaction of each lift using the oven method (ASTM D2216), and density was monitored by means of a nuclear gage (Troxler Model 3411-B, Troxler Electronic Laboratories Inc., Research Triangle Park, N.C.). Once the subsoil had been placed, the GCL was hydrated without applied stress by gradually applying water to the upper surface until the desired initial water content was reached, as determined by weighing the GCL periodically. The GCL was then placed, followed by a high-density polyethylene geomembrane. The upper portion of the cell was then placed and the system sealed. A period of time was allowed to pass for equilibrium to be established within the cell (see Table 3). Following this period, heat and pressure were applied and maintained until termination.
The initial and boundary conditions for each test may have a significant impact on the observed behavior. The principal variables that were controlled in the study were the test duration, the initial water content, and density of the subsoil, the initial water content of the GCL, the applied overburden pressure, and the applied temperature gradient. A summary of the testing conditions for each test is presented in Table 3. The nomenclature used to name the tests may be interpreted as follows: \( G\# \) refers to the GCL used, \( S\# \) refers to the silty sand subsoil used, and \( L\# \) refers to the test number, where \( L \) indicates large scale.

With reference to Table 3, for each of the two GCL–subsoil combinations (\( G1-S1 \) and \( G2-S2 \)), tests may be grouped based on the initial subsoil density and water content. Tests with lower initial water contents tended to have lower initial subsoil densities as well, due to the difficulty in compacting the drier soil. The choice of initial water content of the GCLs was based on observations from small-scale tests conducted in association with the tests reported herein (Southen and Rowe 2004). The range of 70–110% is typical of what would be expected based on uptake of water into an initially dry GCL placed above a moist subsoil of varying water content under applied surcharge pressures of 0–100 kPa (Southen and Rowe 2004). The temperature gradient applied during the tests was kept relatively constant between tests at 25–29°C/m. The temperature at the upper surface was kept at approximately 55°C, while the lower surface was left open to the atmospheric conditions of the laboratory, with an average temperature of 30°C. The applied pressures were meant to simulate the overburden stress applied by waste. The range of 15–95 kPa is representative of waste heights of approximately 2–14 m, based on a typical unit weight of waste of 7 kN/m². Although
Table 1. Subsoil Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silty sand S1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Optimum water content (%)</td>
<td>12.0%</td>
<td>ASTM D698-00ae1</td>
</tr>
<tr>
<td>Maximum dry density (g/cm³)</td>
<td>1.95</td>
<td>ASTM D698-00ae1</td>
</tr>
<tr>
<td>Specific gravity</td>
<td>2.71</td>
<td>ASTM D854-02</td>
</tr>
<tr>
<td>Grain size distribution (USCS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>classification)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Silt content</td>
<td>19%</td>
<td>ASTM D422-63(2002)</td>
</tr>
<tr>
<td>Sand content</td>
<td>79%</td>
<td></td>
</tr>
<tr>
<td>Gravel content</td>
<td>2%</td>
<td></td>
</tr>
<tr>
<td>Hydraulic conductivity (m/s)</td>
<td>2.5 × 10⁻⁸–7.0 × 10⁻⁷ m/s</td>
<td>Falling head</td>
</tr>
<tr>
<td>Silty sand S2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Optimum water content (%)</td>
<td>10.0%</td>
<td>ASTM D698-00ae1</td>
</tr>
<tr>
<td>Maximum dry density (g/cm³)</td>
<td>1.91</td>
<td>ASTM D698-00ae1</td>
</tr>
<tr>
<td>Specific gravity</td>
<td>2.74</td>
<td>ASTM D854-02</td>
</tr>
<tr>
<td>Grain size distribution (USCS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>classification)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Silt content</td>
<td>12%</td>
<td>ASTM D422-63(2002)</td>
</tr>
<tr>
<td>Sand content</td>
<td>82%</td>
<td></td>
</tr>
<tr>
<td>Gravel content</td>
<td>6%</td>
<td></td>
</tr>
<tr>
<td>Hydraulic conductivity (m/s)</td>
<td>1.5 × 10⁻⁷–7.5 × 10⁻⁷ m/s</td>
<td>Falling head</td>
</tr>
</tbody>
</table>

actual landfills may be constructed with greater waste heights than this, the physical capabilities of the test apparatus did not permit applied stresses greater than −100 kPa.

In addition to the large-scale tests discussed above, a series of small scale tests were also conducted. These tests utilized 25 cm high, 15 cm diameter cells tested under conditions similar to those of the large tests. Details of the testing procedure and results have been previously reported by the authors (Southen and Rowe 2004). A summary of these tests is given in Table 4.

No baseline tests were conducted under isothermal conditions since, based on theoretical considerations, such a condition is unlikely to lead to desiccation. Assuming that Darcy’s law is applicable, vertical fluid flow within the unsaturated soil will be governed by \( q = -ki \), where \( k \) is the unsaturated hydraulic conductivity (a function of matric suction) and \( i \) is the hydraulic gradient \( = (dh_m + dh_j)/dz \). Following placement of the soil, water will flow until static conditions are reached, i.e., \( q = 0 \). Under these conditions, the total head is constant throughout the soil column (i.e., \( i = 0 \)), such that \( dh_m = -dz \), where \( h_m = (u_w - u_a)/\gamma_w \). Thus, for the 1 m soil column used in the large-scale tests, a matric potential gradient of −10 kPa/m would be expected under static isothermal conditions.

Supporting this theory are the preheat results of test G2–S2–S4. One of the soil columns (Cell 1) was left unheated for a period of 153 days. The volumetric water content distribution measured during excavation of this test (Fig. 3) is in keeping with the theoretical considerations mentioned above. The volumetric water content of the subsoil was found to range from 0.107 at the upper surface to 0.121 at the lower boundary. Based on the soil–water characteristic curve for this soil, such water contents correspond to suctions of 21.0–19.2 kPa. The expected variation in suction at steady state for the 25 cm soil column would be 2.5 kPa, suggesting that a steady state has not yet been reached. The overall shift to lower water contents is attributed to uptake of water by the GCL, which increased in gravimetric water content from ~65 to ~105%.

Further supporting this point is the result of numerical modeling conducted using the model of Zhou and Rowe (2003). Results

Table 2. Geosynthetic Clay Liner Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Method</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>GCL G1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nominal mass/unit area</td>
<td>ASTM D5993</td>
<td>4.65 kg/m²</td>
</tr>
<tr>
<td>Bentonite mass/unit area</td>
<td>ASTM D5993</td>
<td>4.34 kg/m²</td>
</tr>
<tr>
<td>Lower geotextile</td>
<td>ASTM D5261</td>
<td>Polypropylene slit-film woven 105 g/m²</td>
</tr>
<tr>
<td>Upper geotextile</td>
<td>ASTM D5261</td>
<td>Polypropylene virgin staple fiber nonwoven 200 g/m²</td>
</tr>
<tr>
<td>Construction</td>
<td></td>
<td>Needlepunched</td>
</tr>
<tr>
<td>As-manufactured water content</td>
<td>ASTM D2216</td>
<td>7%</td>
</tr>
</tbody>
</table>

GCL G2                          |                |                               |
| Nominal mass/unit area          | ASTM D5993    | 5.50 kg/m²                    |
| Bentonite mass/unit area        | ASTM D5993    | 5.00 kg/m² (including 800 g/m² in NW GT) |
| Lower geotextile                | ASTM D5261    | Polypropylene slit-film woven 200 g/m² |
| Upper geotextile                | ASTM D5261    | Polypropylene nonwoven 300 g/m² (impregnated with 800 g/m² bentonite) |
| Construction                    |                | Needlepunched                 |
| As-manufactured water content   | ASTM D2216    | 9%                            |
Table 3. Test Conditions for Large-Scale Tests

<table>
<thead>
<tr>
<th>Test</th>
<th>Preheat duration (days)</th>
<th>Test duration (days)</th>
<th>Initial subsoil water content w (%)</th>
<th>Initial subsoil dry density (g/cm³)</th>
<th>Initial geosynthetic clay liner (GCL) bulk water content w (%)</th>
<th>Applied pressure (kPa)</th>
<th>Applied temperature gradient (°C/m)</th>
<th>Final GCL water content w (%)</th>
<th>Final subsoil water content w (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>G1-S1-L1</td>
<td>126</td>
<td>149</td>
<td>12.1</td>
<td>1.96</td>
<td>70</td>
<td>70</td>
<td>29.0</td>
<td>90</td>
<td>10.0–14.0</td>
</tr>
<tr>
<td>G1-S1-L2</td>
<td>38</td>
<td>76</td>
<td>12.5</td>
<td>1.82</td>
<td>80</td>
<td>95</td>
<td>25.0</td>
<td>110</td>
<td>8.5–16.0</td>
</tr>
<tr>
<td>G1-S1-L3</td>
<td>13</td>
<td>22</td>
<td>12.7</td>
<td>1.82</td>
<td>72</td>
<td>95</td>
<td>26.0</td>
<td>92</td>
<td>9.5–18.0</td>
</tr>
<tr>
<td>G1-S1-L4</td>
<td>60</td>
<td>90</td>
<td>4.5</td>
<td>1.76</td>
<td>110</td>
<td>15</td>
<td>25.0</td>
<td>12.1</td>
<td>0.2–7.0</td>
</tr>
<tr>
<td>G1-S1-L5</td>
<td>50</td>
<td>232</td>
<td>4.2</td>
<td>1.75</td>
<td>105</td>
<td>50</td>
<td>27.0</td>
<td>9.5</td>
<td>0.1–9.0</td>
</tr>
<tr>
<td>G2-S2-L1</td>
<td>42</td>
<td>109</td>
<td>13.0</td>
<td>1.85</td>
<td>80</td>
<td>80</td>
<td>25.5</td>
<td>112</td>
<td>9.0–17.0</td>
</tr>
<tr>
<td>G2-S2-L2</td>
<td>54</td>
<td>88</td>
<td>6.6</td>
<td>1.78</td>
<td>72</td>
<td>30</td>
<td>25.0</td>
<td>28.6</td>
<td>1.1–18.6</td>
</tr>
<tr>
<td>G2-S2-L3</td>
<td>49</td>
<td>233</td>
<td>6.3</td>
<td>1.79</td>
<td>81</td>
<td>70</td>
<td>24.8</td>
<td>15.6</td>
<td>0.3–16.6</td>
</tr>
</tbody>
</table>

obtained by modeling the preheat stage of test G1-S1-L5 are shown in Fig. 4. It may be seen that after 50 days (corresponding to the start of heat application in this test) suction has increased in the upper portion of the cell and decreased in the lower portion, although a steady state has not been reached. Suction within the GCL has decreased significantly from the as-placed value of 84 kPa. By 1,000 days, equilibrium has been reached. Suction within the subsoil varies linearly from ~33 kPa at the base to ~43 kPa at the upper surface, in keeping with the theoretical considerations discussed above. Since the goal of the testing program was to identify conditions likely to lead to GCL desiccation and such desiccation is unlikely under isothermal conditions, no baseline tests were conducted.

Results

Temperature Variation

Thermocouples installed in the subsoil during compaction allowed continuous monitoring of the thermal gradient through the system. Fig. 5 shows the variation in temperature with depth for tests G1-S1-L5 and G2-S2-L3 at various times. It can be seen that the thermal gradient develops rapidly, with significant changes in temperature noted in the upper 50 cm of the soil column within the first 20 h following the application of heat. A nearly steady state is reached within 200 h. The slope of the temperature gradient is steepest in the upper portions of the column. This arises because the thermal conductivity of an unsaturated soil increases with water content (de Vries 1963). The net effect of the higher temperature and lower water content in the upper portion of the subsoil may thus be seen to be a reduction in the thermal conductivity of the soil, with correspondingly steeper temperature gradients when compared with the wetter and cooler soil near the bottom of the cell.

Fig. 6 shows the variation of temperature for test G1-S1-L5 along horizontal planes 0 and 50 cm below the GCL at times of 800 and 5,800 h after the start of heating. It may be seen that at 50 cm, the change in temperature from the central axis to the cell wall is negligible. At a height of 100 cm, there was a small horizontal temperature gradient from the 15 cm point to the boundary but this was roughly 1 order of magnitude smaller than the vertical temperature gradient in this region. There was virtually no horizontal temperature gradient in the central portion of the cell suggesting that one-dimensional thermal conditions have been adequately achieved.

Series 1 Water Contents

Five tests were conducted using the silty sand No. 1 subsoil and the nonbentonite impregnated G1 GCL. This group of tests may be further subdivided based on the initial water content of the subsoil. The first three tests used a relatively high initial subsoil gravimetric water content averaging 12.1–12.7%. Other initial and boundary conditions were similar between the tests, as indicated in Table 3. The water contents measured during the excava- tion of tests G1-S1-L1 to -L3 are presented in Fig. 7. The similar initial and boundary conditions resulted in similar final water contents through the soil profile. Water contents at the upper surface of the subsoil were 2–4 percentage points lower than the initial values. Water contents at the base of the cell were 2–4 percentage points higher than the initial values. The GCL water contents (presented as an inset to Fig. 7) also show similar trends for the three tests. On average, a 20 percentage point increase in GCL water content was observed over the duration of these tests due to uptake of water from the underlying subsoil. As a result, no desiccation was observed.

The remaining two tests in the series adopted lower initial subsoil water contents averaging between 4.2 and 4.5%. Other test conditions are given in Table 3 and are similar to those of the
first three tests, with the exception of the applied pressure. G1-S1-L4 was conducted under a low applied pressure of 15 kPa, while G1-S1-L5 used a pressure of 50 kPa. The results of these tests are shown in Fig. 8. Water contents at the upper surface of the subsoil were approximately 4 percentage points lower than initial values, resulting in the soil being essentially dry. Water contents at the base of the cell were 3–4.5 percentage points higher than the initial ones. The inset to Fig. 8 indicates that significant drying of the GCLs occurred during these tests. Water contents decreased by approximately 95 percentage points to near residual values. As a result, significant desiccation cracking was observed for these tests, as shown in Fig. 9. The similarity in results between these two tests tends to indicate that applied stress is of relatively less importance than other variables for the range of stresses adopted.

**Series 2 Water Contents**

Three tests were conducted using the silty sand #2 subsoil and the bentonite-impregnated G2 GCL. The first test, G2-S2-L1, used a high initial subsoil water content averaging 13.0%. The subsequent two tests used a lower initial subsoil water content averaging between 6.3 and 6.6%. The final water contents measured during the excavation of the three tests are presented in Fig. 10. The effects of the variation in initial subsoil water content between the first test and the subsequent tests may be seen. Little variation in water content with depth was observed for G2-S2-L1, while G2-S2-L2 and -L3 showed significant variation. G2-S2-L1 showed water contents at the top surface 2 percentage points lower than initial and base water contents 2–4 percentage points higher than initial. The inset to Fig. 10 indicates that the GCL water content increased by more than 30 percentage points during this test. No evidence of desiccation was observed for the GCL in this test.

For G2-S2-L2 and -L3 the upper surface of the subsoil was essentially dry at the termination of the tests, as was the case for the tests using lower initial subsoil water contents in Series 1. Water contents in this region were approximately 6 percentage points lower than initial values. At the base of the cell, water contents had increased by 10–12 percentage points. As depicted in the inset to Fig. 10, significant drying occurred in the GCLs used for these tests. In G2-S2-L2, the GCL water content decreased by 43 percentage points, while for G2-S2-L3 the water content increased by more than 30 percentage points during this test. No evidence of desiccation was observed for the GCL in this test.

*Fig. 3. Isothermal behavior of G2-S2-S4*

*Fig. 4. Model results for preheat stage of G1-S1-L5*

*Fig. 5. Temperature variation for G1-S1-L5 and G2-S2-L3*

*Fig. 6. Horizontal temperature variation for G1-S1-L5*
content of the GCL was 54 percentage points lower than the initial value. Significant desiccation cracking was observed in these GCLs, as indicated in Fig. 11.

Temporal Variation

In addition to the gravimetric water contents taken at the beginning and end of the tests, TDR probes were used to assess the temporal variation in water content within the cell. The TDR readings at various times are shown for $G_2-S_2-L_3$ and $G_1-S_1-L_5$ in Fig. 12. For $G_2-S_2-L_3$, it may be seen that at the start of heating (~50 days following placement of the soil and GCL) water contents in the upper portion of the cell have decreased by approximately 1 percentage point, while those in the lower portion of the cell have increased by approximately 3.5 percentage points. This redistribution is attributed to the effects of gravity, as discussed in the test description. For $G_2-S_2-L_3$, after 225 days of heating, a reduction in volumetric water content of ~7 percentage points from values at the start of heating may be noted at the uppermost TDR location, while at the lowermost TDR an increase in water content of equal magnitude has occurred. The lowermost TDR probe failed during test $G_1-S_1-L_5$, but a decrease in volumetric water content of more than 5 percentage points is noted for the uppermost TDR probe. Very little variation may be noted after 200 days, corresponding to 150 days of heating, for either test, suggesting that near-steady-state conditions had been achieved at this time.

Comparison with Small-Scale Tests

A series of tests similar to those discussed above were conducted at a smaller scale. A full discussion of these tests has been previously reported by the authors Southen and Rowe (2004), and will not be repeated here. These tests used the $G_2$ GCL product in conjunction with the silty sand #2 subsoil, and thus the pertinent results will be compared in this section to those obtained for the $G_2-S_2-L_3$ series of tests. The small scale of the tests allowed greater flexibility in the testing conditions, enabling an evaluation of the uptake of water prior to heating and the influence of temperature gradient and temporal aspects.

To examine the behavior of the system prior to the application of heat and pressure, a number of tests were terminated at different times prior to the start of the test. Fig. 13 presents the results of such an investigation for one series of small-scale tests conducted with an initially dry GCL. It can be seen that the GCL takes up water rapidly from the underlying soil. Within 7 days, the GCL water content increased from an air-dry value of approximately 3% to nearly 70%. After 23 days, the water content
was more than 80%. The subsoil water contents decreased at the upper surface of the cell due to this uptake, as well as gravity-induced moisture redistribution.

Fig. 14 gives the GCL water contents measured at the end of each test in three of the small-scale series, plotted against time. The primary difference between these tests was the applied temperature gradient. For $G_2-S_2-S_2$, the gradient was 25°C/m through the system, while for $S_2-S_3$ it was 40°C/m for the bulk of the test and for $S_2-S_4$ it was 100°C/m. Each gradient relates to the large-scale tests discussed previously, as follows:

1. $S_2-S_2$—25°C/m gradient. This gradient is approximately the same as that adopted in the large-scale tests reported in the previous sections. The temperature acting at the top boundary was 29°C, while that at the lower boundary was 22.5°C.

2. $S_2-S_3$—40°C/m gradient. This gradient is approximately the same as that in upper 25 cm of the large-scale tests. The gradient in this region was larger than the overall average gradient, as discussed in the results section. The temperature acting at the top boundary was 39°C, while that at the lower boundary was 29°C.

3. $S_2-S_4$—60°C top temperature. This top temperature is approximately the same as the top temperature in the large-scale tests. The temperature at the lower boundary was 35°C, resulting in a temperature gradient of 100°C/m.

From Fig. 14, it appears that increasing the temperature gradient has the effect of increasing the rate of moisture movement in the system. For the tests at a temperature gradient of 25°C/m, the GCL water content was relatively constant after 77 days, while significant decreases in GCL water content were noted for the test at 100°C/m in less than 30 days. The ultimate water content of

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**Fig. 11.** Desiccated geosynthetic clay liner sample for $G_2-S_2-L_2$ with initial subsoil $w_0=6.6\%$, initial geosynthetic clay liner $w_0=72\%$, temperature gradient 25°C/m, and applied surcharge = 30 kPa

**Fig. 12.** TDR volumetric water contents for $G_2-S_2-L_3$ and $G_1-S_1-L_5$

**Fig. 13.** Preheat water contents for $G_2-S_2-S_2$

**Fig. 14.** Final geosynthetic clay liner water contents for small-scale tests
the GCL also appears to be lower for those tests with higher temperature gradients. Further discussion of these trends and other aspects of the small-scale tests may be found in Southen and Rowe (2004).

Also plotted in Fig. 14 are the initial and final GCL water contents measured for tests G2-S2-L2 and -L3. Similar trends of decreasing water content with time are noted for these tests. The large-scale data fits reasonably well with the small-scale data for tests conducted under a 40°C/m temperature gradient, i.e., that which mimics the temperature gradient in the upper 25 cm of the large-scale test cell.

Permeability Testing

The self-healing capacity of GCLs when hydrated following desiccation or other damage has been frequently cited as an advantage for the product over other alternative materials. To investigate whether thermally induced desiccation has a permanent impact on the fluid retention performance of a GCL, samples were taken from the G2 GCL following the S2-L3 test and the G1 GCL following the S1-L5 test. These samples were tested using de-aired water in a flexible wall permeameter under effective stresses of 70 and 50 kPa, corresponding to the stresses applied to the GCLs in the large-scale tests. Fig. 15 gives the calculated hydraulic conductivity over time. The G2 specimen exhibits a high hydraulic conductivity of $1 \times 10^{-9}$ m/s initially due to flow through the deep cracks within the bentonite layer. Over time, the bentonite hydrates and swells, sealing the cracks and resulting in a hydraulic conductivity of $4.0 \times 10^{-12}$ m/s. During the test, the specimen increased in height from 4.1 to 6.9 mm and the diameter increased from 50 to 56 mm. A similar trend is noted for the G1 specimen, where hydraulic conductivity decreases from $1 \times 10^{-8}$ m/s initially to final values of $3 \times 10^{-11}$ m/s. During the test, the G1 specimen increased in height from 6.1 to 6.6 mm and the diameter increased from 50 to 56 mm.

Discussion

Observations of both small- and large-scale tests suggest that the initial subsoil water content and the applied temperature gradient are key parameters affecting moisture redistribution. Fig. 16 presents the relationship between initial subsoil water content and final GCL water content for the eight large-scale tests conducted. The strong correlation that exists indicates the primary role that this variable plays. The effect of temperature gradient was not examined on the large scale, but results from the small-scale tests presented above indicate the importance of this variable. Other factors such as the applied surcharge and the initial GCL water content do not show strong correlations with final GCL water content, suggesting that they are secondary influences in moisture redistribution behavior, at least for the conditions studied.

Fig. 17 shows two different GCL products taken from otherwise similar tests G1-S1-L5 and G2-S2-L3. Both products are desiccated, however the cracks in the G1 product are much wider than the more prevalent but thinner cracks observed in the G2 product. The water content of the G2 product was slightly higher than that of the G1 product, but the pattern of cracking was consistent between tests, indicating that the G2 product appears to be more resistant to desiccation cracking. This may be due to the higher bentonite mass per unit area of the G2 product, resulting from the 800 g/m² of bentonite powder impregnated in the cover nonwoven geotextile. Additionally, the heavier woven carrier geotextile of the G2 product may act as a capillary barrier, allowing the bentonite core of the GCL to remain hydrated at higher levels.
of suction within the underlying subsoil. This latter issue requires further investigation.

It is important to stress that these tests are not and were not meant to be exhaustive. It is acknowledged that in order to fully investigate the influence of factors such as applied pressure, temperature gradient, initial water content, etc., many more tests than the ones conducted would be necessary. Since each test took anywhere from 100 to 300 days to conduct, it was not feasible to conduct an exhaustive experimental program. The primary objective of the experiments was to identify reasonable worst-case conditions that might give rise to desiccation with the objective of providing data that can subsequently be used to check numerical models and thence develop design recommendations that will minimize the risk of desiccation. The testing program described in this paper achieves this goal, considering the following:

1. The provision of a zero-flux (i.e., sealed) lower boundary limits the amount of water available for upward transport under matric potential gradients that can balance downward liquid and vapor flux. This condition is akin to a field situation where the distance from the liner to the groundwater table is large.

2. The ~60°C temperature applied to top of the test cell is based on reported landfill temperatures that are among the highest observed. The temperature gradient adopted thus represents the highest likely to be observed, with a resulting increased risk of desiccation.

3. The applied surcharges are lower than may be expected for a typical landfill with a height of waste of greater than 15 m. Since compressive stresses induced by surcharge loading offset the tensile stresses induced by high matric potentials, it may be expected that higher surcharges would result in decreased risks of desiccation cracking.

Subsequent work is being conducted involving parametric studies using the numerical model of Zhou and Rowe in order to more fully investigate the relative importance of various initial and boundary conditions.

Conclusions

This work has shown that under certain adverse conditions (i.e., low initial subsoil water content, high temperature gradient, low applied overburden stress) thermally driven moisture redistribution can cause desiccation of GCLs, while for other initial conditions but a similar temperature gradient no desiccation was observed. The primary variables examined were the initial water content of both the GCL and the subsoil, the type of GCL used, the applied surcharge, and the applied temperature gradient. Laboratory permeability tests were also performed on the desiccated GCL samples using de-aired water to establish whether the GCL could self heal to acceptably low hydraulic conductivity upon rehydration. Based on these tests it is concluded that:

1. For a given temperature gradient, the initial moisture content of the foundation soil below the GCL is a critical factor affecting the potential desiccation of a GCL. Lower initial subsoil water contents result in greater desiccation potential.

2. For the particular two GCL products and conditions tested, the desiccated GCL self healed during permeation and the hydraulic conductivity decreased from about $10^{-9}$ to $10^{-8}$ to between $10^{-12}$ to $10^{-11}$ m/s. While this is encouraging, it is noted that these tests did not examine the effect of any change in the GCL due to chemical interaction with either a leachate permeant or groundwater.

3. The nature of the GCL product may have some effect on the nature of desiccation that occurs, with one of the products tested being somewhat less prone to cracking under otherwise similar conditions. Higher bentonite mass per unit area and carrier geotextile thickness appear to result in lesser desiccation potential.

4. The higher the temperature gradient, the greater the potential for desiccation cracking.

5. Although the applied stress may be important with respect to self healing after desiccation, for the relatively low-stress conditions examined, the magnitude of applied stress had little effect on whether or not desiccation occurred.

Since the water content of the underlying subsoil and the magnitude of the temperature gradient acting on the lining system appear to be controlling factors, steps should be taken in the design of landfill facilities to minimize the potential effects of these factors. Placement of a GCL over dry subsoils should be avoided for landfill applications. Efforts should also be made to control the temperature gradient by ensuring a well-designed and functioning leachate collection system. The findings of this paper also indicate that particular care is needed to assess the potential effect of high temperatures due to leachate recirculation/moisture addition (e.g., for operating a bioreactor) or hydration of ash fills (see Rowe et al. 2004) on the potential for desiccation of any underlying composite liner (with a CGL or compacted clay).

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