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Hydraulic conductivity of bentonite–polymer geosynthetic clay liners subject to wet–dry cycles used in landfill cover systems

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Abstract: This study evaluated the hydraulic conductivity of bentonite–polymer (B-P) geosynthetic clay liners (GCLs) subjected to wet-dry cycles that simulated seasonal conditions on a GCL installed in a landfill cover system. Hydraulic conductivity tests were conducted on B-P GCLs and NaB GCLs at 10 kPa in accordance with the ASTM D5084 standard. Two wet–dry methods were used to investigate the hydraulic conductivity of the GCLs under different field exposure conditions. The hydraulic conductivities of the NaB and B-P GCLs gradually increased during four wet–dry cycles. However, the hydraulic conductivity of the B-P GCL (K = 2.3×10^{-12} m/s) was lower than that of the NaB GCL (K = 6.3×10^{-11} m/s) by two orders of magnitude after four permeation–drying cycles. In addition, the hydraulic conductivity of the B-P GCL was lower (K = 5.8×10^{-12} m/s) than that of the NaB GCL (K = 7.8×10^{-10} m/s) by two orders of magnitude after four saturation–drying cycles. The results suggest that B-P GCLs can enhance the effectiveness of landfill cover systems compared to Na-B GCLs in managing conditions during wet and dry seasons.

1. Introduction

Geosynthetic clay liners (GCLs) consist of a layer of sodium bentonite (NaB) sandwiched between two geotextiles, and are commonly used in landfill cover liner systems owing to their low hydraulic conductivity, which may be attributed to the swelling of bentonite when hydrated with a liquid [1–7]. The swelling of bentonite results in a decrease in the intergranular pore size [1]. However, the subsequent shrinkage of bentonite during the dry season may result in the formation of cracks between the intergranular pores of bentonite. Although re-swelling of bentonite occurs during the subsequent wet season, the cracks that developed during the dry season may not seal fully. These cracks may lead to an increase in the hydraulic conductivity of the GCL [2-7].

Bentonite modified with polymers has been fabricated and applied in GCLs, also referred to as bentonite–polymer GCLs (B-P GCLs) [8-16]. The B-P GCLs exhibit increased resistance to cracking and enhanced durability compared to NaB GCLs [8-16]. De Camillis et al. [9] investigated the impact of wet–dry cycles on untreated sodium bentonite and bentonite modified with a polymer known as HYPER clay in seawater. The results showed that the height and swelling index of HYPER clay were higher than those of untreated sodium bentonite after six wet–dry cycles, and that the hydraulic conductivity of HYPER clay was lower than that of untreated sodium bentonite by three orders of magnitude [9]. However, studies on B-P GCLs used in landfill cover systems under wet–dry conditions during operation are limited. Thus, the hydraulic conductivity of B-P GCLs requires further research.

This study aimed to evaluate the hydraulic conductivity of B-P GCLs when subjected to different wet–dry cycles that simulated seasonal conditions on a GCL installed in a landfill cover system. The B-P GCLs contained 2% linear polymers; Na-B GCLs were used as a control. Two wet–dry cycle methods were used to simulate the behavior of geosynthetic clay liners (GCLs) under various field exposure conditions. The first method ("saturation–drying") mimicked a GCL directly exposed to cover. The second method ("permeation–drying") simulated a GCL overlain by a geomembrane. Hydraulic conductivity tests were conducted on B-P and NaB GCLs at 10 kPa in accordance with the ASTM D5084 and ASTM D6766 standards after the wet–dry cycles.

2. Materials and Methods

2.1. GCLs

Two commercial GCLs were used in this study—a conventional NaB GCL and a B-P-2 GCL containing 2% linear polymer. The B-P-2 GCL was prepared by mixing the dry polymer with bentonite. Both the GCLs consisted of one nonwoven cover geotextile and one nonwoven carrier geotextile. The dry mass per areas of NaB and B-P-2 were 6.8 and 8.0 kg/m^2, respectively. The swell index of the GCLs was determined according to ASTM D5890; the NaB GCL and B-P-2 possessed swelling indexes of 28 mL/2 g and 31 mL/2 g, respectively, in DI water.

2.2. Permeation solutions

The relative abundances of monovalent and polyvalent cations (RMD) and ionic strength (I) are known to affect the hydraulic conductivity of GCLs and can be defined by equation (1) [1, 5, 6]:

$$\mathrm{RMD} = \frac{M_\mathrm{M}}{\sqrt{M_\mathrm{D}}}, \quad (1)$$

where M_M is the total molarity of the monovalent cations, and M_D the total molarity of the divalent cations. The ionic strength (I) is defined using equation (2):

$$I = \frac{1}{2}\sum_{i=1}^{n} c_i z_i^2 , \quad (2)$$

where c_i is the molar concentration of the ith ion in the solution, and z_i is the valence of the ith ion. Leachates with a preponderance of polyvalent ions and high concentrations of ions, that is, low RMD or high I, can inhibit the swelling of bentonite, resulting in a high hydraulic conductivity of the GCLs.

Tests were conducted with one synthetic leachate, referred to as Ca-rich leachate, which represents the most aggressive leachate (highest I and lowest RMD) collected from landfill cover soil permeating synthetic rainwater, as discussed by Benson et al. [6]. The concentration of major cations and anions in synthetic leachate are Na^+, Ca^{2+}, and Cl^-. The I and RMD values are 25 mM and 0.007 M$^{1/2}$, respectively. Synthetic leachates were prepared by dissolving reagent-grade NaCl and $CaCl_2$ in Type II DI water, in accordance with the ASTM D1193 standard.

2.3. Swell index

The NaB and B-P composites were extracted from the GCLs and carefully separated from the nonwoven geotextiles. The free-swell index tests were conducted according to the ASTM D5890 standard. DI water and Ca-rich solutions were used for the swell index tests. Two grams of NaB and B-P composite were added to a 100-mL graduated cylinder in incremental steps of 0.1 g. The graduated cylinders were initially filled with 90 mL of the solution. After the addition of 2 g of the sample, the graduated cylinder was filled to 100 mL. The swelling index was recorded after a minimum rest period of 16 h.

2.4. Wet–dry cycles methods

Two wet–dry cycle methods were used to simulate the behavior of GCLs under various field exposure conditions. The first method, saturation–drying (SD), mimicked a GCL that is directly exposed to the cover soil. The GCL specimens were fully hydrated for two days and then air-dried to a water content of approximately 55%. Hydraulic conductivity tests were performed on individual GCL specimens after two and four SD cycles, denoted as SD-2 and SD-4, respectively. The second method, called permeation–drying (PD), simulates a GCL that is overlaid by a geomembrane. For each permeation–drying cycle, hydraulic conductivity tests on the GCLs were performed for at least four weeks. After permeation, the GCL specimens were dried in a sealed chamber at a relative humidity of 75% RH until their water content decreased to approximately 55%. Four PD cycles were conducted for each GCL—PD-1, PD-2, PD-3, and PD-4.

2.5. Hydraulic conductivity test
Hydraulic conductivity tests were conducted on the B-P-2 and Na-B GCLs at 10 kPa in accordance with the ASTM D5084 standard. Geotextiles were positioned both above and below the GCL samples to disperse the permeant solution evenly. The GCL samples were enclosed in acrylic plates, which were sealed using a flexible membrane and secured in place with temperature-resistant silicon O-rings to prevent leakage from the sidewalls. The collected outflow was stored in 60-mL polyethylene bottles.

The hydraulic gradient in the tests was three times higher than that of the leachate head under field conditions. Thus, the one-month test represents a three-month permeation of the GCL under field conditions, that is, one wet season. Hydraulic conductivity tests on the GCLs were terminated when a hydraulic equilibrium was achieved, in accordance with the ASTM D5084 standard. The ASTM D5084 standard requires hydraulic equilibrium, which necessitates the outflow-to-inflow volume (Q_{out}/Q_{in}) to be within 0.75 and 1.25 for the last three consecutive flow measurements.

3. Results and Discussions

3.1. Swell index
The swelling indices of NaB and B-P-2 in DI water and Ca-rich leachates are shown in Figure 1. The swelling index of NaB was 28 mL/2 g in DI water, and it decreased to 24 mL/2 g in the Ca-rich leachate. The swelling index of B-P-2 also decreases as the divalent cation (Ca^{2+}) leachate concentration increased. However, B-P-2 exhibited a higher swelling index than NaB in the same solution. For example, the swelling index of B-P-2 was 26 mL/2 g, whereas that of Na-B was 24 mL/2 g in the Ca-rich leachate.

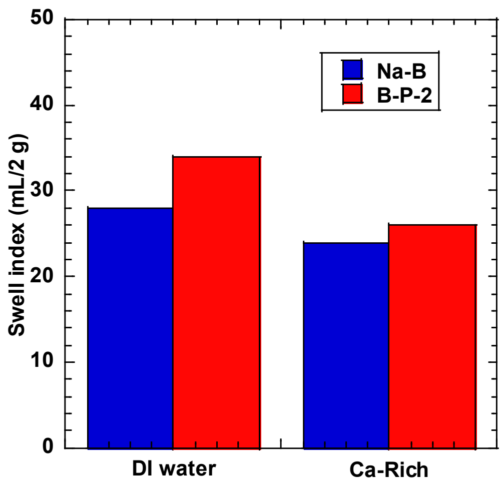

Figure 1. Swell index of NaB and B-P-2 GCLs in DI water and Ca-rich leachates.

3.2. Hydraulic conductivity
The hydraulic conductivities of the NaB and B-P-2 GCLs under SD cycles are shown in Figure 2. The hydraulic conductivity of the Na-B GCLs under two and four SD cycles achieved hydraulic equilibrium at approximately 1–2 PVF per the ASTM D5084 standard. The hydraulic conductivity of NaB GCLs under the SD-2 cycle was 6×10^{-10} m/s (Figure 2a). The hydraulic conductivity of NaB GCLs under the SD-4 was higher than that of NaB GCLs under two SD cycles (6×10^{-10} m/s vs. 6×10^{-7} m/s) by three orders of magnitude (Figure 2a). The hydraulic conductivity of the B-P-2 GCLs gradually decreased at the starting point of the SD-2 and SD-4 cycles owing to the hydration process; the B-P-2 GCLs achieved

hydraulic equilibrium at approximately 2–4 PVF. The hydraulic conductivity of the B-P-2 GCLs under the SD-4 cycle was slightly greater than that under the SD-2 cycle, for example, $K = 5.8 \times 10^{-12}$ m/s vs. $K = 4.6 \times 10^{-12}$ m/s (Figure 2b). In addition, the hydraulic conductivity of B-P-2 GCLs under the SD-2 cycle ($K = 4.6 \times 10^{-12}$ m/s) was lower than that of NaB GCLs ($K = 6 \times 10^{-10}$ m/s) by approximately two orders of magnitude. A significantly lower hydraulic conductivity of the B-P-2 GCLs was also observed under the SD-4 cycle.

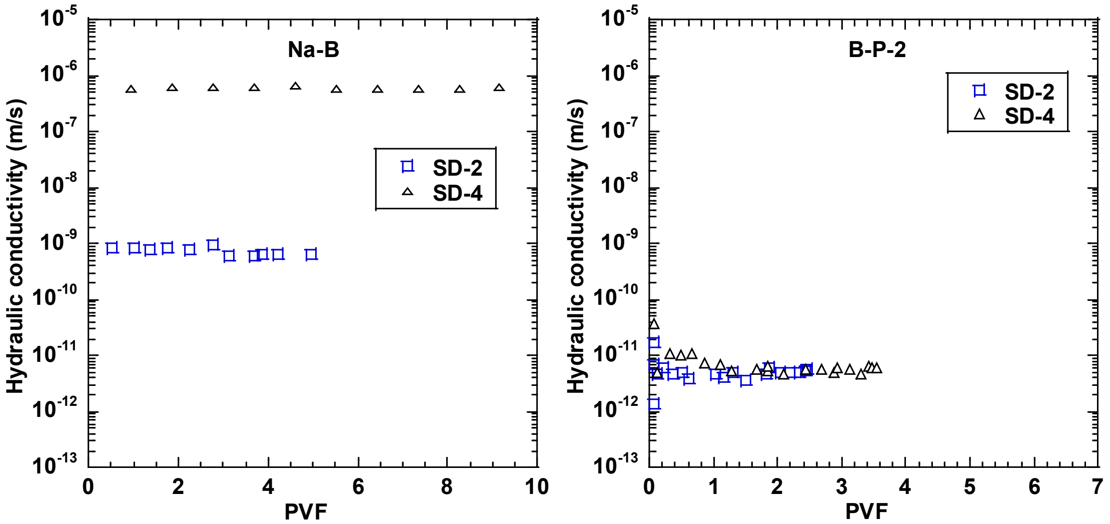

Figure 2. Hydraulic conductivity of (a) NaB GCLs and (b) B-P-2 GCLs under the saturation–drying (SD) cycle method.

The hydraulic conductivities of the NaB and B-P-2 GCLs under permeation–drying (PD) cycles are shown in Figure 3. The hydraulic conductivity of the NaB GCLs gradually decreased at the starting point of each PD cycle owing to the hydration process. Subsequently, the NaB GCLs under each PD cycle achieved hydraulic equilibrium within 1–2 PVF according to the ASTM D5084 standard. The hydraulic conductivity of NaB GCLs under the PD-1 and PD-2 cycles was similar, e.g., $K = 3.2 \times 10^{-12}$ m/s to 3.5×10^{-12} m/s. Subsequently, the hydraulic conductivity gradually increased to 8.9×10^{-11} m/s after the PD-4 cycle (figure 3a). A similar hydration process was observed in the hydraulic conductivity testing of the B-P-2 GCLs using the PD method (figure 3b). The hydraulic conductivity of the B-P-2 GCLs (e.g., $K = 1.8 \times 10^{-12}$ m/s to 3.0×10^{-12} m/s) was similar under all PD cycles. The hydraulic conductivity of the B-P-2 GCLs ($K = 3.2 \times 10^{-12}$ m/s) was lower than that of the NaB GCLs ($K = 8.9 \times 10^{-11}$ m/s) by one order of magnitude under the PD-4 cycle.

The hydraulic conductivities of the NaB and B-P-2 GCLs at each wet–dry cycle are shown in Figure 4. The hydraulic conductivity of the NaB GCLs under the PD method was significantly lower than that under the SD method for the same wet–dry cycle. For example, the hydraulic conductivity of the NaB GCLs under the PD-4 method ($K = 8.9 \times 10^{-11}$ m/s) was lower than that under the SD-4 ($K = 6.0 \times 10^{-7}$ m/s) by approximately four orders of magnitude. The hydraulic conductivity of the B-P-2 GCLs obtained using the PD method was slightly lower than that obtained using the SD method. For example, the hydraulic conductivity of B-P-2 GCLs under the PD-4 was lower than that under the SD-4 by a factor of 1.8, for example, $K = 3.2 \times 10^{-12}$ m/s vs. $K = 5.8 \times 10^{-12}$ m/s. In addition, the hydraulic conductivity of the B-P-2 GCLs was lower than that of the NaB GCLs under the same PD and SD cycles.

3.3. Height of GCLs

The heights of the GCLs after the hydraulic conductivity test at PD and SD for each wet–dry cycle are shown in Figure 5. The height of the NaB GCLs gradually decreased from 9.7 mm at the PD-1 cycle to 8.9 mm at the PD-4 cycle. The height of the NaB GCLs under the SD method decreased as the number of cycles increased. However, the height of the B-P-2 GCLs under both the SD and PD methods increased as the test continued from one to four cycles. For example, the heights of the B-P-2 GCLs were 11.4 mm in the PD-1 cycle and 12.3 mm at the PD-4 cycle. In addition, the height of the B-P-2 GCLs exceeded that of the NaB GCLs under identical conditions.

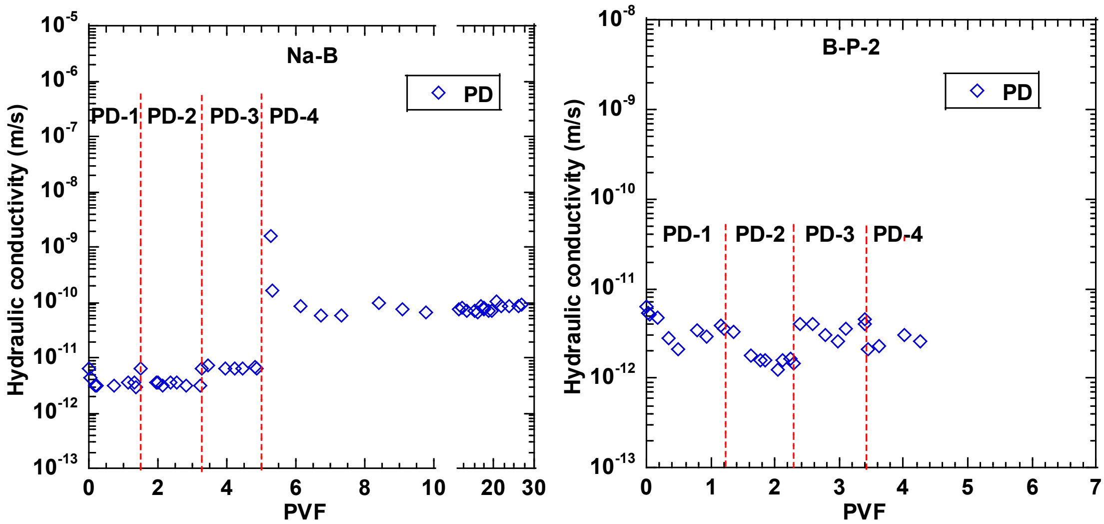

Figure 3. Hydraulic conductivity of (a) Na-B GCLs and (b) B-P-2 GCLs under the permeation–drying (PD) cycle method.

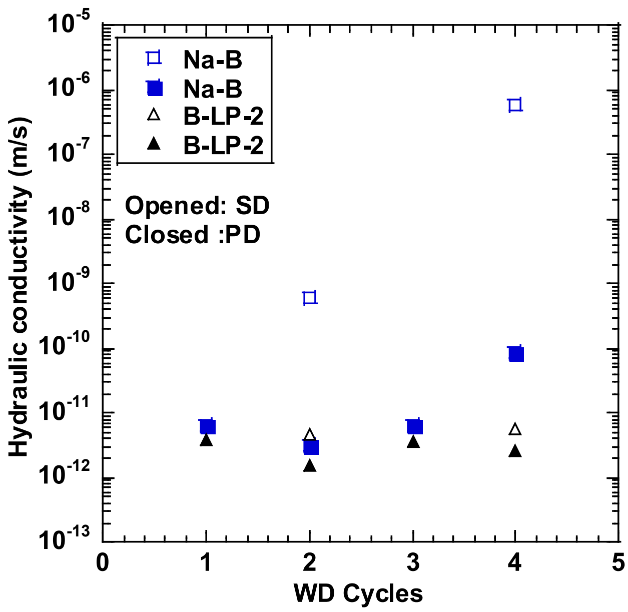

Figure 4. Hydraulic conductivity of Na-B GCLs and B-P-2 GCLs at each wet–dry cycle.

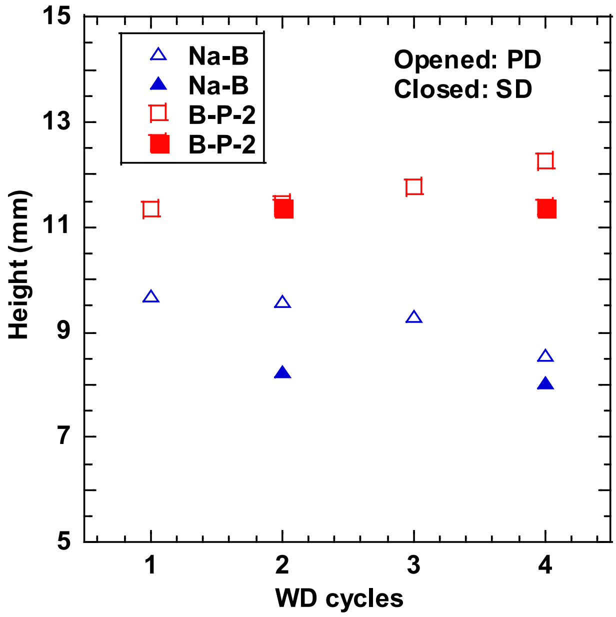

Figure 5. Height of GCLs after hydraulic conductivity test at each wet–dry cycle.

4. Conclusion

Hydraulic conductivity tests were conducted on B-P GCLs to evaluate their hydraulic performance when subjected to different wet–dry cycles. Two wet–dry cycle methods were used to simulate the behavior of geosynthetic clay liners (GCLs) under various field exposure conditions. The first method mimicked a GCL that was directly exposed to the cover soil, and the second method simulated a GCL overlaid by a geomembrane. The conclusions of the study are summarized as follows:

1. The swell index of the Na-B GCLs and B-P-2 GCLs in DI water was higher than that of the GCLs in Ca-rich leachate. Further, the swell index of the Na-B GCLs was lower than that of the B-P-2 GCLs in DI water and Ca-rich leachate.
2. The hydraulic conductivity of the NaB GCLs under both SD and PD methods significantly increased as the wet–dry cycles continued for four cycles, whereas the B-P-2 GCLs under both SD and PD methods exhibited low hydraulic conductivity as the wet–dry cycles continued for four cycles.
3. The hydraulic conductivity of the NaB GCLs and B-P-2 GCLs under the SD method was higher than that under the PD method at the same wet–dry cycle. However, the differences in the hydraulic conductivities of the NaB GCLs between the SD and PD methods were greater than those of the B-P-2 GCLs.

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