Hydraulic Conductivity of Partially Prehydrated GCLs Under High Effective Confining Stresses For Three Real Leachates

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Abstract:

Reinforced GCL samples from three different projects were partially pre-hydrated on native damp subgrade soils for several weeks, and were then tested for hydraulic conductivity using three real leachates under a variety of effective confining stresses. The samples permeated with MSW leachate were tested under effective stresses of 240, 480, and 720 kPa. The samples permeated with MSW-incinerator ash leachate were tested under effective stresses of 180, 360, and 530 kPa. The samples permeated with pulp & paper waste leachate were tested under effective stresses of 165, 340, and 475 kPa. All of the results showed decreasing hydraulic conductivity with increasing effective stress with the ash leachate being the most sensitive to effective stress, and the pulp& paper leachate being the least sensitive. The hydraulic conductivity of the GCL samples to all of the leachates tended to level off to a common value of about 2×10^{-12} m/s at effective stresses above 475 kPa.

Introduction

The scope of this paper relates to the hydraulic conductivity of geosynthetic clay liner (GCL) samples obtained from three different projects subjected to relatively high effective stresses and three different leachates. The significance of this study is that it provides some preliminary indications of the performance of GCLs to act as a fluid barrier to real leachates under the effective stresses characteristic of landfill bottom liners.

Effective stress is a significant variable that controls the behavior of bentonite (Shackelford et al., 2000), decreasing both hydraulic conductivity and the susceptibility of bentonite to chemical alterations. Increasing the effective stress on a GCL decreases the void ratio (or porosity) within the bentonite layer, which tends to lower its hydraulic conductivity.

Other Studies

Landfill leachates can alter the hydraulic conductivity of GCLs. Ruhl and Daniel (1997) present test data on five different GCL products using several different permeant liquids, three different conditions of hydration, and an effective confining stress of 35 kPa. These GCLs maintained relatively low hydraulic conductivity (generally $< 2\times10^{-11}$ m/s) whether they were permeated with simulated hazardous waste leachate, real MSW leachate, or simulated fly ash leachate. The hydraulic conductivity of the GCLs was not adversely affected when real leachate was used as compared to distilled water. The GCLs had a relatively high hydraulic conductivity when permeated with a strong calcium solution or strong acids and bases.

Rowe (1998) suggests that the real leachate used by Ruhl and Daniel (1997) had a low concentration of cations, and he reports test values for a synthetic leachate that was modeled to have a composition quite similar to that of real leachate from the Keele Valley Landfill. (The chemical composition of the MSW leachates used by Ruhl and Daniel (1997) and by Rowe (1998) are summarized in Table 1). Rowe's results showed that, under a relatively low effective stress of 36 kPa, the hydraulic conductivity of the GCL increased by approximately a factor of 6 when permeated with the synthetic leachate as compared to distilled water. However, Ruhl and Daniel (1997) found that while a synthetic leachate did cause some increases in hydraulic conductivity, the real MSW leachate did not. One factor to bear in mind is that although real leachates may contain calcium and other conductivity-increasing chemicals, they also contain suspended solids (including biologically active materials) that may tend to plug the pores of the bentonite and reduce hydraulic conductivity. Impacts from actual leachates may vary considerably from one leachate to another.

As mentioned in the previous subsection, the effective stress placed on sodium bentonite influences hydraulic conductivity, and may have a significant impact on the susceptibility of GCLs to alterations caused by cation exchange. This issue was limitedly explored by Thiel et al. (2001) and is illustrated in Figure 1 for a geotextile-encased GCL that was permeated with either distilled water or a 0.125 molar solution of calcium chloride ($CaCl_2$ containing 5,000 mg/l of calcium). In the tests using $CaCl_2$, a worst-case condition was employed of hydration with the same $CaCl_2$ solution that was used for permeation. At low effective stress, the GCL was about three orders of magnitude more permeable to the $CaCl_2$ solution than to distilled water. However, at an effective stress of about 400 kPa, the hydraulic conductivity was about the same for water as for the $CaCl_2$ solution. Although calcium tends to cause shrinkage of the bentonite and the development of a more permeable fabric of bentonite particles, the application of a high effective stress was presumed to squeeze the bentonite particles together strongly enough to prevent deleterious alterations in the arrangement of bentonite particles.

Table 1. Comparison of Leachate Constituent Concentrations (mg/l except pH)

Chemical Constituent	Real MSW Leachate Used By Ruhl and Daniel (1997)	Simulated Leachate Used by Rowe (1998)	Landfill Leachates Used in the Present Study		
			MSW Landfill Leachate	Ash Landfill Leachate	Pulp&Paper Landfill Leachate
Sodium	368	1615	2900	5060	4350
Potassium	N/A	354	188	3170	331
Calcium	112	1224	337	8170	105
Magnesium	100	473	359	311	374
Chloride	520	4414	5600	33000	3000
Ammonia (NH4)	N/A	618	260	16	94
BiCarb. (HCO3)	N/A	4876	2500	7	7670
SO4	N/A	137	55	800	120
TDS	1800	N/A	11000	50000	12000
TOC	312	N/A	310	30	460
pH	7	6.2	8.5	7.0	7.6

N/A = Not available

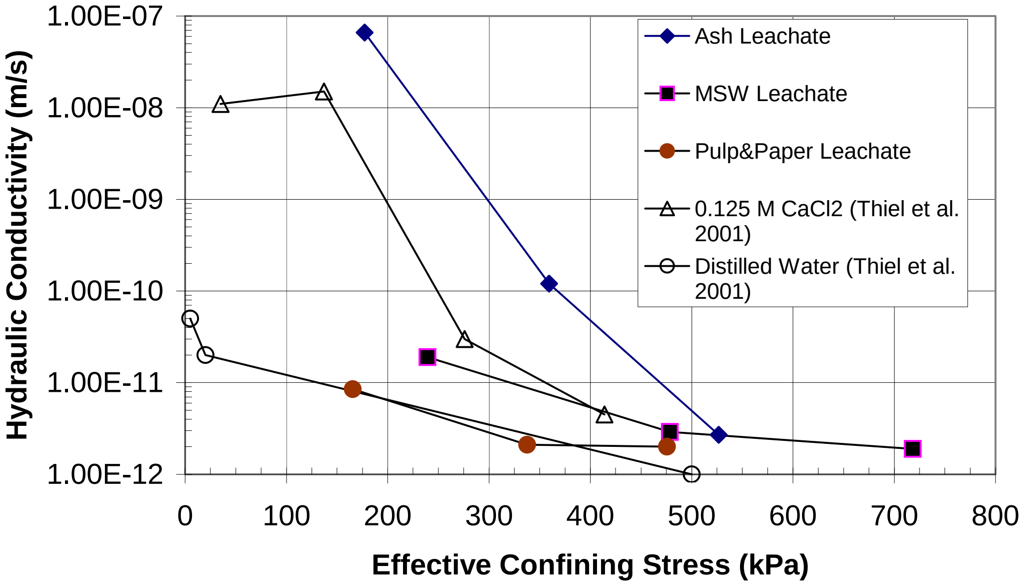

Figure 1. Summary Results for Hydraulic Conductivity of GCL vs. Effective Confining Stress for Three Real Leachates, and Comparison with Previous Study.

Outline Of Laboratory Investigation

The laboratory investigations presented in this paper were performed to determine the hydraulic conductivity of GCLs when permeated with three different types of waste leachate under various effective stresses. The duration of the testing ranged from approximately 4-11 weeks and was dictated by project and laboratory constraints, but which well-exceeded the time to meet the termination criteria given by ASTM D5084. Although the GCL samples came from three different projects, all three were a double-nonwoven needlepunched GCL provided by CETCO (“DN” product), having an average bentonite mass per unit area of 4,170 g/m^2. The following three leachates were provided:

- Leachate from a “standard” large MSW landfill (MSW)
- Leachate from incinerator ash that was created from burning MSW (ASH)
- Leachate from a forest-products landfill whose waste consisted primarily of pulp & paper sludge and boiler ash from a paper mill. This is referred to as pulp&paper (P&P) leachate (PPL)

A summary of the more pertinent leachate constituents is presented in Table 1 to allow side-by-side comparisons. Table 2 presents a summary of the test program showing the initial and final water contents for the bentonite, effective stress applied to the various specimens, time periods of testing, estimated number of pore volumes passed through the specimens, and hydraulic conductivity results.

Bentonite Pre-hydration on Subgrade Soils In the field GCLs will generally be in place on a natural soil subgrade for weeks, if not months, before there is an opportunity for exposure to leachate. Daniel et al. (1993) has shown that the high matric-suction of bentonite will cause it to undergo substantial hydration under these conditions even with relatively dry natural subgrade soils. This phenomenon was simulated in the current test program by placing the as-received GCL samples on project-specific subgrade soils representing two of the projects for which the testing was being performed. The soil was a silty-sand with natural water content of approximately 27%. The samples tested with the MSW and incinerator ash leachates were removed from the subgrade soil after 3 weeks. The samples tested with the P&P leachate were left on the subgrade soil an additional 2 weeks before commencing hydraulic conductivity testing. The water contents for the specimens as received and after this pre-hydration procedure are presented in Table 2.

Permeability Testing – General Procedure The samples were tested for hydraulic conductivity in flexible-wall permeameters in accordance with ASTM D5084. Test specimens were 100mm diameter. All of the samples were backpressure saturated using their respective leachates as the saturating fluid and permeant. Table 2 presents details related to effective stresses, and hydraulic gradients used during the testing. For purposes of calculating the hydraulic conductivity during testing, the initial thickness of the samples was used. The hydraulic conductivity was corrected using the final sample thickness that was determined after testing. The permeability tests were conducted using the falling-head, rising-tailwater method (Method C). Hydraulic gradients vary during the testing for this method. For this test program the gradients ranged from 10 to 500. The higher gradients were used where the samples exhibited lower hydraulic conductivity so that meaningful test results could be obtained in a reasonable period of time. Although this range of gradients exceeds the maximum gradient of 30 recommended by ASTM D5084, data published by Shackelford et al. (2000) have reported that higher gradients are acceptable for testing GCLs.

The effective stresses were selected unique to the landfills for which the tests were being performed, and were therefore not the same stresses for each of the three leachates. The original intent of the work was to evaluate the hydraulic performance of the GCL material to each of the leachates at pre-selected effective stresses that were to be held constant. The stresses selected for the basic testing program are presented on Table 2. During the testing of the MSW and incinerator-ash leachates, however, there was a compressor failure and accidental pressure changes occurred that led to further investigation on the results of pressure changes. The series of pressure changes that occurred with the MSW and incinerator ash leachates (either accidentally or intentionally) are described later in the paper.

Measurement of Specimen Thickness The test method for hydraulic conductivity requires measurement or estimation of the specimen thickness, *L*. The reported hydraulic conductivity values in ASTM test method D5084 are directly proportional to the measured or estimated values of *L*. Normally, with soil specimens prepared for this test method, *L* is measured before and after the test with a calipers or other direct-measuring device. With fabric-supported GCLs the measurement is complicated by the presence of the geotextiles. The estimated value of *L* used to calculate the hydraulic conductivity of a GCL is intended to represent the thickness of the bentonite portion of the GCL. The thickness of the entire GCL specimens may or may not be representative of the value *L* depending on whether or not the bentonite extrudes into all of the pore spaces of the geotextiles, or only a portion of them. Limited guidance provided in ASTM D5887 (Appendix X2) suggests that the geotextiles could be cut away from the tested specimen and the thickness of the remaining bentonite measured directly with calipers. For purposes of this study, the hydraulic conductivity values were calculated using values of *L* wherein the thickness of the geotextile was subtracted from the total specimen thickness. Note that Table 2 reports the estimated thickness of the bentonite, and the footnote at the bottom gives the average thickness of the textiles that would be added to the estimated bentonite thickness to obtain the total end-of-test specimen thickness, if desired.

Table 2. Summary of hydraulic conductivity test parameters and results

SAMPLE DESCRIPTION: (a)	**MSW-1**	**MSW-2**	**MSW-3**	**ASH-1**	**ASH-2**	**ASH-3**	**PPL-1**	**PPL-2**	**PPL-3**
Water content as recevied. %	41	34	38	39	36	42	34	39	36
Water content, after prehydration %	61	55	58	59	57	66	67	70	66
Pre-Hydrated Thickness, L, mm	5.9	5.7	5.5	5.0	6.0	5.0	6.2	5.7	5.7
Effective confining stress, kPa	239	478	718	177	359	527	165	338	476
Test Time, days	14	13	13	6	13	13	27	27	27
Estimated Flow, Pore Volumes [c]	2.7	2.1	0.2	4.7	46	0.7	1.5	1.8	1.7
Hydraulic Conductivity, m/sec. [b]	6E -12	1E -12	4E-13	5E-8	3E-11	9E-13	6E-12	1E-12	1E-12
AIR COMPRESSOR FAILURE									
New Effective confining Stress, kPa	SAME	SAME	SAME	SAME	SAME	SAME	**TEST STARTED AFTER COMPRESSOR FAILURE**		
Additional Test Time, days	36	39	35	16	19	36			
Hydraulic Conductivity, m/sec. [b]	3E -12	1E -12	5E-13	8E-8	3E-11	2E-12			
EFFECTIVE CONFINING STRESS CHANGED									
New Effective confining Stress, kPa	478	239	239	NA	718	359	**NOT INCREASED**		
Additional Test Time, days	16	25	33	NA	44	32			
Hydraulic Conductivity, m/sec. [b]	1E-12	3E-13	4E-13	NA	2E-10	3E-12			
Final Thickness, L, mm	3.0	2.1	2.6	3.8	2.1	3.0	4.4	3.0	3.0
Final water content, %	109	93	101	71	48	92	91	79	70
Gradiant Range	370-50	500-400	360-230	280-90	510-10	360-70	185-90	250-150	310-220
Total Test Time, days	66	77	81	22	76	81	27	27	27

NOTES:

(a) MSW-1,2 & 3 are specimens permeated with standard MSW-Leachate
ASH -1,2 & 3 are specimens permeated with incenterator Ash Leachate
PPL -1,2 & 3 are specimens permeated with Paper & Pulp Leachate

(b) Hydraulic conductivities are based on the final measured bentonite thickness (L) not including the textile thickness

(c) The estimated pore volumes are based on the end of test bentonite volume.

(d) The estimated textile thickness is 3mm.

Results

General Trends. A summary of the hydraulic conductivity results after 3 to 6+ weeks of testing at the selected effective stresses are presented graphically in Figure 1. The results reported by Thiel et al. (2001) are shown on Figure 1 for comparison. The results from the current program show a similar pattern to the results reported by Thiel et al. (2001), and indicate that the relationship between hydraulic conductivity and effective confining stress is specific to a given liquid chemistry, but that at effective stresses greater than 400 to 500 kPa the hydraulic conductivity of a GCL is independent of the liquid.

Relative to each of the liquids tested, the following results can be stated:

- For the P&P leachate, the GCL hydraulic conductivity behavior is similar to that of distilled water over the range of effective confining stresses of 150-500 kPa.
- For MSW leachate the hydraulic conductivity at the 240-kPa load is approximately three times higher than for distilled water. At the higher effective stresses of 480 and 720 kPa the results could be considered nearly equal to that of distilled water.
- The incinerator ash leachate is definitely the most aggressive and the GCLs hydraulic conductivity with it shows the highest sensitivity to effective stress. It appears even more aggressive than the 0.125M $CaCl_2$ solution results reported by Thiel et al. (2001). Even so, at an effective stress of 500 kPa the results with the ash leachate were equivalent to the results for the other leachates.

Variation of Testing Stresses: After approximately 12 to 13 days of testing the MSW and incinerator ash leachates there was an air compressor failure. This had the effect of reducing the effective pressure to near zero for a period of approximately 24 hours. During this time the samples would have had the opportunity to swell, absorb more leachate, and possibly more easily allow chemical degradation of the bentonite. In the interest of investigating the effects of pressure changes, the testing was continued to see what would happen to the hydraulic conductivity. Due to the uncontrolled volume swings and potential leaks in the system during the compressor failure, the hydraulic conductivity readings in the period of time for several days after the compressor failure are not considered valid. Eventually, the samples re-stabilized under the original pressure. With the exception of test nos. ASH-2, ASH-3, and MSW-1 all of the measured hydraulic conductivities returned to the pre-failure readings and some even decreased. The specimen for ASH-3 increased in hydraulic conductivity only very slightly. A summary of the results is presented in Table 2.

After the experience of the compressor failure and re-stabilization, there was still enough leachate to continue running the samples for one to two more weeks. A decision was made to intentionally change the effective confining stresses and note the effects. The effective stress was doubled (increased by 100%) on test nos. MSW-1 and ASH-2; reduced by 32% on test no. ASH-3; reduced by 50% on test no. MSW-2; and reduced by 66% on test no. MSW-3.

Test no. MSW-1 behaved as might have been predicted. That is, the hydraulic conductivity showed a decreasing trend after increasing the effective pressure. This cause-and-effect conclusion may not be so clear, however, when the results for test nos. MSW-2 and MSW-3 are examined. In these cases, the effective stress was decreased. Initially after the decrease in effective stress the hydraulic conductivity increased, as would be expected. After several days, however, and until the end of the tests, the final hydraulic conductivity decreased to below its starting value, which is exactly the opposite of what would have been predicted.

Test no. ASH-2 appeared unaffected by an increase in effective stress. Results for test no. ASH-3 was only slightly affected by the decrease in effective stress.

General Discussion Regarding Testing Procedure

The testing described in this paper was run up to 10 times longer than standard hydraulic conductivity testing that is performed on a production basis in accordance with ASTM D5084. Even so, the testing described herein would not be considered “long-term”. Shackelford et al. (2000) have suggested that “long-term” testing of GCLs might require on the order of 30 pore volumes of liquid to be confident that chemical equilibrium is achieved. They also suggested that chemical properties of the influent and effluent could be measured (e.g. pH, electrical conductivity, and concentration of various ions) for further verification that equilibrium had been achieved. There were no provisions to measure the chemical properties of the effluent in this study, although that would be a good recommendation for future studies. In addition to the question of reaching true equilibrium in the test, the authors provide the following additional speculations of testing conditions that could affect the results based on their experience:

- One of the subtleties of long-term hydraulic conductivity testing is the potential problem with bacteria buildup on the specimens. This condition may lead to a decrease in the apparent hydraulic conductivity. This may be the reason that the hydraulic conductivity decreased even after the effective stress was decreased for the MSW leachate test nos. 2 and 3. This phenomenon might tend to occur more often with landfill leachates that are rich in certain nutrients. Many laboratory technicians can testify to the odor that is experienced when the tests are finished and cells are taken apart as being indicative of biological activity. Additionally, black stains are a common observation, seen on filter papers, textiles, and membranes surrounding specimens after long term testing. If the bacteria occur in the laboratory, there is a good chance it may also occur in the field, and artificial sterilization during testing may not be representative of field conditions.

Adding chemicals to kill the bacteria can have the influence of altering the leachate chemistry and hydraulic conductivity.

- Leachates that are high in salt content can influence flow when the temperature changes and re-crystallization of the salts occurs. As biological and chemical reactions tend to increase landfill and leachate temperatures, a decrease in temperature may occur as the leachate travels away from the center of chemical activity towards the liner containment system, causing temperatures to decrease and crystallization to occur, blocking pore space. Some sodium, calcium, and magnesium salt solutions may start to re-crystallize.

- Long-term tests can also allow air and gas to migrate, grow, or evolve into the pore water of the specimen causing de-saturation. Air may be a result of chemical reaction or from the apparatus back-pressure. As specimens become unsaturated, their hydraulic conductive values tend to become lower. This could have occurred when the air compressor failed.

- The calculations of pore volumes and of hydraulic conductivity from the test data are significantly influenced by the estimation of specimen thickness, L. Exactly how the effect of the geotextiles is taken into account to accurately estimate the specimen thickness that exists during the test on these types of GCLs is a subject for future investigation.

Conclusions

The following conclusions were derived from the limited laboratory test data described in this paper:

- The hydraulic conductivity of a GCL is a function of effective confining stress. The relationship is fluid-specific.

- For the test durations described in this paper, the following relative hydraulic conductivity results were observed for a type of GCL (CETCO “DN”) that was saturated and permeated with the following leachates:

    - Leachate derived from the waste stream of a mixed newspaper recycling and kraft pulp & paper mill appeared to result in hydraulic conductivities that were essentially the same as those obtained from distilled water over the range of effective stresses tested.

    - Leachate derived from an MSW landfill appeared to result in a hydraulic conductivity that was approximately three times greater than distilled water at an effective stress of 240 kPa, but was essentially the same as that obtained from distilled water at effective stresses greater than 475 kPa.

  - Leachate derived from an ash landfill, whose waste was obtained from incinerating MSW, appeared to result in hydraulic conductivities that ranged from approximately 5,000 times greater than that obtained with distilled water at effective stresses below 200 kPa, to a value that was essentially the same as that obtained from distilled water at effective stresses greater than 500 kPa.

  - The measured hydraulic conductivity of sodium-bentonite GCLs appears to be independent of the fluid chemistry at effective stresses greater than 400 to 500 kPa.

  - The results presented in this study show trends consistent with data previously reported by Thiel et al. (2001).

- The duration of testing, and consequently the number of pore-volumes of leachate that permeated through the GCL specimens, was limited in the present study such that it may not be considered to represent long-term results. Additional investigations having more pore-volumes of fluid transfer through GCL samples are needed to assess the true long-term performance of GCLs when permeated with non-standard liquids.

- Long-term testing programs may need to address practical testing issues related to bacteria buildup in the samples, and gas accumulation in the permeating liquids.

References

ASTM D5084, "*Standard Test Methods for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter*", Annual Book of ASTM Standards, Vol. 04.08, American Society for Testing and Materials, West Conshohocken, Pennsylvania, USA.

ASTM D5887, "*Standard Test Methods for Measurement of Index Flux Through Saturated Geosynthetic Clay Liner Specimens Using a Flexible Wall Permeameter*", Annual Book of ASTM Standards, Vol. 04.13, American Society for Testing and Materials, West Conshohocken, Pennsylvania, USA.

Daniel, D.E., Shan, H.Y., and Anderson, J.D., 1993, "Effects of Partial Wetting on the Performance of the Bentonite Component of a Geosynthetic Clay Liner", *Proceedings of Geosynthetics '93 Conference*, Vancouver, B.C., IFAI, Roseville, MN, pp. 1483-1496.

Rowe, R.K., 1998, “Geosynthetics and the Minimization of Contaminant Migration through Barrier Systems Beneath Solid Waste”, *Proceedings of the Sixth International Conference on Geosynthetics*, IFAI, Atlanta, GA, March 25-29, pp. 27-102.

Ruhl, J.L. and Daniel, D.E., 1997, “Geosynthetic Clay Liners Permeated with Chemical Solutions and Leachate”, *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, V123, No. 4, pp. 369-381.

Shackelford, C.D., Benson, C.H., Katsumi, T., Edil, T.B., and Lin, L., 2000, “Evaluating the Hydraulic Conductivity of GCLs Permeated with Non-standard Liquids”, *Geotextiles and Geomembranes*, V18, Nos. 2-4, pp. 133-161.

Thiel, R., Daniel, D.E., Erickson, R., Kavazanjian, E., and Giroud, J.P. (2001) *The GSE GundSeal GCL Design Manual*. Published by GSE Lining Technology, Inc., Houston, TX. 370 p.