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What is This?
Geosynthetic clay liners shrinkage under simulated daily thermal cycles

Hamid Sarabadani and Mohammad T Rayhani

Abstract
Geosynthetic clay liners are used as part of composite liner systems in municipal solid waste landfills and other applications to restrict the escape of contaminants into the surrounding environment. This is attainable provided that the geosynthetic clay liner panels continuously cover the subsoil. Previous case histories, however, have shown that some geosynthetic clay liner panels are prone to significant shrinkage and separation when an overlying geomembrane is exposed to solar radiation. Experimental models were initiated to evaluate the potential shrinkage of different geosynthetic clay liner products placed over sand and clay subsoils, subjected to simulated daily thermal cycles (60°C for 8 hours and 22°C for 16 hours) modelling field conditions in which the liner is exposed to solar radiation. The variation of geosynthetic clay liner shrinkage was evaluated at specified times by a photogrammetry technique. The manufacturing techniques, the initial moisture content, and the aspect ratio (ratio of length to width) of the geosynthetic clay liner were found to considerably affect the shrinkage of geosynthetic clay liners. The particle size distribution of the subsoil and the associated suction at the geosynthetic clay liner–subsoil interface was also found to have significant effects on the shrinkage of the geosynthetic clay liner.

Keywords
Geosynthetic clay liners (GCLs), shrinkage, daily thermal cycles

Introduction
Geosynthetic clay liners (GCLs) may be employed as part of composite liner systems in municipal solid waste landfills to minimize the advection and diffusion of the contaminated leachate into the ground water. GCLs normally consist of a layer of bentonite sandwiched between geotextiles that have been needle-punched or stitched together (Rowe et al., 2010). The hydraulic performance of GCLs, at least in part, depends on the rate of hydration from the underlying subsoil (Rowe et al., 2010).

Previous research has shown that the rate of hydration of the GCL could be affected by the GCL manufacturing techniques, the subsoil particle size distribution, and initial water content (Anderson et al., 2012; Azad et al., 2011; Chevrier et al., 2012; Rayhani et al., 2011; Rowe et al., 2011b).

In current design practice, GCL panels are placed with an overlap of 150–300 mm in the longitudinal direction of the GCL panels (Rowe, 2012), and typically covered by a minimum 300 mm of drainage layer or cover soil to isolate the liner from solar exposure (Daniel and Koerner, 1993). However, it is not uncommon for a composite liner to be left exposed to weather prior to deposition of the cover soil. During this period, the temperature of the geomembrane component of the composite liner may reach over 60 °C owing to daily solar radiation (Koerner and Koerner, 1993; Pelte et al., 1994), which in turn can induce drying of the underlying GCL panels. This drying and subsequent overnight cooling could cause significant amounts of accumulated shrinkage, and large separation of the GCL panels (Thiel et al., 2006).

Exposure of GCL panels to weather have shown to induce gaps of 200–1200 mm between GCL panels, which originally had 150 mm overlaps (Koerner and Koerner, 2005a, 2005b; Thiel and Richardson, 2005; Thiel et al., 2006). Evaluating the shrinkage of GCL specimens in aluminium baking pans in the laboratory while exposed to wet–dry cycles, Thiel et al. (2006) demonstrated 23% shrinkage for a needle-punched nonwoven/nonwoven GCL. Thiel et al. (2006) also reported that the geotextiles tested showed relatively minor shrinkage of 0.3%–2.4%, indicating that geotextiles did not contribute significantly to the overall shrinkage of GCLs. A similar study by Rowe et al. (2011a) showed a different amount of shrinkage for different types of GCL products, and GCL manufacturing techniques have been shown to affect the shrinkage of GCLs (Thiel et al., 2006; Rowe et al., 2011a). Rowe et al. (2011a) also reported that the maximum shrinkage of scrim-reinforced thermally treated GCLs is
The shrinkage data derived in previous studies provide information as to the expected effect of various factors on the shrinkage of GCLs subjected to thermal cycles (e.g. Rowe et al., 2011a). These experiments, however, did not represent field conditions expected for a landfill where GCL specimens are placed over subsoil where GCL absorbs moisture from the subsoil. Daily thermal cycles were shown to affect the rate of hydration of GCLs when placed in contact with underlying subsoil (Rowe et al., 2011b). However, the effect of daily thermal cycles on GCL shrinkage in conjunction with subsoil hydration has not been largely documented. Rowe et al. (2013) examined the shrinkage of a nonwoven/nonwoven GCL, placed in contact with silty sand subsoil, under simulated daily thermal cycles and measured a maximum shrinkage of 4.5%. The potential shrinkage of other GCL products placed over subsoils other than silty sand is currently unknown. The objective of this article is to investigate the shrinkage of GCLs under simulated field conditions where the hydration of the GCLs is influenced by the water retention curve (WRC) of both subsoil and GCL, as well as the initial moisture content of the subsoil. The effects of initial moisture content and the aspect ratio of GCL specimens on the maximum shrinkage of GCLs are also discussed.

Material properties

GCLs

Three types of GCLs with different properties were investigated in this study (Table 1). All GCLs consisted of a core of granular bentonite clay with variations in smectite content ranging from 50% to 58%. GCL1 and GCL3 both had fine grained bentonite with $D_{50}$ of 0.35 mm while GCL2 had coarse grained bentonite with $D_{50}$ of nearly 1.0 mm. GCL1 and GCL3 had similar swell and plasticity indices of 24 ml/2 g min. and 216% (ASTM D 4318, 2005), respectively. GCL2 had a swell index of 23 ml/2 g min. and plasticity index of 262%

<table>
<thead>
<tr>
<th>Table 1. Properties of GCLs examined.</th>
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<tbody>
<tr>
<td>GCL</td>
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<tr>
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<tr>
<td></td>
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<tr>
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</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
</tbody>
</table>

GCL: geosynthetic clay liner; GT: Geotextile; NP: Needle punched; NPTT: Needle punched and thermally treated; NW: Nonwoven; SRNW: Scrim reinforced nonwoven; W: Woven.

*Tests performed by M Hosney, Queen’s University.

Soil properties

Sand (SP in USCS classification system, ASTM D2487, 2005), and Ontario Leda clay (CL) from the Navan landfill near Ottawa, Ontario, Canada, were utilized as the subsoil in this study. The maximum dry density ($\rho_{\text{d(max)}}$) was found to be 1.68 and 1.43 Mg m$^{-3}$ at the optimum gravimetric moisture contents ($w_{\text{opt}}$) of 10% and 28.3% for the sand (SP) and clay (CL), respectively, in accordance with the standard Proctor test (ASTM D698, 2005). The particle size distributions for both soils are demonstrated in Figure 1 (ASTM D422, 2005). The sand was nonplastic, and contained approximately 5% fines passing through the 0.075 mm sieve. The clay had a plasticity index of 21.6% (ASTM D4318, 2005). The database in the computer program GeoStudio (2007) was used to estimate the WRC of the sand, based on the particle size distribution and the saturated moisture content of the soil (Figure 1). Also, a Van Genuchten (1980) model was used to derive the WRC of the clay (Taha, 2010).

Experimental method

Model preparation

Rectangular wooden containers with internal dimensions of 650 $\times$ 300 $\times$ 300 mm and 1520 $\times$ 300 $\times$ 300 mm were used to investigate the shrinkage of GCL specimens under simulated daily thermal cycles. The smaller container was utilized for experiments with the AR of 2.2 while the larger container was used for those with an AR of 5. The AR was defined as the ratio of the length (L) to the width (W) of the GCL specimen, i.e. $AR = L/W$. The outer sides of the containers were insulated with fiberglass in order to simulate a one-dimensional heat transfer owing to solar radiation. In order to prevent the escape of water outside the container, a rubber membrane was stretched inside the soil containers.

Tap water was used to moisten the dried sand and clay. The moisture content of the subsoil was set at 2% more than the standard Proctor optimum gravimetric moisture content, i.e. $w_{\text{opt}} + 2\%$. 

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This water content was used to simulate the moisture content utilized in the construction of barrier systems. Hence the initial moisture content of the sand and clay subsoils was 12% and 30%, respectively. The sand was compacted into the container in five layers, with a final thickness of 250 mm, and a dry density of 1.51 Mg m⁻³, i.e. a dry density equivalent to 90% of the maximum standard Proctor dry density (0.9 × ρ_{max}). Similarly, the clay was compacted into the container to a dry density of 1.29 Mg m⁻³. Afterwards, the containers were closed and left for 24 hours in order that the soil cures and attains moisture equilibrium.

GCL specimens with dimensions of 710 × 300 mm and 1600 × 300 mm were cut from the roll for the experiments with AR = 2.2 and AR = 5, respectively. A border was drawn around all sides of the specimens to outline an area of interest of 600 × 270 mm and 1350 × 270 mm for the specimens with AR = 2.2 and AR = 5, respectively. The length of the area of interest for the specimens with the AR of 2.2 was divided by lines at 100 mm intervals, which were numbered from 1 to 7. Similarly, the specimens with the AR of 5 were divided by 10 lines with 150 mm spacing. This was done in order to measure the value of shrinkage of the specimens along the transverse direction once subjected to daily thermal cycles.

In order to hydrate the GCL specimens, water was sprayed uniformly over the GCL specimens using a commercial garden sprayer. The GCL specimens were then wrapped in a plastic bag, and left for 24 hours to attain moisture equilibrium. The boxes were opened after 24 hours in order to place the GCL samples over the subsoils. All samples were clamped to the container at both ends along the vertical direction to simulate field conditions where panels of GCLs are anchored at either end. The normalized moisture content defined as the ratio of gravimetric moisture content of the GCL to the maximum moisture content (w_{ref}), i.e. maximum gravimetric moisture content of the GCL while immersed in water, was used to investigate and compare the shrinkage of GCLs with different manufacturing techniques (Table 2).

### Monitoring

Temperature and moisture content measurement (TM) sensors were embedded within the soil to obtain the moisture content and temperature profile of the subsoil during the thermal cycles. Measurement errors of the instruments (both moisture content and temperature) associated with soil salinity are minimized by signal filtering. The temperature data derived from the sensors were verified by thermocouples that were embedded at the same depths as the sensors. Also, an additional thermocouple was utilised to measure the temperature of the space on top of the GCL, and hence control the heat transferred to the GCL. In order to conduct the tests in a closed system, the container was closed and sealed by silicone caulking and a transparent Plexiglas fixed to

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**Table 2.** Details of experiments conducted for shrinkage analysis of GCLs under simulated thermal cycles.

<table>
<thead>
<tr>
<th>Type</th>
<th>Initial *w/*w_{ref} (%)</th>
<th>Initial MC (%)</th>
<th>AR</th>
<th>Subsoil Type</th>
<th>Shrinkage (%)</th>
<th>No. of thermal cycles</th>
<th>Final MC of GCL%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3 days</td>
<td>1 week</td>
<td>Max. Shrinkage</td>
</tr>
<tr>
<td>1</td>
<td>85</td>
<td>100</td>
<td>5</td>
<td>Sand 12</td>
<td>4.6</td>
<td>10.7</td>
<td>11.3</td>
</tr>
<tr>
<td>1</td>
<td>85</td>
<td>100</td>
<td>5</td>
<td>Sand 3</td>
<td>5.9</td>
<td>11.0</td>
<td>11.2</td>
</tr>
<tr>
<td>1</td>
<td>25</td>
<td>30</td>
<td>5</td>
<td>Sand 12</td>
<td>4.6</td>
<td>4.9</td>
<td>5.0</td>
</tr>
<tr>
<td>1</td>
<td>85</td>
<td>100</td>
<td>2.2</td>
<td>Sand 12</td>
<td>2.1</td>
<td>6.0</td>
<td>8.1</td>
</tr>
<tr>
<td>1</td>
<td>85</td>
<td>100</td>
<td>2.2</td>
<td>Clay 30</td>
<td>1.7</td>
<td>4.4</td>
<td>5.5</td>
</tr>
<tr>
<td>2</td>
<td>85</td>
<td>100</td>
<td>2.2</td>
<td>Sand 12</td>
<td>9.1</td>
<td>14.9</td>
<td>14.6</td>
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<tr>
<td>2</td>
<td>85</td>
<td>100</td>
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<td>Clay 30</td>
<td>3.5</td>
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<td>8.6</td>
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<tr>
<td>3</td>
<td>85</td>
<td>100</td>
<td>2.2</td>
<td>Sand 12</td>
<td>10.6</td>
<td>14.8</td>
<td>14.7</td>
</tr>
</tbody>
</table>

* w/*w_{ref} (%) = normalized moisture content.
AR: aspect ratio; GCL: geosynthetic clay liner; MC: Moisture content.
the top of each container. This was intended to simulate the GCL panels underlain by a wrinkled geomembrane that are subjected to thermal cycles in field conditions.

**Experimental procedure**

In order to simulate the daily heating cycle induced by solar radiation, a heating blanket set to the temperature of 60 °C was placed over the Plexiglas. Heat was applied for 8 hours only to the surface of the Plexiglas, while the container was surrounded by fiberglass insulation. The container was placed on the floor with a constant temperature of 20 °C at the bottom of the container. This was intended to simulate the one-dimensional thermal gradients developed in field conditions. The heating blanket was subsequently removed and the container was left in a room at a temperature of 22 °C for 16 hours in order to simulate a typical overnight cooling cycle under field conditions. Therefore, the cycle time was 24 hours. The heating temperature of 60 °C represents the typical temperature that could be generated in a black geomembrane subjected to solar radiation (Thiel et al., 2006).

**Shrinkage analysis**

The shrinkage of the GCL specimens along the transverse direction was measured over the length of the numbered grids. No shrinkage was expected nor observed along the length of the specimens owing to the anchorage at both ends. This anchorage was to simulate the anchorage normally provided by sand bags along the edge of GCL panel width in field conditions. The GCL specimens were only visible through the Plexiglas after the heating portion of the heat–cool cycle. Condensed water beneath the Plexiglas after the cooling portion obscured the GCL specimens. Hence, digital images were taken at specified times using a 10 megapixel digital SLR camera at the end of the heating portion of each daily thermal cycle. The camera was fixed to a stand above the containers. A commercial Photogrammetry program (Grapher) was employed to digitize the images and measure the length of the grids. The shrinkage of the GCL specimens was then calculated between the measure lines in comparison to their initial dimensions.

**Results**

**Temperature profile**

The temperature of the subsoil after the heating portion was significantly higher compared with the cooling portion of the daily thermal cycles. In particular, much higher temperature variation and values of temperature after the heating portion within the top 60 mm was observed, which ranged between 34 °C and 53.4 °C (Figure 2). Furthermore, heat accumulated in the approximate bottom of the container, which in turn induced a temperature increase of 6 °C at the end of the simulated daily thermal cycles (Z = 240 mm).

![Figure 2. Applied temperature and temperature profile in sand subsoil during a thermal cycle.](image)

**Moisture content profile**

The gravimetric moisture content of the sand subsoil at depths of less than 60 mm decreased noticeably to an average of 6%. This could be attributed to the particle size distribution and lower field capacity of the sand, which in turn resulted in the downward movement of water within the subsoil. Thus, as could be expected, the gravimetric moisture content at the bottom of the container increased to approximately 18% for the sand subsoil. More notable is the fact that no significant variation was observed between the initial and final gravimetric moisture content of the clay subsoil, possibly owing to the high field capacity of the clay.

**Shrinkage of GCLs**

GCL specimens were subjected to daily thermal cycles until they attained equilibrium, i.e. their shrinkage levelled out (Figure 3). Only the results for half of the specimen (grids 1, 2, 3, 4, and 5) were plotted owing to symmetry of the shrinkage mirrored in the other half of the specimen. The shrinkage along the grids increased as the number of thermal cycles applied to the GCL
specimens increased. In general, the maximum shrinkage was observed at the midpoint of the GCLs. The restraint induced by the clamps at either end prevented shrinkage along the grids adjacent to the clamps, while grid 5 underwent the maximum equilibrium shrinkage of 5% for this experiment.

**Analysis and discussion**

**GCL manufacturing techniques**

GCL1 was found to undergo a maximum shrinkage of 8.1%, which was approximately half that of the other GCL specimens (Figure 4(a)). Also, the rate of shrinkage for GCL1 was significantly less than that of the other specimens. The shrinkage of GCL2 and 3 reached a plateau within one week of daily thermal cycles, while it took 10 thermal cycles for GCL1 to stabilize. The shrinkage behaviour of GCLs could be attributed to the different techniques utilized in interlocking the carrier and cover geotextiles. Although all GCLs were initially hydrated to 85% normalized moisture content, GCL1 had the lowest initial gravimetric moisture content (100%) compared with the other GCL specimens (127% and 187%). The final moisture content for all GCLs after the termination of daily thermal cycles was found to be approximately 20% (Table 2). Hence, it could be concluded that GCL1 experienced the smallest variation in moisture content during each thermal cycle, which in turn resulted in the least shrinkage compared with the other GCL types. This is owing to the fact that the better anchorage provided in GCL1 induced less swelling and as a result less moisture uptake during the cooling portion of the daily thermal cycles. GCL3 and GCL2 experienced similar values of shrinkage (14.6 and 14.7%, respectively). The main difference in their manufacturing techniques is that GCL3 has fine granular bentonite with a thermally treated connection layer, while GCL2 has coarse granular bentonite with a needle-punched connection layer. On the other hand, the average peel strength of GCL3 (94 N m⁻¹) is significantly less than that of GCL2 (204 N m⁻¹) (Table 1). Hence, it might be inferred that thermal treatment of the connection layer alone may not guarantee less shrinkage compared with simply needle-punched GCLs.

The better performance of GCL1 is consistent with the results reported by Rowe et al. (2011a) and Thiel et al. (2006), indicating that the thermally treated, needle-punched, and scrim-reinforced nonwoven GCL underwent less shrinkage compared with the needle-punched GCL with a simple nonwoven carrier geotextile. The maximum shrinkage measured in the current study (8.1%) for GCL1 was found to be less than the values reported by Rowe et al. (2011a) (10.8%) and Thiel et al. 2006 (12.8%). This could be attributed to the difference in the GCL foundation conditions, which was placed over subsoil in this research, but simply placed over a pan in the previous studies (Rowe et al., 2011a; Thiel et al., 2006). The temperature of the subsoil was clearly lower than that of the pans placed in the oven. The frictional force induced by the subsoil may have also hindered the movement and shrinkage of the GCL (Rowe et al., 2013).

**GCL initial moisture content**

GCL rolls typically have different initial moisture contents when they are placed over subsoil. In order to investigate the effect of the initial moisture content on the potential shrinkage behaviour of GCLs subjected to thermal cycles, the results derived for the GCL specimens hydrated to initial normalized moisture contents of 25% and 85% were juxtaposed for comparison. Specimens of GCL1 with ARs of 5 were placed over sand subsoil with an initial normalized moisture content during each thermal cycle, which in turn caused much more shrinkage. When the composite liner is heated by
Hence, the difference in suction between the GCL and sand occurs in the cooling portion of each daily thermal cycle (Figure 1). This could be explained by analysis of the hydration behaviour of GCLs from the sand subsoil. The initial suction of sand is relatively lower than that of the clay during the hydration, which in an increase in the initial moisture content led to higher values of shrinkage after five thermal cycles.

The results could also be clarified by the WRCs of the GCLs. Beddoe et al. (2011) reported that the wetting path WRC and the drying path (which closely follows the wetting curve) will be a good combination to study the shrinkage behaviour of GCLs. Interestingly, their results also showed that the aforementioned curves followed the same path, i.e. either of them could be utilized to analyse the wetting and drying portions of the thermal cycles. Considering the wetting path WRC for GCL1 derived by Beddoe et al. (2010, 2011), the corresponding initial suction in GCL1 for 85% and 25% initial normalized moisture content will be approximately 5 and 3000 kPa, respectively. Hence, it could be concluded that the higher initial moisture content resulted in more variation of suction during each thermal cycle, which in turn resulted in significantly more accumulated shrinkage.

**GCL AR**

In order to evaluate the potential effect of the AR on GCL shrinkage, the results derived for two specimens of GCL1 with aspect ratios of 2.2 and 5 were compared (Figure 4(c)). Both GCL specimens were hydrated to an initial normalized moisture content of 85%, and were placed over sand subsoil with an initial gravimetric moisture content of 12%. There was a noteworthy increase in the maximum shrinkage from 8.1% to 11.3% as the AR increased from 2.2 to 5. In other words, the required overlap to prevent panel separation for typical 4.5 m wide GCL panels with an AR of 2.2 and 5 would be approximately 360 mm and 500 mm, respectively. The maximum shrinkages of 8.1% (AR = 2.2) and 11.3% (AR = 5) in the current study are less than those reported by Bostwick et al. (2006) which an increase in the initial moisture content led to higher suction values (i.e. lower moisture contents) caused significantly smaller suction cycles and lower shrinkage. Hence, it could be higher for GCLs with higher initial moisture content. During the cooling period, the water vapour in the airspace condenses and leads to an increase in the moisture content of the GCL. Similar results were also reported by Rowe et al. (2011a), in which an increase in the initial moisture content led to higher values of shrinkage after five thermal cycles.

It should be noted that the results of pan tests conducted by Thiel et al. (2006) could also corroborate more shrinkage for a GCL placed over sand subsoil. Thiel et al. (2006) reported that a decrease in the volume of water added to GCL1 during each cycle from 500 ml to 300 ml (i.e. approximate reduction of normalized moisture content (w/wref) from 55% to 33%) induced a decrease in the maximum shrinkage from 19.2% to 14.4% after 40 wet–dry cycles. However, Rowe et al. (2011a) demonstrated that increasing the moisture content of GCL1 at the beginning of each thermal cycle from 65% to 100% (i.e. approximate increase of normalized moisture content (w/wref) from 55% to 85%) did not significantly affect the maximum shrinkage. This could be elucidated by the wetting WRC given by Beddoe et al. (2011). That said, owing to the logarithmic feature of the WRC and a lower slope in the high suction region, decreasing the moisture content of the GCL in higher suction values (i.e. lower moisture contents) caused significantly smaller suction cycles and lower shrinkage. Hence, it could be concluded that the GCL with sand subsoil is expected to undergo more shrinkage than that with clay subsoil, provided that the sand subsoil provides the sufficient moisture for hydration of the GCL in the cooling portion of thermal cycles.

**Subsoil particle size distribution**

The results indicated that the GCL specimen placed over sand subsoil experienced more shrinkage compared with the specimen with clay subsoil (Figure 5(a)). The former was found to stabilize at the maximum shrinkage of 8.1% while the latter had the maximum shrinkage of 5.5% at the end of the daily thermal cycles. This could be explained by analysis of the hydration behaviour of GCLs from the sand subsoil. The initial suction of sand is relatively lower than that of the clay during the hydration, which occurs in the cooling portion of each daily thermal cycle (Figure 1). Hence, the difference in suction between the GCL and sand subsoil is more than that of the GCL–clay interface, which causes much more moisture uptake during the cooling period. This would induce higher moisture variation during daily thermal cycles, which in turn causes much more accumulated shrinkage for the GCL placed over sand subsoil.

Figure 5. Effects of subsoil particle size distribution [a] and the initial moisture content of the subsoil [b] on GCL shrinkage.
Subsoil initial moisture content

The initial moisture content of the subsoil may vary based on the field conditions, i.e. the groundwater level, the type of subsoil, the weather conditions, etc. Hence, the maximum shrinkage results obtained on sand subsoil with initial gravimetric moisture contents of 3% and 12% were compared to investigate the potential effects of the initial moisture content of the subsoil on the shrinkage of GCLs. Both GCL specimens (GCL1) were hydrated to an initial normalized moisture content of 85%, and had an AR of 5. As shown in Figure 5(b), no significant difference between the shrinkage of the GCL specimens was observed, and they both levelled out at shrinkage of approximately 11% (Table 2). This could be owing to the low field capacity water content of the sand. The sand subsoil with a higher initial moisture content of 12% ended up at a final moisture content of approximately 5% near the soil surface. This moisture content is close to the initial moisture content used in the other experiment (3%), leading to a small difference between the moisture contents of both subsoils. This shows that there was no significant difference in either experiment in terms of providing water for the GCL during the cooling, which in turn induced no considerable change in the values of the shrinkage.

Conclusions

A series of experimental models were utilized to evaluate the effect of daily thermal cycles on the shrinkage of three different GCL products placed in contact with different subsoils. The GCL specimens were subjected to an elevated temperature of 60 °C for 8 hours and subsequent cooling at room temperature (22 °C) for 16 hours. This simulated the typical field conditions where the geomembrane placed over the GCL roll is exposed to solar radiation. The following conclusions were drawn from these experiments.

- The needle-punched and thermally treated GCL with scrim-reinforced nonwoven carrier geotextile (GCL1) experienced a maximum shrinkage of 8.1%, which was significantly less than that of the other two products (14.6%–14.7%). This could be attributed to the better anchorage of GCL1, which limited the range of moisture variation in the GCL during the thermal cycles and, hence, limited the shrinkage of the GCL.
- The initial moisture content of the GCL significantly affected the maximum shrinkage under daily thermal cycles. The maximum shrinkage increased from 5% to 11.3% as the initial normalized moisture content of GCL increased from 25% to 85%. Higher variation of the moisture content associated with the specimens with higher initial moisture contents could be considered as the reason for more shrinkage of the GCLs.
- Increasing the ratio of the GCL panel length to width (AR) could lead to more shrinkage. This could be owing to the lesser effect of the clamps at either end in hindering the movement and shrinkage at the midpoint of the GCL panel.
- The particle size distribution of the subsoil could affect the maximum shrinkage owing to the difference in moisture content variation during each daily thermal cycle. GCL1 with sand subsoil (SP) underwent more shrinkage (8.1%) compared with the same GCL with clay subsoil (CL) (5.5%).
- The initial moisture content of the sand subsoil was found to have no significant influence on the maximum shrinkage of GCL with initial normalized moisture content (w/wref) of 85%. This could be attributed to the low field capacity moisture content of the sand. Increasing the initial moisture content of the subsoil from 3% to 12% did not seem to make any significant difference in the amount of the moisture available to the GCL and, consequently, the GCL shrinkage.
- The final gravimetric moisture content of all GCL specimens at the end of daily thermal cycles was found to be approximately 20% regardless of their initial moisture content. This shows the severe effect of thermal cycles on impeding the moisture uptake by the GCL, which in turn reduces the hydraulic performance of the GCL. Thus, the liner should be covered by the cover soil or Leachate Collection System (LCS) shortly after its installation. This would prevent the loss of moisture as well as significant shrinkage of the GCL panels induced by solar radiation.

The values of shrinkage given in the current study indicate the potential effect of thermal cycles on the shrinkage of GCLs, which is influenced by the GCL and subsoil properties. It should be noted that the results reported could only be considered for the careful design in composite landfill liners. This is owing to the fact that there are many other factors that could affect the maximum shrinkage of GCLs, including the bentonite mass distribution (Bostwick et al. 2010) and the severity of field conditions.

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Declaration of conflicting interests

The authors declare that there is no conflict of interest.

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