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The paper was published in the proceedings of the 3rd International Symposium on Coupled Phenomena in Environmental Geotechnics and was edited by Takeshi Katsumi, Giancarlo Flores and Atsushi Takai. The conference was originally scheduled to be held in Kyoto University in October 2020, but due to the COVID-19 pandemic, it was held online from October 20th to October 21st 2021.
Challenges and solutions in using geosynthetic clay liners exposed to thermal desiccation risks

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ABSTRACT

Geosynthetics Clay Liners (GCLs) are widely used in geoenvironmental engineering as part of groundwater protection barrier systems. The dehydration and desiccation of bentonite in the GCLs under high temperatures, together with its suppressed self-healing when exposed to aggressive chemicals, has led to concerns about its performance and the durability of engineering barriers in these environments. In this paper, key parameters influencing chemo-thermo-hydro-mechanical behavior of GCLs under high temperature and salinity are reviewed, based on experimental evidence generated by the authors over the last four years. Next, a thermo-hydro-mechanical model is used to analyze the effects of subsoil characteristics on GCL dehydration. Finally, a new concept (I-GCLS), is proposed and experimentally investigated with the aim of preventing dehydration and desiccation cracking.

Keywords: composite liner, GCL, desiccation, healing, column experiment, numerical model

1 INTRODUCTION

Over the last few decades, composite lining systems made of geosynthetic material such as geosynthetic clay liner (GCL), geomembrane (GMB), geogrids and geotextiles, etc., have been widely used in geotechnical and geoenvironmental engineering practice (Bouazza, 2002; Rowe, 2005). The GCL-GMB composite liners are particularly popular, thanks to their construction efficiency and high levels of performance (Shackelford et al., 2000; Bouazza, 2002; Rowe, 2005). However, the GCL-GMB composite liners are very often exposed to chemically aggressive environments under elevated temperatures, as is the case in landfills, as well as brine, solar and tailing ponds. Several studies have confirmed that GCLs experience dehydration and desiccation under such conditions (Southen and Rowe, 2005; Azad et al., 2011; Hoor and Rowe, 2013; Ghavam-Nasiri, 2017). Moreover, the capacity of the GCL’s bentonite to self-heal can be affected by the presence of chemical compounds (Benson and Meer, 2009; De Camillis et al., 2016 and 2017). That is to say that cracks developed during GCL desiccation may not completely close upon exposure to chemical liquids (e.g., MSW leachates, brines, heavy metal contaminated solutions) as they would when rehydrated with clean water.

In this paper, the desiccation and healing behaviors of GCLs under conditions typical of brine ponds (i.e., high temperature, high sodium concentration, low overburden pressure) are reviewed, based on experimental and numerical work conducted by the authors over the last four years (Yu et al., 2018; Yu and El-Zein, 2019; Yu et al., 2020; Yu and El-Zein, 2020; Yu, 2020). The high levels of desiccation risk of conventional GCL-GMB composite liners are discussed, focusing on key factors, including GCL type, temperature exposure, and subsoil type. A validated thermo-hydro-mechanical (THM) model further expand the investigation on the GCL desiccation in clayey subsoils. At the end of the paper, the authors propose the concepts of I-GCLS (irrigated geosynthetic clay liner system) and validate their efficiency in preventing GCL desiccation under the thermal gradients.

2 MATERIALS AND METHODOLOGIES

2.1 Materials

Four needle-punched and thermally reinforced GCLs were investigated in this study (see Table 1). It is noted here that the bentonite in GCL_4 was amended with a polyacrylamide compound.

In column experiments, a well-graded (SW) Sydney river sand was adopted as subsoils because it low water retention capacity had been found to increase the rate of thermal dehydration of the overlying GCL. Its details are provided in Table 2.

2.2 Column experiments

Diagrams of the column apparatus adopted in this study are shown in Fig. 1. Two instruments were used to conducting two sets of tests. The medium-sized column contained a 25 cm subsoil (SW), and a heating chamber which applied ~4 kPa overburden pressure on the top of GCL-GMB composite liner (Fig. 1a). GCLs were first hydrated to gravimetric water content (w) ~85-100%
before they were installed in the column and subjected to a 14-day long heating.

Table 1. Basic properties of the GCLs used in this study.

<table>
<thead>
<tr>
<th></th>
<th>GCL_1</th>
<th>GCL_2</th>
<th>GCL_3</th>
<th>GCL_4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bentonite type</td>
<td>Powder Na-bentonite</td>
<td>Granular Na-bentonite</td>
<td>Granular polymer bentonite</td>
<td></td>
</tr>
<tr>
<td>Bentonite dry mass per unit area (g/m²)</td>
<td>4200</td>
<td>4710</td>
<td>4341</td>
<td>4173</td>
</tr>
<tr>
<td>Swell index (mL/2g)</td>
<td>29</td>
<td>27</td>
<td>28</td>
<td></td>
</tr>
<tr>
<td>Cover geotextile type</td>
<td>Nonwoven</td>
<td>Nonwoven</td>
<td>Nonwoven</td>
<td></td>
</tr>
<tr>
<td>Cover geotextile mass per unit area (kg/m²)</td>
<td>290</td>
<td>280</td>
<td>255</td>
<td>253</td>
</tr>
<tr>
<td>Carrier geotextile type</td>
<td>Woven + Nonwoven</td>
<td>Woven + Nonwoven</td>
<td>Woven + Nonwoven</td>
<td></td>
</tr>
<tr>
<td>Carrier geotextile mass per unit area (kg/m²)</td>
<td>415</td>
<td>440</td>
<td>251</td>
<td>253</td>
</tr>
</tbody>
</table>

Table 2. Basic properties of the SW used in this study.

<table>
<thead>
<tr>
<th>Contents</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil classification</td>
<td>SW</td>
</tr>
<tr>
<td>Specific gravity, (G_s)</td>
<td>2.65</td>
</tr>
<tr>
<td>Optimum water content, (w_o) (%)</td>
<td>13.5</td>
</tr>
<tr>
<td>Maximum dry density, (\rho_d) (kg/m³)</td>
<td>1874.4</td>
</tr>
</tbody>
</table>

The large-sized column (Fig. 1b) had two temperature control cells sandwiching the GCL-GMB composite liner and a 60 cm subsoil layer. The subsoils (SW) were compacted into the columns with an initial gravimetric water content (\(w\)) of 11% and dry density (\(\rho_d\)) of 1780 kg/m³. Initially dry GCLs were installed and allowed to hydrate from the subsoil under 20°C isothermal conditions and 20 kPa overburden pressures. After 7 to 9-week hydration, when measured GCL swelling had ceased, temperature was applied on top of the liner and the heating stage started, and continued for 2 to 6 weeks until no further GCL shrinkage was observed. During the tests, moisture and temperature in the subsoils, as well as GCL properties (e.g., water contents, crack development) were monitored.

At the end of both set of tests, desiccated samples were imaged by x-ray and their hydraulic conductivity measured using deionized water and a sodium rich brine solution as permenters.

Five copies of the medium-sized instruments and two copies of the large-sized instruments were built. The medium-sized instruments were not only easier to build but their tests were faster to run (14 days) because the samples were hydrated outside the column. Tests conducted with the large-sized instruments took longer to complete (up to 8 weeks) but they simulated site conditions and more closely generated more data because of more elaborate instrumentation (see Fig. 1).

More details of the tests can be found in Yu and El-Zein (2019) and Yu et al. (2018 and 2020).

2.3 Numerical modelling and validation

A thermo-hydro-mechanical (THM) numerical model was used to simulate the large column experiment. The model was built using CODE_BRIGHT, a finite element computation code developed at the Polytechnic University of Catalunya (Olivella et al., 1994; Olivella et al., 1996a; Olivella et al., 1996b). The numerical study presented continued the work carried out by Ghavam-Nasiri (2017), Ghorbani et al. (2018) and Ghavam-Nasiri et al. (2019). Yu (2020) further refined the THM model by acknowledging the slower vapour diffusion and unsaturated moisture exchange that occurred during the GCL hydration from the subsoil. The main constitutive equations adopted in the model are listed in Table 3. For details of the model readers are refer to Yu (2020). Fig. 2 compares the model’s predictions of moisture and strain to experimental observations from the large-sized columns, which indicates a satisfying match between model prediction and experiment results under 78°C heating temperature.

Table 3. Constitutive models adopted in the THM model.

<table>
<thead>
<tr>
<th>Coupled phenomenon</th>
<th>Constitutive model adopted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stress-strain relations</td>
<td>Elasto-plastic model based on BBM</td>
</tr>
<tr>
<td>Unsaturated water transport</td>
<td>Van Genuchten model</td>
</tr>
<tr>
<td>Vapor mitigation</td>
<td>Fick’s law</td>
</tr>
<tr>
<td>Heat mitigation</td>
<td>Fourier’s law</td>
</tr>
</tbody>
</table>

3 EFFECTS OF BENTONITE PROPERTIES

Fig. 3 presents the gravimetric water contents of the four different GCLs before and after application of 78°C on top of the liner in the large column experiment. The
GCLs were hydrated by the subsoils for 44 days (GCL_1), 56 days (GCL_2) and 49 days (GCL_3 and 4) (Yu et al., 2018). In each case, heating was applied (and hence hydration stage terminated) when no more GCL swelling was recorded. Fig. 3 shows that compared to granular bentonite GCLs (GCL_3/4), higher water contents were achieved in powder bentonite GCLs (GCL_1/2).

Fig. 2. Comparison between THM predictions and measurement data for column experiment of GCL_3 under 78°C heating.

The heating stage was ceased when no more shrinkage was recorded. Hence, GCL_1 and 2 were subjected to 78°C for 39 days and 28 days respectively, while GCL_3 and 4 were exposed to the same temperature for only 14 days. In all cases, GCL shrinkage data indicated that dehydration happened mostly in the first 7 days (Yu et al., 2018; Yu and El-Zein, 2019; Yu et al., 2020). Fig. 3 shows that all GCLs were severely dehydrated upon heating. It shows that none of the variables studied here, i.e., higher mass of bentonite per surface area $M_a$ (GCL_2 compared to GCL_1), powder rather than granular bentonite (GCL_1/2 versus GCL_3/4), polymer amendment (GCL_4 versus GCL_3), were able to prevent or significantly reduce thermal dehydration.

Unsurprisingly, desiccation cracks were observed in all four GCLs, using x-ray imaging. Comparisons of crack properties in Table 4 show that GCL_3/4 had smaller crack areas and crack width, compared to GCL_1/2. This is likely due to the smaller proportion of water lost in GCL_3 and 4 (88.6% and 86.5%) compared to GCL_1 and 2 (118.2% and 112.5%) during the heating stage, and hence smaller tensile stresses developing.

The self-healing capacities of GCL_2, 3 and 4 desiccated samples were evaluated by rehydrating them in a permeameter, using deionized water (DI) and a sodium rich brine (contained 0.325 mol/L Na+). Table 5 shows the measured saturated hydraulic conductivities. GCLs showed significant healing, except that the hydraulic conductivity of the GCL_2 sample was 2.7-times its design value. This is likely due to the wider cracks, which may not completely heal during permeation (Yu and El-Zein, 2018).

Table 5. Hydraulic conductivities tested on desiccated sample.

<table>
<thead>
<tr>
<th>GCL</th>
<th>$k_{\text{design}}$ (m/s)</th>
<th>$k_{\text{DI}}$ (m/s)</th>
<th>$k_{\text{Brine}}$ (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GCL_2</td>
<td>1.3x10^{-11}</td>
<td>3.5x10^{-11}</td>
<td>6.0x10^{-11}</td>
</tr>
<tr>
<td>GCL_3</td>
<td>3.0x10^{-11}</td>
<td>3.0x10^{-11}</td>
<td>8.0x10^{-11}</td>
</tr>
<tr>
<td>GCL_4</td>
<td>1.0x10^{-11}</td>
<td>1.0x10^{-11}</td>
<td>6.0x10^{-10}</td>
</tr>
</tbody>
</table>

When permeating the GCLs with brine, self-healing was hampered in all GCLs. The hydraulic conductivities ($k$) of GCL_2 and 3 were found to be 4.6- and 2.7-times higher than their design values, respectively. On the other hand, the $k$ of GCL_4 was 60 times higher than its design value. This surprising result indicates that, while polymer amendment of bentonite is expected to improve its performance under wet-dry cycles in saline environments (Scalia et al. 2011; Athanassopoulos et al. 2015; Arndt et al. 2015), it seems reduce self-healing of thermally desiccated clay when rehydrated with brine.

4 EFFECTS OF ENVIRONMENTAL FACTORS

4.1 Heating temperatures

Batch experiments were conducted using GCL_3 (granular bentonite) and 4 (granular bentonite with polymer amendment) in the medium column apparatus.
to investigate GCL desiccation under different applied temperatures (35°C to 60°C). Fig. 4 shows that when the GCLs were heated under 4 kPa overburden pressure overlying a SW subsoil, desiccation cracking occurred at applied temperatures as low as 35°C. The lower temperatures resulted in smaller proportion of cracked area (10.5~12.1% under 35°C compared to 22.2~22.8% under 60°C) and smaller crack width (0.82~0.84 mm under 35°C compared to 0.94~1.07 mm under 60°C). The smaller crack width generated by lower temperatures favored subsequent self-healing of bentonite when the GCLs where rehydrated with DI and brine solutions, as demonstrated by gains in hydraulic conductivity (see Table 6).

Desiccation cracking was not prevented. However, similar results were observed for GCL_3 and 4, also shown in Table 6.

![X-ray images of desiccated GCLs after 14 days heating in the medium column apparatus.](image)

**Fig. 4.** X-ray images of desiccated GCLs after 14 days heating in the medium column apparatus.

Table 6. Hydraulic conductivities tested on desiccated sample.

<table>
<thead>
<tr>
<th>Temperature</th>
<th>$k_{\text{DI}}$ (m/s)</th>
<th>$k_{\text{Brine}}$ (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GCL_2 78°C</td>
<td>$3.5 \times 10^{-11}$</td>
<td>$6.0 \times 10^{-11}$</td>
</tr>
<tr>
<td>52°C</td>
<td>$1.6 \times 10^{-11}$</td>
<td>$3.5 \times 10^{-11}$</td>
</tr>
<tr>
<td>44°C</td>
<td>$1.6 \times 10^{-11}$</td>
<td>$3.5 \times 10^{-11}$</td>
</tr>
<tr>
<td>GCL_3 40°C</td>
<td>$1.7 \times 10^{-11}$</td>
<td>$3.0 \times 10^{-11}$</td>
</tr>
<tr>
<td>80°C</td>
<td>$3.0 \times 10^{-11}$</td>
<td>$8.0 \times 10^{-11}$</td>
</tr>
<tr>
<td>GCL_4 40°C</td>
<td>$1.0 \times 10^{-11}$</td>
<td>$2.0 \times 10^{-11}$</td>
</tr>
<tr>
<td>80°C</td>
<td>$1.0 \times 10^{-11}$</td>
<td>$6.0 \times 10^{-10}$</td>
</tr>
</tbody>
</table>

4.2 Subsoil types

The SW subsoil used in this study, was able to achieve faster hydration of GCLs compared to sands with more fine contents (Ghavam-Nasiri, 2017). However, as discussed by Yu and El-Zein (2019), the low water retention capacity and high $k$ value ($\approx 3 \times 10^{-4}$ m/s) of the subsoil lead to faster dehydration of the GCLs when under thermal gradient. Bouazza et al. (2017) also suggested that GCL dehydration under 70°C may be avoided by adopting a clayey subsoil.

The validated THM model was hence used here to investigate the effects of adopting three different subsoils (including the SW subsoil discussed above) on GCL dehydration when subjected to 78°C at the top for 14 days. The two additional subsoils were used in experiments conducted by Southen and Rowe (2011) and Bouazza et al. (2014) and their properties hence reported in these papers. The two soils are silty clay (SC) and clay (CL), which are less permeable compared to the SW adopted in the column experiment. A comparison between the SWCCs and intrinsic permeabilities ($K$) of the 3 subsoils is shown in Fig. 5. CL-2 have the highest retention and SW the lowest. In the model, the volumetric water contents (VWCs) of GCL before heating was set at 0.53 for all 3 cases.

The final VWCs of GCLs at the end of the 14-day heating under 78°C, predicted by the THM model, are shown in Table 7. These calculations suggest that placing the liners on a subsoil with smaller hydraulic conductivity and higher water retention capacity can significantly reduce GCL dehydration under thermal gradients.

Assuming bentonite has no tensile strength, a negative net horizontal stress ($\sigma_{xx}$) developed in the middle of the GCL has been used as a sign of development of tensile stress and desiccation crack initiation in the bentonite (Döll, 1997; Ghavam-Nasiri, 2017; Ghorbani et al., 2018; Ghavam-Nasiri et al., 2019). Using the same approach here, Fig. 6 confirms that the higher water-retention soils, SC and CL, may help in preventing cracking. The two soils yield stable positive $\sigma_{xx}$ in the middle of GCLs, compared to the negative $\sigma_{xx}$ found in the case using SW. However, caution must be exercised when designers try to use clays or clayey soils as subsoils for several reasons. First, high levels of water retention and low permeabilities of clayey subsoil can be detrimental to GCL hydration, with longer hydration times required, and lower equilibrium saturation degrees achieved (Rayhani et al., 2011; Anderson et al., 2012; Chevrier et al., 2012; Sarabadani and Rayhani, 2014). Second, when a significant clay fraction exists in the subsoil, porewater may contain Ca$^{2+}$ and other cations which may cause changes to the microstructure of the GCL’s bentonite during hydration (Rowe, 2005; Bouazza and Gates, 2014). Finally, compared to sandy soils, clayey soils may require more effort and labor when compacted to the desired dry density.

Table 7. Water contents in GCLs after 14 days heating predicted by the THM model.

<table>
<thead>
<tr>
<th>VWC at the end of 14-day heating</th>
<th>SW</th>
<th>SC</th>
<th>CL</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.02</td>
<td></td>
<td>0.32</td>
<td>0.63</td>
</tr>
</tbody>
</table>
5 CONCEPTS OF I-GCLS

The results discussed above indicate conclusively that GCLs in the GCL-GMB composite liner systems, with either granular or powder bentonite, are prone to desiccate under temperature gradients, especially when placed on high-permeability, low-retention subsoils. Furthermore, the additional experiments we conducted using higher mass of bentonite per unit surface area or polymer amendments (Yu et al., 2018; Yu et al., 2020) or lowering temperatures to which the GCLs are exposed (Yu and El-Zein, 2019; Yu et al., 2020) did not succeed in preventing desiccation and cracking.

Therefore, we have proposed a new liner design concept called Irrigated Geosynthetics Clay Liner System (I-GCLS), based on a) active irrigation of GCLs after placement and b) the cutting off of moisture and air exchange between the subsoil and the GCL. Multiple designs, following combinations of the above two principles and involving single and double GCL designs were investigated by testing their hydration and dehydration behavior in the large column apparatus. The apparatus had to be modified to allow for active irrigation of the GCL. GCL_3 (granular bentonite) was used in all the tests. Result of only the best performing design are reported here and the reader is referred to Yu and El-Zein (2020) for more details.

Experimental testing showed that a design containing single liner made of a GMB-GCL-Geocomposite (GC)-GMB (Fig. 7) was able to significantly enhance GCL hydration speed and equilibrium water content and prevent dehydration and desiccation cracking of GCL under high temperatures. Three different working scenarios were tested on the I-GCLS. Under scenario 1, irrigation continued during the 28-day long test, under isothermal conditions (20°C) for the first 14 days, followed 78°C heating at the top for the final 14 days. Scenario 2 was similar to scenario 1, except that the irrigation was stopped after 14 days, i.e., at the same time that heating started. Scenario 3 represented a worst-case scenario in which the GCL was exposed to 78°C heating from day 1 (before it is hydrated) and irrigation was stopped after 14 days, while heating continued for another 14 days.

Comparisons between the GCL_3 water contents at each stage of the column experiments, in GCL-GMB liner and the proposed I-GCLS design are listed in Table 8. Compared to the conventional GCL-GMB case, the GCL specimens from the I-GCLS, under all 3 scenarios, after 14 days of irrigation, achieve hydration water contents that are significantly higher than those obtained through hydration by subsoil after 49 days. In addition, specimens from the new design remained well-hydrated (w>100%) after 14 days of temperature exposure. This was the case even under worst-case scenario 3. No desiccation was found in GCL specimens in the I-GCLS.

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