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Effect of hydrating liquid on the hydraulic properties of geosynthetic clay liners

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Abstract

The engineering properties of geosynthetic clay liners (GCLs) are closely related to the chemistry of pore liquid. For applications in lining systems or cover systems of landfills, covers for remediation sites, and secondary containment systems, GCLs are likely to be permeated by more than one type of liquid. In this study, GCL specimens were hydrated and permeated with different liquids. The hydraulic conductivity of these GCL specimens was determined. The results showed that the hydraulic conductivity of GCLs was controlled by both hydrating and permeating liquid. In addition, even if GCLs were hydrated with aqueous phase liquids other than fresh water, they still have the ability to retard infiltration effectively. © 2002 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Geosynthetic clay liners (GCLs) have been widely used as hydraulic barrier in landfills, remediation projects of contaminated sites, and secondary containment systems (Rowe, 1998). GCLs are either laid beneath geomembranes in composite liners or, in some other cases, installed as a single liner.

Although GCLs are well known for their low hydraulic conductivity to water, in some cases they will have to limit the flow of liquids other than fresh water. For example, some landfills may be located near coastlines since finding suitable sites for landfills has become very difficult. In this case, the liner, which can be a GCL, may be

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in contact with seawater before it is subjected to permeation of leachate. Another possible scenario is that, in areas with or near heavy industry, acid rain may be one of the major environmental impacts. For landfills in these regions, acid rainwater may be the liquid that hydrates the GCL. Furthermore, the GCLs in the cover systems will subject to long-term infiltration by acid rainwater.

1.1. Hydraulic conductivity of GCLs

There have been several studies that looked into the effect of pore liquid on the engineering properties of GCLs. Most of these investigations focused on the variation of hydraulic conductivity. For example, Schubert (1987), Shan and Daniel (1991), Daniel et al. (1993), and Ruhl and Daniel (1997) have permeated GCLs with various chemical solutions including real or synthetic landfill leachate.

The cations, the concentration and/or the dielectric constant of the permeant and hydrating fluid has a strong influence on the hydraulic conductivity of bentonite in the GCLs. Shan and Daniel (1991) permeated a tap water-hydrated GCL specimen with 0.25-M $CaCl_2$ solution under an effective stress of 35 kPa. The hydraulic conductivity of the GCL specimen increased almost 10 times. Tests performed by Gleason et al. (1997) showed that the hydraulic conductivity of a compacted sand-bentonite mixture increased about 100 times when permeant was switched from tap water to 0.25-M $CaCl_2$ solution. In addition, Dobras and Elzea (1993) described a field installation of GCL where the sodium on the bentonite's exchange sites were replaced by calcium leached from overlying limestone, causing a large increase in hydraulic conductivity.

Ruhl and Daniel (1997) concluded from their experiments that the most important factor that governs GCLs' ability to impede permeation of chemical solutions is the hydrating liquid. When a GCL specimen had been hydrated with water prior to permeation of other liquids, the hydraulic conductivity of the GCL remained quite low (in the range of 10^{-11}–10^{-10} m/s). In addition, permeation of GCLs with real leachate resulted in lower hydraulic conductivity (10^{-12}–10^{-10} m/s). They concluded that since the real leachate contained roughly equal amounts of monovalent and polyvalent cations, the monovalent cations offset the effect of polyvalent cations.

The results of the tests conducted by Petrov and Rowe (1997) showed that for GCL specimens prehydrated with distilled water, the hydraulic conductivity of the GCL increases by approximately 1.5–2 orders of magnitude as the NaCl concentration increases from 0.01 to 2.0 M, with the increase in hydraulic conductivity being slightly greater for GCLs with higher void ratios. This increase in hydraulic conductivity due to concentration is approximately the same order as the overall effect of void ratio. In contrast, for the GCL specimens prehydrated with NaCl solution, the hydraulic conductivity of the GCL increases approximately 2.5–3 orders of magnitude as the NaCl concentration increases from 0.1 to 2.0 M. They concluded that the effect of thickness of the adsorbed layer is more influential than void ratio when the GCL is permeated directly with NaCl solution relative to initial permeation with distilled water.

Petrov et al. (1997a) investigated the effect of an increase in salt concentration on the hydraulic conductivity of a needle-punched GCL. They found that the hydraulic conductivity of the GCL increased with the NaCl concentration regardless of whether the GCL is first permeated with distilled or is permeated directly with NaCl solution. The results indicated that the increasing concentration of salt solutions shrinks the adsorbed layer and increases the hydraulic conductivity significantly, even when the permeant liquid contains only monovalent cations.

Jo et al. (2001) performed swelling tests and hydraulic conductivity tests on GCLs with various salt solutions. Their results indicate that GCLs permeated with solutions containing divalent or trivalent cations had higher hydraulic conductivity and lower free swell ratios than GCLs permeated with monovalent solutions or deionized water. In addition, they also concluded that pH only influenced swelling and hydraulic conductivity when the pH was very low (<3) or very high (>12).

Shackelford et al. (2000) discussed the factors and testing considerations effecting the hydraulic conductivity of GCLs permeated with non-standard liquids. Their test results showed that non-standard liquids containing both high concentrations of monovalent cations and low concentrations of divalent cations can cause significant increases in hydraulic conductivity provided the test is performed sufficiently long to allow for exchange of adsorbed cations. They pointed out that termination of hydraulic conductivity tests involving prehydrated GCLs before chemical equilibrium is established might result in measured hydraulic conductivities that do not represent equilibrium and might be unconservatively low.

Furthermore, there were other investigations that involved permeating GCLs with Non-Aqueous Phase Liquids (NAPLs). Geoservices (1989) used gasoline, diesel fuel, and jet fuel to permeate GCL specimens prehydrated with water. The results showed that the hydraulic conductivity of the specimens was below 1×10^{-11} m/s under an effective stress of 207 kPa (30 psi). Shan and Daniel (1991) and Daniel et al. (1993) also found that the hydraulic conductivity of water-hydrated GCLs did not show a drastic increase when permeated with a range of chemical solutions and organic liquids.

Petrov et al. (1997b) studied the effect of ethanol concentration on the hydraulic conductivity of a needle-punched GCL. For ethanol concentration $\leqslant 50\%$, the hydraulic conductivity of the GCL actually decreased, whereas the hydraulic conductivity progressively increased as the ethanol concentration increases above 50%. Petrov et al. (1997b) explained this behavior in terms of contrasting effects of viscosity and thickness of the adsorbed layer.

2. Experimental program

In order to evaluate the performance of GCLs in landfills or secondary containment facilities in coastal areas or areas with acid rain, a series of sequential permeation tests were conducted. The types of hydration/permeation liquids and the sequence they were applied were chosen to be representative of what GCLs might actually come across.

In addition, free swell tests of the bentonite in the GCLs were performed using the same array of liquids to help assessing the results of the hydraulic conductivity tests.

2.1. Geosynthetic clay liners

The GCLs used in this study are Bentomat® ST and Claymax® 200R, which are designated as GCL-A and GCL-B, respectively. The following descriptions of the GCLs are based on the information provided by the manufacturer (CETCO, 1997). GCL-A is comprised of a non-woven needle-punched geotextile that is needle punched again through a layer of bentonite into a woven slit-film geotextile. The bentonite content is $3.6 \, kg/m^2$. The water content of the "dry" bentonite in GCL-A is about 10–12%. In GCL-B, $3.6 \, kg/m^2$ of bentonite is glued between a woven geotextile above and an open-weave woven geotextile below. The thickness of both GCLs is about 6 mm when they are dry.

2.2. Hydration and permeation liquids

The liquids selected to hydrate and permeate the GCLs include tap water, acidic water, seawater, MSW leachate, and gasoline. Selected properties of these liquids are listed in Table 1.

The acidic water was prepared by adding hydrochloric acid to deionized-distilled water. The pH value was adjusted to 5.0, which corresponds to the pH of most acid rain. It has to be mentioned that in some of the regions suffering from heavy industrial pollution, the pH value of rainwater can even be as low as 4.5.

The seawater was retrieved from the water body near the seaside landfill of Hsinchu City, Taiwan. The MSW leachate was sampled from the treatment plant of the same landfill. The concentrations of the major constituents of the leachate are listed in Table 2.

2.3. Testing equipment and procedures

2.3.1. Free swell test

In order to obtain information on the response of the bentonite to the test liquids, a series of free swell tests were performed. The tests were conducted according to

Table 1
Water quality data of testing liquids

	DDW	Tap water	Acidic water	Seawater	MSW leachate
pH	7.08	6.93	5.07	7.93	7.35
Electrical conductivity (ms/cm)	0.02	0.226	0.277	30.6	9.0
$[Na^+]$ (M)		—	ND[a]	0.20	1.8×10^{-2}
$[Ca^{++}]$ (M)		—	5.0×10^{-4}	1.2×10^{-2}	2.7×10^{-4}
$[K^+]$ (M)		1.6×10^{-4}	6.5×10^{-5}	7.3×10^{-3}	1.0×10^{-2}

[a] Below detection limit.

Table 2
Water quality data of leachate sampled from Hsinchu City landfill

Item	Value (mg/l)	Item	Value (mg/l)
PH	7.43	Chlorides	959.2
Alkalinity	5750.5	Sulfates	23.7
Suspended solids	190.5	Fe	1.21
N as NH_3	810.2	Pb	0.11
TKN[a]	914.2	Zn	0.61
BOD	400.7	Cr	0.37
COD	1737.5	Cd	0.0037
BOD/COD	0.251	Cu	0.031

[a] TKN: Total Kjeldahl nitrogen.

ASTM D5890-95 except that the bentonite was allowed to swell in the liquids of interest as well. For each test, 2 g of oven-dried bentonite was put in a 100-ml graduated cylinder with 90 ml of hydration liquid. After approximately 18 h of hydration, the volume of the bentonite was measured.

2.4. Hydraulic conductivity test

The diameter of the GCL specimens for hydraulic conductivity tests was 100.0 mm (3.94 in). The tests were conducted with flexible-wall permeameters following the procedures described in ASTM D5887-95. Permeant interface devices (PID) were used as the reservoirs of the permeation liquids. The specimens were hydrated and backpressured to 516.8 kPa (75.0 psi) to enhance saturation. The effective stress on the specimens was maintained at 34.5 kPa (5.0 psi). Volume change of the specimens was monitored as an indicator of the degree of hydration. Typical hydration time was 48 h. For specimens hydrated with distilled deionized water and tap water, the hydration time was approximately a week.

According to Petrov et al. (1997a), the height of the GCL should be constant before terminating compatibility tests. In this study, the volume change of the specimens was monitored during both the hydration and the permeation periods by recording the volume change of water in the cell. At the end of all the hydraulic conductivity tests, the volume of the specimens had reached constant. In addition, the heights of all specimens were measured after the tests.

The sequence of hydration/permeation of the GCL specimens with various liquids is listed in Table 3. For permeation, the influent and effluent pressure was adjusted to give a head difference of 13.8 kPa (2.0 psi), which corresponded to a hydraulic gradient of about 150. For each test, the permeation of any single liquid continued until apparent equilibrium was established, i.e., the ratio of effluent flow rate to influent flow rate maintained at 1 ± 0.1 and the variation of computed hydraulic conductivity was $<25\%$ of the average value for four consecutive measurements. Chemical equilibrium condition was assessed using pH and electrical conductivity (EC) measurements as suggested by Shackelford et al. (1999).

Table 3
Liquid for each stage of permeation

Hydration	Permeation sequence 1	Permeation sequence 2
Deionized distilled water (DDW)	DDW	
Tap water (TW)	TW	
	Landfill leachate	
	Seawater	Gasoline
Landfill leachate	Landfill leachate	
Acidic water (pH = 5)	Acidic water	Landfill leachate
	Acidic water	Gasoline
Seawater	Seawater	Landfill leachate

3. Results and discussion

3.1. Results of free swell tests

The results of free swell tests are listed in Table 4. As described by the Guoy–Chapman theory (Gouy, 1910; Chapman, 1913) the swelling of bentonite is related to the cation valence of the solute, the electrolyte concentration and the dielectric constant of the solution. As expected, the bentonite soaked with seawater demonstrated the least swelling. The high electrolyte concentration of the seawater and the polyvalent cations in it inhibited the swelling of the bentonite. On the other hand, it is interesting to find that the bentonite hydrated by the acidic water swelled the most. It has to be mentioned that the pH of bentonite slurry ranges from 8 to 9, depending on the liquid/solid ratio of the slurry. Thus, a possible reason for this result is that the acid neutralized the alkalinity of the pore water, which allowed the bentonite to swell more. In addition, the bentonite hydrated with MSW leachate only swelled half as much as in deionized water, which is caused by the solutes in the leachate.

3.2. Results of hydraulic conductivity tests

Table 5 is a summary of the results of the hydraulic conductivity tests. The physical properties of the specimens measured after the tests are given in Table 6. It is interesting to note that the hydraulic conductivity of GCLs to acidic water and MSW leachate was as low as that to deionized water. Detail discussions of the hydraulic conductivity tests with various liquids are presented below.

3.2.1. Water
For the specimens permeated with both tap water and deionized water, the hydraulic conductivity of the specimens became steady relatively fast. For GCL-A and GCL-B specimens permeated with tap water, the hydraulic conductivity was

Table 4
Results of free swell tests on bentonite in the GCLs (ml/2 g)

Hydration liquid	GCL-A	GCL-B
Deionized distilled water	28.0	26.0
Tap water	28.5	24.0
Acidic water (pH = 5)	29.5	26.4
Landfill leachate	14.5	14.5
Seawater	6.0	5.5

Table 5
Results of sequential hydraulic conductivity tests[a]

Permeant	Hydraulic conductivity k (m/s)	
	GCL-A	GCL-B
Tap water	4.4×10^{-11}	4.8×10^{-11}
Deionized distilled water	2.7×10^{-11}	2.7×10^{-11}
Seawater	1.7×10^{-7}	1.2×10^{-8}
Acidic water (pH = 5)	2.5×10^{-11}	2.8×10^{-11}
Landfill leachate	3.0×10^{-11}	2.6×10^{-11}
Tap Water → Seawater	2.3×10^{-10}	1.1×10^{-10}
Tap Water → Leachate	3.7×10^{-11}	1.9×10^{-11}
Seawater → Leachate	1.5×10^{-9}	2.0×10^{-11}
Acidic water → Leachate	4.8×10^{-11}	2.3×10^{-11}
Acidic water → Gasoline	No flow	No flow
Tap Water → Seawater → Gasoline	No flow	No flow

[a] The hydraulic conductivity values listed are the results at the end of the tests.

Table 6
Physical properties of GCL specimens after hydraulic conductivity tests

Permeant	Thickness (mm)		Water content (w%)		Void ratio, e	
	GCL-A	GCL-B	GCL-A	GCL-B	GCL-A	GCL-B
Distilled deionized water	8.7	9.0	174.0	182.1	4.79	5.01
Seawater	5.7	5.4	93.0	84.9	2.56	2.33
Tap water → Seawater	7.4	5.8	107.8	94.4	2.96	2.60
Leachate	6.8	5.9	111.0	98.4	3.05	2.71
Tap water → Leachate	6.9	9.1	125.4	151.3	3.45	4.16
Seawater → Leachate	5.8	5.6	92.3	85.6	2.54	2.35
Acidic Water → leachate	9.3	8.1	157.1	142.8	4.32	3.93

4.4×10^{-11} and 4.8×10^{-11} m/s, respectively. The hydraulic conductivity to deionized water for both GCLs was both 2.7×10^{-11} m/s. However, at the end of permeation with water, the specimens could still be hydrating as indicated by the ratio of amount of effluent and influent liquid (Figs. 1 and 2). In addition, the
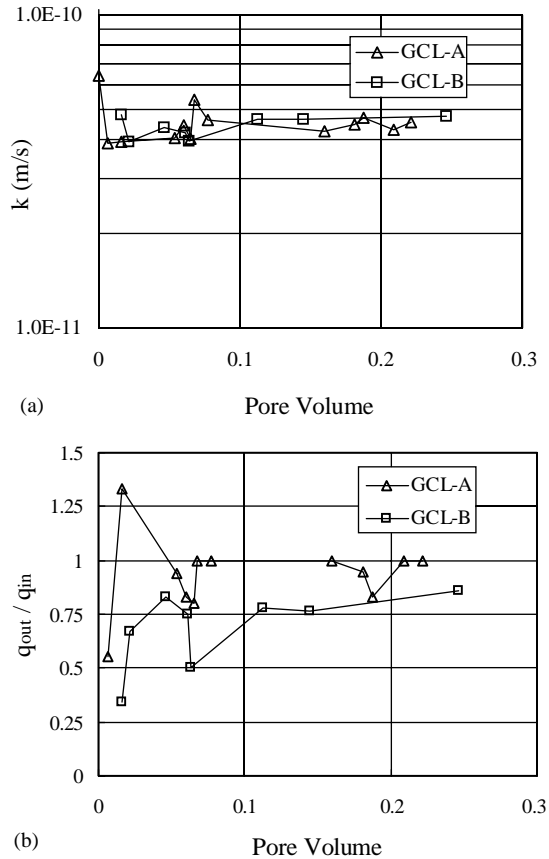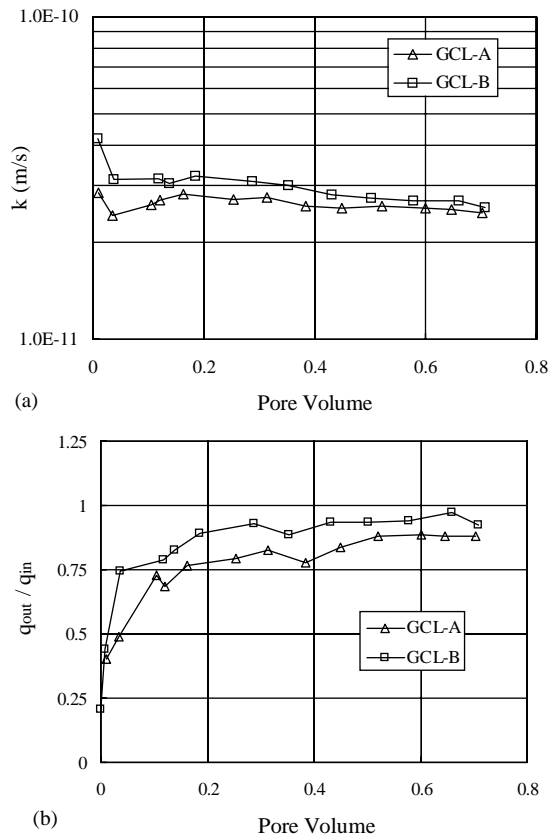
Fig. 1. Results of hydraulic conductivity tests with tap water. (a) Hydraulic conductivity, (b) ratio of q_{out}/q_{in}.

volume of the specimens were still increasing, although very slowly. For permeation with water, the hydraulic conductivity of both types of GCLs was almost the same.

3.2.2. Seawater

The hydraulic conductivity of GCL-A and GCL-B specimens directly permeated with seawater was 1.7×10^{-7} and 1.2×10^{-8} m/s, respectively. The results were part of the seawater→leachate series hydraulic conductivity tests. The hydraulic conductivity of both GCL specimens remained nearly constant during the permeation (Fig. 3). However, the hydraulic conductivity of GCL-A was 15 times that of GCL-B. The EC of the effluent kept decreasing through out the permeation and finally approached the EC of seawater (Fig. 3(b)). The pH value of the effluent decreased a little as the test went on, as shown in Fig. 3(c). The variations of the concentrations of Na^+, Ca^{2+}, and K^+ in the effluent are shown in Fig. 3(d). The

Fig. 2. Results of hydraulic conductivity tests with deionized water. (a) Hydraulic conductivity, (b) ratio of q_{out}/q_{in}.

trend of the variation of the cation concentrations was the same for GCL-A and GCL-B. At the beginning of the permeation, the concentration of Na^+ of the effluent liquid was greater than that in the seawater but gradually decreased to eventually lower than the concentration in seawater. On the other hand, the concentration of Ca^{2+} of the effluent liquid was constantly lower than that of seawater. Furthermore, the concentration of K^+ was constantly higher than that of seawater and can be concluded that K^+ ions in the bentonite were also being replaced. Obviously the cation exchange process kept on going on the surface the bentonite particles. The initial increase of Na^+ concentration and the overall ionic strength might have been the reason for the higher EC at the initial stage of the tests (Fig. 3(b)).

On the other hand, for permeation of water-hydrated GCL specimens with seawater, the hydraulic conductivity of the GCL specimens did not stop increasing until approximately 4 pore volumes of seawater had been permeated (Fig. 4(a)). For
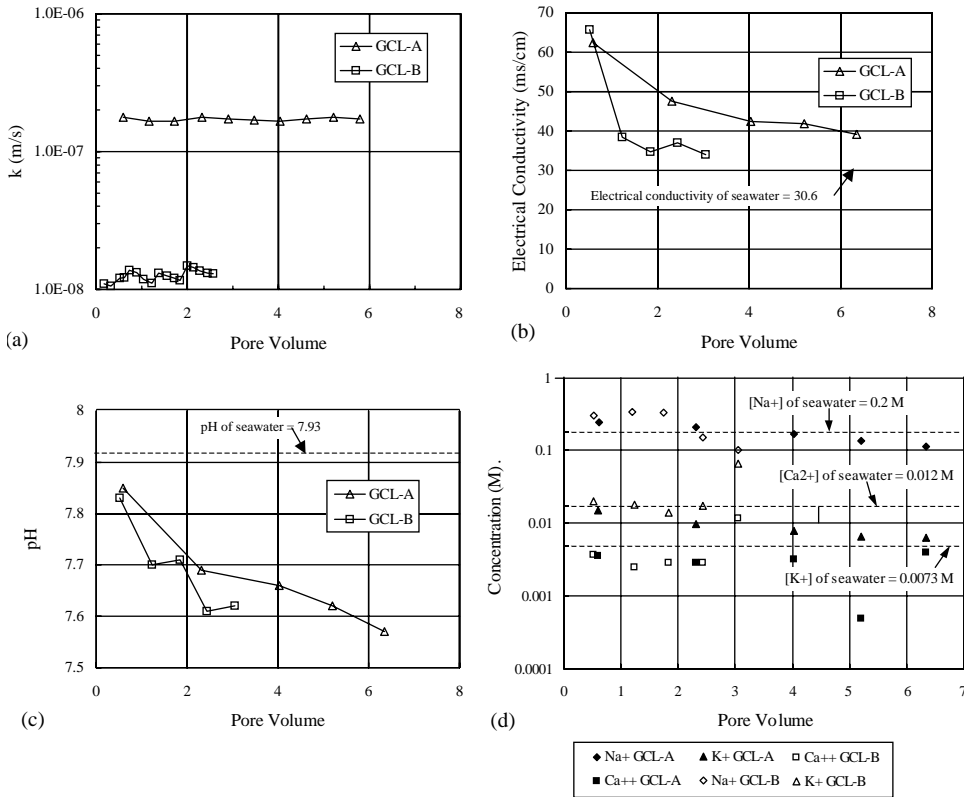
Fig. 3. Results of hydraulic conductivity tests with seawater. (a) Hydraulic conductivity, (b) variation of EC of the effluent liquid, (c) variation of pH of the effluent liquid, (d) concentration of cations in the effluent liquid.

GCL-A and GCL-B specimens, the hydraulic conductivity to seawater increased from 3.0×10^{-11} and 2.5×10^{-11} m/s to 2.2×10^{-10} and 1.2×10^{-10} m/s, respectively. These hydraulic conductivity values were much lower than when the GCL specimens were directly permeated with seawater. The rate of outflow (q_{out}) was greater than that of inflow (q_{in}) once the permeant had been switched from tap water to seawater. This phenomenon is similar to what Shan and Daniel (1991) reported when they permeated distill deionized water hydrated GCL with CaCl solution. The elevated ratio of q_{out}/q_{in} might have been caused by the shrinkage of the diffuse double layer of bentonite. The release of adsorbed water contributed to increased effluent flow rate. The ratio of q_{out}/q_{in} reached the maximum at about 1 pore volume of permeation (Fig. 4(b)) and maintained slightly greater then unity afterwards. In addition, during the permeation, the volume of the GCL specimens was constantly decreasing (Fig. 4(c)). The EC of effluent liquid showed a steep increase at the first stage of the tests and then gradually decreased (Fig. 4(d)). Finally the EC of the
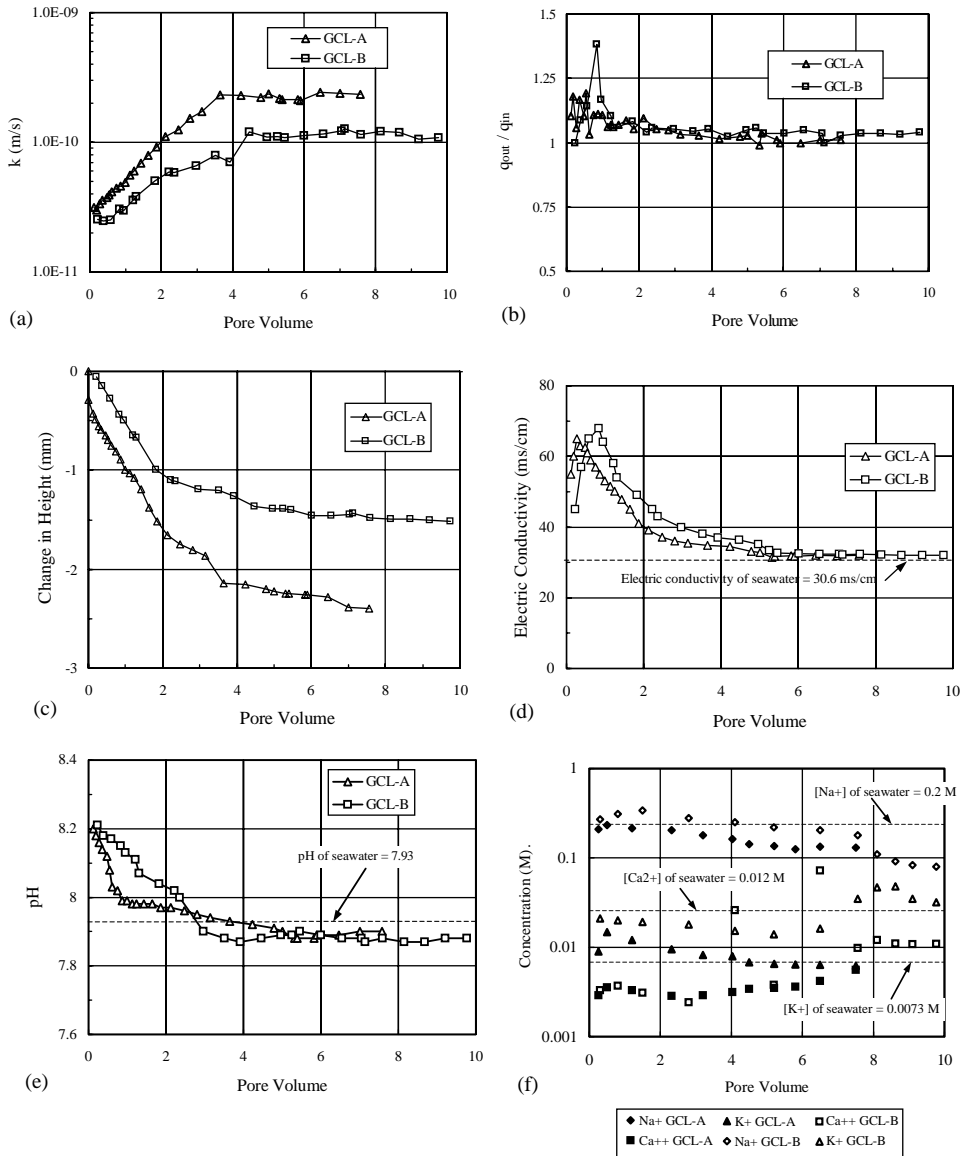
Fig. 4. Results of hydraulic conductivity tests on tap water-hydrated GCLs with seawater. (a) Hydraulic conductivity, (b) ratio of q_{out}/q_{in}, (c) volume change, (d) variation of EC of the effluent liquid, (e) variation of pH of the effluent liquid, (f) concentration of cations in the effluent liquid.

effluent liquid became almost the same as the influent seawater. The pH of the effluent started around 8.2 and then decreased continuously (Fig. 4(e)).

The peak value of the EC occurred after there was 1 pore volume of flow. It can be seen from Fig. 4(b) that the peak q_{out}/q_{out} ratio also occurred at about 1 pore

volume. The concentrations of Na^+, Ca^{2+}, and K^+ in the seawater were 4600, 480, and 290 mg/l (0.2, 0.012, and 0.0073 M), respectively. The presence of high valence cations and the high electrolyte concentration of the seawater caused the increase of the hydraulic conductivity, which has also been shown by other studies (Alther et al., 1985; Keren and Singer, 1988; Shan and Daniel, 1991; Dobras and Elzea, 1993; Gleason et al., 1997; Jo et al., 2001). Again, the exchange of cations on the surface of bentonite particles was the reason for the variation of EC of the effluent (Fig. 4(f)). In addition, the variation of the q_{out}/q_{out} ratio might be caused by the shrinkage of the diffuse double layer of bentonite particles.

However, as far as hydraulic conductivity is concerned, the results of this study demonstrated that hydrating the GCLs with fresh water could in some degree reduce negative impact of liquids such as seawater on bentonite. Therefore the hydraulic conductivity of the tap water-hydrated GCLs to seawater were lower than the hydraulic conductivity of seawater-hydrated GCLs.

3.2.3. Acidic water

When acidic water was used as the hydration and permeation liquid, the effect on the hydraulic conductivity was not significant (Fig. 5(a)). The EC of the effluent was much higher than that of the acidic water (Fig. 5(b)). This might have been caused by the release of some salts from the bentonite into the acidic water. The pH of the effluent liquid was monitored in that series of test (Fig. 5(c)). Since the GCL specimens were hydrated with acidic water from both influent and effluent sides, the pH of the effluent liquid showed a steady increase as more effluent liquid was collected. The increase of pH demonstrated that the bentonite has considerable buffering capacity. However, it is expected that long-term leaching by the acid liquid would ultimately exhaust the buffering capacity of the bentonite. As shown in Fig. 5(c) the pH of effluent showed a decreasing trend near the end of the tests. Had the hydraulic conductivity test been conducted longer the pH of the effluent should have been the same as the influent. However, as suggested by Jo et al. (2001) since the pH of acidic water used in this study was > 3, the hydraulic conductivity may still remain in the range of 10^{-11} m/s.

3.2.4. MSW leachate

The hydraulic conductivity of GCL specimens hydrated and permeated with MSW leachate was monitored continuously until at least 1 pore volume of leachate had permeated through the specimens. The hydraulic conductivity and the q_{out}/q_{in} ratio became steady soon after the permeation began (Fig. 6(a)). The final hydraulic conductivity of GCL-A and GCL-B to MSW leachate was 3.0×10^{-11} and 2.6×10^{-11} m/s, respectively. The EC of the effluent liquid decreased as the permeation went on while the pH remained almost constant (Figs. 6 (b) and (c)).

However, for GCL-A and GCL-B specimens prehydrated with tap water, the hydraulic conductivity of GCL-A and GCL-B to MSW leachate was 3.7×10^{-11} and 1.9×10^{-11} m/s, respectively. Switching the permeant to leachate did not lead to any significant increase of hydraulic conductivity (Fig. 7(a)). In addition, the q_{out}/q_{in}
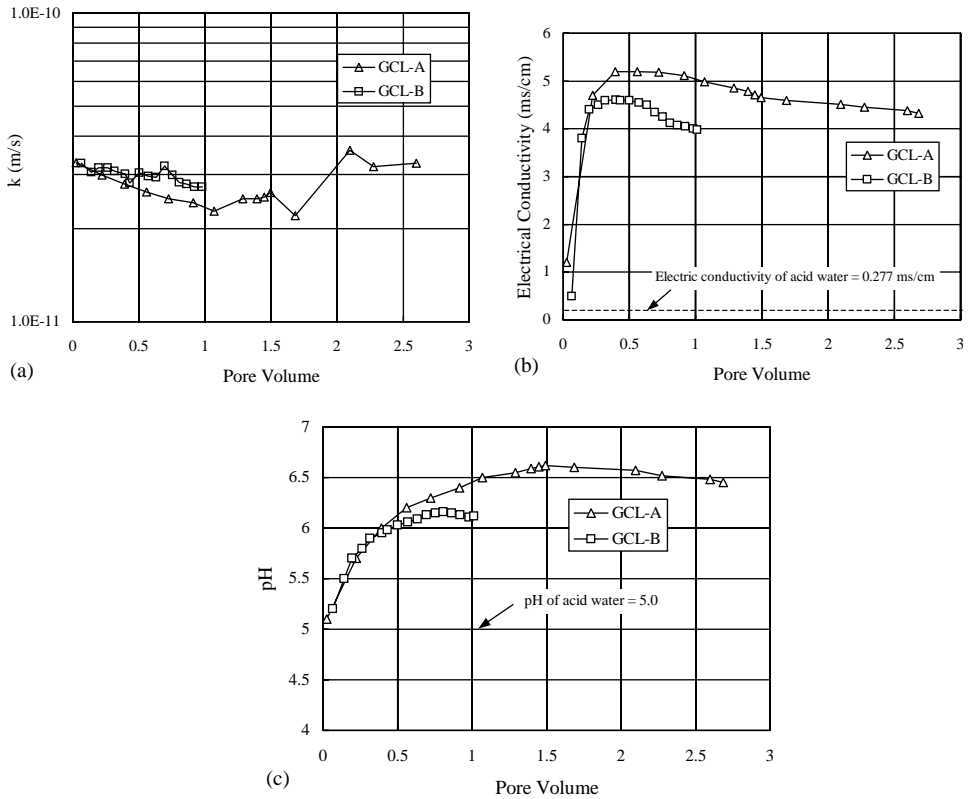
Fig. 5. Results of hydraulic conductivity tests with acidic water. (a) Hydraulic conductivity, (b) variation of EC of the effluent liquid, (c) variation of pH of the effluent liquid.

ratio remained close to 1. However, it is interesting to note that the EC (Fig. 7(b)) of the effluent liquid was higher than that shown in Fig. 6(b). The GCL specimens prehydrated with tap water seemed to release some salts into the permeant and caused the increase of EC.

This finding that the hydraulic conductivity of water-hydrated GCLs to MSW leachate remains almost unchanged agrees with the findings of Ruhl and Daniel (1997). Although the leachate contains considerable amount of various types of cations, the effect on the hydraulic conductivity is negligible since the concentrations of higher valence cations were relatively lower than the concentration of sodium ions. In the meantime, the pH of the effluent started out higher than the permeating MSW leachate and gradually reached equilibrium (Fig. 7(c)).

For the specimens hydrated and permeated with seawater first, the hydraulic conductivity decreased rapidly once the permeation with MSW leachate started. The hydraulic conductivity of GCL-A and GCL-B dropped from 1.7×10^{-7} and 1.2×10^{-8} m/s to 1.5×10^{-9} and 2.0×10^{-11} m/s, respectively (Fig. 8(a)). The
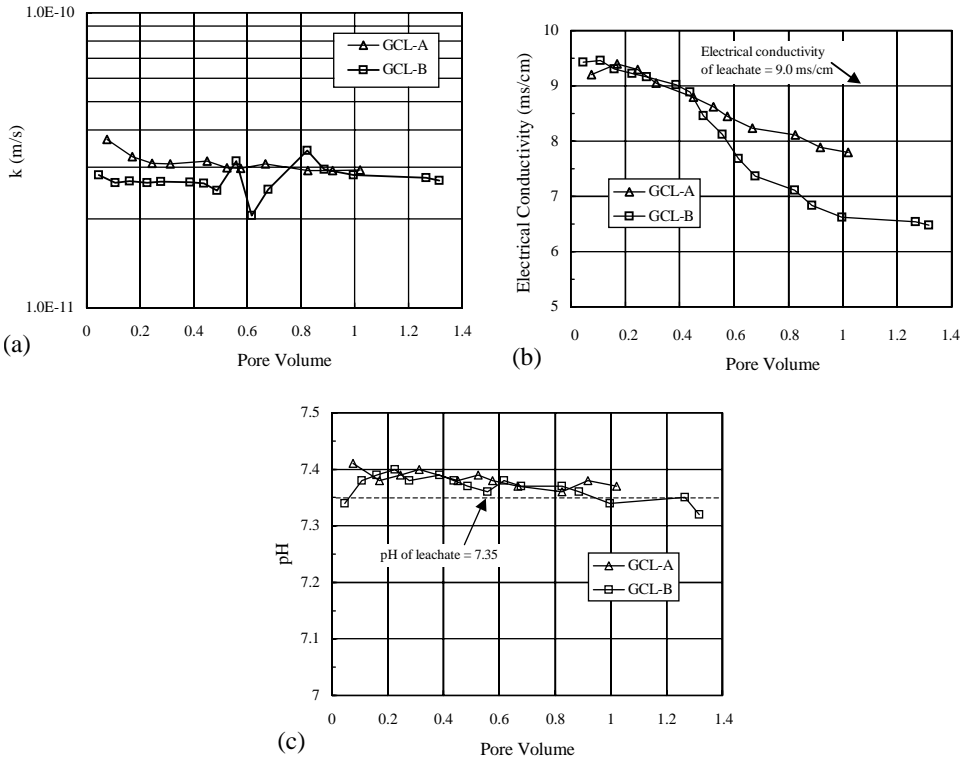
Fig. 6. Results of hydraulic conductivity tests with MSW leachate. (a) Hydraulic conductivity, (b) variation of EC of the effluent liquid, (c) variation of pH of the effluent liquid.

hydraulic conductivity of seawater-hydrated GCL-A to the MSW leachate was much higher than GCL-B. Furthermore, the q_{out}/q_{in} ratio became <1 during the permeation of MSW leachate (Fig. 8(b)). However, the q_{out}/q_{in} ratio maintained close to 1.0 and there was no significant volume change observed. The reason for the dramatic decrease of hydraulic conductivity may have to do with the re-hydration of the bentonite by the MSW leachate. This can be indicated by the increase of the volume of the GCL specimens (Fig. 8(c)). In the meantime, the EC of effluent experienced a significant decrease when the permeant was switched from seawater to MSW leachate (Fig. 8(d)). Finally, it has to be pointed out again that seawater had a more significant effect on GCL-A since the hydraulic conductivity of seawater-hydrated specimen to MSW leachate was much higher than that for GCL-B. Furthermore, judging from the results of EC and pH measurement, the tests were near equilibrium at the end of the tests (Figs. 8(d) and (e)).

For the GCL specimens hydrated with acidic water, the results of the hydraulic conductivity tests to MSW leachate are shown in Fig. 9. The hydraulic conductivity of the specimens increased after the permeant had been switched to the MSW
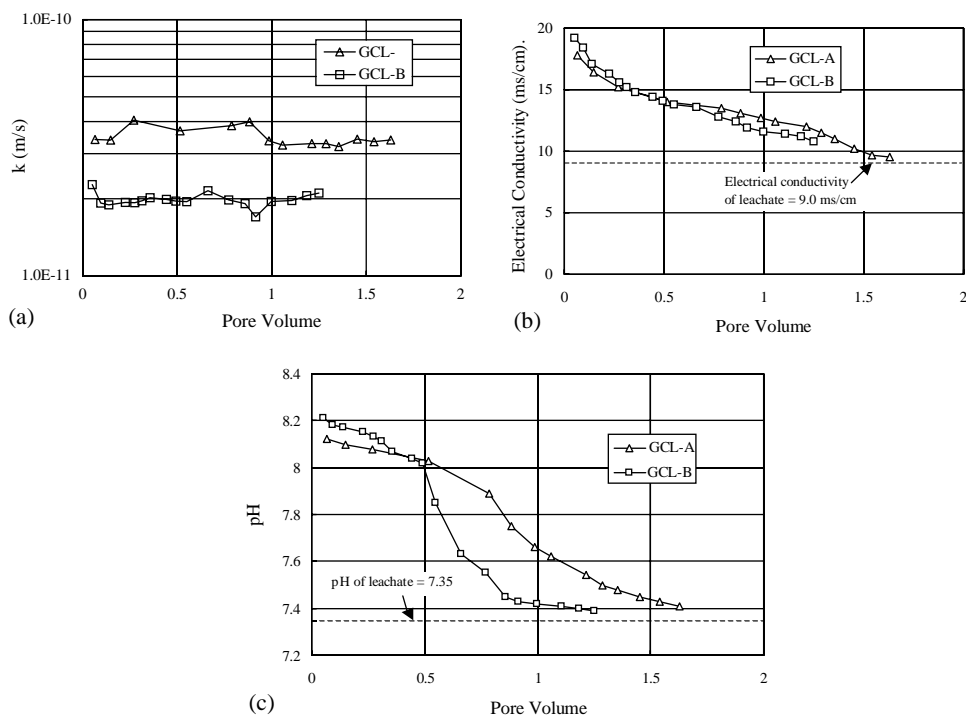
Fig. 7. Results of hydraulic conductivity tests on tap water-hydrated GCLs with MSW leachate. (a) Hydraulic conductivity, (b) variation of EC of the effluent liquid, (c) variation of pH of the effluent liquid.

leachate. The final values of hydraulic conductivity of GCL-A and GCL-B specimens to MSW leachate were 4.8×10^{-11} and 2.3×10^{-11} m/s, respectively (Fig. 9(a)). The q_{out}/q_{in} ratio exhibit some fluctuation during the initial stage of permeation with the MSW leachate but as the test progressed the average value was close to 1.0 (Fig. 9(b)). The reason for the fluctuation of the q_{out}/q_{in} ratio was not clear. It might have been caused by the variation of the amount of adsorbed water in the diffuse double layer resulted from the cation exchange process when the MSW leachate was permeated to replace seawater or the clogging of pores by suspended solids and microorganisms in the MSW leachate. Furthermore, the MSW leachate was close to fully replace the acidic water at the end of the permeation, since the EC of the effluent liquid had almost reached equilibrium (Fig. 9(c) and (d)).

In general, the hydraulic conductivity to MSW leachate for GCLs hydrated with leachate, tap water, seawater, and acidic water are all very similar. The only exception is the case when GCL-A was prehydrated with seawater before permeation of MSW leachate.

To sum up, it can be concluded that despite the difference of hydration liquids, the hydraulic conductivity of GCL specimens to MSW leachate were all still very low.
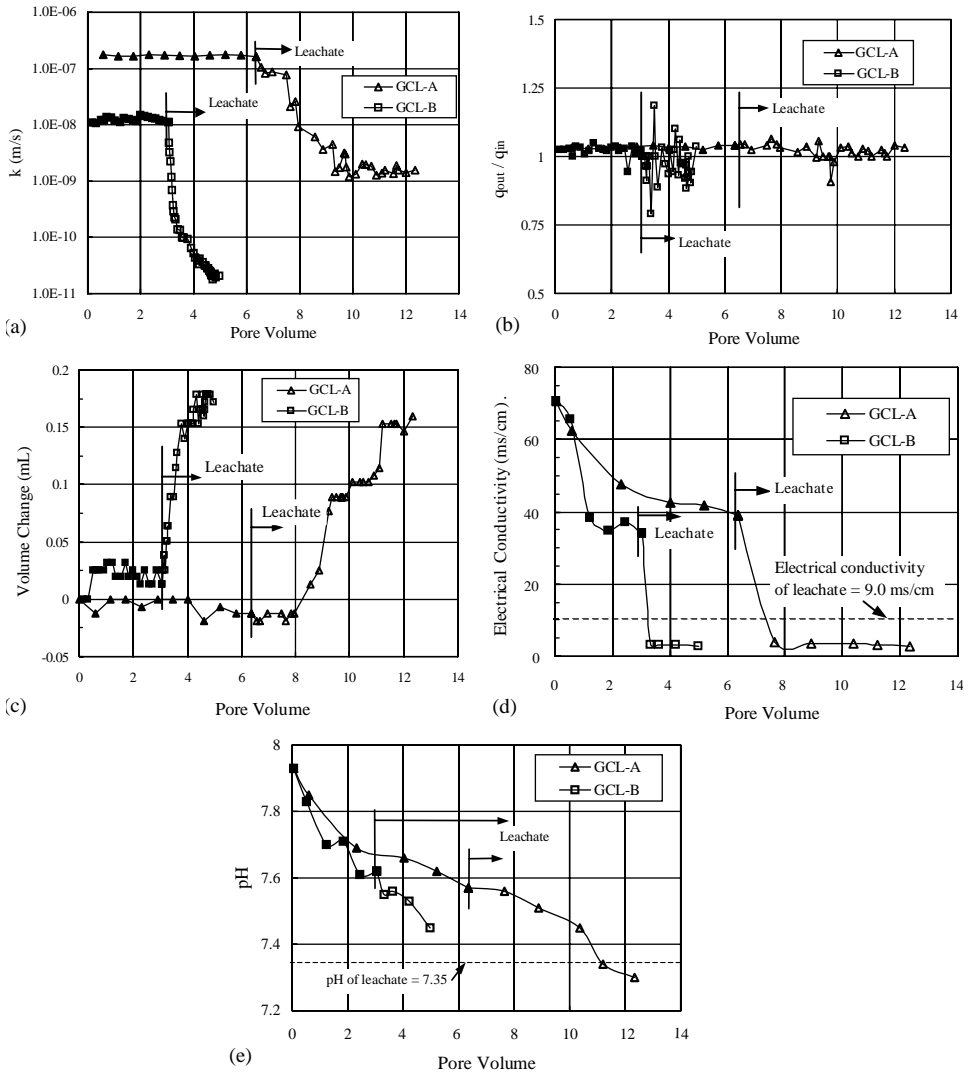
Fig. 8. Results of hydraulic conductivity tests on seawater-hydrated GCLs with MSW leachate. (a) Hydraulic conductivity, (b) ratio of q_{out}/q_{in}, (c) volume change, (d) variation of EC of the effluent liquid, (e) variation of pH of the effluent liquid.

3.2.5. Gasoline

For the tap water–seawater–gasoline series, which was continued from the tests shown in Fig. 1, the effluent liquid collected after switching to gasoline was <0.1 pore volume. The small volume permeated through the GCL specimens came from the acidic water or seawater in the porous disks at the influent end. The hydraulic gradient imposed was not able to overcome the entry pressure such that the gasoline cannot enter the pores. The permeation with gasoline showed that the GCL
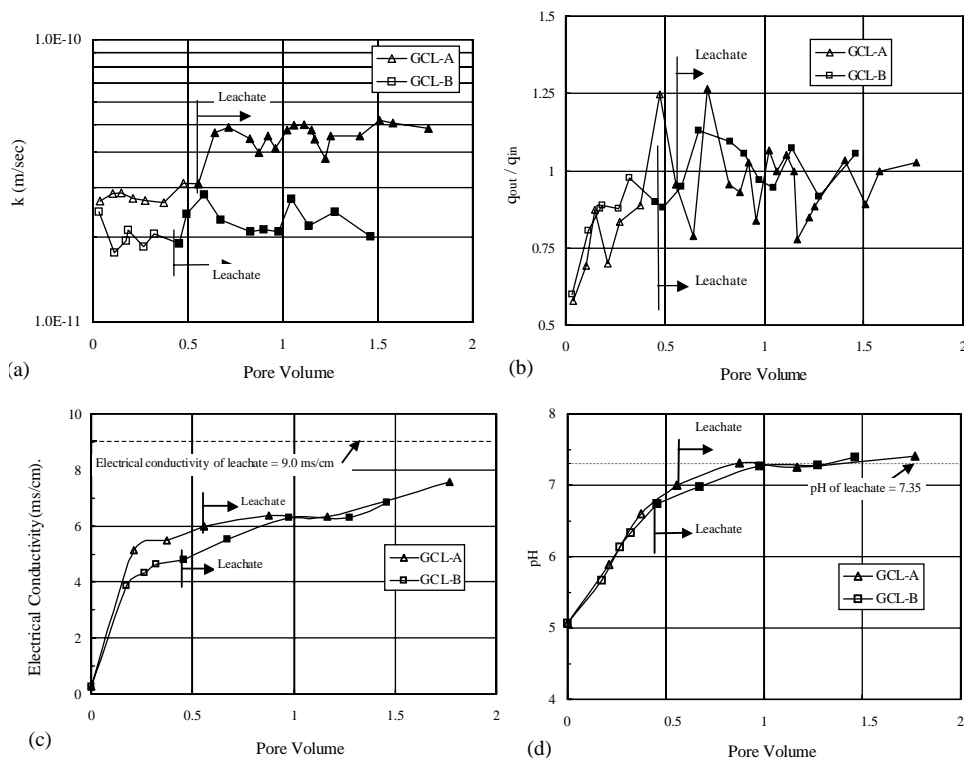
Fig. 9. Results of hydraulic conductivity tests on acidic water-hydrated GCLs with MSW Leachate. (a) Hydraulic conductivity, (b) ratio of q_{out}/q_{in}, (c) variation of EC of the effluent liquid, (d) variation of pH of the effluent liquid.

specimens hydrated with acidic water was impermeable to gasoline. The hydraulic conductivity tests with acidic water shown in Fig. 5 were the first stage of this series. After the permeant had been switched from acidic water to gasoline, only 0.2 pore volume of effluent was collected before the permeation completely stopped. The tests were continued for at least 3 weeks after the final measurement of hydraulic conductivity was made. Thus it can be concluded that gasoline was not able to permeate through the GCL specimens hydrated with water, whether the water is seawater or acidic water. It is suspected that diffusion of gasoline into the pore water may eventually cause the hydraulic conductivity of the GCL specimens to increase significantly due to the low dielectric constant of the gasoline. However, it would require further hydraulic conductivity tests with much longer permeation duration to access the effect.

3.2.6. Correlation with the results of the free swell tests

The results of hydraulic conductivity tests are closely related to the results of free swell tests. The hydraulic conductivity of the GCL specimens was lower when
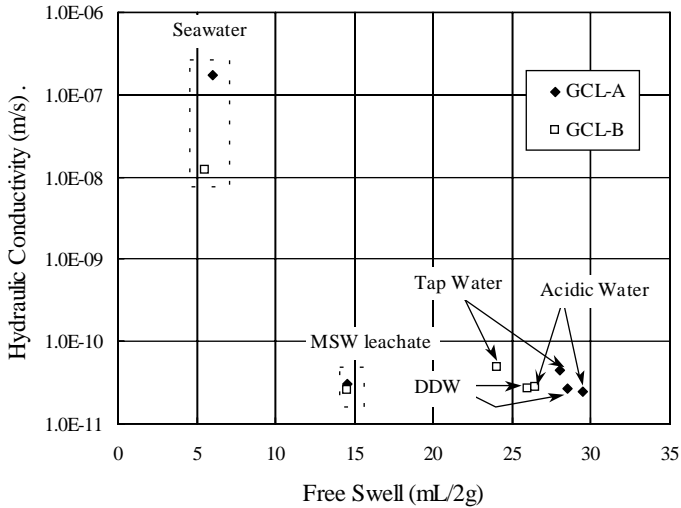
Fig. 10. Relation between the results of hydraulic conductivity tests and free swell tests.

permeated with the liquids that caused the bentonite to swell more (Fig. 10). However, the chemistry of the permeant is not the only factor that controls the hydraulic conductivity. For example, the suspended solids and microorganisms in MSW leachate could further lower the hydraulic conductivity of the GCLs.

4. Practical implications

The results of the study provide some insight on application of GCLs in landfills and secondary containment systems in coastal area and area with acid rain.

When GCLs are installed as the hydraulic barriers in the final covers, they should be able to minimize the infiltration of water into the landfills effectively, even if the infiltration liquid is acid rain water. For GCLs in the lining systems at the bottom of landfills, they will remain effective to impede the leachate advection even if they are hydrated with seawater or the leachate itself.

For GCLs serving as a barrier in secondary containment systems, they would remain effective in containing the gasoline or other organic liquids as long as they had been hydrated with water no matter whether the water is acid rain water or seawater.

5. Summary

The effect of pore liquid on the engineering properties of two GCLs was investigated in this study. One of the GCLs has internal reinforcing fibers while the other does not.

The hydraulic conductivity of both GCLs depends on the chemistry of both the hydration liquid and the permeant. As long as the GCLs are hydrated or permeated with aqueous solution, the hydraulic conductivity will remain low.

For GCL specimens that had been hydrated and permeated with aqueous solutions, the hydraulic conductivity was controlled by the last permeation liquid. For permeation with gasoline, the results showed that as long as the GCLs were hydrated with aqueous solutions, gasoline would not be able to permeate through them since the hydraulic head difference was lower than the entry pressure. Therefore, it can be concluded that even if the GCLs were hydrated with seawater, acid rain water, or leachate, they would remain to be effective hydraulic barrier to leachate and gasoline.

Furthermore, the results of free swell tests can be used to predict the effect of hydration liquid or permeant on the hydraulic conductivity of GCLs. The larger the free swell of the bentonite, the lower the hydraulic conductivity.

To sum up, the GCLs can served as effective hydraulic barrier for applications in landfills and secondary containment systems where acidic water, seawater, or leachate, instead of fresh water, is the hydration liquid.

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