HYDRAULIC CONDUCTIVITY OF DESICCATED GEOSYNTHETIC CLAY LINERS

A number of large scale laboratory tests were conducted to determine the effects of wetting and drying on the hydraulic conductivity of geosynthetic clay liners (GCLs). Geosynthetic clay liners were installed into tanks measuring 2.4m in length by 1.2m in width. The GCLs were backfilled with 0.6m of pea gravel and permeated with water in a constant head condition. Water was collected from the bottom of the tank after steady state conditions were reached and hydraulic conductivity values were calculated. Testing was conducted on intact specimens (GCLs with no seams), and GCL with an overlap seam to determine the effectiveness of the overlap seam. After a baseline hydraulic conductivity was determined, the specimens were dried with the application of hot air in an effort to create desiccation cracks in the bentonite component of the GCL. Specimens were then re-hydrated and tested for hydraulic conductivity.

Test data indicates that the wetting and drying cycle did not cause any irreversible desiccation cracks to form and the Claymax® and Bentomat® specimens tested swelled and self-sealed upon re-hydration. The long-term steady state hydraulic conductivity was essentially the same before and after the desiccation cycle. Furthermore, the wetting and drying cycle did not cause any irreversible desiccation cracks to form in the overlapped seams in any of the GCLs tested.

Hydraulic Conductivity of Desiccated Geosynthetic Clay Liners

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Abstract: Large-scale tests were performed to determine the effect of a cycle of wetting and drying on the hydraulic conductivity of several geosynthetic clay liners (GCLs). The GCLs were covered with 0.6 m of pea gravel and permeated with water. After steady seepage had developed, the water was drained away, and the GCL was desiccated by circulating heated air through the overlying gravel. The drying caused severe cracking in the bentonite component of the GCLs. The GCLs were again permeated with water. As the cracked bentonite hydrated and swelled, the hydraulic conductivity slowly decreased from an initially high value. The long-term, steady value of hydraulic conductivity after the wetting and drying cycle was found to be essentially the same as the value for the undesiccated GCL. It is concluded that GCLs possess the ability to self-heal after a cycle of wetting and drying, which is important for applications in which there may be alternate wetting and drying of a hydraulic barrier (e.g. within a landfill final cover).

INTRODUCTION

The primary purpose of a hydraulic barrier within a bottom liner or final cover system for a waste-containment facility is to minimize infiltration of water or leachate through the hydraulic barrier. Hydraulic barriers in modern landfills are typically composed of a relatively impermeable layer of compacted soil that may be overlain by a geomembrane. A relatively new type of material that may be a useful alternative to a layer of low-permeability compacted soil is a geosynthetic clay liner (GCL). Geosynthetic clay liners are manufactured by sandwiching a thin layer of bentonite between two geotextiles or attaching a layer of bentonite to a geomembrane with an adhesive (Koerner and Daniel 1992; Daniel 1993; Koerner 1994).

It is well known that dry bentonite swells when wetted and shrinks when dried. Shan and Daniel (1991) performed laboratory hydraulic conductivity tests on small samples of one GCL that had been subjected to several wet-dry cycles and reported that severe desiccation cracks developed when the wet GCLs were dried; however the hydraulic conductivity after several wet-dry cycles was the same as the conductivity of the nondisiccated material. These tests were on small laboratory-scale samples and did not include overlapped zones between panels.

The purpose of the research described in this paper was to determine the effect of wetting and drying on the hydraulic conductivity of three large-scale GCLs. Overlapped panels were tested, and, for control, nonoverlapped GCLs were tested, as well. Conclusions are drawn concerning the ability of GCLs to self-heal after a severe wet-dry cycle. These findings are of interest to designers of final cover systems for landfills and site remediation projects, and for designers of landfill liners in areas where drying of a liner can occur.

MATERIALS TESTED

Three commercial products were used in this study to cover the range of types of GCLs available. One material (Bentomat, Colloid Enviromental Technologies Co., Arlington Heights, Ill.), which is a geotextile-encased, needle-punched GCL, is produced by needle-punching two polypropylene geotextiles that contain approximately 4.9 kg/m^2 of loose, granular sodium bentonite between them. After hydration, the bentonite swells around the impermeable fibers to form a hydraulic barrier. The manufacturer recommends that 0.4 kg/m of loose, dry bentonite be placed along the centerline of the overlap when installing the GCL to ensure that the material self-seals along the overlap and forms a continuous barrier. A 100 g/m^2 woven upper geotextile, a 200 g/m^2 nonwoven lower geotextile, and a treated bentonite (''SS'' grade) were used in the material tested for this study.

A second material tested (Claymax 200R, Claymax Div., Colloid Environmental Technologies Co.), which is a geotextile encased, adhesive-bonded GCL, is produced by mixing sodium bentonite with an adhesive and sandwiching approximately 4.9 kg/m^2 of bentonite between two geotextiles. A 130 g/m^2 upper, woven geotextile and a 25 g/m^2 lower, open-weave, polyester geotextile were used in this study.

The third material tested (Gundseal, GSE Lining Technology, Inc., Houston) is produced by mixing sodium bentonite with an adhesive and attaching approximately 4.9 kg/m^2 of bentonite to a geomembrane. A 0.5-mm-thick, smooth, high-density polyethylene (HDPE) geomembrane constituted the geomembrane component of the GCL used in this study. The GCL was tested with the bentonite side facing downward.

EXPERIMENTAL PROCEDURE

Testing was carried out in rectangular steel tanks measuring 2.4 m in length, 1.2 m in width, and 0.9 m in depth (Estornell and Daniel 1992). A 12-mm-diameter drainage port located in the center of the base of each tank provided an outlet from which water that had passed through the GCL was collected (Fig. 1). Copper tubing led from the drainage port to a collection container located beneath each tank. The container was

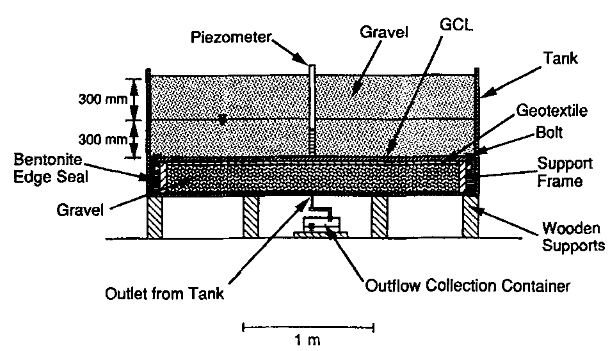

FIG. 1. Tank Used for Experiments

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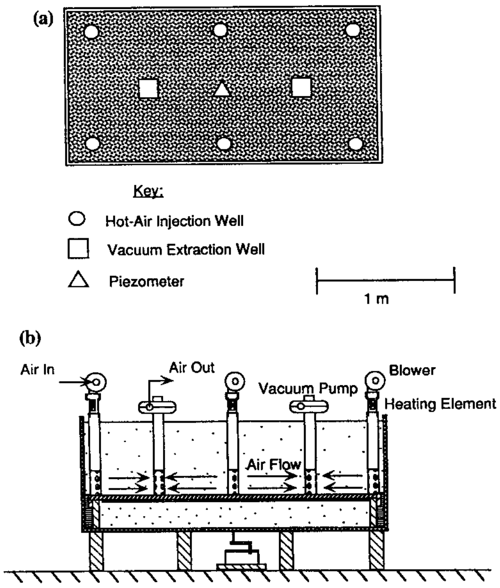

FIG. 2. Arrangement of Six Hot-Air Injection Wells and Two Vacuum Extraction Wells: (a) Plan View; (b) Cross-Sectional View

periodically removed and weighed to determine the quantity of flow through the GCL over a known interval of time.

Each test specimen was cut by hand from rolls supplied by the GCL manufacturer. Through the use of templates, holes spaced about 300 mm apart were cut through the GCL along the edges. The holes were then grommeted, and the GCL attached to a rigid steel frame resting on top of a wood frame located in the bottom of each tank. Attaching the GCL to the steel frame ensured that the GCLs would crack during desiccation rather than shrink dimensionally and pull away from the walls of the tank.

Overlapping samples were installed with a 230-mm-wide overlap, which is within the range recommended by the GCL manufacturers. The centerline of the overlap conincided with the centerline of the tank (lengthwise). In an effort to restrict shrinkage of the GCL in the overlap region, overlapping samples were not attached to the steel frame near the overlap.

After the GCL was attached to the frame, loose, powdered bentonite was then spread along the edge of the installed GCL. The combination of attaching the GCL to the steel frame, and the placement of loose bentonite along the edge of the GCL has been shown to prevent sidewall leakage (LaGatta 1992; Estornell and Daniel 1992). The loose bentonite was approximately 50 mm thick and 75 mm wide. Three gypsum resistivity blocks were then placed in this bentonite edge seal on top of the GCL for all the GCLs tested. The electrical resistivity of the blocks depended on the water content of the gypsum, which in turn was a function of the water content of the surrounding bentonite. The gypsum blocks provided a simple indication of the relative dryness of the bentonite edge seal, which, when coupled with other observations, helped to confirm that complete drying (following a wetting cycle) of the GCL had occurred. After the GCL had been installed, a 25-mm-diameter polyvinyl chloride (PVC) piezometer was placed on top of the GCL in the center of the tank (Fig. 1) to determine the water level in the gravel that would later cover the GCL.

Prior to placement of the gravel above the GCL, eight 100-mm-diameter PVC pipes were placed above the GCL vertically in the pattern shown in Fig. 2. Six of the pipes were used to inject hot air and two pipes were used to extract air from the gravel that was placed over the GCL. Small holes were drilled through all of the pipes every 25 mm along the circumference, and every 25 mm (vertically) along the lower 300 mm of the pipe resulting in the circulation of hot air across the upper surface of the GCL. The lower end of each pipe was sealed with a PVC cap. A 6-mm-thick layer of gravel separated the capped end of each pipe from the upper surface of the GCL.

Once the piezometer, 6 hot-air injection wells, and 2 vacuum extraction wells were in place, the GCL was covered with 600 mm of pea gravel. The GCL was then slowly hydrated with tap water until a final head of water of 300 mm acted on the GCL. The water head was maintained at 300 mm as the GCL was permeated. The dry unit weight of the pea gravel was approximately 15.7 kN/m^3, and the saturated unit weight was 19.5 kN/m^3. The average vertical effective stress was 7.7 kPa during permeation, and the average total vertical stress was 9.6 kPa during drying.

Temperatures were measured in the gravel above the GCL by lowering a thermometer down a piezometer in the center of the tank. After water was drained out of the tank, the temperature in the gravel was approximately 18°C. Air blowers and heating elements were installed on top of the six air injection pipes, and air extraction blowers were installed on top of two pipes (Fig. 2). Once the heating system was turned on, the temperature within the tank slowly rose as the gravel and GCL dried out. The maximum temperature reached during the test ranged from 27°C to 32°C. These values are similar to the in-situ temperatures measured by Corser and Cranston (1991) within a compacted clay liner buried beneath soil cover at an arid site in California. Care was taken not to overheat the gravel or GCL. The time required to dry out the gravel and GCL ranged from 2 to 3 weeks.

It was assumed that if the 50-mm-thick, 75-mm-wide bentonite edge seal was desiccated, then the GCL was desiccated, as well. To confirm this assumption, two tests were conducted in which the GCL was wetted and then dried with the procedure just described. When resistivity readings from the gypsum blocks located in the bentonite edge seal indicated that the bentonite was dry, one test was dismantled and the GCL was examined. The other sample was left undisturbed and was later rehydrated. The bentonite in the excavated GCL, as well as in the edge seal, was dry (water content = 12%) and severely cracked. The typical crack pattern of the bentonite in the GCL is shown in Fig. 3. A photograph is shown in Fig. 4. Due to a limited number of tanks and the time and effort required to set up a single test, only this one tank was dismantled to examine the physical condition of the GCL after desiccation. The gypsum blocks were used to confirm desiccation in the other tests.

Once the gypsum-block readings showed that the bentonite in the edge seal was dry, the GCL was rehydrated with water at a flow rate corresponding to 40 mm/h. The water was added by moving a hose, at the lowest possible flow rate, across the upper surface of the overlying gravel. This wetting rate would correspond to an extreme rainfall event, assuming that the GCL was located at the surface or was buried near the surface under a thin layer of gravel. If soil overlies the GCL, the rate of wetting of the GCL would be much slower. The objective of this study was primarily to determine whether the GCL would swell and self-seal, and not to study the effect of rate of wetting upon the tendency to eventually self-seal.

Hydraulic conductivity readings were then taken every 10–15 min to determine how quickly the desiccated GCL could swell and self-seal. Hydraulic conductivity was computed from measured flow rates, the measured head of water acting on the liner, and the assumed thickness of the GCL. The thickness was determined from laboratory testing (Boardman 1993) and was 12 mm for the fully hydrated GCLs, and 5 mm and 8 mm for Claymax and Bentomat, respectively, for the dried

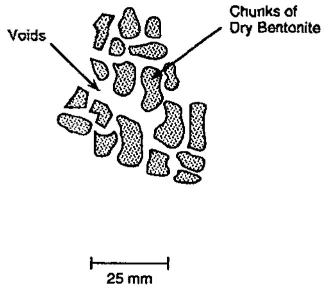

FIG. 3. Crack Pattern Observed in Bentonite Component of Claymax 200R after Wet-Dry Cycle

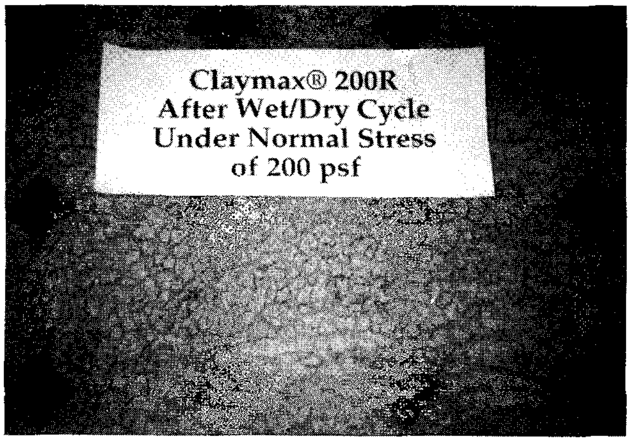

FIG. 4. Cracked Bentonite Component of GCL after Wetting and Drying Cycle (Note: Upper Geotextile Component of GCL Has Been Pulled Back to Reveal Cracking Pattern in Bentonite; 1 psf = 48 Pa)

GCL undergoing initial rehydration. When outflow through the GCL sample stopped after the initial rehydration, the water head was raised in increments of 100 mm to 300 mm over several days. Then the head was kept constant at 300 mm.

When steady flow was reached after rehydration, the water was siphoned out of the tank and the gravel was removed by hand. The GCL was then inspected. The experimental procedure is described in greater detail by Boardman (1993).

RESULTS

Claymax 200R

Two tests were performed on Claymax 200R: one on a intact sample (with no overlap) and the other on overlapping panels.

Intact Sample (No Overlap)

The intact sample was flooded with a water head of 300 mm and was permeated until, after 3 weeks, outflow occurred from the tank and the hydraulic conductivity became steady and equal to 6×10^{-9} cm/s. This compares well with the findings of Lagatta (1992), who measured values of 7 and 8 $\times 10^{-9}$ cm/s on two tests on the same GCL.

The intact sample was desiccated, then rehydrated. Desiccation caused severe cracking within the bentonite of the GCL (Fig. 4). There was flow through the cracked GCL immediately after water was initially introduced. The hydraulic conductivity dropped from its initial peak value of approximately 1×10^{-3} cm/s to a value of 1×10^{-5} cm/s during the first 90 min after the sample was rehydrated (Fig. 5). By the next day, all outflow had ceased. Hydration and swelling of the bentonite in the GCL is assumed to be responsible for the rapid drop in hydraulic conductivity of the bentonite. Although

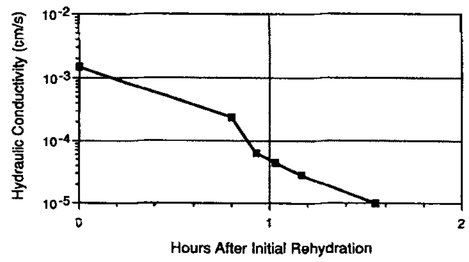

FIG. 5. Short-Term Hydraulic Conductivity versus Time for Initial Stage of Rehydration of Desiccated Claymax 200R (Intact Sample with No Overlap)

some of the large flow could have been through the desiccated edge seal, the fact that the GCL was obviously severely cracked (Fig. 4) and the comparatively massive nature of the edge seal leads the authors to believe that virtually all of the high initial flow was through the GCL, not the edge seal.

The head of water was then slowly increased over the next two days. By the third day after rehydration, outflow resumed. An hydraulic conductivity of 1×10^{-8} cm/s was measured over the next week of permeation (Fig. 6). The final hydraulic conductivity was 1×10^{-8} cm/s, which is similar to the initial value (prior to desiccation) of 6×10^{-9} cm/s. When the test was dismantled, no abnormalities were observed in the GCL; its physical appearance was the same as that of a GCL that had not been desiccated.

The pattern of high initial outflow, followed by no flow, followed by steady low flow was similar to that found by Shan and Daniel (1991) on desiccated, small-scale samples of this same type of GCL. The significance of high initial hydraulic conductivity during the rehydration phase would depend on the specific field application. The desiccated GCL was wetted initially at an input flux of 40 mm/h of water. For a GCL located near the surface and overlain by gravel, the conditions in these experiments would be fairly similar to conditions in the field during a heavy rainstorm. The high initial hydraulic conductivity might or might not be acceptable, depending on the specific application. However, for a GCL that is overlain by soil, e.g., cover soil and topsoil in a final cover system, the water flux reaching the GCL would be much lower than 40 mm/h, which would allow time for the GCL to absorb water and swell before much, if any, water could pass through the GCL. The significance of the high initial hydraulic conductivity upon rehydration of a desiccated GCL will have to be evaluated for each individual project.

Overlapped Panels

The overlapped panels were permeated for 3 weeks prior to desiccation. Some outflow occurred, but steady state conditions were not reached. Experience has shown that many weeks or months of permeation can sometimes be necessary to obtain steady values of hydraulic conductivity for GCLs tested in these tanks (Estornell and Daniel 1992; LaGatta 1992). Rather than delay the wet-dry cycle for weeks or months while waiting for steady flow, it was decided to proceed with the desiccation cycle as the GCL was assumed to be fully hydrated. (Previous experience in similar tests has shown that the GCL is very nearly saturated after 3 weeks of soaking.) The hydraulic conductivity prior to desiccation was assumed to be 7×10^{-9} cm/s, based on nearly identical tests by LaGatta (1992), and the tanks were drained.

The overlapped sample was desiccated, then rehydrated. There was flow through the GCL immediately after the sample was rehydrated. The hydraulic conductivity ranged from 1×10^{-5} to 1×10^{-6} cm/s for the first 3 h after rehydration (Fig. 7). The outflow dropped to essentially zero over the next 2

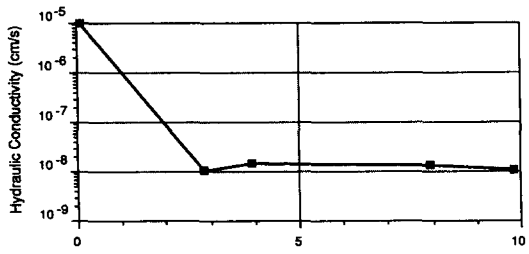

FIG. 6. Long-Term Hydraulic Conductivity versus Time for Rehydration of Desiccated Claymax 200R (Intact Sample with No Overlap)

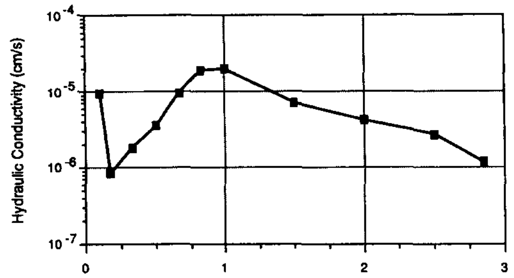

FIG. 7. Short-Term Hydraulic Conductivity versus Time for Initial Stage of Rehydration of Desiccated Claymax 200R (Overlapped Panels)

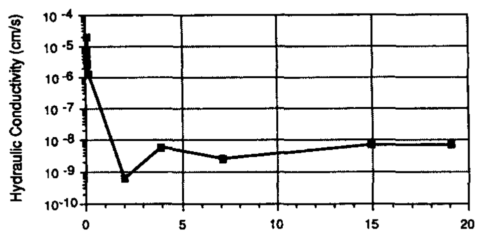

FIG. 8. Long-Term Hydraulic Conductivity versus Time for Rehydration of Desiccated Claymax 200R (Overlapped Panels)

days. As the head of water was increased, the outflow resumed, and the hydraulic conductivity slowly increased to an approximate value of 7×10^{-9} cm/s [same value as measured by LaGatta (1992) for nondesiccated samples] after 19 d of permeation (Fig. 8).

At the completion of the test, the condition of the overlapped panels was examined. The width of the overlap was still 225 mm. The combination of the attachment of the GCL to the steel frame and the compressive stress provided by the overlying gravel prevented the overlapped panels from pulling apart during shrinkage. Experience has shown that wet GCLs will pull apart along the overlap during drying if there is no overburden soil (for instance, during construction, if the GCL is not promptly covered), although the severity of shrinkage in the overlap width depends on the extent of hydration of the bentonite and varies from one type of GCL to another. The overlapping panels appeared to have self-sealed along the overlap in two different ways. First, hydrated bentonite had extruded out of the edges of the upper and lower panels and appeared to form a seal along the lines of contact between the two panels. Second, the thickness of the upper panel increased at the edge of the lower panel (almost as if the upper panel had swelled around the lower panel when both panels were hydrated).

Bentomat

Two sets of tests on Bentomat were performed: one on an intact sample (no overlap) and the other on two overlapping panels.

Intact Sample (No Overlap)

The intact sample was permeated for 3 weeks, but no outflow occurred. A value of hydraulic conductivity prior to desiccation of 1×10^{-9} cm/s was assumed [based on results of tests performed by LaGatta (1992)], and the tanks were drained. The sample was desiccated, then rehydrated. There was no measured outflow through the GCL after two weeks of permeation. After dismantling the test, no abnormalities were found across the surface of the GCL. It was decided not to continue permeating the sample indefinitely due to time constraints and because the practical conclusion was obvious: the wet-dry cycle appeared to cause no deleterious effect on the hydraulic integrity of the sample tested. Perhaps the needle-punched reinforcement of the GCL limited the amount of shrinkage and cracking within the bentonite as the GCL dried.

Overlapped Panels

The hydraulic conductivity of the overlapped panels prior to desiccation did reach steady state and was 1×10^{-9} cm/s. The sample was desiccated and then rehydrated. There was essentially no flow through the GCL immediately after the sample was rehydrated. As the head of water was slowly increased, some flow occurred through the sample. After 10 d of permeation, the hydraulic conductivity was approximately 1×10^{-9} cm/s (Fig. 9), which was the same as the value before desiccation. The wet-dry cycle appeared to cause no increase in the hydraulic conductivity of the GCL.

After completion of the test, the GCL was inspected. The loose bentonite that had been placed along the overlap (per the manufacturer's recommendation) was hydrated and intact, and appeared to have molded into the overlying panel. The width of the overlap was still 225 mm. Bentonite appeared to have extruded out of the edges of both panels along the overlap, which may have helped to limit the amount of flow through the overlap.

Gundseal

One test was performed on overlapping panels of Gundseal. The panels were installed with the geomembrane component facing upwards. An intact sample was not tested because experience has shown that there is no outflow from such tests, given the essentially impermeable nature of the geomembrane component (Estornell and Daniel 1992).

There was no measured outflow through the overlapped panels after three weeks of initial permeation. Since Estornell and Daniel (1992) found no outflow from overlapped panels tested under nearly identical conditions after 5 months of permeation, it was decided to initiate the desiccation process rather than continue to permeate the overlapped GCL panels

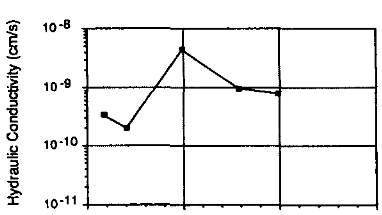

FIG. 9. Long-Term Hydraulic Conductivity versus Time for Rehydration of Desiccated Bentomat (Overlapped Panels)

with water. The tank was drained, and the GCL was desiccated until the resistivity blocks indicated that the bentonite in the edge seal was dry. The sample was then rehydrated. There was no measured outflow through the desiccated sample after another three weeks of permeation.

After the test, the gravel was removed from the tank and the condition of the GCL was observed. The width of the overlap was still 225 mm after the test. The bentonite was hydrated 25 mm to 50 mm into the overlap—the hydrated bentonite in the overlap prevented outflow through the overlap during the period of testing.

CONCLUSIONS

The purpose of this study was to determine the effect of a cycle of wetting and drying on the hydraulic conductivity of large-scale geosynthetic clay liners (GCLs). Each GCL was buried under 600 mm (2 ft) of pea gravel and permeated with water for several weeks. Then the water was removed from the gravel and the GCLs were desiccated by circulating heated air through the gravel using a system of hot air blowers and vacuum pumps. Severe drying and cracking occurred in the bentonite component of the GCLs. After drying, each GCL was slowly rehydrated. The hydraulic conductivity was then monitored to determine the ability of the desiccated GCL to rehydrate and self-seal.

Based on the results of this study, the following conclusions are drawn.

1. The geotextile-encased GCLs (Bentomat and Claymax 200R) swelled and self-sealed upon rehydration, after a cycle of wetting and drying. When the desiccated GCLs were rehydrated, water initially flowed rapidly through most of the desiccated samples, but the bentonite quickly expanded and the hydraulic conductivity decreased as the cracked bentonite began to adsorb water and swell. The long-term, steady value of hydraulic conductivity was essentially the same before and after the desiccation cycle.
2. In tests performed on a GCL containing bentonite attached to a geomembrane (Gundseal), there was no outflow of water either before or after the wetting and drying cycle. Due to the presence of the geomembrane, very little of the GCL actually became hydrated, but the bentonite in the overlapped area did self seal.
3. The wetting and drying cycle did not cause any irreversible shrinkage to occur along the overlap for overlapping samples of any of the GCLs tested. However, samples were partially attached to a rigid, steel frame in these tests, and performance of the materials in the field might be different.
4. Although the bentonite did form open cracks upon drying, the cracks swelled and closed upon wetting. The geosynthetic component of the GCL (geotextile or geomembrane) prevented any intrusion of overlaying pea gravel into the cracks. Designers should be careful that the openings in the geotextile component of the GCL are small enough to prevent the overlying soil from migrating into cracks that develop in the bentonite.
5. The initially high value of hydraulic conductivity of the desiccated GCLs may not be representative of true field conditions because the overlying cover soils would likely adsorb some of the incoming rainfall and cause a more gradual wetting of the GCL. In addition, the rehydration rate of 40 mm/h used in these tests would correspond to an extreme infiltration rate, and the GCL would either have to be overlain by extremely permeable material (e.g., gravel) or buried at extremely shallow depth for a flux of water of 40 mm/h to be applied to the GCL in the field. If the GCL is slowly wetted (which would be the case in many field situations), the GCL would have time to absorb water and to swell without allowing seepage through the GCL. The significance of high initial hydraulic conductivity should be considered on a project-specific basis.

The self-sealing capability of GCL's makes them a viable hydraulic barrier for situations in which the barrier may undergo cyclic wetting and drying, e.g., within a landfill final cover. However, the reader is cautioned not to inappropriately extrapolate the results of these tests. The tests were performed under carefully controlled conditions with a single, severe wetting and drying cycle. Such a severe cycle of wetting and drying is not likely to occur in the field. Numerous but less severe cycles of wetting and drying are more likely to occur in the field. Further research (particular field data) is needed before a final conclusion can be drawn concerning the ability of GCLs to safely withstand numerous wetting and drying cycles under the full range of possible field conditions. Nevertheless, these results are encouraging and suggest that GCLs may be an attractive material to use when some degree of cycling in water content is anticipated within the hydraulic barrier.

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