Technical Paper by R.S. Thiel and K. Criley

HYDRAULIC CONDUCTIVITY OF A GCL UNDER VARIOUS HIGH EFFECTIVE CONFINING STRESSES FOR THREE DIFFERENT LEACHATES

ABSTRACT: Reinforced GCL samples were partially pre-hydrated on native damp subgrade soils for several weeks, and were then tested for hydraulic conductivity using three different leachates under a variety of effective confining stresses. The samples were received with an initial moisture content of approximately 35%, and gained in moisture content at a rate of about 1% per day over a three week period while sitting in an unconfined condition on a silty-sand material in a closed container. The subgrade soil had a moisture content of 27%, with a negligible change in moisture content over this period The samples tested with MSW leachate were tested under effective stresses of 240, 480, and 720 kPa. The samples tested with MSW-incinerator ash leachate were tested under effective stresses of 180, 360, and 530 kPa. The samples tested 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 results correlate fairly well with data previously published in the literature regarding the hydraulic conductivity of GCLs at different effective stresses when permeated with tap water and a calcium-chloride solution. The hydraulic conductivity of the GCL 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. Some interesting results are presented in the paper showing the effects of changing the effective confining stresses during the tests.

KEYWORDS: Geosynthetic clay liner, hydraulic conductivity, leachate

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1. INTRODUCTION

The scope of this paper relates to the hydraulic conductivity of a geosynthetic clay liner (GCL) subjected to various normal loads and three different liquids (waste leachates) having different dissolved chemical compositions.

Estimates and calculations regarding leakage rates through intact geosynthetic clay liners (GCLs) are directly related to the assumed hydraulic conductivity of the bentonite clay. The hydraulic conductivity of the sodium bentonite clay component of GCLs is based on fluid flow through a porous medium, in accordance with Darcy's Law, and is typically measured by ASTM D 5084. When the GCL is placed as a primary liquid barrier without a geomembrane, liquid flow rate through the GCL would generally be estimated by Darcy's law as:

$$Q = kiA$$

where q = liquid flux in units of $m^3/s/m^2$; k = hydraulic conductivity of the GCL in units of m/s; i = hydraulic gradient across the GCL, and A = area of the GCL normal to the flow in units of m^2. This equation assumes that the GCL is the predominant barrier, and that planar-series effects of other layers are negligible in the cross-plane hydraulic conductivity.

If the GCL is used as part of a composite liner in contact with a geomembrane, the liquid flow rate through a defect in the geomembrane is generally estimated using the "Giroud equation" as follows:

$$Q = C\,[1 + 0.1(h_w / t)^{0.95}]\, a^{0.1}\, h_w^{0.9}\, k^{0.74} \tag{3.1}$$

where: C = a constant related to the quality of the intimate contact between the geomembrane and underlying clay liner; h_w = head of liquid on top of the geomembrane (m); t = thickness of the soil component of the composite liner (m); a = area of defect in geomembrane (m^2).

In either case, it can be seen that the value of the GCL hydraulic conductivity, k, is a predominant factor in controlling the leakage rate. The hydraulic conductivity of sodium bentonite is affected by two principal variables: (1) the level of normal or effective stress applied to the GCL, and (2) chemical alterations caused by different permeating liquids that change the hydraulic conductivity of the sodium bentonite. This paper reports the results of laboratory testing that explores the combined effects of both of these two variables.

2. BACKGROUND DISCUSSION RELATED TO EFFECTS OF EFFECTIVE STRESS

Effective stress is a significant variable that controls the behavior of bentonite. It decreases both hydraulic conductivity, and the susceptibility of bentonite to chemical alterations (discussed in Section 3). Increasing the effective stress on a GCL decreases the void ratio (or porosity) within the bentonite layer, which tends to lower its hydraulic conductivity. This tendency toward decreased hydraulic conductivity in response to increased effective stress is a basic characteristic of virtually all soils and other porous materials.

Figure 1 shows the relationship between hydraulic conductivity to water and effective stress for several types of GCLs as reported by Dr. Dave Daniel (Thiel et al., 2001). The differences in hydraulic conductivity between various GCLs are minimal, except at very low effective stresses where internally reinforced and non-internally reinforced GCLs behave slightly different in response to variations in effective stresses. The GCLs that have internal reinforcement (e.g., geotextile-encased, needlepunched GCLs) tend to have lower hydraulic conductivity with minimal confinement because as the bentonite hydrates and swells, the needlepunched fibers hold the encasing geotextiles together, thereby providing confinement and effective stress upon the bentonite. At high normal stresses, the differences in hydraulic conductivity between the various commercial GCLs tend to be subtle.

3. BACKGROUND DISCUSSION RELATED TO EFFECTS OF CHEMICAL INTERACTIONS

3.1 General Parameters Affecting Bentonite Hydraulic Conductivity

Chemical interactions and their effect on the hydraulic conductivity of sodium bentonite in GCLs have been studied by several researchers and evaluated for numerous projects. Four chemical-interaction parameters can influence the hydraulic conductivity of bentonite: 1) dielectric constant of permeating liquid, 2) salt concentration of the permeating liquid, 3) predominant cation of the bentonite vs. those in the permeating liquid, and 4) pH of the permeating liquid.

- <u>The dielectric constant of the permeating liquid</u>. Water-based (aqueous) liquids all have a dielectric constant of ≈ 80, but organic liquids such as gasoline have a much lower dielectric constant (often in the range of 1 to 5). The lower the dielectric constant of the liquid in the bentonite, the less the swelling mechanisms of the bentonite are activated, and the higher is its hydraulic conductivity. Bentonites tend to swell and to be impermeable when contacted by fresh water, but not when they are contacted by chemicals such as gasoline, jet or diesel fuel, or solvents such as trichloroethylene or acetone that have a low dielectric constant. Nearly all organic liquids have a much lower dielectric constant than water, so they can therefore cause potentially large increases in the hydraulic conductivity of bentonite. Dilute organics (for example, a few parts per million of organics dissolved in water), however, do not significantly alter the dielectric constant of water, do not impede swelling in bentonite, and do not threaten to increase its hydraulic conductivity.

- The salt concentration of the permeating liquid. Bentonites swell the most, and tend to maintain the lowest hydraulic conductivity, when contacted by typical ground- or tap-water. Salt concentrations in the tens or hundreds of parts per million are not particularly high and do not tend to greatly alter hydraulic conductivity. However, concentrations in the thousands or tens of thousands of parts per million may be sufficiently high to negatively effect significant changes in hydraulic conductivity. For example, ordinary bentonite does not swell much when mixed with seawater. If a GCL were used to contain seawater, the hydraulic conductivity of the GCL would be relatively high because of the high salt concentration in seawater. The concentration of salt in seawater is about 30,000 parts per million. In general, salt concentrations in the tens of parts per million, and perhaps up to several hundred parts per million (depending on the type of salt – see the discussion below), are not sufficiently large to pose a serious threat to GCLs in most applications. When concentrations are of a thousand parts per million or more, they become large enough to cause concern. For concentrations less than about 500 parts per million, it is the type of salt rather than the concentration that is critical.

- The cations. Perhaps the most important factor affecting the hydraulic conductivity of GCLs from a practical standpoint is the type of cation in the bentonite and the charge (called *valence*) of that cation relative to the cations in the permeating liquid. Cations are positively charged ions, and the ones most commonly found in the ground in significant concentrations exist as salt, such as NaCl. The key cations typically found in GCLs are Na^+, K^+, Ca^{++}, Mg^{++}, and Al^{+++} (sodium, potassium, calcium, magnesium, and aluminum, respectively). With bentonites, the higher the positive charge of the cation, the more permeable the bentonite. Thus, the most beneficial cations in the water are sodium and potassium, which both have a charge of +1. The least favorable cations are the polyvalent cations, which have a charge of +2 or more. Several polyvalent cations are found in soils, but calcium tends to produce by far the most significant adverse effects on bentonite swelling. The reason sodium bentonite is used in GCLs is that with sodium in the bentonite, hydraulic conductivity tends to be extremely low. If the sodium is replaced by calcium, the hydraulic conductivity can increase as much as one to two orders of magnitude. Thus, if a GCL is permeated with a calcium-rich liquid in the field, its hydraulic conductivity may increase significantly, and its sealing capacity be reduced to the point that the GCL may fail to meet the designer's expectations. Cation replacement is a potentially serious issue that should be evaluated carefully. A good discussion of the basic principles of cation exchange in GCLs can be found in Egloffstein (1997).

- The pH of the permeating liquid. The pH of the permeating liquid can also affect the hydraulic conductivity of bentonite. In cases of extremely acidic or caustic liquids (i.e., pH less than 2 or greater than 13), the liquid may be sufficiently aggressive to literally dissolve some of the bentonite clay. If the clay is dissolved, the liquid can "eat through" the GCL and dramatically increase hydraulic conductivity. However, liquids with this capability are rare. More common are less extreme ranges of pH. Also, the greater the amount of dissolved material in the leachate, the less bentonite is affected directly by pH because the dissolved ions are much more significant than pH itself.

3.2 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 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 tap 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 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 tap water. However, Ruhl and Daniel (1997) found that while a synthetic leachate did cause 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 tend to plug the pores of the bentonite and reduce hydraulic conductivity. Impacts from actual leachates may vary considerably from one leachate to another. Some of the subtleties of testing are discussed in Section 6.

Table 1. Comparison of Leachate Constituent Concentrations (mg/l unless otherwise stated).

Chemical Constituent	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 (pH units)	7	6.2	8.5	7.0	7.6

N/A = Not available

As mentioned in the previous subsection, the effective stress placed on sodium bentonite influences hydraulic conductivity. Effective stress has a major impact on the susceptibility of GCLs to alterations caused by cation exchange. This issue was limitedly explored by Dave Daniel (Thiel et al., 2001) and is illustrated in Figure 2 for a geotextile-encased GCL that was permeated with either distilled water or a 0.125 molar solution of $CaCl_2$ (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 calcium chloride 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 calcium chloride 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.

4. 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. The material that was tested was a double-nonwoven needlepunched GCL provided by CETCO, 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.
- Leachate from incinerator ash that was created from burning MSW.
- 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.

A summary of the more pertinent constituents is presented in Table 1 to allow side-by-side comparisons. Laboratory testing was performed in accordance with ASTM D5084. Table 2 presents a matrix showing the effective stress applied to the various specimens, time periods of testing, and estimated number of pore volumes passed through the specimens.

4.1 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. Work by 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 a natural water content of approximately 27%. The gain in water content versus time for the GCL samples is presented in Figure 3. 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.

4.2 Permeability Testing – General Procedure

The samples were tested for hydraulic conductivity in triaxial pressure cells in accordance with ASTM D5084. All of the samples were backpressure saturated using their respective leachates as the saturating fluid. Table 2 presents details related to effective pressures, and hydraulic gradients used during the testing. For purposes of calculating the conductivity during testing, the initial thickness of the samples was used. The 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) and others have reported that higher gradients are acceptable for testing GCLs. The main reason that higher gradients might be acceptable for GCLs is that the variation in effective stress due to the hydraulic gradient across a specimen is far less for thin GCLs than for thicker soil specimens. The range of hydraulic gradients used in the test program described herein is considered quite appropriate and representative of the standard of practice applied to GCLs.

The effective pressures were selected unique to the landfills for which the studies were being performed, and were therefore not the same pressures 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 pressures that were to be held constant. The pressures 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 in the Section 5.

4.3 Measurement of Specimen Thickness

The test method for hydraulic conductivity requires measurement or estimation of the specimen thickness, *t*. The reported hydraulic conductivity values in ASTM test method D5084 are directly proportional to the measured or assumed values of *t*. Normally, with soil specimens prepared for this test method, *t* 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 assumed value of *t* 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 *t* 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 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 *t* wherein the thickness of the geotextile was subtracted from the total specimen thickness by the method described in the following paragraph. Note that Table 2 reports the assumed thickness of the bentonite, and the footnote at the bottom gives the average thickness of the textiles that would be added to the assumed bentonite thickness to obtain the total end-of-test specimen thicknesses, if desired.

First a 0.1 m round duplicate GCL specimen was cut from the sample next to the test specimen. The upper and lower textiles were carefully separated by cutting the connecting needle-punched fibers with a razor knife. The bentonite was carefully removed taking care to avoid additional damage to the textiles. With the bentonite removed, the halves were placed on top of each other between two 0.1 m diameter steel calibration spacers. The assembly was placed in a load frame and compressed using a 72 kPa stress. The total height of the spacer with the compressed textile was measured with a caliper in three places 120° apart. The compressed textile thickness was determined by subtracting the known calibration spacer thickness.

The same thickness measurement procedure using the steel calibration spacers was then performed on each of the hydraulic conductivity test specimens both before and after the hydraulic conductivity tests were performed. The values of *t* for each of the test specimens was calculated by subtracting the predetermined textile thicknesses from the total specimen thicknesses.

Table 2. Summary of hydraulic conductivity test parameters and results.

SAMPLE DESCRIPTION:	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
Initial 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 Pore Volumes (c)	2.7	2.1	0.2	4.7	46	0.7	1.5	1.8	1.7
Hydraulic Conductivity, m/sec. (a)	$6E^{-12}$	$1E^{-12}$	$4E^{-13}$	$5E^{-8}$	$3E^{-11}$	$9E^{-13}$	$6E^{-12}$	$1E^{-12}$	$1E^{-12}$
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. (a)	$3E^{-12}$	$1E^{-12}$	$5E^{-13}$	$3E^{-8}$	$3E^{-11}$	$2E^{-12}$			
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. (a)	$1E^{-12}$	$3E^{-13}$	$4E^{-13}$	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, (conductivity) days	66	77	81	22	76	81	27	27	27

NOTES:

a) Hydraulic conductivities are based on the final measured bentonite thickness obtained by subtracting the measured textile thickness from the over-all, end of test specimen thickness.

b) The average textile thickness which was subtracted from the total end-of-test specimen thickness was 3 mm

c) The estimated pore volume is based on the end of test bentonite thickness.

5. RESULTS

5.1 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 4. The results reported by Daniel (shown in Figures 1 and 2) are repeated on Figure 4 for comparison. The results from the current program show a similar pattern to the results reported by Daniel, and indicate that the relationship between hydraulic conductivity and effective confining stress is specific to a given liquid chemistry, but that at effective pressures 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 tap water.
- For MSW leachate the hydraulic conductivity at the 240-kPa load is approximately three times higher than for tap water. At the higher effective stresses that were tested of 480 and 720 kPa the results appear that they might be slightly greater than that of tap water, but for all practical purposes could be considered equal to that of tap 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 $CaCl_2$ solution results reported by Daniel (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.

5.2 Variation of Testing Pressures

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 are presented in Table 2, and the hydraulic conductivity values vs. time and pressure-change events are shown in Figure Nos. 5-13.

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. Part of this phenomenon may be due to biological activity, as discussed later.

Test no. ASH-2 appeared unaffected by an increase in effective stress, and towards the end of the test showed possible signs of hydraulic conductivity increases. The test was terminated too early, in the opinion of the authors, to allow any conclusion regarding the final trend in the hydraulic conductivity caused by the last few data points.

Results for test no. ASH-3 were only slightly affected by the decrease in effective stress. The higher hydraulic conductivity value for the last data point would be considered an outlier, and cannot be considered statistically significant to establish any trend at the end of the test. The test had to be terminated at that point for logistical reasons.

6. DISCUSSION

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. 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, 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.

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 organic 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.

The calculations of pore volumes and of hydraulic conductivity from the test data are significantly influenced by the estimation of t. Consolidation during the test, and changes in the effective stresses during testing, changes the specimen thicknesses during the course of the test. How these changes occur during the course of testing, and how the effect of the geotextiles is taken into account, are subjects for future investigation.

7. 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 GCL 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 tap 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 tap water at an effective stress of 240 kPa, but was essentially the same as that obtained from tap 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 tap water at effective stresses below 200 kPa, to a value that was essentially the same as that obtained from tap 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 Daniel.

- After initial conditions stabilized in the hydraulic conductivity tests, short-term perturbations of effective stress during further testing did not appear to substantially affect the results within the time frames and number of pore volumes investigated in this study.

- 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.

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NOTATIONS

Basic SI units are given in parentheses.

a = area of defect in geomembrane (m^2)

A = cross sectional area of fluid flow (m^2)

C = constant related to the quality of the intimate contact between the geomembrane and underlying clay liner (dimensionless)

h_w = head of liquid on top of the geomembrane (m)

i = fluid gradient (dimensionless)

k = hydraulic conductivity of soil or geosynthetic to a particular fluid (m/s)

Q = volumetric flow rate (m^3/s)

t = thickness of soil component of composite liner (m)

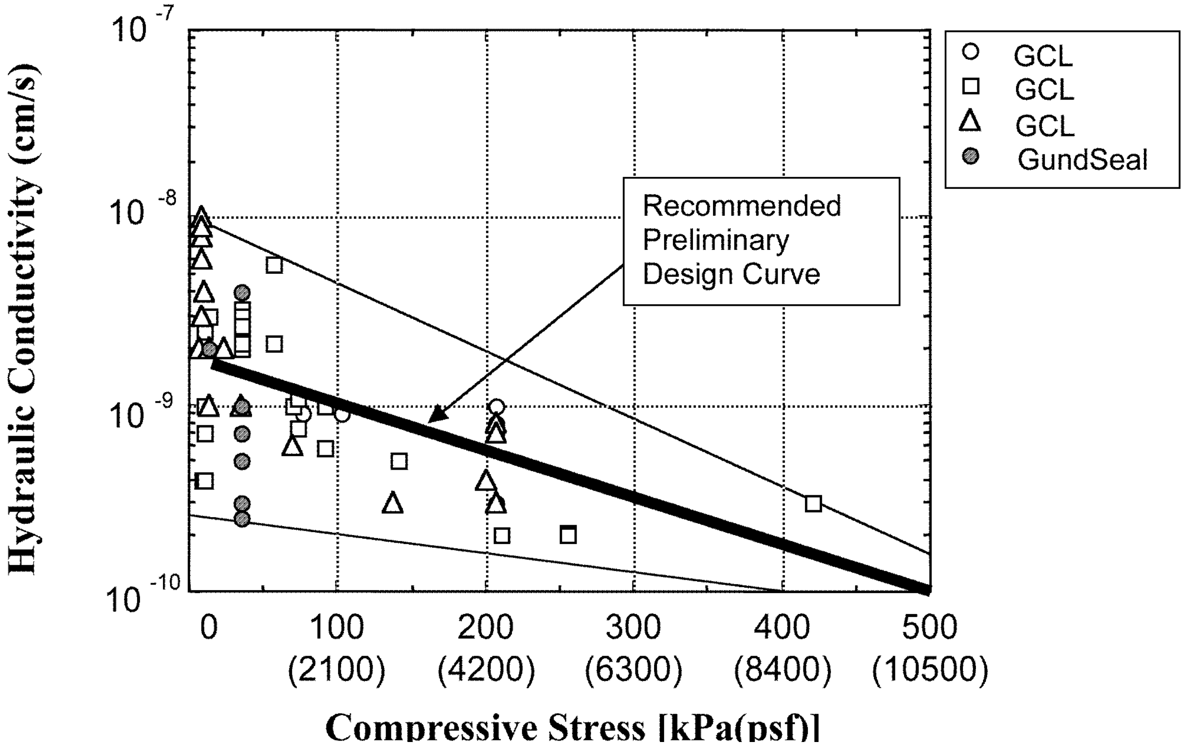

Figure 1. Hydraulic Conductivity as a Function of Effective Confining Stress. (from Thiel et al., 2001) ***[Note: Hydraulic conductivity units are presented in non-SI units of cm/s because the figure was obtained from the original reference. This is being corrected.]***

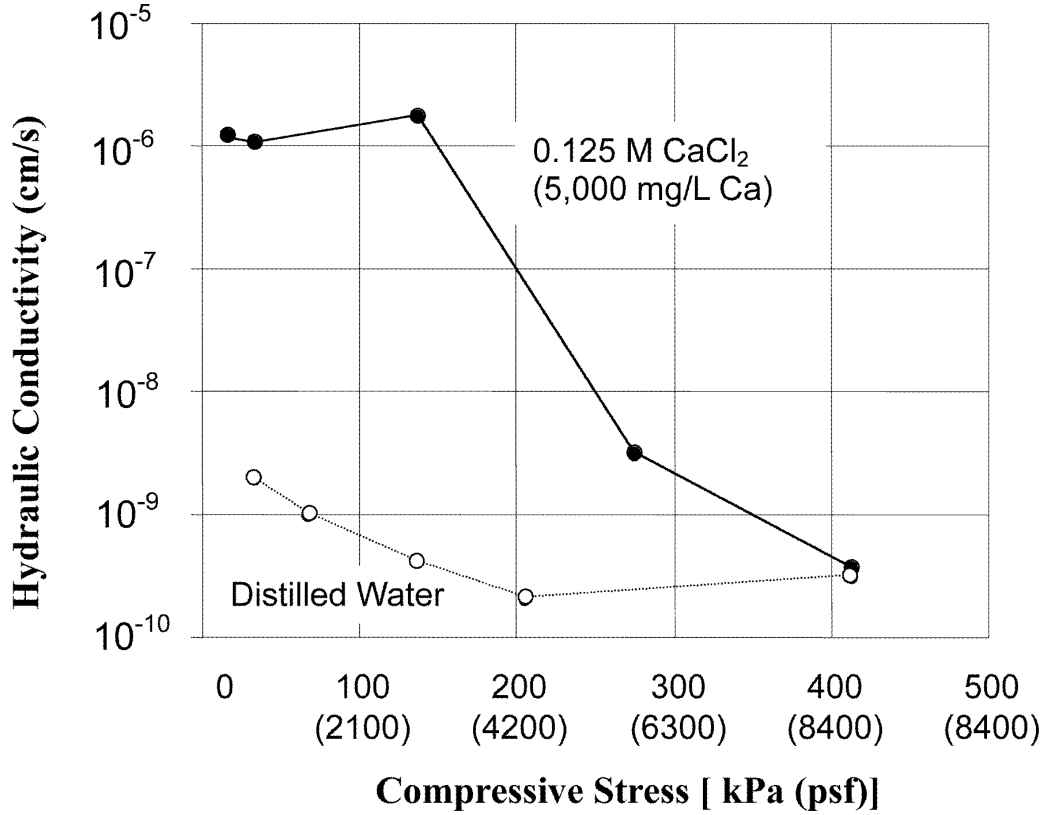

Figure 2. Influence of Effective Stress on the Hydraulic Conductivity of GCLs Permeated with Distilled Water or with a Very Strong Calcium Solution (from Thiel et al., 2001) ***[Note: Hydraulic conductivity units are presented in non-SI units of cm/s because the figure was obtained from the original reference. This is being corrected.]***

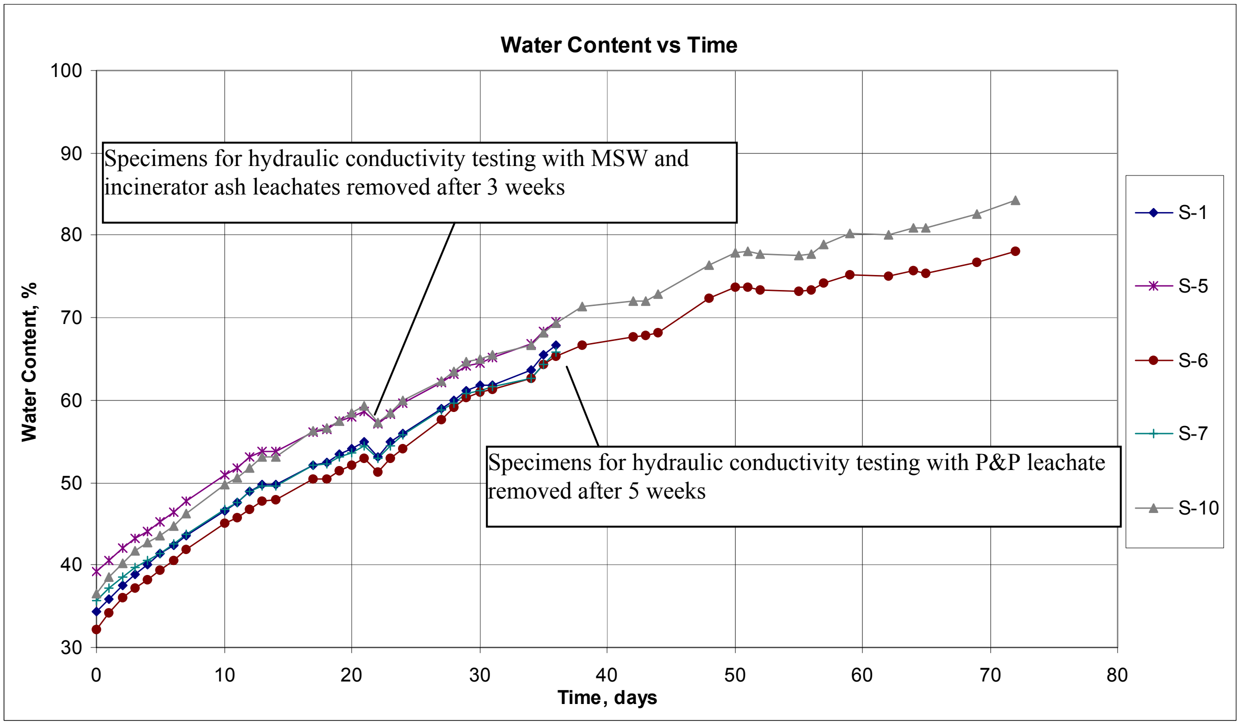

Figure 3. Water Content vs. Time for GCL Samples on Silty Sand Soil with Soil wc = 27%

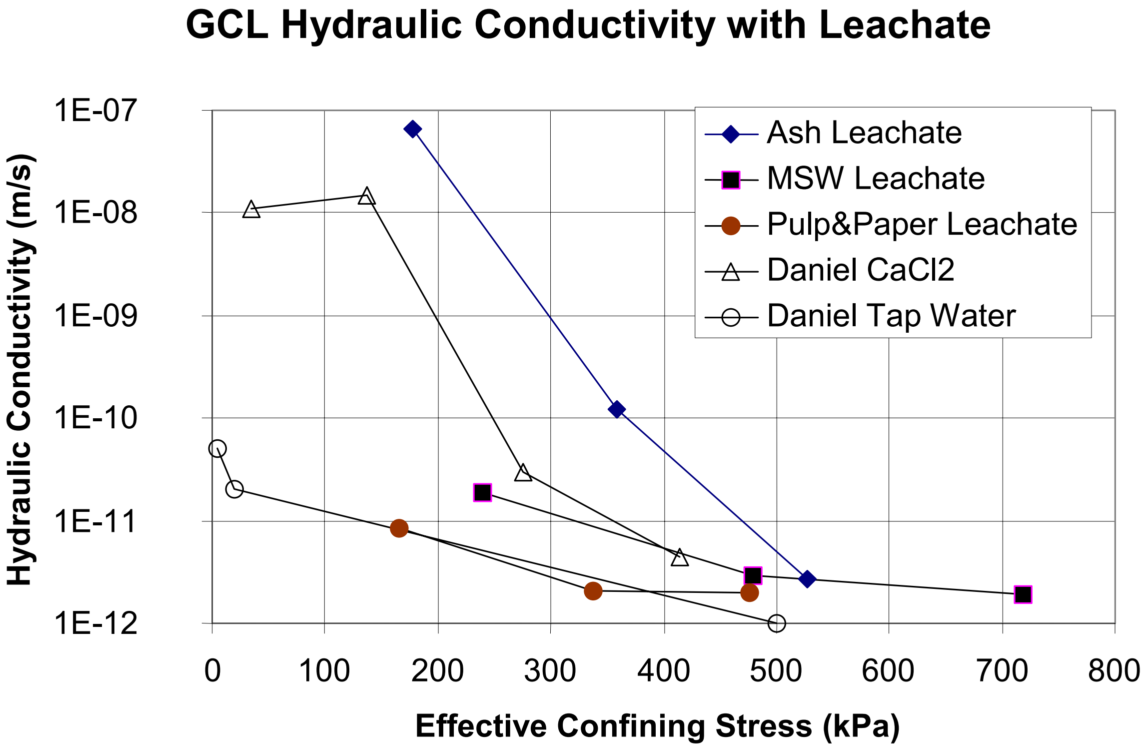

Figure 4. Summary Results for Hydraulic Conductivity of GCL vs. Effective Confining Stress for Three Different Leachates.

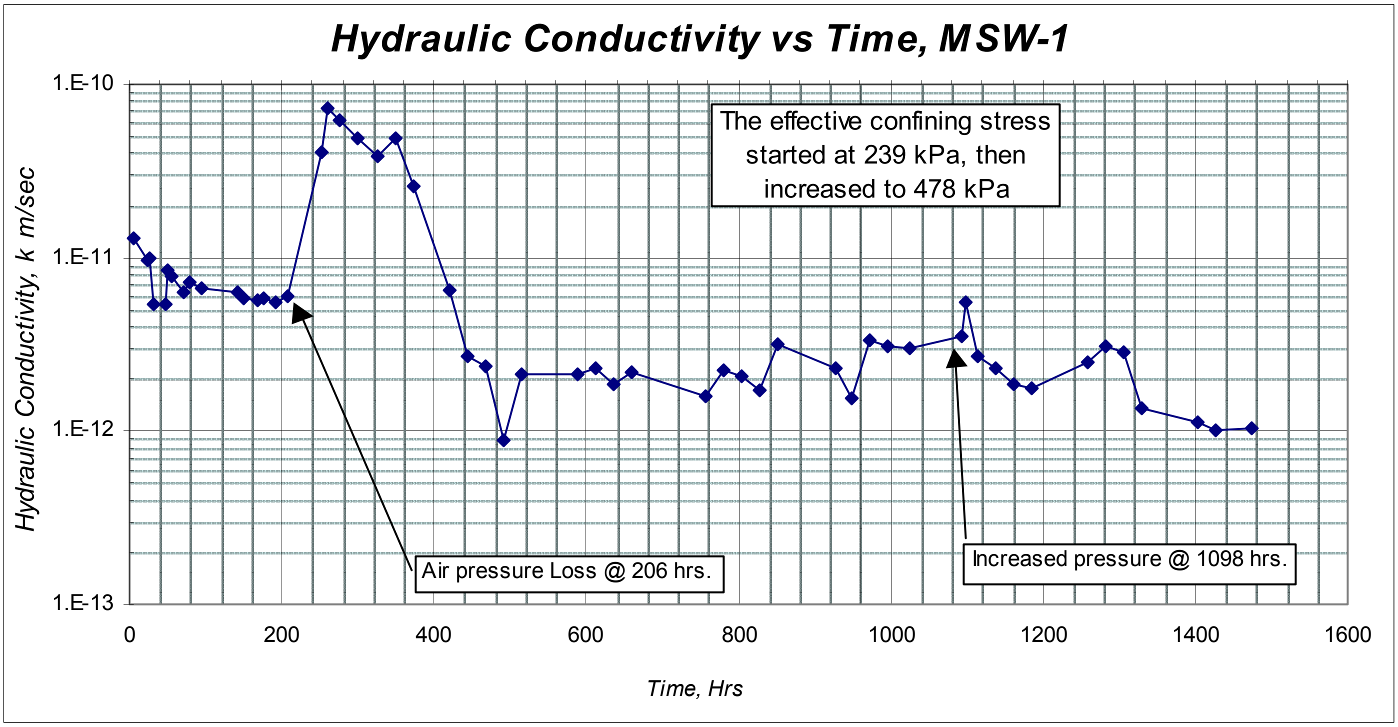

Figure 5. Time vs. hydraulic conductivity for specimen MSW-1 tested with MSW leachate at low initial effective stress (239 kPa).

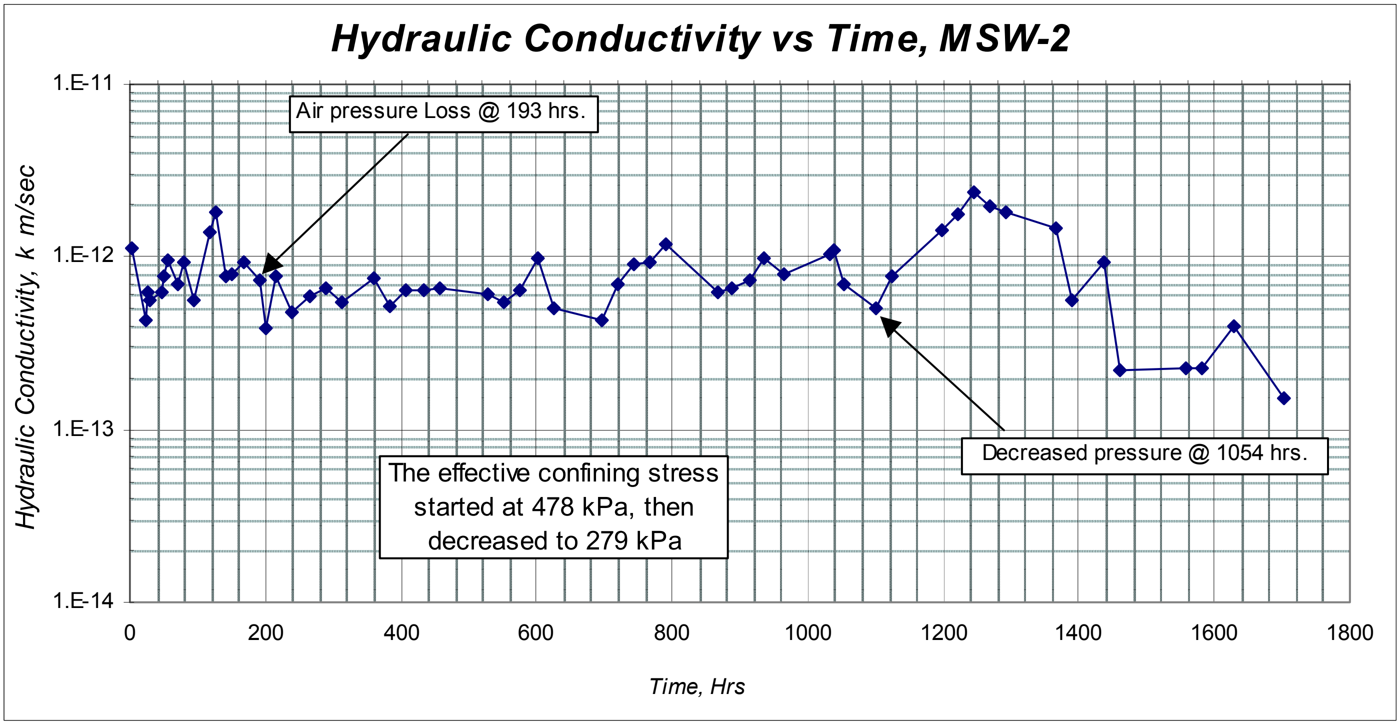

Figure 6. Time vs. hydraulic conductivity for specimen MSW-2 tested with MSW leachate at medium initial effective stress (478 kPa).

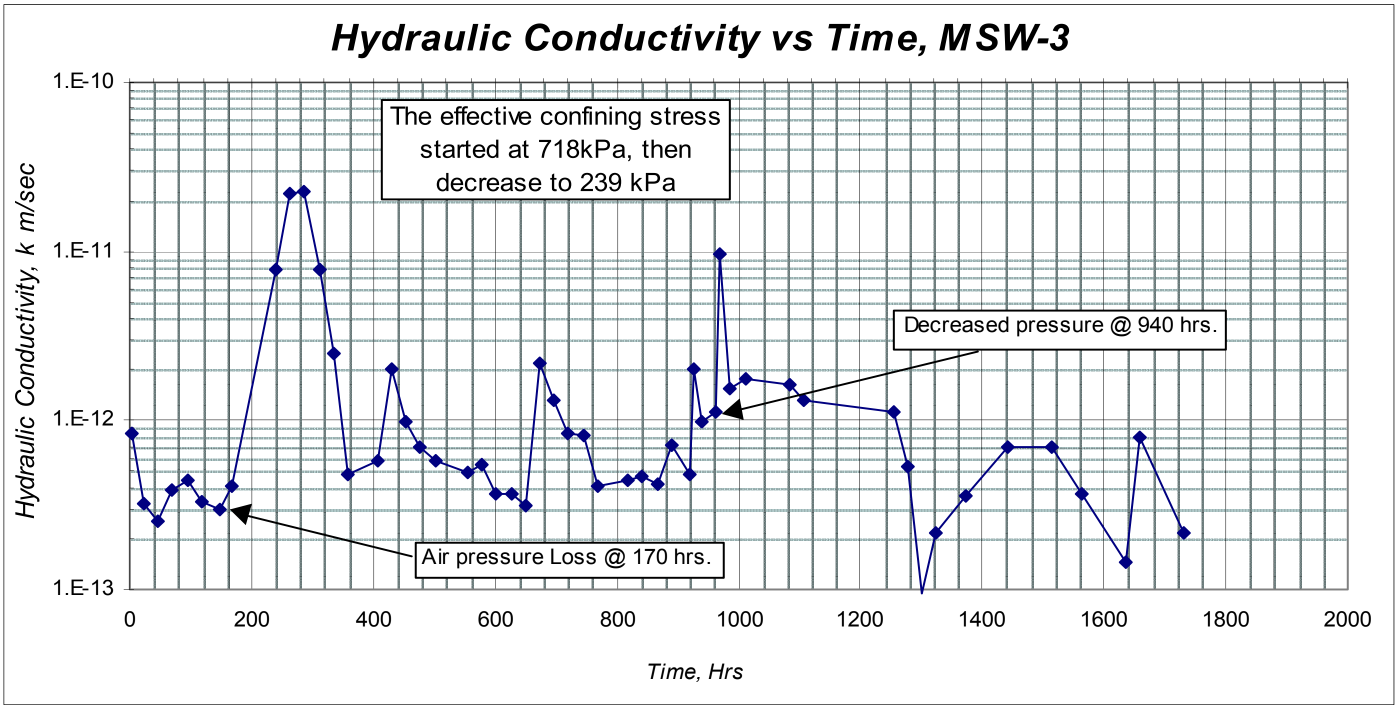

Figure 7. Time vs. hydraulic conductivity for specimen MSW-3 tested with MSW leachate at high initial effective stress (718 kPa).

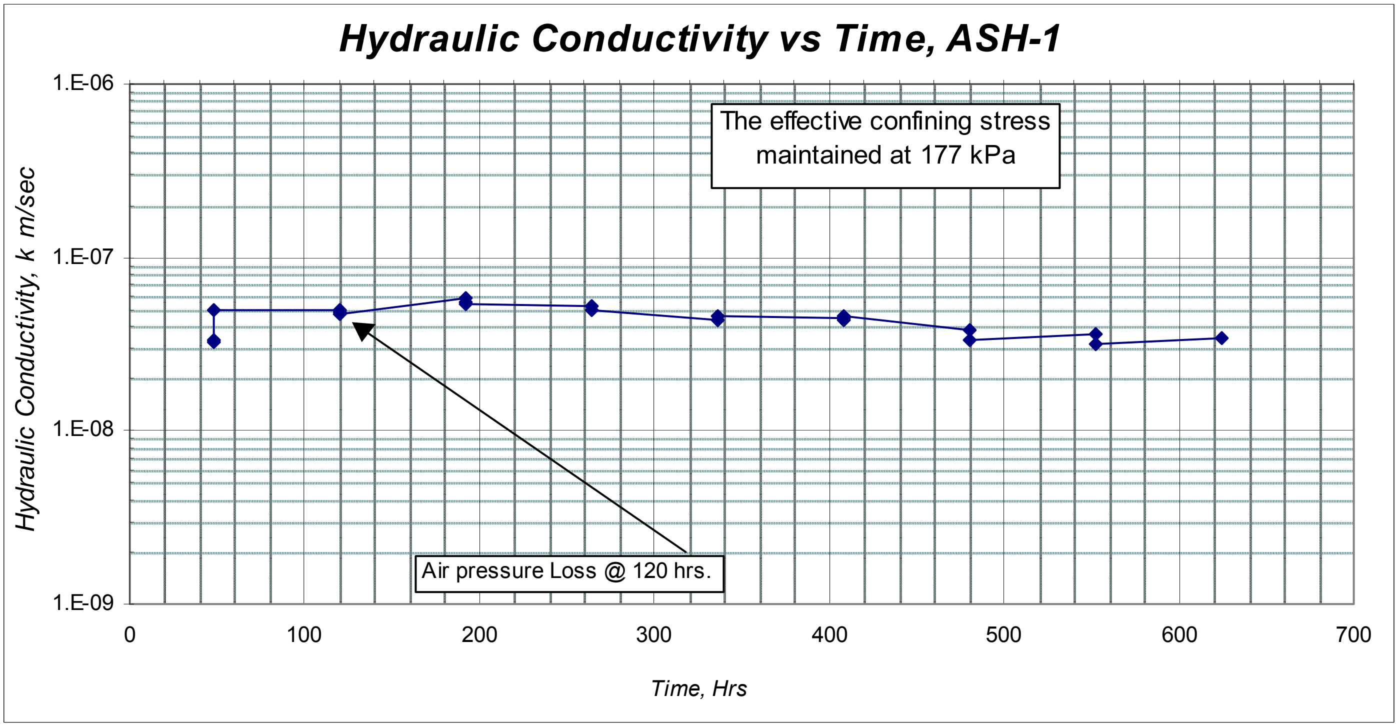

Figure 8. Time vs. hydraulic conductivity for specimen ASH-1 tested with incinerator ash leachate at low initial effective stress (177 kPa).

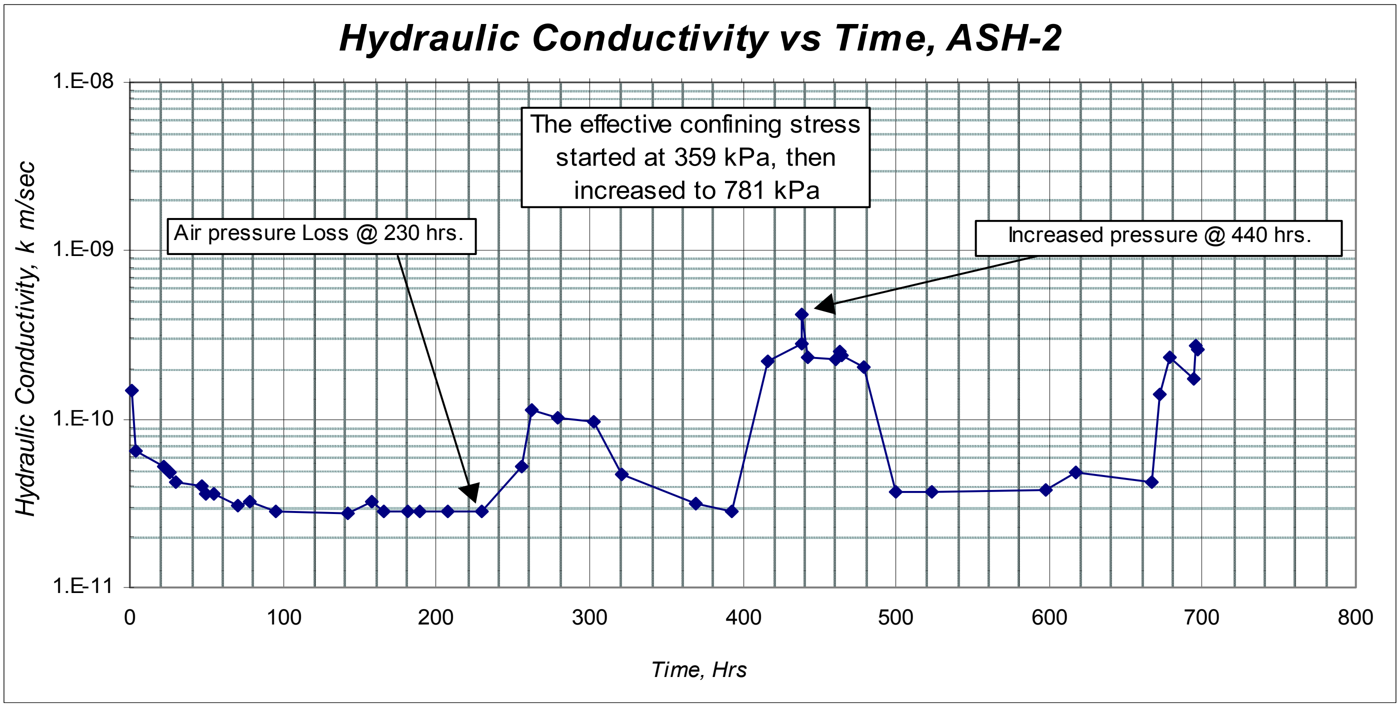

Figure 9. Time vs. hydraulic conductivity for specimen ASH-2 tested with incinerator ash leachate at medium initial effective stress (359 kPa).

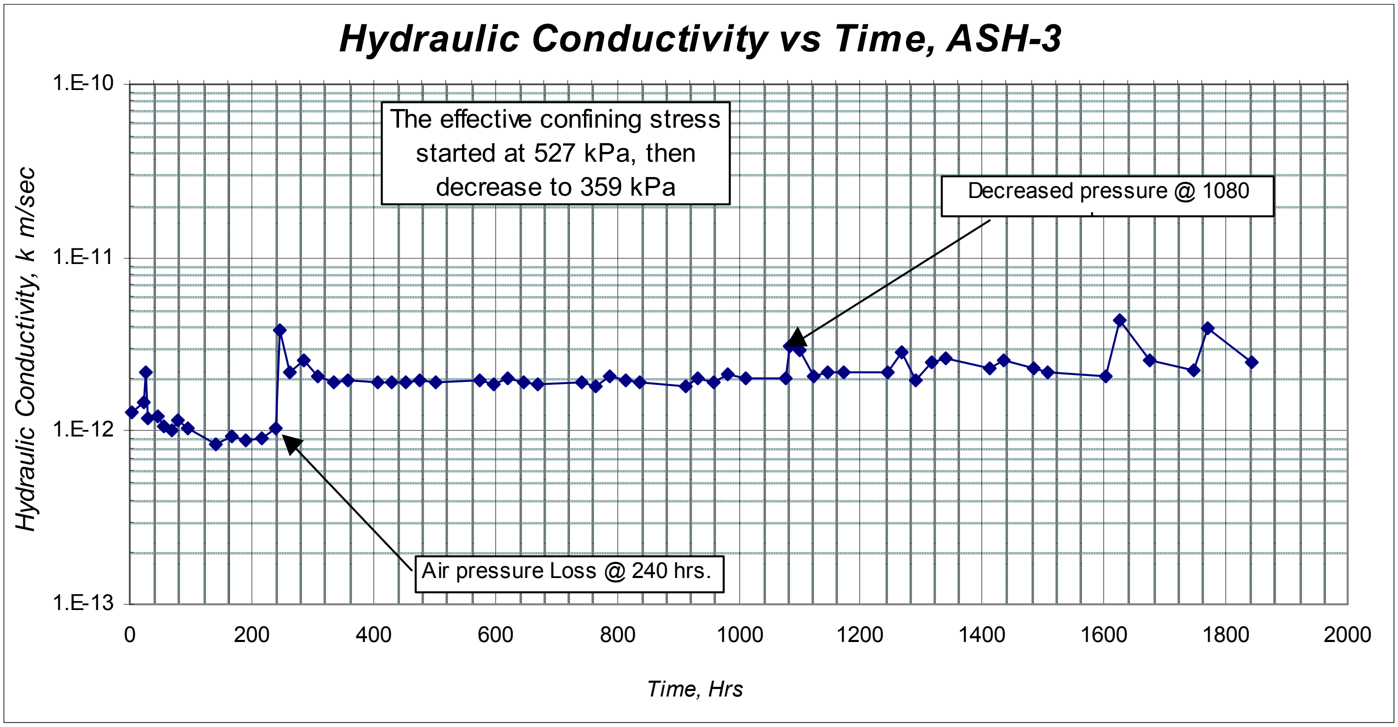

Figure 10. Time vs. hydraulic conductivity for specimen ASH-2 tested with incinerator ash leachate at high initial effective stress (527 kPa).

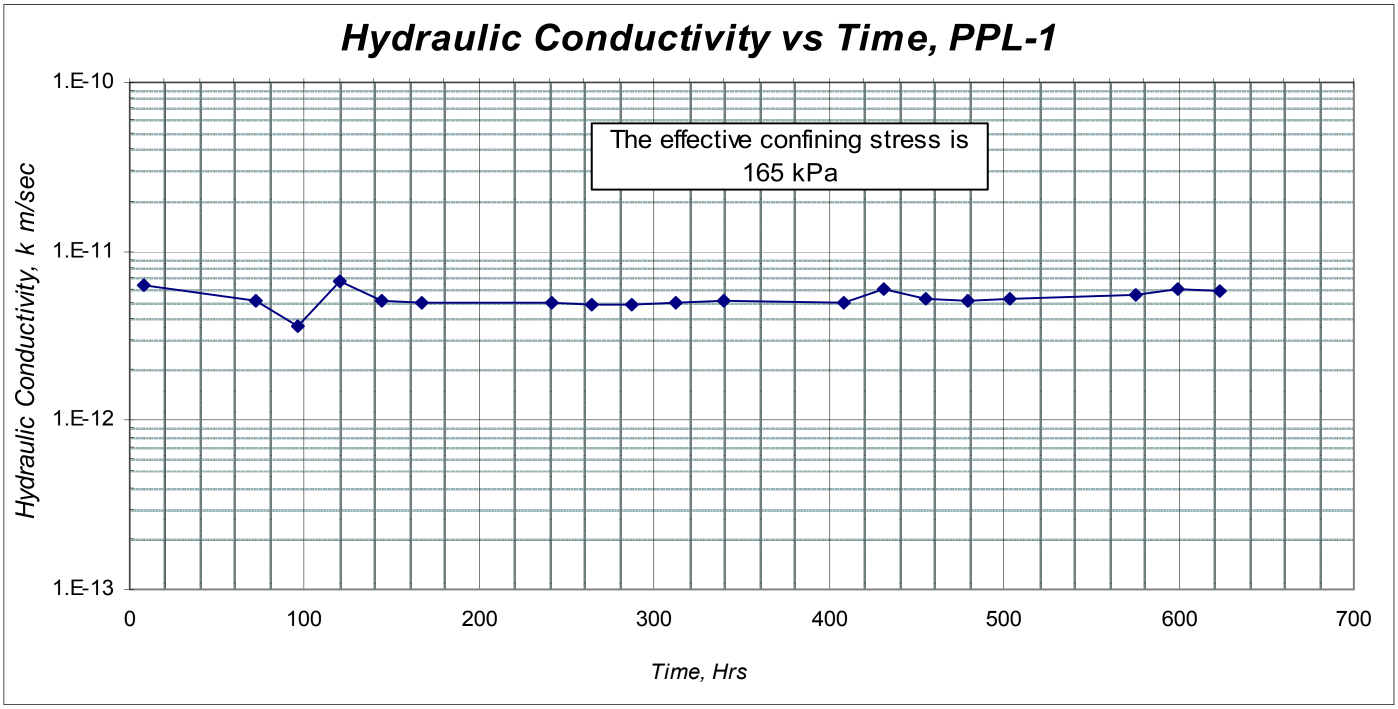

Figure 11. Time vs. hydraulic conductivity for specimen PPL-1 tested with pulp&paper waste leachate at low initial effective stress (165 kPa).

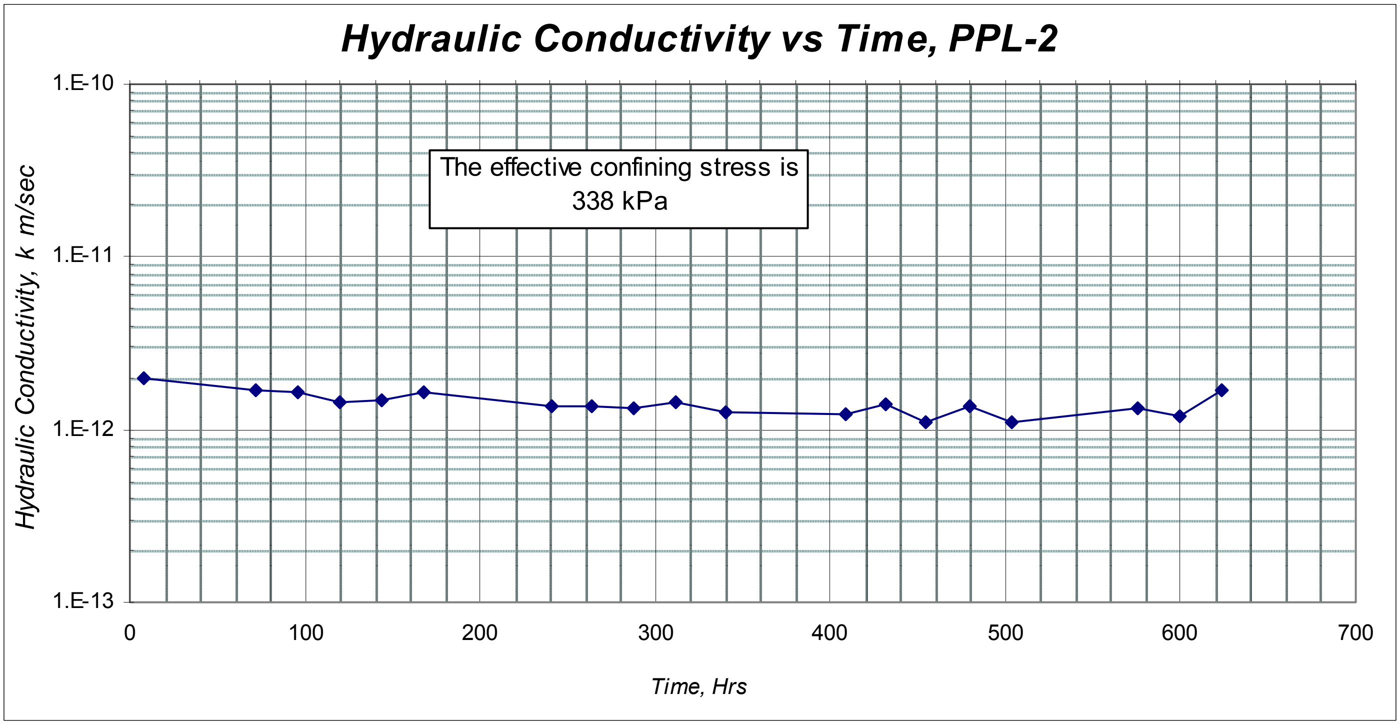

Figure 12. Time vs. hydraulic conductivity for specimen PPL-2 tested with pulp&paper waste leachate at medium initial effective stress (338 kPa).

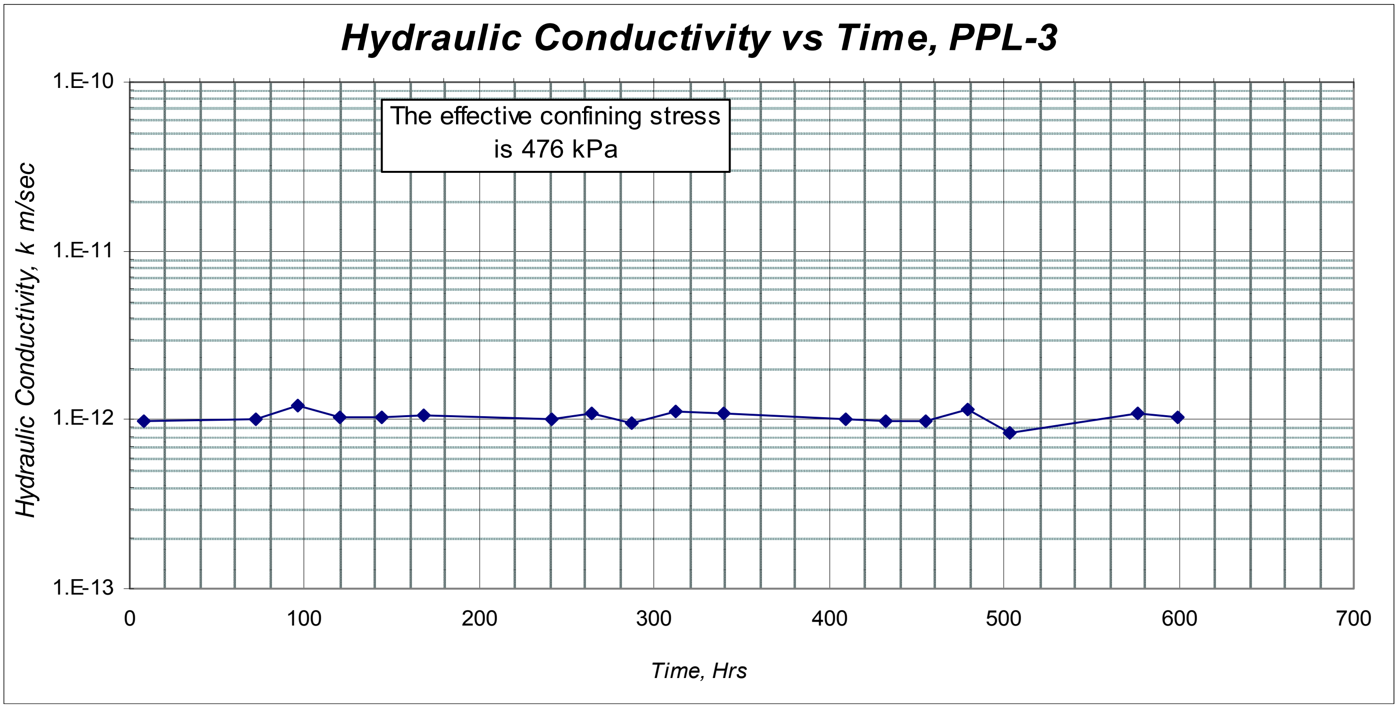

Figure 13. Time vs. hydraulic conductivity for specimen PPL-3 tested with pulp&paper waste leachate at medium initial effective stress (476 kPa).