Visualization of bentonite desiccation during thermal cycling using X-ray CT

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ABSTRACT: Composite liners left exposed to solar radiation can experience large daily thermal cycles ranging from the daily low air temperature at night to upwards of 70℃ during the day. These variations in temperature can drive cyclic evaporation and hydration processes within air gaps between the geomembrane and the top surface of the geosynthetic clay liner. This paper explores the use of X-ray CT to investigate the onset of cracking and the progressive desiccation of geosynthetic clay liners under two sets of boundary conditions – a highly saturated foundation soil representative of a base liner, and an unsaturated foundation soil representative of a side slope.

Keywords: GCL, bentonite shrinkage, cracking, X-ray CT

1 INTRODUCTION

A composite liner comprising a geomembrane (GMB) liner used in combination with a geosynthetic clay liner (GCL) has been shown to act as a highly effective barrier system. The inner bentonite core of a GCL is initially placed as a low moisture content powder or granular layer during the manufacturing process and only hydrates via moisture transfer from the foundation soil after installation in the field. Hydration causes swelling of the bentonite until restrained by the needle-punched fibers that lock the cover and carrier geotextiles of the GCL (Beddoe et al. 2011). Once mobilized, these fibers provide additional confining pressure to resist further swelling, resulting in a continuous low permeability bentonite gel structure within the inner core of the GCL. However, if the composite liner is left exposed to solar radiation, the resulting thermal and moisture cycles can result in desiccation and shrinkage of the GCL, and in extreme cases, this GCL shrinkage can result in the loss of panel overlap (e.g. Rowe et al. 2017). Figure 1 illustrates three different exposure conditions for the GCL which will likely affect the magnitude of the moisture cycles experienced at each location. Position A includes a slope but no wrinkle, position B includes a wrinkle on a non-sloped surface, and position C includes a wrinkle on a sloped surface. This paper focuses on positions B and C. Two limiting sets of possible boundary conditions for thermally-driven moisture cycling of GCLs can be hypothesized at these two locations. Firstly, with respect to foundation soil moisture content, it is assumed that the initial moisture content of the foundation soil can be higher within a base liner (location B) than a side slope (location C). Furthermore, additional differences could arise with

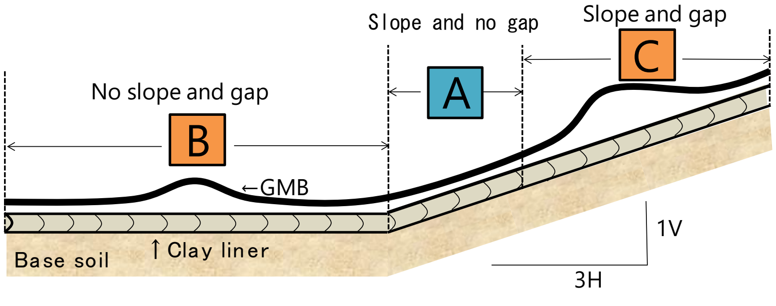


Table 1. Test condition of desiccation

	Case 1	Case2
Position	B	C
Saturation degree of base soil (%)	100	60
Thermal condition at heat source (°C)	20-70	15-70

Figure. 1 Assumed condition at the site.

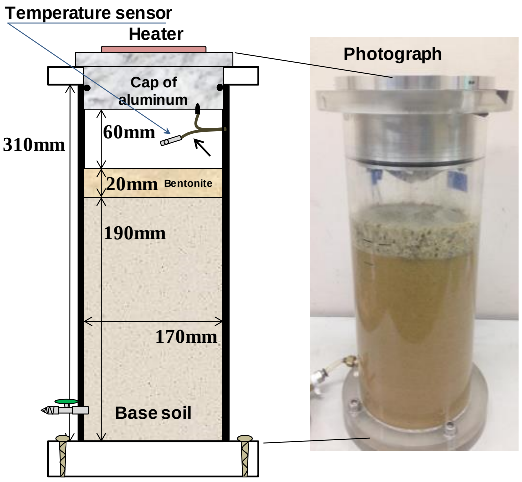


Figure 2. Schematic of desiccation test apparatus for scenario B in Figure 1.

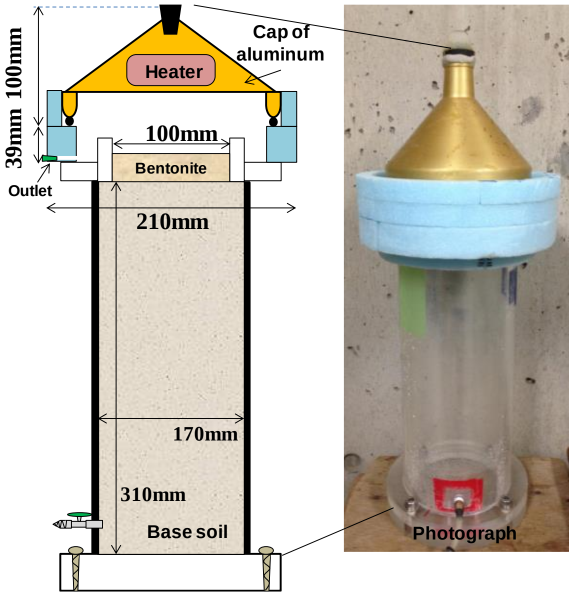


Figure 3. Schematic of desiccation test apparatus for scenario C in Figure 1

respect to moisture migration due to condensation. For a base liner (location B), it could be argued that water evaporating from the GCL into the airspace will subsequently condense and return to a similar location on the GCL surface upon cooling. In this case, the total moisture in the local area can be assumed to be constant (i.e. "closed system"). In contrast, at location C, moisture condensing on the underside of the GMB surface is prone to downslope migration. At the crest of such a slope, it is therefore possible that the entirety of the mass of condensation water does not return to the top of the slope in the form of water vapour on the next heating cycle. A second possible boundary condition is therefore the removal of a portion of the condensed water during each cycle (i.e. "open system").

In this paper, preliminary results are provided of two experiments conducted to investigate the response of a bentonite layer to daily thermal cycles under these two limiting boundary conditions. The bentonite and foundation soil were scanned via an X-ray CT scanner to visualize the development of cracks and the accumulation of shrinkage strains. These initial results are used to illustrate the effectiveness of the X-ray CT technique at investigating this phenomenon and to provide observations on the rate of accumulation of dimensional shrinkage of bentonite over the course of up to 11 cycles.

2 METHODS

2.1 *Imposed boundary conditions*

Test cells for the investigation of GCL moisture uptake and retention for use in an X-ray CT apparatus developed by Mukunoki and Maeda (2013) are presented in Figure 2. These test cells consist of a sealed 170 mm internal diameter acrylic column containing 190 mm of foundation soil, 20 mm of bentonite, and a 60 mm air gap. Mukunoki and Take (2015) used these cells to investigate the isothermal cyclic wetting and drying behavior of a GCL coupon on a fully saturated foundation soil. The current study extends this work through the addition of daily thermal cycles to be more representative of the boundary conditions experience in an exposed composite landfill liner. Firstly, given that composite liners left exposed to solar radiation can experience large daily thermal cycles ranging from the daily low air temperature at night to upwards of 70°C during the day (Take et al. 2015b), a heater with thermal control betwen18−75 °C was placed as a top boundary condition. When filled with a saturated foundation soil, these cells were used to model the scenario of a composite base liner on saturated foundation soil (case B). Secondly, a new cell was created (Figure 3) in which a portion of the condensed water could collect on a conical aluminum cap and run downhill under the action of gravity to an outlet port. Thus, when filled with an unsaturated foundation soil, this cell represents the case of a composite liner placed on a side slope in which a portion of the mass of water vapour extracted from the bentonite is lost from the system (case C). Temperature and relative humidity were measured in the air gap and the bentonite was scanned via an industrial X-ray CT

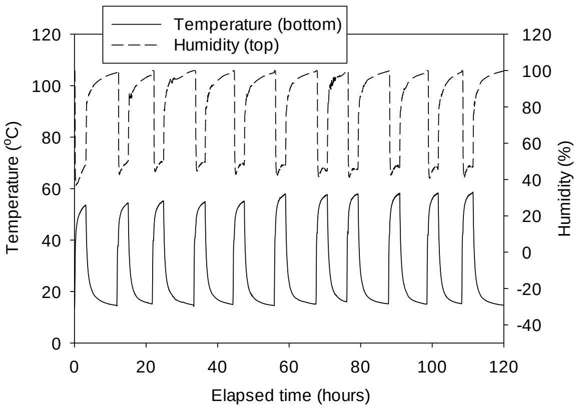


Figure 4. Temperature and humidity profiles

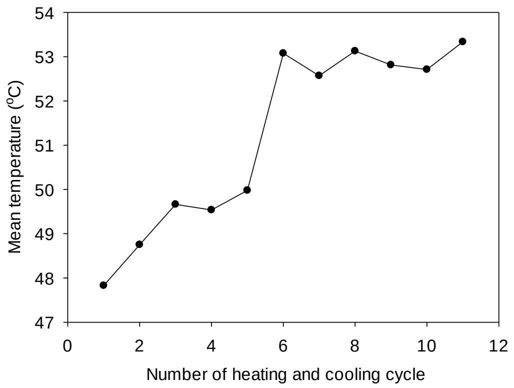


Figure 5.Temperature in gap corresponding to increase in thermal cycles

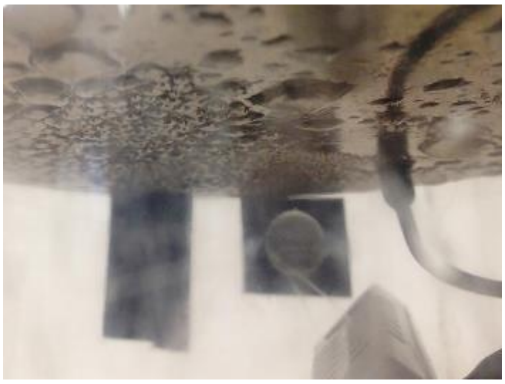


Figure 6. Image of condensation

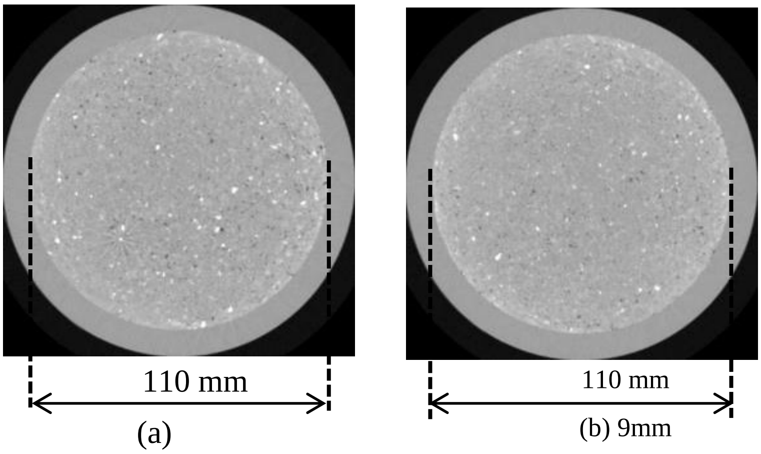


Figure 7. CT images of bentonite after 10 thermal cycles

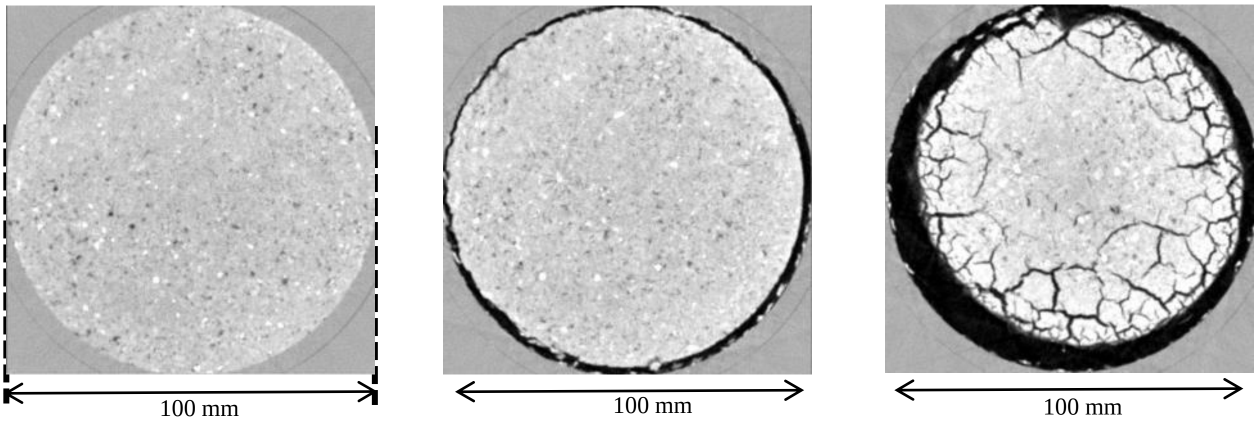
after the 0th, 5th, and 11th heating and cooling cycles. The test conditions for each test are summarized in Table 1.

3 RESULTS AND DISCUSSION

3.1 *Desiccation of bentonite layer on a saturated foundation soil (Case B)*

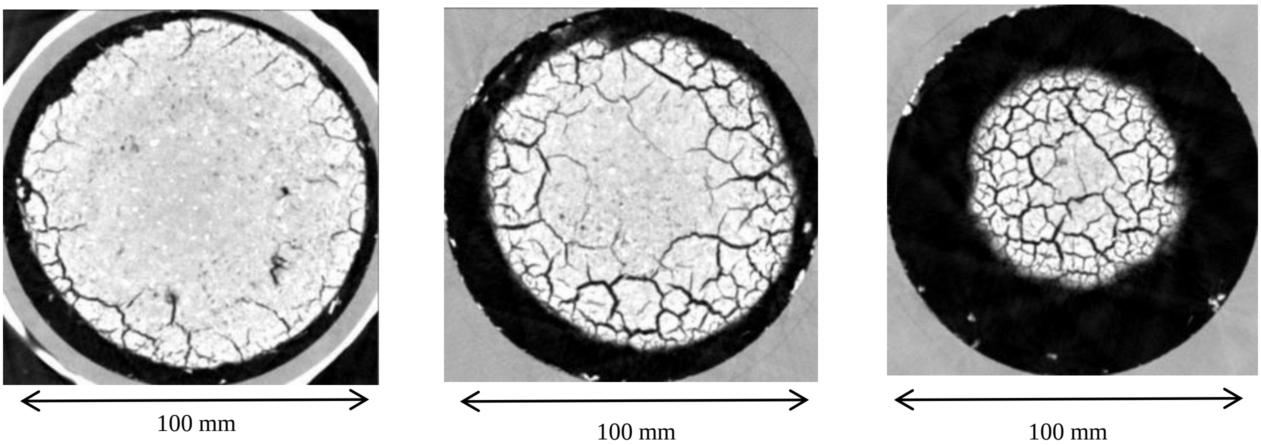
A saturated foundation soil was prepared and a 20 mm thick bentonite layer was subjected to thermal cycles within a closed cell modelling Case B. The time history of the imposed thermal boundary condition is presented in Figure 4, illustrating the temperature of the air space rising from the ambient room temperature (18 °C) approximately 50 °C, with a corresponding cycle of relative humidity from approximately 70% to 100%. The addition of heat into the column during these thermal cycles were observed to slowly raise the temperature of the column as over the course of 11 thermal cycles, the maximum temperature increased from 47.8 to 53.4 °C as shown in Figure 5.

The test apparatus shown in Figure 2 represented the closed condition; hence, no mass of water was allowed to exit the system. Therefore, water condensing on the top of the cell (e.g. Figure 6 shows an image of the surface of the aluminum cap) fell back onto the bentonite layer or evaporated back into the airspace during the next heating cycle. The impact of these cycles on the potential desiccation and shrinkage behavior of the bentonite layer was then observed by taking an X-ray CT image after 10 thermal cycles at elevations of 6 mm and 9 mm above the foundation soil. This image, presented in Figure 7, illustrates the bentonite layer remains a homogeneous gel (i.e. there are no black lines representing cracks in the CT image) and has not experienced any visually observable shrinkage. These results indicate that thermal cycles of a bentonite layer on a saturated foundation layer do not result in significant desiccation and shrinkage strains. This observation is consistent with the findings of Rowe et al (2011) that a simulated daily thermal cycle did not affect the final hydration moisture content of GCLs when placed on a saturated foundation layer.



(a) 0th cycle (b) 5th cycle (c) 11^{th} cycle

Figure 8. X-ray CT images taken during different thermal cycles



(a) 9mm (b) 14mm (c) 19mm

Figure 9. X-ray CT images at different heights during the 11^{th} thermal cycle.

3.2 *Desiccation of bentonite layer on an unsaturated base soil (Case C)*

An unsaturated foundation soil (Sr = 60%) was prepared and a 20 mm thick bentonite layer was subjected to thermal cycles with an "open cell" condensation collection system modelling Case C. Figure 8 shows an X-ray CT image of a bentonite sample subjected to 0, 5, and 11 thermal cycles at a 12 mm depth from the surface of the sample. These scans indicate an initial homogeneous bentonite structure (Figure 8a) which experiences sufficient shrinkage to detach from the sides of the column after the 5^{th} cycle (i.e. the black ring observed in Figure 8b represents the lack of X-ray attenuation associated with an air gap). Further cycles cause the bentonite layer to experience further shrinkage and the formation of significant desiccation cracks (i.e. the growth of the air gap in Figure 8c and the formation of air filled cracks in the core of the bentonite layer). These results indicate that the imposed thermal cycles on the unsaturated foundation soil inhibit the bentonite layer's ability to uptake moisture leading to progressive shrinkage strains and eventual formation of a fully cracked cross section.

A unique feature of X-ray CT imaging is the ability to observe the internal structure of the bentonite layer in three dimensions. This feature is illustrated through the presentation of cross-sections at three additional elevations of the bentonite layer after the 11^{th} thermal cycle. At an elevation of 9 mm above the foundation soil (Figure 9a) the magnitude of shrinkage is considerably less than at elevations of 12 mm (Figure 8c), 14 mm (Figure 9b), and 19 mm (Figure 9c). These finding illustrate that the bentonite layer within a GCL would preferentially shrink most rapidly at the top surface in the absence of the effect of the needle punched fibres. These fibres linking the cover and carrier geotextile components of the GCL maintain confinement of the bentonite layer, and will likely play a significant role in the shrinkage and development of crack patterns within GCLs illustrating that this tool is uniquely suited to perform the non-destructive observation of the internal structure of these vital liner components.

4 CONCLUSIONS

Composite liners left exposed to solar radiation can experience large daily thermal cycles which drive cyclic evaporation and hydration processes within air gaps between the geomembrane and the top surface of the geosynthetic clay liner. This paper explored the use of X-ray CT to investigate the onset of cracking and the progressive desiccation of geosynthetic clay liners under two sets of boundary conditions – a highly saturated foundation soil representative of a base liner, and an unsaturated foundation soil representative of a side slope. Thermal cycles above a bentonite layer placed on a saturated foundation layer were observed to not result in significant desiccation and shrinkage strains, a finding consistent with the physical modelling results of Rowe et al (2011) that a simulated daily thermal cycle did not affect the final hydration moisture content of GCLs when placed on a saturated foundation layer. In contrast, the same thermal cycles imposed on a bentonite layer placed on an unsaturated foundation soil were observed to lead to progressive shrinkage strains and eventual formation of a fully cracked cross section. The ability of the X-ray CT technique to capture three-dimensional shrinkage and cracking within the bentonite layer illustrates that this tool is uniquely suited to perform the non-destructive observation of the internal structure of these vital liner components.

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