A NOVEL MULTIPLE-LINER DESIGN FOR PREVENTING DESICCATION OF GEOSYNTHETIC CLAY LINERS

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ABSTRACT

Geosynthetic clay liners (GCLs) covered by geomembranes (GMB) often constitute a major component in barrier systems. They are used in waste containments systems such as landfills, brine ponds and solar ponds. In many of these cases, high temperatures can develop as a result of exothermic biodegradation or direct solar radiation and can cause significant desiccation of the bentonite in the GCLs. In addition, the self-healing ability of bentonite may be compromised by exposure to chemically aggressive permeants that are commonly found in such applications.

A new multiple-liner design is proposed in this paper, with two GMB-GCL composite liners sandwiching one layer of geocomposite (GC). The new design is able to actively hydrate top and bottom GCLs through the middle GC layer with clean water. A set of column model experiments simulating a typical bottom profile under a brine pond were conducted to investigate GCL hydration before and after continuous heating at 78±1°C for 14 days. The results were compared to the more conventional GCL-GMB designs. The findings revealed that the new multiple-liner system speeds up hydration of bentonite in the GCL by a factor of more than 3, increase its water content at the end of the hydration stage by up to 50%, and prevent its desiccation when exposed to high temperatures.

Key words: GCLs, desiccation, hydration, multiple-liner, active hydration

1 INTRODUCTION

Geosynthetic clay liner (GCL) is generally composed of a thin layer of powder or granular bentonite clay that is either glued to a geotextile or sandwiched by two geotextiles. Although the thickness of GCLs is typically than 1 cm, they exhibit extremely low hydraulic conductivities ($\sim 10^{-10}$ to 10^{-11} m/s) when sufficiently and properly hydrated (Bouazza, 2002; Rowe, 2005). GCLs have been widely adopted together with geomembrane (GMB), as the GCL-GMB composite liner system, to serve as barriers in waste containing facilities such as landfills and other industrial reservoirs like brine ponds and solar ponds.

Traditionally, before coming into service, GCLs are first covered with GMB and a thin protective layer of soil, then allowed hydrate from the subsoil on site, before any waste or contaminants are placed in the system. A gravimetric water content of around 100% or more is usually required for acceptable performance. Studies have revealed that reaching such a hydration require consideration of subsoil characteristics, including grain distribution (Rayhani et al., 2011; Anderson et al., 2012; Chevrier et al., 2012), initial water contents (Southen and Rowe, 2005; Anderson et al., 2012), pore water chemistry (Rowe, 2005; Bouazza and Gates, 2014), as well environmental and operational factors such as temperature and stress conditions (Chevrier et al., 2012; Barclay and Rayhani, 2013; Sarabadani and Rayhani, 2014) during the liner placement and operation.

On the other hand, in many cases, GCLs are exposed to elevated temperatures during their service life. For example, biodegradation in landfills can lead to temperatures higher than 50°C in the containment chamber (Rowe, 2005; Southen and Rowe, 2005), and direct exposure to sunshine increase liquid temperatures up to 90°C in industrial waste ponds (El-Zein et al., 2013). Exposure to high temperature can lead to dehydration of the GCLs and eventually desiccation cracks can develop throughout the bentonite layers (Southen and Rowe, 2005; Azad et al., 2011; Ghavam-Nasiri, 2017; Ghavam-Nasiri et al., 2017; Yu and El-Zein, 2019). Yu and El-Zein (2019) reported that the desiccation risks were especially high when highly permeable sands are selected as the subsoil, as temperatures as low as around 40°C can lead to significant desiccation of a GCLs, even those with high bentonite mass per unit area (M_a).

In this paper, a new multiple-liner design consisting of two sets of GCL-GMB and a layer of geocomposite (GC) is proposed as a way of preventing desiccation under thermal gradients, and consequent loss of performance. The new design was tested using a set of instrumented soil column experiments that replicate the operation of a barrier system in brine ponds. In the tests, the new liner design was subjected to the high temperatures observed in such systems during daytime (78°C) for 14 days. The performance of the new design was compared to that of a more conventional GCL-GMB composite liner system, which had been found in the past to develop severe desiccation during the same tests.

2 DESCRIPTION OF NEW DESIGN

Conventional composite liner system design has been revealed to be prone to desiccate when exposed to high temperature applications and Figure 1 shows samples of these designs. The simplest design with GCL-GMB liners shown in Figure 1a can show severe desiccation in GCL when subjected to high temperatures (Southen and Rowe, 2005; Ghavam-Nasiri, 2017; Yu and El-Zein, 2019). Bouazza et al. (2017) suggested an extra layer of geocomposite liner (GC) may decrease the top temperature applied on the top of GCL and thus might decrease the risk of GCL desiccation (see Figure 1b). Further investigations show that in certain conditions (i.e., high temperature, low overburden stress and highly permeable subsoils) the extra GC can decrease the top temperatures but not able to avoid the desiccation (Yu and El-Zein, 2019). More complex design like double composite liner system (Figure 1c) has also been tested and desiccation was also observed in the top GCL layer (Azad et al., 2011).

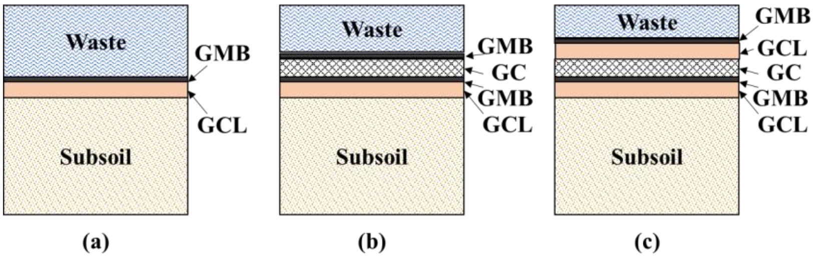


Figure 1: Conventional composite liner system designs

The new multiple-liner design presented in this study (see Figure 2), is modified from the double composite liner system in Figure 1c by introducing two changes. First, the secondary GMB is placed below rather than above the secondary GCL. Second, artificial hydration is conducted through the geonet, now that both GCLs are in direct contact with the geonet. Hence, in the new design, the top and bottom GCLs are sandwiched by two GMBs, making possible artificial hydration (by liquid water or water vapor) through the centre GC layer. In addition, the top GMB layer prevents the contaminant liquids from entering the liner, while the bottom GMB adds extra protection against any leakage and/or diffusion of contaminants through the liner. In conventional designs, no GMB is placed between the GCL and the subsoil because it would prevent hydration of the former by the latter, a requirement that is obsolete in the proposed design. Artificial hydration has the following advantages: (1) avoiding of cation exchanges due to any salinity in the subsoil's pore water; (2) ensuring sufficient and quicker hydration before the liner system is put in use; and (3) keeping GCLs in hydrated condition during the service life by supplying water or vapor where necessary.

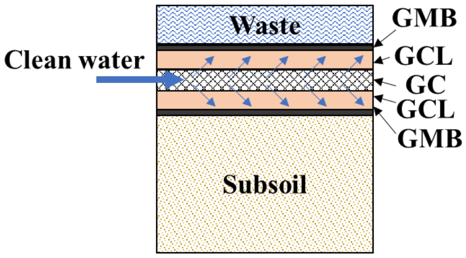


Figure 2: A schematic diagram of the novel multiple-liner design

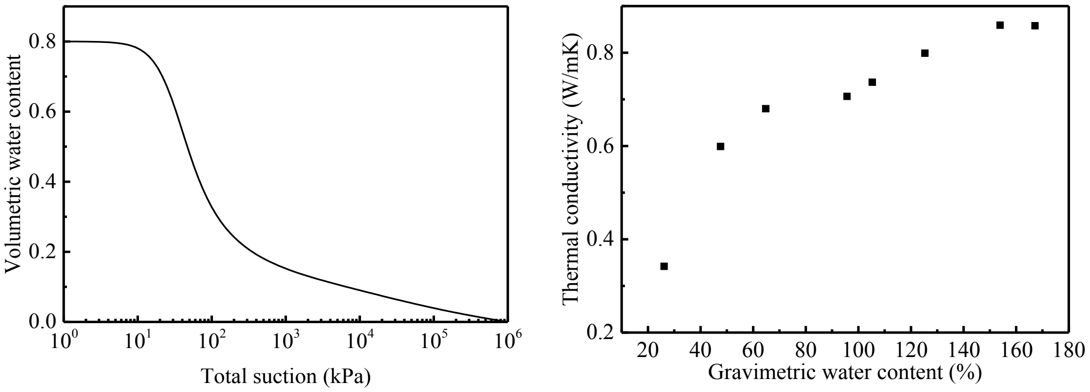
3 MATERIALS AND METHODS

3.1 GCL AND SUBSOILS

The GCL used in this study was a needle-punched and thermally reinforced type, with granular Na-bentonite, provided by Terrafix Geosynthetic Inc. Canada. The basic properties and configurations of the GCL are shown in Table 1. Its soil-water characteristic curve (SWCC) and thermal conductivity (λ_k) variations under different water contents can be found in Figure 3.

Table 1: Basic properties and configuration information of GCL used in this study

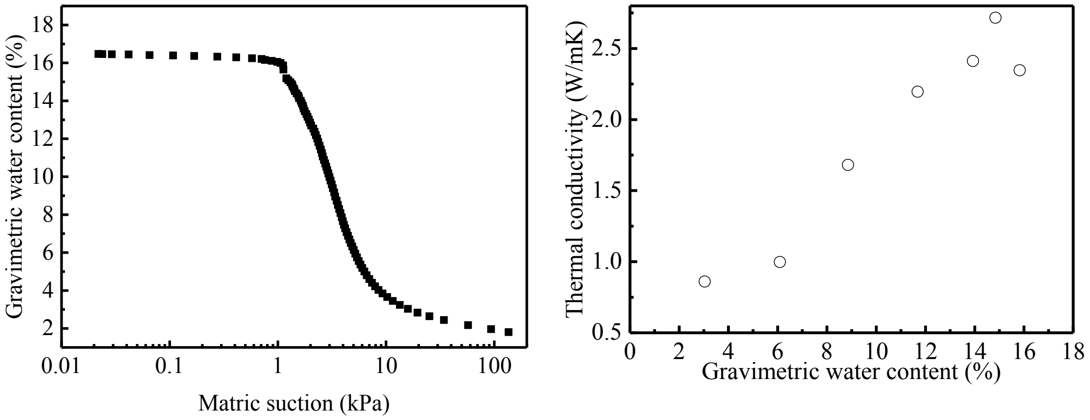
	Values or Descriptions
Top Geotextile	Nonwoven
Dry mass per unit area (g/m^2)	200 (MARV) 255 (Tested)
Carrier Geotextile	Scrim Reinforced Nonwoven
Dry mass per unit area (g/m^2)	200 (MARV) 249 (Tested)
Bentonite type	Granular Na-bentonite
Swelling indexes (mL/2g)	>24
Dry mass of bentonite per unit area (g/m^2)	3660 (MARV) 4341 (Tested)



(a) SWCC (b) Thermal conductivity

Figure 3: Hydraulic and thermal properties of GCL used in this study

The subsoil selected in this study was a well-graded river sand (SW) collected from Sydney, Australia. Previous studies have shown that this specific type of sand can sufficiently hydrate GCL specimens in 7-8 weeks thanks to its low water retention and high hydraulic conductivities (k_s=3×10^{-4} m/s). The subsoil was compacted into the columns with a predetermined dry density (ρ_d=1.78 g/cm^3) and water contents (w=11%) as illustrated in detail in Ghavam-Nasiri et al. (2017) and Yu and El-Zein (2019).



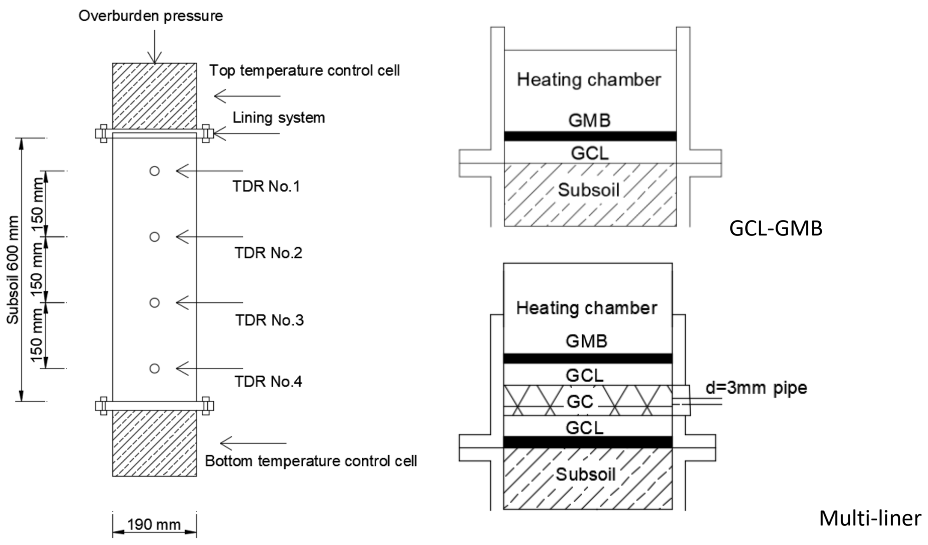
(a) SWCC (b) Thermal conductivity

Figure 4: Hydraulic and thermal properties of subsoil used in this study

3.2 COLUMN MODEL EXPERIMENTS

The column model apparatus (Figure 5a) adopted in this paper was similar to the one described in Ghavam-Nasiri (2017) and Yu and El-Zein (2019) but modified to allow the testing of the new design as described in the next paragraph. For details on this apparatus, readers are referred to these two sources. For tests on conventional GCL-GMB composite liners, GCL specimens were installed in the column with as-arrived water contents (w≈6-9%) and hydrated from subsoils under a 20 kPa overburden stress for 7 weeks. After that, the heating stage started and the temperature on top of GCL was kept at 78±1°C for 14 days, then the specimen was removed, and x-rayed to assess the extent of desiccation. At the end of each stage (hydration+ heating), the specimens were carefully taken out and their weight and height were measured.

To investigate the performance of the new multiple-liner design, several modifications were made to enable the active hydration of GCLs, as shown in the close-up in Figure 5b. A pipe is run through a slot on the side to connect the top chamber to the water supply, in order to use external water supply to irrigate/hydrate the GCLs. The slot connection was designed so as to allow the pipe to move freely in the vertical direction as specimens' height changed during the tests. The hydration stage elapsed for 14 days, when the LVDT suggested no further hydration swellings were observed from the specimens (see Figure 6); hence, reducing hydration time to less than one third of its value under passive hydration from the subsoil. The heating stage was made to last for 14 days, which was the same as tests for GCL-GMB composite liners.



(a) Column test appratus (b) Close-up of liner installation

Figure 5: Design diagram of the column tests with close-up on composite liner installations

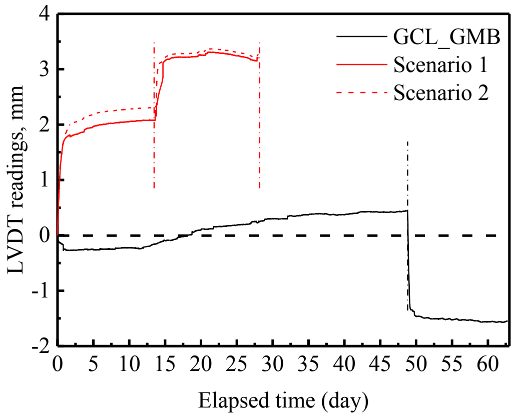


Figure 6: Comparison of stable temperature profile during heating stages in column test

Two scenarios (namely scenario 1 and scenario 2) were tested in the column model tests for the multiple-liner design. The differences between the two scenarios occurred at the heating stages whereby, under scenario 1, active irrigation continued while, in scenario 2, water supply was cut off prior to the heating stage.

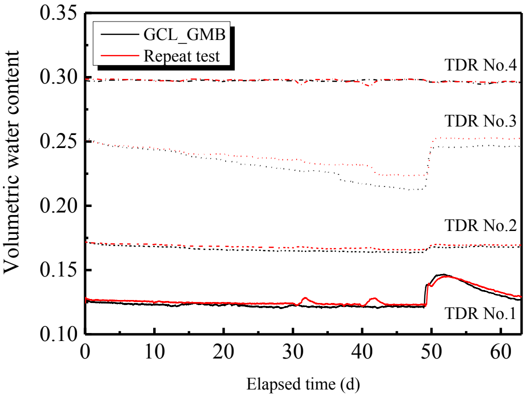
3.3 X-RAY IMAGING TESTS

X-ray imaging technology was used to detect the desiccation crack patterns in GCL specimens in the DynamiX laboratory of the University of Sydney, Australia. Specimens were carefully put on a detection board located 1.2 m away from the X-ray source with a small filament. The X-ray power was kept at 60 kV and 2 mA, which was consistent with Yu and El-Zein (2019). For specimens that show clear crack patterns, the Particles (Pores) and Cracks Analysis System (PCAS v2.319) was adopted to conduct image analysis on the crack properties, e.g., the crack areas, crack width, etc. (Liu et al., 2011 and 2013; Yu and El-Zein, 2019).

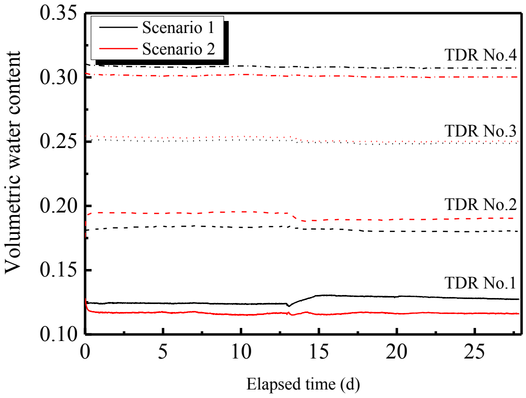
4 RESULTS AND DISCUSSION

4.1 MOISTURE AND TEMPERATURE PROFILE VARIATIONS DURING COLUMN TESTS

The variations of water contents in subsoils recorded by the four TDR sensors are shown in Figure 7. Results for the conventional GCL-GMB liner, including a repetition test, can be seen in Figure 6a. The consistent patterns of the two tests confirm the reliability and repeatability of the column model tests. In GCL-GMB liner test, heating starts from the 49th day when temperature on top of the composite liner system is increased to 78±1°C. Within several hours significant changes can be observed in the top three sensors, especially for TDR sensor No.1 (changes from 0.12 to 0.15 and then gradually falls back to around 0.13) and No.3 (increases from 0.22 and 0.23, then gradually up to 0.26). The results are similar to those reported in Yu et al. (2018) and Yu and El-Zein (2019), for a powdered-bentonite GCL. Specifically, the sharp increase in TDR No.1 indicates downward moisture movements from GCL and upper subsoil caused by the high temperature.



(a) GCL_GMB group



(b) Multiple-liner design group

Figure 7: Comparison of subsoil moisture redistribution during column test

Very different patterns are revealed by the tests on the proposed multiple liner under both working scenarios. Once the heating stage starts around the 13th day, much slower and gentler increases are recorded by TDR sensor No.1, suggesting only liquid water and vapour at top of the subsoil sand, not the liner, are driven down by the high temperature, because water in the liner system is contained by the top and bottom GMBs.

The temperature profiles at the heating stage are plotted in Figure 8. Averages of the last 7 days sensor reading values are shown here, because temperatures along the column depth remained stable during the last week of heating in all tests. Figure 8 shows a non-linear temperature profile in all tests. In the subsoils (depth<0), slightly lower temperatures occur for the multiple liner, compared to the GCL-GMB liner, due to the larger thickness of multiple-liner system. The large decreases in temperatures (lower from 78±1°C to around 25-28°C) at the top of columns suggest very high temperature gradients can be found between the top and bottom of liner system, which can lead to significant desiccations of GCLs in GCL-GMB composite liner system under similar conditions, reported by Yu et al. (2018) and Yu and El-Zein (2019).

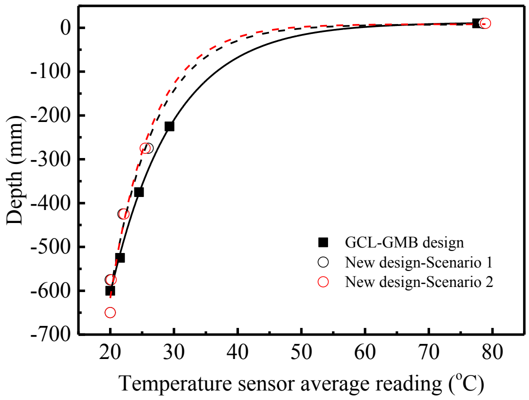


Figure 8: Comparison of stable temperature profile during heating stages in column test (average of last 7 days)

4.2 LINER PROPERTY VARIATIONS

The LVDT sensor data collected from the column tests are shown in Figure 8. The LVDT sensor data cannot be regarded as the actual liner thickness variations because other factors such as subsoil consolidation and column diameter variation due to temperature also contribute to their change (Yu et al., 2018). However, LVDT readings are still expected to be a good indicator of the swelling or shrinkage of the clay layers in the liner system. At the hydration stage, in the conventional GCL-GMB system, where GCLs hydrate from subsoils, after the initial consolidation caused by the 20 kPa overburden pressure, very little swelling occurs in the first 14 days. Once the heating stage starts at 49th day, instant drop in LVDT reading indicates fast shrinkage and desiccation.

LVDT data patterns for the new multiple liner design are completely different. GCLs start swelling almost as soon as external water supply is introduced into the GC layer. The fast hydration of the two multiple-liner groups end around day 2 and they both reach to around 1.8 to 2 mm, which are significantly higher than the 0.5 mm reached by GCL-GMB group after 49 days hydration, confirming the efficiency of irrigation/hydration in the new design. The GCLs in these two groups keep swelling at a slower rate for another 11 days until they stabilize around 2 mm. What's more, significant increase in LVDT data upon the heating stage indicate the new designs do prevent the dehydration of GCLs with the help of the bottom GMB. Although from Table 2 it can be seen that under both scenarios GCLs showed increasing water contents after 14 days heating, the significant differences in final stage water contents found in GCLs from the two scenarios weren't accompanied by differences in the LVDT readings. Therefore, the observed sudden increase in LVDT readings was more likely resulted from the heat expansion of GCLs.

The hydraulic and swelling states of the GCLs at the end of the irrigation/hydration and heating stages can be seen in Table 2. For the GCL in the GCL-GMB group, it takes 49 days to hydrate to w=94.5% (S_r=74.1%). On the other hand, after 13 days of hydration, all GCLs in the multiple-liner groups exceed the water content of 100%. After 14 days of heating, significant water content drop can be seen in GCL from GCL-GMB group, down to a residual w of 5.9%. On the other hand, GCLs in both testing scenarios of multiple-liner design show increases of w after 14 days heating, which confirm the LVDT sensor data.

Table 2: GCL index variations during column tests

Designs and Scenarios	Properties	Initial conditions	End of hydration stage	End of 14 days heating stage
GMB-GCL	Water content, w (%)	7.9	94.5	5.9
	Height (mm)	7.4	9.0	7.5
Multiple liner design Scenario 1	Water content, w (%) Top Bottom	10.4 9.8	117.0 110.3	183.7 191.1
	Height (mm) Top Bottom	6.9 6.7	8.5 8.8	12.7 13.1
Multiple liner design Scenario 2	Water content, w (%) Top Bottom	11.8 10.2	109.9 116.3	115.5 133.5
	Height (mm) Top Bottom	6.3 6.8	9.2 9.1	10.1 10.0

GCLs in scenario 1 show the largest increases of w, as moisture in the top GCL increases from 117.0% to 183.7% and bottom GCL increase from 110.3% to 191.1%, thanks to the continuous external water supply during the heating stage. In scenario 2, as water supply is cut out during heating, the GCLs can only obtain moisture from the water left in the GC layer. Therefore, the increase in *w* is more moderate in this case with moisture in the top GCL rising slightly from 109.9% to 115.5% and from 116.3% to 133.5% in the bottom GCL. More importantly, the results confirm that the new design, which places the GCLs between two GMB has succeeded in preventing water escape out of the liner system.

4.3 DESICCATION AND HEALING OF GCLS

Photos of the vertical sides of the GCLs after heating are shown in Figure 9. While cracks can be directly observed in the bentonite of the GCL-GMB design, all GCLs in the multiple-liner design remain sufficiently hydrated and their bentonites in gel form where with no cracks apparent. An X-ray photo of the desiccation cracks of GCL at the end of the heating stage of GCL-GMB is shown in Figure 10, which shows cracks develop throughout the bentonites as water is driven out by the temperature gradient. Details on the crack properties are shown in Table 3. For GCLs, remaining sufficiently and properly hydrated is critical to remain their hydraulic barrier performances when they are exposed to chemical aggressive conditions, as many previous studies have revealed (Petrov and Rowe, 1997; Lin and Benson, 2000; Bouazza et al., 2007).

a. GCL-GMB   b. Multi-liner-Scenario 1   c. Multi-liner-Scenario 2

Figure 9: GCL side shots after 14 days heating stage

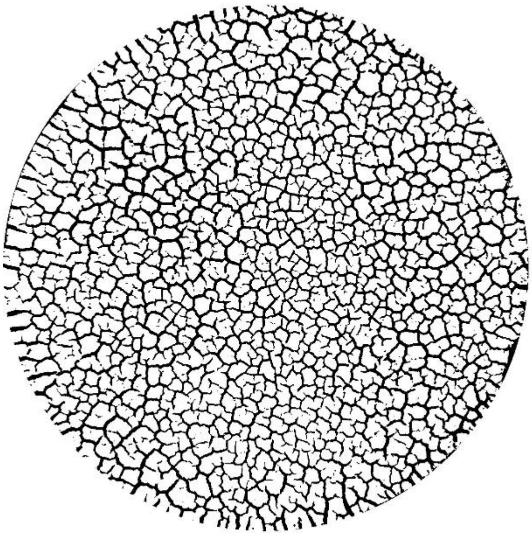


Figure 10: Desiccation cracks of GCL in GCL-GMB group

Table 3: Desiccation information of GCLs after column tests

	Water content, w (%)	Desiccation crack	Crack area proportion (%)	Average crack width (mm)
GCL-GMB	5.9	Y	28.44	0.728
Multiple-liner				
Scenario 1: Top GCL	173.2	N	/	/
Bottom GCL	181.0	N	/	/
Scenario 2: Top GCL	106.5	N	/	/
Bottom GCL	125.6	N	/	/

5 CONCLUSIONS

A new type of multiple-liner design with two different operation modes are proposed to prevent desiccation when liners are exposed to thermal gradients. The proposed design is characterised by two key modifications compared to conventional double composite liners: a) geomembranes (GMBs) are placed at the top and bottom of the liner to minimise dehydration under thermal gradients and b) a geocomposite (GC) layer allows faster artificial hydration of the geosynthetic clay liners (GCL) with clean water. Experimental testing was conducted to compare the performance of the proposed design to that of a more conventional GMB-GCL liner. The results confirmed the advantages of the proposed design, namely faster moisture uptake, higher water content at the hydration stage and no loss of moisture at the heating stage, even when no irrigation is provided after heating starts. Future research needs to confirm our findings which can be relevant to other types of GCLs (e.g., powder-bentonite). In addition, conducting field testing for new designs would be necessary to confirm their practicality.

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