Visualization of a desiccated geosynthetic clay liner due to dehumidification using micro-focused X-ray computed tomography

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ABSTRACT

The objective of this study was to evaluate the change in the barrier performance of a geosynthetic clay liner (GCL) as a result of desiccation due to dehumidification at 55°C. Specimens of GCL that were damaged by desiccation were scanned using a micro-focused X-ray computed tomography (CT) scanner, and crack generation under two different dehumidification conditions was examined using the results of image analysis. Permeability tests were performed to estimate the hydraulic conductivity of GCL damaged by desiccation with respect to a calcium chloride solution. The results obtained indicate that dehumidification and a space between a GCL and a membrane sheet are key factors in the generation of cracks in the bentonite layer of a GCL at 55°C.

Keywords: geosynthetic clay liner (GCL), desiccation, dehumidification, X-ray computed tomography (CT)

1 INTRODUCTION

A clay liner under a hydraulic barrier sheet is likely to be affected by daily cyclic drying and moisture absorption and long-term exposure to sunlight (Azad et al. 2010, Hoor and Rowe, 2013). It has been reported that the surface temperature of a barrier sheet can reach approximately 60°C in the daytime (Brachman et al. 2014, Rowe et al. 2014, and Take et al. 2014). When a barrier is influenced by a temperature increase, for example, the durability performance of the barrier sheet becomes worse, and a barrier such as a geosynthetic clay liner (GCL) can be damaged by desiccation (Southern and Rowe, 2002 and Rowe et al. 2014). The Japanese standard for design of landfill barriers requires a barrier with a thickness of 50 cm and a hydraulic conductivity of 1.0 x 10⁻⁸ m/s. The standard does not address the effect of desiccation. If a bentonite liner cracks because of desiccation and leachate seeps into the bentonite near the crack, the bentonite will not swell well. As a result, the barrier performance of the bentonite liner will be diminished.

The objective of this study was to evaluate the change in the barrier performance of a GCL as a result of desiccation due to dehumidification at 55°C. Specimens of GCL that were damaged by desiccation were scanned using a micro-focused X-ray computed tomography (CT) scanner, and crack generation under two different dehumidification conditions was examined using the results of image analysis. Permeability tests were performed to estimate the hydraulic conductivity of GCL damaged by desiccation with respect to a calcium chloride solution. The key factors in the desiccation of GCL were identified from the results of the dehumidification model testing and the image analysis.

2 MATERIALS AND EXPERIMENT

2.1 GCL

The specifications of the GCL examined in this study are listed in Table 1. The GCL is composed of a non-woven cover geotextile, a layer of granular sodium bentonite, and a woven carrier geotextile. The mass per unit area of GCL specimens tends to be unstable; therefore, we calculated the mean for the specimens examined by taking measurements at more than five locations on the GCL liner sheet. The GCL specimens were prepared by making circular cuts (50 mm in diameter) in the liner sheet. Each 50-mm-diameter sample of the GCL used in this study contained approximately 12.6 g of bentonite.

Table 1. Specifications of geosynthetic clay liner (GCL) examined in this study

| Specimen Type          | Thickness (mm) | Mass per unit area (kg/m²) | Density (kg/m³) |
|------------------------|----------------|---------------------------|-----------------|
| Non-woven geotextile   | 1.41           | 0.29                      | 180             |
| Bentonite              | 6.0            | 6.4                       | -               |
| Woven geotextile       | 0.59           | 0.15                      | 249             |

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Figure 1 shows the grain size distribution curve of the bentonite in the tested GCL. The grain size distribution curve was determined using a dry dispersion method and a wet dispersion method using ethanol. In the case of the dry dispersion method, the particle size was overestimated because the fine particles absorbed moisture and clumped together. This may have been the result of the moisture content of the bentonite having been approximately 12%. Figure 2 shows the spectrum of the bentonite obtained from X-ray diffraction (XRD) analysis. This bentonite was a sodium-type montmorillonite, and therefore, the tested GCL would be expected to swell considerably as a result of water hydration. The application of post-hydration to the GCL after leachate permeation would result in a different degree of swelling of the bentonite, compared with that obtained as a result of pre-hydration with water.

### Table 2. Test cases and scanning stages

| Case    | Dehumidification          | Stage Duration |
|---------|---------------------------|----------------|
| A       | One-sided dehumidification| Initial 0 h    |
|         |                           | Stage 1 4 h    |
|         |                           | Stage 2 8 h    |
|         |                           | Stage 3 24 h   |
|         |                           | Stage 4 46.5 h |
|         |                           | Stage 5 65 h   |
|         |                           | Stage 6 79 h   |
| B       | Two-sided dehumidification| Initial 0 h    |
|         |                           | Stage 1 4 h    |
|         |                           | Stage 2 8 h    |
|         |                           | Stage 3 24 h   |
|         |                           | Stage 4 46.5 h |
|         |                           | Stage 5 68 h   |

### 2.2 Dehumidification model test

The model experiment for desiccation visualization in GCL involves applying heat to a GCL specimen in a model ground specimen obtained during the construction of a landfill barrier. Figures 3(a) and (b) are a photograph and an illustration, respectively, of the test system. A heat source was set up at the top of an acrylic cell, as shown in Figure 3. A high-density polyethylene (HDPE) geomembrane was placed at the bottom of the heat source. Sufficient heat was applied to the GCL through the HDPE sheet to produce a temperature of 60°C at the top of the GCL. The acrylic cell was overlapped by an insulation material. A humidity sensor was installed in an external box to measure the humidity in the test cell. When both of the valves at the side wall of the cell between the GCL and HDPE sheet were opened, a gap was created that allowed air to be circulated in the cell and the external box. This allowed the humidity outside and inside of the cell to be the same under steady-state conditions. In this experiment, the volume of the space was set to be five times the pore volume of the GCL tested. We maintained the bulk density of the base soil at 1.5 t/m³ for each set of test conditions considered.

In this study, we examined and compared cracks caused by desiccation of the GCL under two different sets of dehumidification conditions, as shown in Table 2. The one-sided dehumidification condition (Case A) was created by setting up fully saturated base sand, and the two-sided dehumidification condition (Case B) was created by setting up dried base soil. In Case A, the GCL specimen was hydrated from the base soil. In Case B, GCL specimen was hydrated in another box under the same conditions as in Case A, and the GCL specimen was then moved from the preparation cell to the testing cell used for Case B and placed on the dry base soil. Strictly speaking, some water from the hydrated GCL should be expected to be absorbed into the base soil. The water on the carrier geotextile was removed as much as possible by wiping with a paper towel. The dry-condition base soil was then prepared.
2.3 X-ray CT scanning test

The GCL was scanned using a micro-focused X-ray CT scanner (Toshiba Co. TOSCANER 32300 FPD), and the bentonite in the GCL was observed. Table 3 shows the scanning conditions. The base soil was scanned using an industrial X-ray CT scanner (Toshiba Co. TOSCANER 20000 mini) to determine the degree of saturation of the base soil. In this scan, the voltage was set at 150 kV, and the current was set at 4 mA. Samples of the base soil for which the degree of saturation was regulated were prepared and scanned. The values obtained from CT scans are proportional to the bulk density of the soil (Otani et al. 2000). A CT value can be converted into bulk wet density for the model soil; hence, the degree of saturation of the base soil can be evaluated from X-ray CT images, as long as the moisture content and dry density of the model soil are regulated.

Table 3. Scan conditions for the micro-focused X-ray CT

| Voltage (kV) | Current (μA) | Number of view angles | Resolution |
|--------------|--------------|-----------------------|------------|
| 220          | 300          | 1500                  | 0.134 mm for Figs. 6 and 7, 30 μm for Fig. 10 |

2.4 Constant-flow permeability test

The constant-flow permeability test apparatus can inject a specific amount of liquid, such as distilled and deionized water or other chemical solutions into low-permeability materials over a given period at a constant rate, such as 3.18 cc/day. This test system allows the measurement of the fluid pressure on the GCL using a pressure gauge when the liquid inside the four cylinders is injected into the four cells (Petrov and Rowe, 1997). A constant-flow permeameter developed by Mukunoki and Maeda (2014), similar to that developed by Petrov and Rowe (1997), was used in this study. The apparatus provides hydraulic pressures of 100 to 300 kPa to the GCL specimens. Pressures that high results in quite high hydraulic gradients; therefore, the authors also evaluated the hydraulic conductivity obtained from the results of a falling-head permeability test. The authors confirmed that the two types of permeameters yielded similar hydraulic conductivity results. Hence, the authors concluded that the effect of the hydraulic gradient on the test results was negligible.

Table 4. Test cases for permeability tests

| Test case | C. P. (kPa) | $S_0$ | Water Permeation | Drying treatment | CaCl$_2$ Permeation |
|-----------|-------------|-------|------------------|------------------|---------------------|
| Case 1    | 60          | 100   | O                | X                | O                   |
| Case 2    | 60          | 100   | O                | O                | O                   |
| Case 3    | 10          | 100   | O                | X                | O                   |
| Case 4    | 10          | 100   | O                | O                | O                   |

C. P.: Confining pressure
$S_0$: Initial degree of saturation of GCL specimen

3 RESULTS AND DISCUSSION

3.1 Temperature and humidity in the gap for one-sided and two-sided dehumidification

Figures 4(a) and (b) show profiles of the temperature (°C) and humidity (%) in the gap illustrated in Figure 3 during dehumidification model tests for Case A and Case B, respectively. For the GCL specimens for both Case A and Case B, the moisture content of the bentonite was 150%. We applied heat to the heat source to produce a temperature of 60°C, but the temperature in the cell did not become steady until 24 hours had passed because the cell was scanned after 8 hours had elapsed and again after 8 hours had elapsed. During the scanning, the heat source had to be shut down; hence, the temperature and humidity profiles exhibited some variation. However, after 24 hours, both the temperature and humidity became consistent. The temperature was maintained at 55°C, whereas it had been 37°C during the CT scanning. When the temperature was 55°C, the humidity was 20%. Hence, two-sided dehumidification was found to result in a lower humidity than one-side dehumidification at 55°C. Meanwhile, it was observed that the humidity was increased 30–35% in the space, as shown in Figure 4(a), because of temperature decrease due to scanning.
3.2 X-ray CT images

Figures 5(a), (b), (c), and (d) show X-ray CT images of bentonite at the center of the test cell. For at least 24 hours, no cracks were observed; however, some cracks started forming around the center of the bentonite part, and gaps were also seen between the inside wall of the cell and the side edge of the bentonite. This gap was caused by heat propagation in the acrylic cell, which is a boundary issue for this model test. In this study, the authors focused only on cracks in the bentonite. Figures 6(a), (b), (c), and (d) show X-ray CT images of the bentonite in the GCL for Case B at 4, 24, 46.5, and 68 hours, respectively. We observed many complicated cracks and a gap between the edge of the GCL specimen and the inner wall of the test cell. Two-sided dehumidification accelerated the desiccation of the bentonite in the GCL, so the volume of the GCL for Case B was less than that for Case A, as shown in Figures 5 and 6. In fact, no cracks were seen at 24 h, but some cracking was seen in the CT image at 46.5 h. This cracking probably started to form sometime between 24 h and 46.5 h.

We also conducted desiccation model testing without dehumidification. Heat sufficient to produce a temperature of 60°C was supplied to the GCL specimen in the acrylic cell for one week. No cracks were observed in the X-ray CT images, unlike those shown in Figures 5(a) and 6(a). This finding indicates that the crack formation in the bentonite was caused not by the heat supply but by dehumidification.

3.3 Crack width generated in the bentonite and degree of saturation of base soil

The X-ray CT images shown in Figures 5(b) and 6(b) can be converted to binary images of the cracked and uncracked parts using the method described by Otsu method (Otsu 1979). Mukanoki and Mikami (2013) developed an image analysis method based on mathematical morphology to evaluate the pore space in sandy soil. The algorithm can be inferred from Mukanoki and Mikami (2013). In this analysis method, a circular element of a known diameter can be filled by the cracked part, i.e., its diameter can be evaluated as the crack width. We employed this technique to evaluate the crack widths in the tested samples. Figures 7(a) and (b) show the crack widths at three locations (upper, middle, and lower) in the bentonite layer for Cases A and B, respectively. The diameter of each element can be obtained from the image analysis using the three-dimensional (3-D) object counter in the
Image J software (Ferreira and Rasband, 2012). The 3-D object counter gives the number of circular elements at each diameter. The vertical axes in Figures 7(a) and (b) represent frequencies normalized by the total number of frequencies. Figure 7(a) indicates that 60–80% of all of the cracks were less than 1 mm in the GCL sample for Case A. Figure 7(b) shows that cracks with widths between 0.1 and 2.6 mm were generated in the GCL sample for Case B. The mean crack width for Case B was greater than for Case A, which suggests that the degree of saturation of the base soil had an effect on the desiccation of the GCL.

3.4 Degree of saturation of base soil

Figures 8(a) and (b) show the distributions of the mean degree of saturation obtained from the CT values versus the depth of the base soil beneath the GCL specimen for Cases A and B, respectively. In Case A, the degree of saturation of the base soil was observed to be very low after 46.5 h elapsed, from the bottom of the GCL to a depth of 4 cm. No cracking formed until 24 h had passed, as shown in Figure 6. Figure 8(a) indicates that the pore water of the base soil remained consistent for at least the first 24 hours and that once cracking had penetrated into the GCL, the pore water started to evaporate, as shown in Figure 8(a).

As Figure 8(b) shows, the degree of saturation increased to 10% due to dehumidification. After 24 hours, the degree of saturation just beneath the GCL increased. This behavior is consistent with the test result shown in Figure 6(b). Two-sided dehumidification permitted the pore water of the GCL to evaporate into the gap and into the pore space in the base soil. During the CT scan process, the test cell could not be maintained at the same temperature as in the dehumidification test, as shown in Figure 4(b). The decrease in temperature caused condensation in both the gap in the test cell and the pore space in the base soil. As a result, the degree of saturation of the base soil increased. This might not happen in the field; however, Figure 8(b) indicates that vapor in the GCL moves into the pore space in the base soil, and it was confirmed that the desiccation of the GCL was affected by the degree of saturation of the base soil.

3.5 Hydraulic conductivity of desiccated GCL

Figures 9(a) and (b) show the profile of the hydraulic conductivity of water and a CaCl₂ solution (with a concentration of 1000 mg/l) during CaCl₂ permeation for Cases 1 and 2, respectively. The concentration of CaCl₂ in the effluent during CaCl₂ permeation was also measured. Table 5 summarizes the results of the hydraulic conductivity tests. No significant differences in the hydraulic conductivity of water were observed between these results and those shown in Table 4. This finding indicates that a GCL could exhibit good barrier performance with respect to water even under confining pressure of 10 kPa. By accident, the authors lost the test data for Case 3 but were able to confirm that the hydraulic conductivity with respect to water was not significantly affected by confining pressures from 10 to 60 kPa without desiccation occurring. However, for
Case 3, the hydraulic conductivity with respect to the CaCl₂ solution was observed to be 9.8 times greater than that for Case 1. These results indicated that CaCl₂ permeation is affected by the confining pressure.

For Cases 2 and 4 we were able to demonstrate the desiccation process after water permeation and before CaCl₂ permeation. The GCL specimens were shrunk due to drying in an oven at 60°C. Before we started the CaCl₂ permeation, after desiccation of the GCL, the cell was filled with the CaCl₂ solution until the bentonite in the GCL had self-healed by absorbing the CaCl₂ solution. A comparison of the results for Cases 1 and Case 2 shows that CaCl₂ permeation caused an increase in the hydraulic conductivity of the GCL, as shown in Figures 9(a) and (b). The desiccation cracks were almost closed by the self-healing effect of the CaCl₂ permeation at a confining pressure of 60 kPa. However, once hydraulic pressure was applied to the top of the GCL, the CaCl₂ solution used for Case 2 broke through faster than for Case 1, so the concentration of Ca²⁺ measured in Case 2 was much greater than for Case 2.

4 CONCLUSIONS

This study was conducted to examine the effect of desiccation on a GCL as a result of a temperature increase caused by solar heating of an exposed geomembrane sheet and dehumidification into the spaces created under wrinkles in the geomembrane at a landfill construction site. The following factors were found to be important in the desiccation of a GCL:
1) Desiccation cracks in the bentonite layer of a GCL are generated by dehumidification in the space between the geomembrane and the GCL. A low degree of saturation of the base soil also causes dehumidification into the pore space.
2) Two-sided dehumidification caused faster desiccation than one-sided dehumidification because two-sided dehumidification results in wider cracks in the GCL one-sided dehumidification.
3) Desiccation cracks were self-healed as a result of permeation of a CaCl₂ solution at a concentration of 1000 ppm under a confining pressure of 60 kPa. However, hydraulic pressure will open desiccation cracks, so the formation of desiccation cracks should be avoided in a landfill.

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