



## Laboratory investigation of thermally induced desiccation of GCLs in double composite liner systems

Farzad M. Azad<sup>a</sup>, R. Kerry Rowe<sup>b,\*</sup>, Abbas El-Zein<sup>a</sup>, David W. Airey<sup>a</sup>

<sup>a</sup>School of Civil Engineering, University of Sydney, NSW 2006, Australia

<sup>b</sup>Department of Civil Engineering, GeoEngineering Centre at Queen's-RMC, Queen's University, Kingston, ON, Canada K7L 3N6

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### ABSTRACT

The potential for desiccation of GCLs in double composite liner systems under thermal gradients is experimentally investigated. The effects of key initial and boundary conditions such as the GCL mass per unit area, initial GCL and subsoil water content, time lag between waste placement and temperature increase, the applied temperature gradient and the foundation layer thickness are investigated and discussed. The results suggest that surface temperatures of 39–45 °C, corresponding to thermal gradients of 59–67 °C/m, can induce sufficient thermally driven moisture redistribution to cause desiccation of GCLs. For surface temperatures of 29–37 °C and thermal gradients of 20–29 °C/m there was occasional slight cracking observed in about a quarter of the cases examined. Results of laboratory permeability tests on the virgin and exhumed samples are used to assess the self-healing capacity of GCLs.

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### 1. Introduction

Geosynthetic clay liners (GCLs) have numerous applications in geoenvironmental engineering including landfill liners for municipal solid waste (Gassner, 2009; Guyonnet et al., 2009; Dickinson and Brachman, 2010) as well as resource recovery (Gates and Bouazza, 2010; Hornsey et al., 2010; Lange et al., 2010; Rowe et al., 2010a; Shackelford et al., 2010). They can be used as a single liner system or as part of a single or double composite liner system (Rowe et al., 2004).

Although geomembranes (GMBs) are excellent barriers to contaminated liquids when they are intact, fluids can readily leak through holes in a GMB unless there is resistance to that flow. The primary role of the GCL in a composite liner is to minimize the leakage of fluids though any hole in the GMB (Rowe, 1998; Nosko and Touze-Foltz, 2000; Rollin et al., 2002; Needham et al., 2004). For this composite action to be most effective, it is important that the GCL below the GMB not be desiccated, over the entire contaminating lifespan of the landfill (Rowe, 2005).

Biodegradation of organic waste and the hydration of ash in waste material can generate heat which reaches its maximum value

in the main body of the waste and decreases toward the landfill base (Collins, 1993). This temperature, and the rate of temperature increase, will depend on the landfill cover, landfill operations, climatic conditions, waste temperature at the time of placement, rate of waste filling, biomass content, leachate level and leachate recirculation (Rowe, 2010).

Several studies have been conducted to define the time-temperature history in the main body of the waste as well as at the base of landfills (Lanini et al., 2001; Yoshida and Rowe, 2003; Rowe, 2005; Yesiller et al., 2005; Koerner et al., 2008; Rowe and Islam, 2009). At the base of MSW landfills with an operating leachate collection system, temperatures of 30–40 °C have been observed. In bioreactor landfills, landfills without a leachate collection system, or where the collection system has failed, higher temperatures of 40–60 °C have been observed. Since the temperatures within an aquifer will remain relatively constant (e.g., at about 10 °C near Toronto in Canada; about 17 °C near Sydney in Australia; about 22 °C near Orlando in Florida), this scenario leads to high temperature gradients which accelerate the aging of the GMB, increase moisture movement, increase the risk of desiccation cracking of the mineral components of the liner, and increase both leakage and diffusion of contaminants (Southen and Rowe, 2005; Rimal and Rowe, 2009; Rowe and Hoor, 2009; Rowe et al., 2010b).

Mechanisms of heat and moisture transport under a GMB due to a temperature gradient are illustrated in Fig. 1. Initially, water within the underlying subsoil is in hydrostatic equilibrium. Under isothermal conditions, once placed, a GCL typically starts to uptake

\* Corresponding author. Tel.: +1 613 533 6933; fax: +1 613 533 6934.

E-mail addresses: [farzad.meysamiazad@sydney.edu.au](mailto:farzad.meysamiazad@sydney.edu.au) (F.M. Azad), [kerry@civil.queensu.ca](mailto:kerry@civil.queensu.ca) (R. K. Rowe), [abbas.elzein@sydney.edu.au](mailto:abbas.elzein@sydney.edu.au) (A. El-Zein), [david.airey@sydney.edu.au](mailto:david.airey@sydney.edu.au) (D.W. Airey).

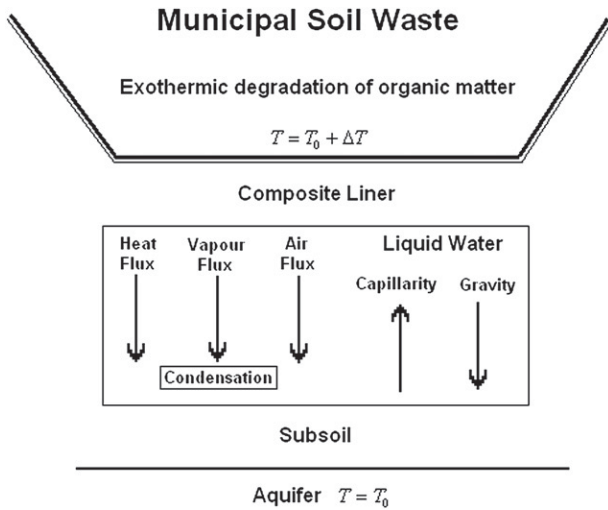


Fig. 1. Heat and mass fluxes in an unsaturated medium within and below a landfill composite liner system. (Adapted from Zhou and Rowe, 2003).

water from the subsoil until equilibrium is reached between the suctions in the GCL and the underlying subsoil (Daniel et al., 1993; Eberle and von Maubeuge, 1997; Rayhani et al., 2011). Under non-isothermal conditions where the landfill provides a source of elevated temperature relative to the soil at depth, heat flows downwards toward the cooler area. Due to the dependence of vapor density on temperature, the temperature gradient induces downward migration of water vapor from the GCL and the underlying subsoil. The water vapor cools in the lower temperature area and results in condensation. Air also moves from the higher air pressure to the lower air pressure area at depth. Because of this downward migration of water vapor, the water content of warmer areas will decrease, which causes liquid water to move upward because of the capillary potential gradient. However, there is a point at which the upward liquid flux cannot balance the downward flux of water vapor. Under these circumstances, the combined effects of liquid water, vapor water and air flow cause a decrease in the water content of the GCL below a GMB at the base of the landfill. This can

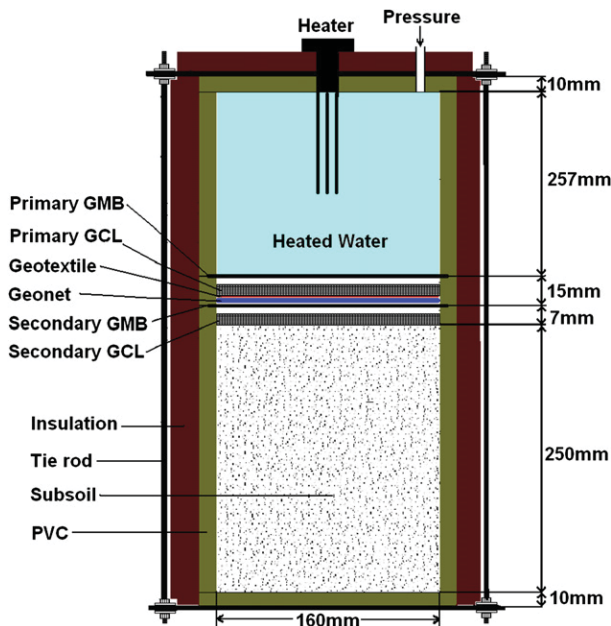


Fig. 2. Schematic of test cell for test series G1.

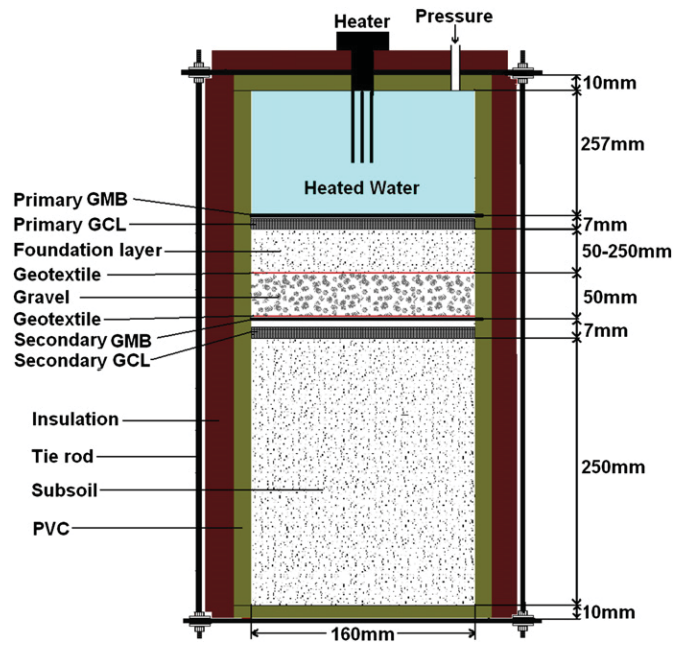


Fig. 3. Schematic of test cell for test series G2.

cause drying and possibly desiccation cracking in clay liners, as reported at various sites and in laboratory experiments (Basset and Bruner, 1993; Collins, 1993; Bowders et al., 1997; Southen and Rowe, 2005).

Investigations into the susceptibility of GCLs to desiccation have been conducted for landfill final covers where seasonal cycling plays a significant role in GCL behavior (Lin and Benson, 2000; Sporer and Gartung, 2002; Sivakumar Babu et al., 2002; Benson et al., 2010; Scalia and Benson, 2011). However the conditions in basal lining systems are different to those in the cover, as they evolve with the application of stress and temperature gradient. Very little research has been performed on the desiccation risk of GCLs in the bottom lining of waste contaminant facilities. Southen and Rowe (2005) presented the only experimental study with small and large scale laboratory tests on GCLs subjected to thermal gradients. Their results demonstrated a high risk of desiccation for single lined landfill barrier systems.

The current study expands on the work of Southen and Rowe (2005) by investigating the behavior of GCL as a part of double composite liner systems (DCLSs). Thus the objective of this paper is

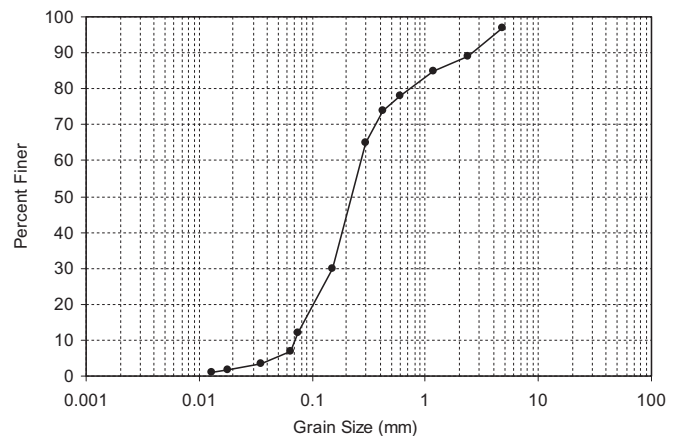


Fig. 4. Grain size distribution of the silty-sand.

**Table 1**  
Geosynthetic clay liner properties (ELCOSEAL X1000).

Property	Unit	Test method	Value <sup>a</sup>	Measured
Total mass/unit area	g/m <sup>2</sup>	ASTM D5993	4390	4527
Hydraulic conductivity <sup>b</sup>	m/s	ASTM 5887	$2 \times 10^{-11}$	$1.4 \times 10^{-11}$ ( $0.5 \times 10^{-11}$ )
Polypropylene nonwoven cover geotextile mass/unit area	g/m <sup>2</sup>	AS 3706.1	270	265
Polypropylene woven carrier geotextile mass/unit area	g/m <sup>2</sup>	AS 3706.1	110	107
Bentonite mass/unit area	g/m <sup>2</sup>	ASTM D5993	4000	4155
Bentonite impregnation mass/unit area	g/m <sup>2</sup>	Strew test	800	–
Bentonite swell index	mL/2g	ASTM D5890	≥24	25
Bentonite liquid limit	%	AS 1289.3.2.1	–	513
Bentonite plastic limit	%	AS 1289.3.9	–	46

<sup>a</sup> Values from Geofabrics Australia literature, www.geofabrics.com.au.

<sup>b</sup> Arithmetic mean of test values (standard deviation in brackets).

to identify conditions likely to lead to GCL desiccation in DCLSs so that such conditions may be avoided in the design stage of landfill construction and, in particular, to obtain experimental data that could subsequently be used to validate a numerical model. In addition to examining the water content of the GCLs in DCLS under different conditions, laboratory permeability tests were performed on the virgin and desiccated GCLs to establish their self-healing capacity and to investigate how thermally induced desiccation has an impact on the GCL hydraulic conductivity.

## 2. Methodology

### 2.1. Apparatus

#### 2.1.1. Testing program G1: DCLS without foundation layer

Ten test cells were developed for a DCLS comprised, from the subsoil up, of a GCL overlain by a 1.5 mm thick secondary HDPE GMB, a 5.3 mm thick geonet, overlain by the primary GCL and

a 1.5 mm thick primary HDPE GMB (Fig. 2). Test cells were made of PVC pipes because of the relatively low thermal conductivity of PVC. In addition, the low friction coefficient of PVC limits any stress reduction from side wall friction. Each cell was 549 mm high, with an internal diameter of 160 mm. Each cell was sealed using a 10 mm PVC plate and adhesive-sealant on the top and bottom boundaries.

The design allowed the pressurization of water within a reservoir above the liners to simulate the waste overburden stress. The top and bottom PVC plates were clamped together using a system of steel bars and tie rods to maintain the seal integrity under the applied pressure. Heat generated by waste decomposition was simulated by heating the water reservoir. The water within the reservoir was instrumented to allow continuous monitoring of temperature on the top of the liners. The cell was also heavily insulated to provide, as far as possible, one dimensional conditions.

#### 2.1.2. Testing program G2: DCLS with foundation layer

Five tests were conducted for a DCLS comprised, from the silty-sand subsoil up, of a GCL overlain by a 1.5 mm thick secondary HDPE GMB, a 50 mm gravel (secondary leachate collection system), 50 mm foundation layer, primary GCL and a 1.5 mm thick primary HDPE GMB (Fig. 3). The same method used in program G1 was used in program G2 to simulate the waste overburden stress and temperature.

### 2.2. Material properties

A silty-sand typical of what might be expected of subsoil beneath a GCL composite liner at the base of a landfill was used as the subsoil. It was produced according to the grain size distribution reported by Southen and Rowe (2005) to be able to use the same soil water characteristic curve in subsequent numerical modeling. The particle size distribution of the soil is given in Fig. 4 with 12% passing the 0.075 mm sieve. The grain size distribution gave a  $D_{10}$  of 0.06 mm and a  $D_{60}$  of 0.27 mm, with a uniformity coefficient,  $C_u$ , of 4.5. A standard proctor compaction test was also performed on the soil (ASTM D698) and gave a maximum dry density of 1.73 g/cm<sup>3</sup> and an optimum water content of 11.0%. The GCL used (ELCOSEAL

**Table 2**  
Laboratory test details for test series G1.

Test	G1-T0	G1-T1	G1-T2	G1-T3	G1-T4	G1-T5	G1-T6	G1-T7	G1-T8	G1-T9
Timeline (days)										
• Cell filled and 1.7 kPa nominal stress applied	0	0	0	0	0	0	0	0	0	0
• 40 kPa pressure applied	–	102	112	105	105	106	102	105	105	96
• Pressure increased to 100 kPa and heat applied	260	270	238	231	231	274	270	231	250	247
• Cell terminated										
Initial subsoil water content	10.9%	11%	11.4%	14.1%	5.1%	10.3%	10.3%	11.5%	10.7%	4.8%
Initial PGCL water content	75%	75%	75%	75%	75%	180%	12%	75%	75%	75%
Initial SGCL water content	75%	75%	75%	75%	75%	75%	75%	12%	75%	75%
Applied thermal gradient (°C/m)	0	28.5	23.0	27.0	27.0	29.0	21.4	25.0	66.5	59.5
Top temperature (°C)	23.0	31.0	29.5	29.5	29.5	31.0	29.0	29.0	42.5	39.5
Bottom temperature (°C)	23.0	23.0	23.0	22.0	22.0	23.0	23.0	22.0	24.0	23.0
Relative mass per unit area <sup>a</sup> (PGCL)	1.04	0.96	1.00	0.88	1.03	0.97	1.13	1.02	1.05	1.00
Relative mass per unit area <sup>a</sup> (SGCL)	0.85	0.97	1.04	1.05	1.17	0.93	0.97	1.01	1.06	0.94
PGCL crack description	No cracks	Narrow cracks	Narrow cracks	Narrow cracks	No cracks	No cracks	No cracks	No cracks	Deep cracks	Deep cracks
SGCL crack description	No cracks	No cracks	No cracks	No cracks	No cracks	No cracks	No cracks	No cracks	No cracks	Narrow cracks
Initial hydraulic conductivity of desiccated PGCL (m/s)	–	$3.0 \times 10^{-10}$	$2.0 \times 10^{-10}$	–	–	–	–	–	$8.4 \times 10^{-10}$	–
Initial hydraulic conductivity of desiccated SGCL (m/s)	–	–	–	–	–	–	$8.8 \times 10^{-11}$	–	–	$8.0 \times 10^{-10}$
Final PGCL water content	61.4%	45.4%	53.2%	51.0%	61.5%	102.2%	13%	60.8%	27.5%	32.5%
Final SGCL water content	138%	62.8%	68.5%	87.0%	58.2%	70.2%	87.1%	64.8%	53.0%	34.1%

Standard deviation of all the samples: 288 (g/m<sup>2</sup>).

<sup>a</sup> Sample mass per unit area divided by the mean (4155 g/m<sup>2</sup>) mass per unit area of all the samples.

**Table 3**  
Laboratory test details for test series G2.

Test	G2-T1	G2-T2	G2-T3	G2-T4	G2-T5
Time line (days)					
• Cell filled and 1.7 kPa nominal stress applied	0	0	0	0	0
• 40 kPa pressure applied	—	88	89	—	—
• Pressure increased to 100 kPa and heat applied	103	102	103	105	105
• Cell terminated	250	249	245	270	231
Initial FL water content	12.6%	10.7%	10.8%	10.5%	11.1%
Initial subsoil water content	11.6%	11%	11.3%	11.2%	11.8%
Initial PGCL water content	75%	75%	12%	75%	75%
Initial SGCL water content	75%	75%	75%	75%	75%
Initial gravel water content	2%	2%	2%	2%	2%
Foundation layer thickness (mm)	50.0	50.0	50.0	50.0	250.0
Applied thermal gradient (°C/m)	24.0	20.0	21.3	61.0	26.0
Top temperature (°C)	32.0	30.5	31.0	45.0	37.0
Bottom temperature (°C)	23.0	23.0	23.0	22.0	22.0
Relative mass per unit area <sup>a</sup> (PGCL)	1.08	1.04	1.02	0.92	0.94
Relative mass per unit area <sup>a</sup> (SGCL)	0.90	1.06	0.96	0.92	0.96
PGCL crack description	No cracks	No cracks	No cracks	Deep cracks	No cracks
SGCL crack description	No cracks	No cracks	No cracks	No cracks	No cracks
Hydraulic conductivity of desiccated PGCL (m/s)	—	—	—	$9.0 \times 10^{-10}$	—
Hydraulic conductivity of desiccated SGCL (m/s)	—	—	—	—	—
Final PGCL water content	67.0%	90.1%	68.6%	29.3%	76.0%
Final SGCL water content	101%	101.2%	110.1%	80.2%	110.5%

Standard deviation of all the samples: 288 (g/m<sup>2</sup>).

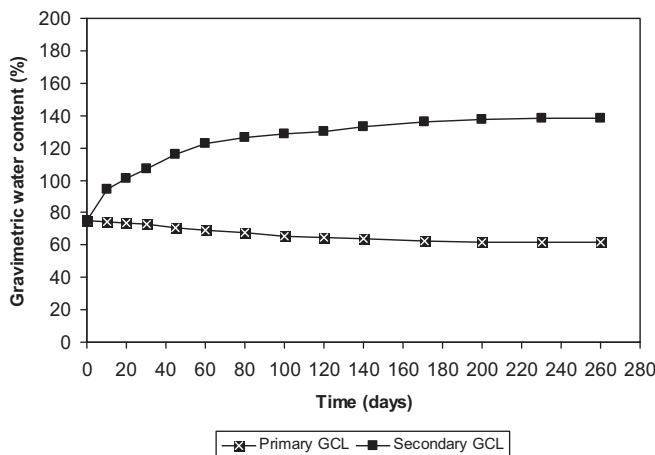
<sup>a</sup> Sample mass per unit area divided by the mean (4155 g/m<sup>2</sup>) mass per unit area of all the samples.

X1000, Table 1) was fiber reinforced by needle-punching and the carrier geotextile had been thermally treated to bond the needle-punched fibers to the carrier geotextile.

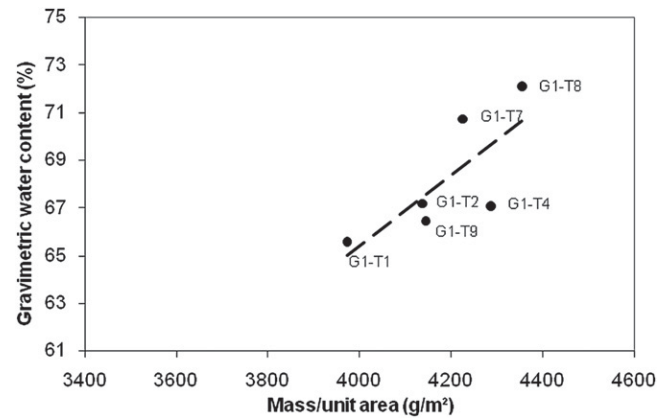
**2.3. Test descriptions**

**2.3.1. Testing program G1**

Soil samples were mixed with water to achieve the desired water content and then stored in plastic bags to allow the water in the soil to reach equilibrium. The test cell was filled by compacting the silty-sand in 50 mm lifts using the equivalent energy to standard compaction test (ASTM D698). To minimize bentonite loss along the edges of the GCL, the GCL samples were cut from the roll



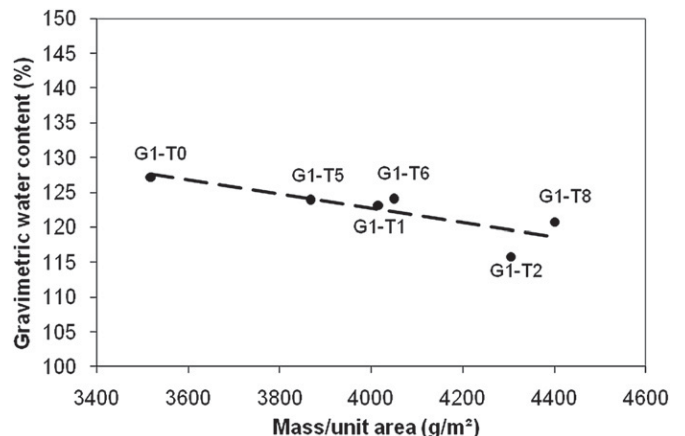
**Fig. 5.** Variation in gravimetric water contents for baseline tests G1-T0 under isothermal conditions at 23 °C. Both GCLs started at 75% water content.



**Fig. 6.** Relationship between PGCL water content and bentonite mass per unit area in test series G1 after 88 days.

using a razor knife. The GCL samples were hydrated (without applied stress) by gradually adding water until the desired initial water content was reached. The secondary GCL (SGCL) was then placed over the subsoil, followed by a 1.5 mm secondary HDPE GMB. A 5.3 mm layer of geonet was then placed over the secondary HDPE GMB to simulate the secondary leachate collection system followed by a geotextile (280 g/m<sup>2</sup>), primary GCL (PGCL) and primary 1.5 mm HDPE GMB. The upper portion of the cell was then placed and the cell was sealed. About 100 days were allowed for equilibrium to be reached under a nominal stress of 1.7 kPa (provided by a steel block to ensure intimate contact between the layers) then heat and pressure were applied. The temperature at the lower surface was controlled by conditions in the laboratory which was maintained at an approximately constant temperature ( $T = 22^\circ \pm 1^\circ\text{C}$ ). The primary GMB was heated to a temperature representative of values that might be expected for different landfill conditions. The applied pressure simulated the overburden stress exerted by the waste. Assuming a unit weight of 7–13 kN/m<sup>3</sup>, an applied pressure of 100 kPa corresponds to a thickness of approximately 8–14 m of waste. This represents a typical lower bound applied stress for many modern landfills. To track the moisture content changes according to ASTM D5993, the cells were opened every 10–30 days and the GCL was removed, weighed, and returned to the column.

A summary of the testing conditions for each test is presented in Table 2 where: G# refers to the test group as described above and



**Fig. 7.** Relationship between SGCL water content and bentonite mass per unit area in test series G1 after 88 days.

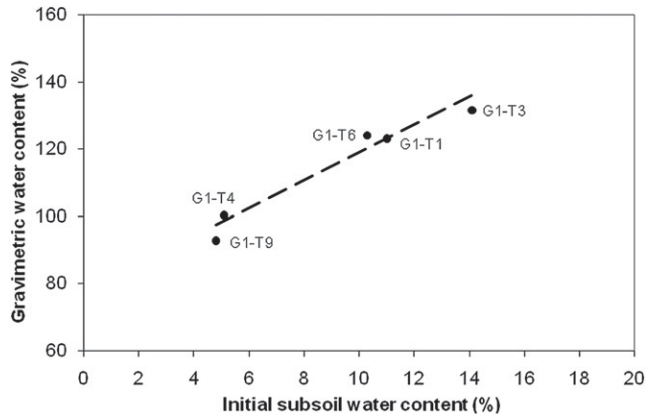


Fig. 8. Relationship between SGCL water content and initial subsoil water content in test series G1 after 88 days.

T# refers to the specific test. Test G1-T0 was conducted under isothermal condition with the initial subsoil water content of 10.9% and initial GCL gravimetric water contents of 75%. The GCL was initially partially hydrated to a water content of 75% to reduce the time required for equilibrium to be reached. The cell was maintained under the nominal stress of 1.7 kPa without applied heat for a period of 260 days. The objective of this test was to investigate the ultimate equilibrium water contents, and the time required to reach this equilibrium, given a starting point of 75% at nominal stress under isothermal conditions.

The principal variables examined in this test group were: the lag between waste placement and temperature increases (G1-T2, G1-T5 and G1-T6), the initial water content of the subsoil (G1-T3 and G1-T4), the initial water content of the PGCL (G1-T5 and G1-T6), the initial water content of the SGCL (G1-T7) and the applied thermal gradient (G1-T8 and G1-T9).

2.3.2. Testing program G2

The same sample preparation techniques and experimental procedure as described for series G1 were followed for series G2. The initial water content of the gravel, about 2%, was selected to reflect field conditions when the groundwater surface is well below the foundation layer (FL). A summary of the testing conditions is presented in Table 3. G2-T1 was conducted as a baseline. The initial water contents were 11.6% and 12.6% for the subsoil and FL,

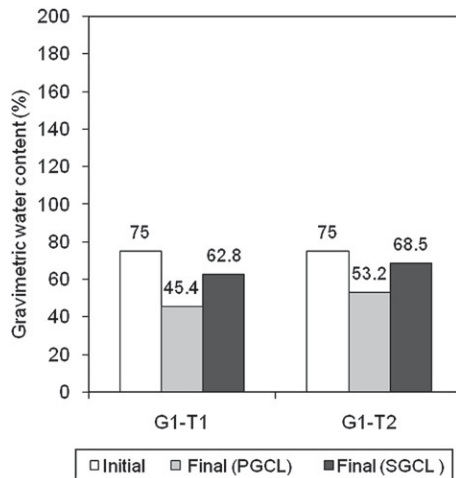


Fig. 9. Gravimetric water contents for tests G1-T1 and G1-T2.

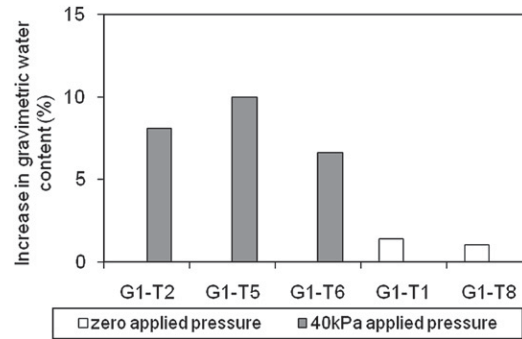


Fig. 10. The effect of overburden stress on SGCL water uptake from subsoil after 14 days (subsoil water content ~11%). Test series G1.

respectively. Following a period of 103 days, intended to allow the GCLs to approach equilibrium under isothermal conditions and a nominal stress, a 100 kPa pressure and 24 °C/m temperature gradient were applied. The principal variables that were controlled in this group of tests were: the applied thermal gradient (G2-T2, G2-T3 and G2-T4) and the FL thickness (G2-T5).

2.3.3. Hydraulic conductivity tests

Hydraulic conductivity tests were conducted on the GCL specimens using a flexible wall permeameter following the procedure in ASTM D5084. The constant head method was employed in a 100-mm diameter apparatus. Samples were hydrated using deionized water in a triaxial cell under an effective stresses of 100 kPa, corresponding to the stresses applied in the experiments. Tests were conducted with an average hydraulic gradient of 35, selected to be similar to that expected in the field under design conditions with a 30 cm thick drainage layer above the GCL.

3. Results

3.1. Testing program G1

3.1.1. Prior to the application of heat and pressure

3.1.1.1. Variation in water content with time and depth. GCLs have been shown to be highly effective hydraulic barriers when adequately hydrated (Daniel et al., 1993; Rowe et al., 2005). Typically, the source of water for GCL hydration is the underlying soil. If the GCLs are installed at low as-delivered roll water content (about 10–15%) the question arises as to the duration of the hydration period. The final water content achieved by the GCL and the length of time needed to achieve this is a function of subsoil type, initial subsoil water content, GCL manufacture, temperature, and confining pressure (Rayhani et al., 2008, 2011; Chevrier et al., 2010).

Table 4 Geosynthetic clay liner properties (Southen and Rowe, 2005).

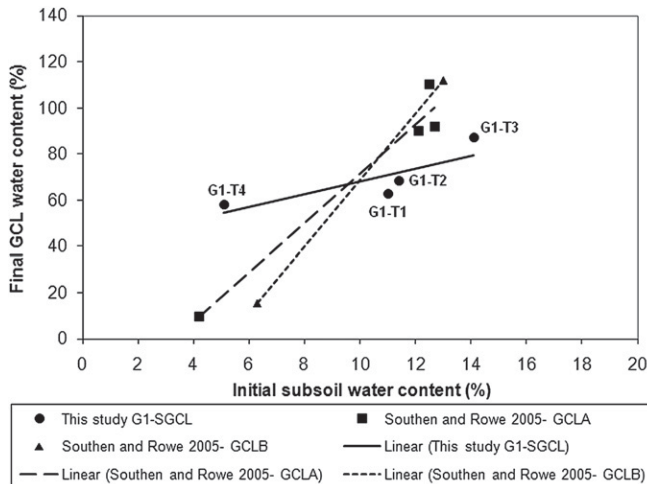
Property	GCL A	GCL B
Nominal mass/unit area	4650 g/m <sup>2</sup>	5500 g/m <sup>2</sup>
Bentonite mass/unit area	4340 g/m <sup>2</sup>	5000 g/m <sup>2</sup>
Carrier GT	Polypropylene slit-film woven-105 g/m <sup>2</sup>	Polypropylene slit-film woven-200 g/m <sup>2</sup>
Cover GT	Polypropylene virgin staple fiber nonwoven 200 g/m <sup>2</sup>	Polypropylene nonwoven 300 g/m <sup>2</sup> (impregnated with 800 g/m <sup>2</sup> bentonite)
Construction	Needlepunched	Needlepunched

**Table 5**  
Laboratory test details (Southen and Rowe, 2005).

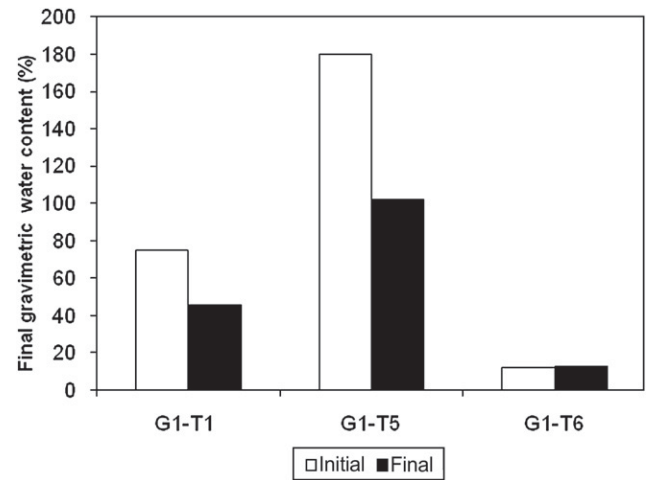
	Initial subsoil water content (%)	Initial GCL water content (%)	Applied pressure (kPa)	Thermal gradient (°C/m)	Final GCL water content (%)	Top boundary temperature (°C)
GCL A	12.1	70	70	29.0	90	58
	12.5	80	95	25.0	110	54
	12.7	72	95	26.0	92	55
GCL B	4.2	105	50	27.0	9.5	56
	13.0	80	80	25.5	112	54.5
	6.3	81	70	24.8	15.6	54

The control case G1-T0 was conducted to establish the GCL gravimetric water content just prior to the placement of the waste as a benchmark, and to investigate the time for water to reach steady-state in DCLS from a starting point of 75% water content (the default case in these experiments). The variation of the GCL water content with time (Fig. 5) showed that most of the change in water content occurred within the first 100 days and subsequent changes were relatively small as a steady state was reached after about 200 days. For the PGCL, there was an approximately 13.5% decrease in gravimetric water content due to evaporation of water into the airspace during measurement. The SGCL took up water from the underlying soil. The final water content of 138% for the SGCL is very similar to the hydrated water content for a similar GCL (denoted GCL1) of 141% reported by Rayhani et al. (2011) under isothermal conditions at a similar nominal stress. Therefore, based on the results presented on Fig. 5, it was concluded that leaving GCLs for about 100 days to equilibrate before applying heat and temperature would be suitable for the other tests in the series.

**3.1.1.2. Effect of mass per unit area of GCL.** The manufacturing process results in some spatial variability in the mass of bentonite throughout any given GCL roll. This variability can influence the distribution of water within the system. Fig. 6 presents the relationship between bentonite mass per unit area and PGCL gravimetric water content after 88 days. A reduction in water content from 75% was due to evaporation of water. With a higher mass of bentonite at constant initial water content (75%), the heavier GCL has more water available for evaporation. Hence, for a given amount of airspace in the geonet, the water content was greatest for the GCL with the greatest mass of bentonite and lowest for the



**Fig. 11.** Variation in final GCL water content with initial subsoil water content.



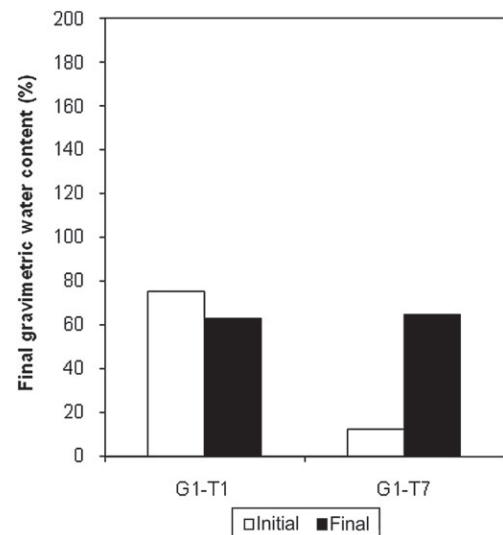
**Fig. 12.** Initial and final PGCL water contents in tests G1-T1, G1-T5 and G1-T6.

GCL with the lowest mass of bentonite (Fig. 6). Since the SGCL was in direct contact with the subsoil, the water in the GCL was controlled by the available water in the subsoil and the effect of the initial mass of bentonite was reversed with the lighter GCL ending up with higher water content (Fig. 7).

**3.1.1.3. Effect of initial subsoil water content.** Fig. 8 shows a linear relationship between the initial subsoil water content and the SGCL water content after 88 days. This is to be expected since higher initial water content in the subsoil provides more water for hydration of the GCL within the 88 day period. Ultimately one would expect equilibrium to be reached when the suction in the GCL is in equilibrium with the suction in the underlying soils, and this will be a function of the available water as demonstrated by Rayhani et al. (2011).

**3.1.2. Effect of time lag between waste placement and temperature increase**

The potential effect of a time lag between waste placement and a temperature increase in waste material may be appreciated by comparing the results of experiments G1-T2 with those of G1-T1. In



**Fig. 13.** Initial and final SGCL water contents in tests G1-T1 and G1-T7.

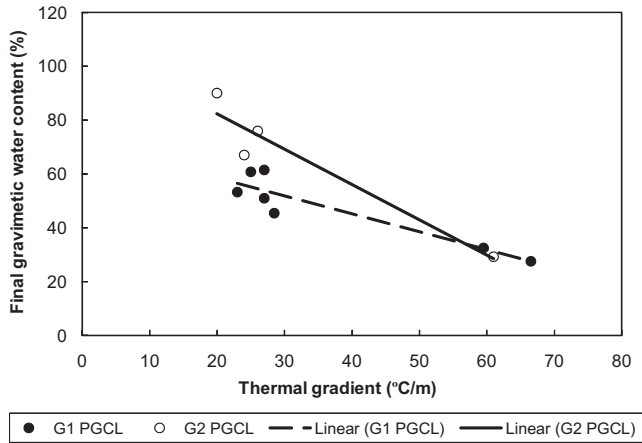


Fig. 14. Relationship between applied thermal gradient and final PGCL water content.

G1-T1 both the temperature and 100 kPa pressure were applied after 102 days of isothermal conditioning at the nominal stress. In test G1-T2, 98 days of conditioning at the nominal stress was followed by the application of an overburden stress of 40 kPa for 2 weeks under isothermal conditions prior to the application of the thermal gradient and increasing the overburden pressure to 100 kPa. The results (Fig. 9) show that the final water contents are higher in G1-T2, when there is a time lag between waste placement and temperature increase. This may be due to the effect of stress on the water retention curve (soil water characteristic curve) (Southen and Rowe, 2007) and the reduction in void ratio of the GCLs due to consolidation at 40 kPa before the thermal gradient was applied, although it could also be related to the longer period of heating in test G1-T1.

The effect of 40 kPa overburden pressure on the SGCL water uptake from subsoil after 14 days is shown in Fig. 10. Application of the 40 kPa confining pressure appears to have led to larger suctions in the GCL compared to the subsoil and has resulted in more water being taken up by the GCL in the 2 week period before the thermal gradient was applied. This is consistent with findings reported by Rayhani et al. (2011) and Chevrier et al. (2010).

3.1.3. Effect of initial subsoil water content

Southen and Rowe (2005) conducted large scale laboratory tests where two different GCLs were subjected to thermal gradients in

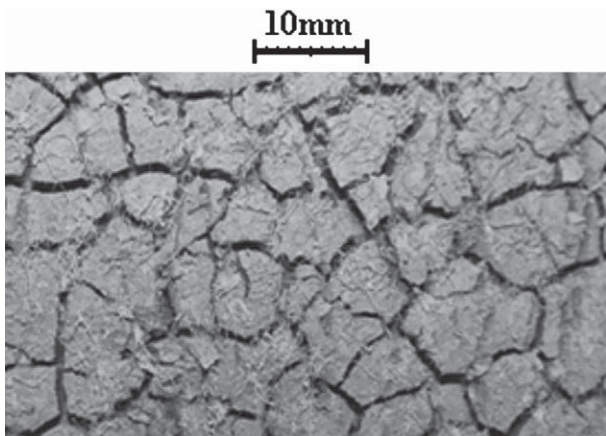


Fig. 15. Photo of exhumed PGCL after careful removal of cover geotextile: Test G1-T8, final water content = 27.5%.

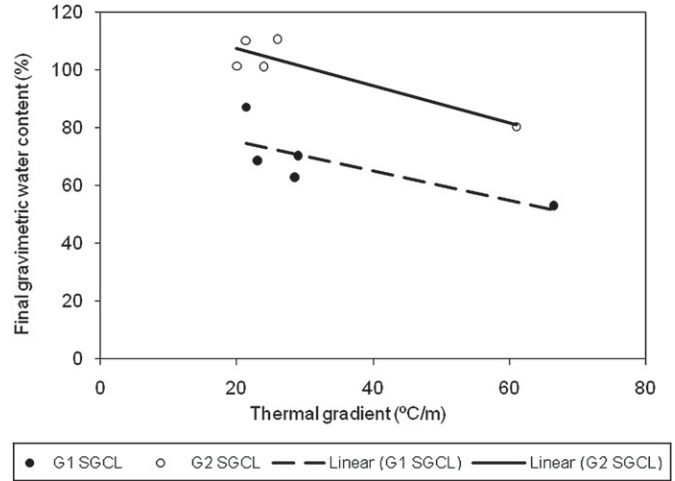


Fig. 16. Relationship between final SGCL water content and the applied thermal gradient.

single composite liner systems. The properties of GCLs and details of these tests are summarized in Tables 4 and 5, respectively. The effect of initial subsoil water content on the final SGCL water contents is compared with the results of Southen and Rowe (2005) in Fig. 11. Although care is required in comparing results due to different test conditions (initial GCL water content, applied pressures and thermal gradient), it is evident that a low initial subsoil water content gives rise to a lower final GCL water content when the GCL is in direct contact with the subsoil. This demonstrates the advantage of ensuring that the subsoil has an adequate water content (typically about 10% or higher) before placing the GCL over the subsoil. The slope of Southen and Rowe’s results is steeper than the current study because of a higher top boundary temperature in their tests. This increases the vapor flux due to the dependence of vapor density on temperature producing lower final water content in the GCL under lower subsoil water contents in the Southen and Rowe (2005) experiments compared to the present experiments.

3.1.4. Effect of initial GCL water content

Initial hydration, with a non-chemically aggressive hydration fluid, is necessary to maximize the hydraulic performance of GCLs subjected to a prolonged contact with leachate (Petrov and Rowe,

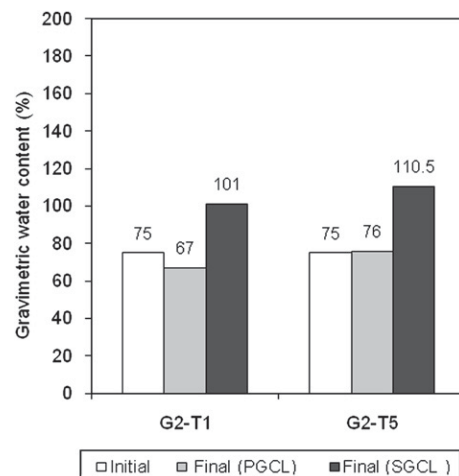


Fig. 17. Initial and final gravimetric water contents for tests G2-T1 and G2-T5.

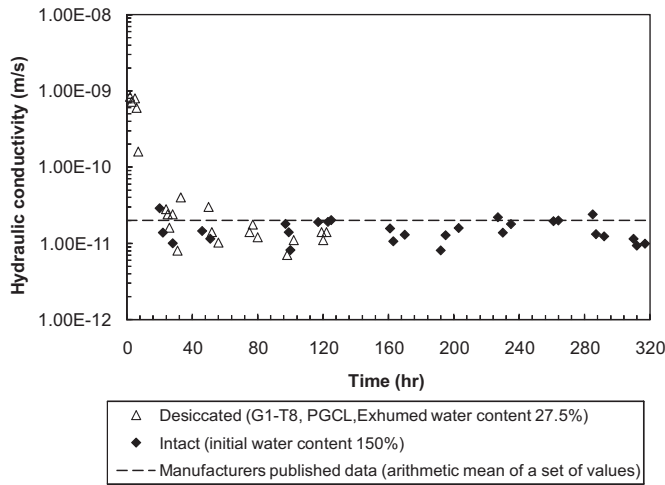


Fig. 18. Variation in post-test GCL hydraulic conductivity in a flexible wall permeameter.

1997; Rowe, 1998; Shackelford et al., 2000; Guyonnet et al., 2005). Fig. 12 compares the initial and final PGCL water contents for three experiments (G1-T1, G1-T5 and G1-T6). The water content of the PGCL in G1-T1 decreased to 45.4% and the GCL experienced some desiccation cracking, while in G2-T5, because of the much higher initial value, the final GCL water content was 102% and no cracking was observed. This highlights the importance of hydrating the GCL before heat is applied. Also presented in Fig. 12 is the final water content measured for G1-T6 where the PGCL was placed over the geonet at the low as-delivered roll water content. Very little variation may be noted within 270 days suggesting that there was not enough water in the air and geonet during the test to hydrate the GCL. As a result, no significant hydration or drying has occurred and the final water content of the bentonite within the GCL is insufficient for the GCL to achieve a low hydraulic conductivity.

Fig. 13 shows that the initial as placed water content of the SGCL had relatively little effect on the final value for cases where there were only mild thermal gradients (surface temperatures of 31 °C and 29 °C for G1-T1 and G1-T7 respectively) and a reasonable amount of initial water in the subsoil (11%). Here the final water contents (63% and 65%) were almost identical despite the substantial difference in the initial GCLs water contents (75% and

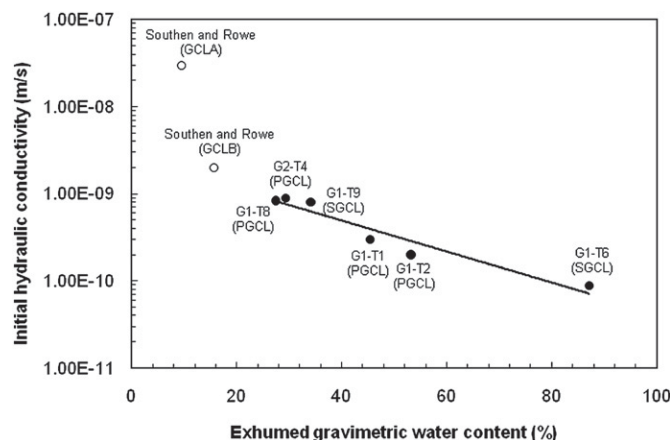


Fig. 19. Variation in initial hydraulic conductivity of exhumed GCLs versus exhumed water content.

12%) and no desiccation cracking of the bentonite was observed in either case.

### 3.2. Testing program G2

#### 3.2.1. Effect of applied thermal gradient

To investigate the effect of the applied thermal gradients, experiments were conducted for a number of different top boundary temperatures. The relationship between applied thermal gradient and final PGCL water contents for experiment series G1 (no foundation layer) and G2 (with a foundation layer) is shown in Fig. 14. The results of G1-T5, G1-T6 and G2-T3 are not presented in this figure because of their different initial PGCL water contents. The final water content of the GCL was lower for those tests with higher thermal gradients. The higher gradient enhances the downward flux of water by inducing downward vapor diffusion due to the dependence of vapor density on temperature (Edlefsen and Anderson, 1943). The higher gradient also leads to a higher temperature of the air in the geonet and increases its capacity to hold water, hence reducing its relative humidity for a given amount of water evaporated from the GCL.

At a thermal gradient of less than 30 °C/m (surface temperatures of 29–32 °C) the presence of a foundation layer (with an initial water content of about 11%) below the PGCL maintained the water content of the GCL at 67% or higher with no cracking. Without the foundation layer the PGCL water content dropped from the initial 75% to between 45% and 61%. For the cases where the water content was lower than 54%, some narrow desiccation cracking was observed. At thermal gradients of 59–67 °C/m (surface temperatures of 39.5–45 °C) the PGCL water contents dropped from 75% to 27–33% and significant desiccation cracking was observed irrespective of whether the foundation layer was present. Fig. 15 shows a photograph of the PGCL sample removed from G1-T8 after careful removal of the cover geotextile. Desiccation cracking can be observed.

Fig. 16 provides similar data for SGCL. The results of G1-T3, G1-T4, G1-T7 and G1-T9 are not presented here because of their different subsoil and SGCL initial water contents. At thermal gradients of 20–67 °C/m (surface temperatures of 29–45 °C) the SGCL water contents remained at 53% or higher with no cracking for these experiments where the subsoil had an initial water content of about 10–11%. However for the case where the subsoil had an initial water content of about 5% desiccation of the SGCL did occur at a thermal gradient of 59 °C/m (surface temperature of 39.5 °C, G1-T9). A comparison of the results from experiments G1-T8 and G1-T9 (Table 2) demonstrates the significant effect of the initial water content of the subsoil on the potential for GCL desiccation when the primary geomembrane reaches a temperature of about 40 °C or higher.

#### 3.2.2. Effect of the foundation layer thickness

The effect of the FL thickness on the final gravimetric water contents of the GCLs was investigated by increasing the FL from 50 mm in G2-T1 to 250 mm in G2-T5. Fig. 17 gives the water contents observed for these tests. It may be seen that FL thickness has an effect on the distribution of water within the system. The PGCL in G2-T5 reached higher water contents in comparison with G2-T1, mainly due to the greater availability of water within the thicker FL. In addition, the distance from thermal boundaries is an important factor influencing the SGCL temperature. An increase in the FL thickness results in lower temperatures on the secondary liner (Rowe and Hoor, 2009). The lower temperature of the SGCL in G2-T5 compared to G2-T1 is an important factor influencing its higher final water content. No cracking was observed for any of the GCLs in these two experiments.

### 3.3. Hydraulic conductivity tests

Although the needle-punched reinforcement of the GCL can limit the amount of cracking within the bentonite as the GCL dries (Broadman and Daniel, 1996), deep cracks were visible in three of the exhumed PGCL samples (Tests G1-T8, G1-T9 and G2-T4) from experiments at thermal gradients of 59–67 °C/m (surface temperatures of 39.5–45 °C). Provided that there has not been excessive cation exchange, GCLs with sodium bentonite have high self-healing capacity when they are hydrated following desiccation (Egloffstein, 1995). To investigate whether thermally induced desiccation has a permanent impact on the hydraulic performance of a GCL, samples were taken from the GCLs after termination of the experiments and hydraulic conductivity tests were performed using deionized water as the permeant. The change in hydraulic conductivity versus time of an exhumed sample from G1-T8 is presented in Fig. 18. A decreasing hydraulic conductivity was observed over the first 35 h. The desiccated GCL exhibited hydraulic conductivity of  $\sim 8.4 \times 10^{-10}$  m/s initially, due to flow through the deep cracks within the bentonite layer. However with time, the bentonite hydrated and swelled, sealing the cracks and resulting in a decrease in hydraulic conductivity to final values of  $\sim 1.6 \times 10^{-11}$  m/s. In all cases studied, the hydraulic conductivity dropped to less than  $\sim 1.8 \times 10^{-11}$  m/s. These tests did not examine the effect of any change in the GCL due to chemical interaction with a leachate permeant. Hence, the values shown in the experiments here, based as they are on deionized water as the permeant, must be seen as lower bounds on the hydraulic conductivity.

The initial hydraulic conductivity of exhumed GCLs versus exhumed gravimetric water content is presented in Fig. 19. The results show that the samples that had lower exhumed water content had higher initial hydraulic conductivity due to deeper cracks in drier samples. The results are consistent with the results reported by Southen and Rowe (2005).

## 4. Conclusions

The experimental results presented in this paper give some insight into the behavior of GCLs under conditions representative of those occurring in double composite liner systems (DCLSs). Under certain conditions, thermally driven water redistribution can cause desiccation of GCLs. As a result, GCLs must be used with care at the base of DCLSs where desiccation of GCL may occur. Based on this investigation, the following conclusions can be drawn:

1. The best means of minimizing the risk of GCL desiccation is to keep the thermal gradient as low as possible.
2. The lower the initial subsoil water content, the greater the risk of desiccation of a GCL. Thus the placement of GCLs over relatively dry subsoils should be avoided for landfill applications. No GCL desiccation was observed in these experiments when the subsoil below the GCL had an initial water content of 10% or higher and the primary geomembrane temperature was about 40 °C or less. However, desiccation cracking did occur a) for GCLs in a primary composite liner on a foundation layer with 10–11% initial water content under a geomembrane with a temperature of 45 °C and b) for GCLs in a secondary composite liner on subsoil with initial water content of about 5% under a geomembrane with a temperature of 40 °C.
3. Low initial GCL water content can increase the risk of desiccation when the GCL is not in direct contact with the subsoil. This shows that there is a need to hydrate the GCL in the primary system before a significant thermal gradient is applied. In the present experiments better performance was observed for GCLs with a higher mass of bentonite at a given water

content. However this may only be true as long as it is possible to hydrate the GCL (e.g., by introducing water to the leak detection system) and may not be true if the only mode of moisture uptake is from the relative humidity in the leak detection system.

4. For the conditions examined with temperatures on the primary geomembrane up to 45 °C, there was a low risk of desiccation of the GCL in the secondary composite liner when the underlying silty-sand subsoil had initial water content of 10–11% or higher.
5. Although the bentonite can form open cracks upon drying, the cracks do not necessarily lead to a permanent increase in hydraulic conductivity of the GCLs. In flexible wall permeameter tests on desiccated samples permeated with deionized water, the bentonite swelled and the cracks closed upon wetting. Thus the high initial hydraulic conductivity decreased with time to values similar to the initial values for the conditions examined. While this is encouraging, the permeation with distilled water is a best-case scenario. In real landfill situations, the hydraulic conductivity may not recover to the same extent because of bentonite chemical interactions with leachate permeant.
6. The key factor in hydraulic performance of desiccated GCL is its exhumed water content. The lower the water content, the higher the initial hydraulic conductivity.

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