Geosynthetic clay liner (GCL) – chemical compatibility by hydraulic conductivity testing and factors impacting its performance

Robert J. Petrov and R. Kerry Rowe

Abstract: The results of confined swell, consolidation, and hydraulic conductivity tests on a needle-punched geosynthetic clay liner (GCL) are reported. The effects of permeant (distilled water, aqueous single salt solutions with concentrations between 0.01 and 2.0 M NaCl, and a synthetic municipal solid waste (MSW) leachate), static confining stress, hydrating medium, and degree of bentonite hydration at the time of the application of the confining stress are examined. Increases in the permeant salt concentration and decreases in the magnitude of the confining stress caused increases in the hydraulic conductivity. It is shown that high salt concentrations in the hydrating fluid increased the hydraulic conductivity. The GCLs permeated with 0.6 and 2.0 M NaCl solutions were more permeable than GCLs initially hydrated with water. The hydrating fluid was not as critical for permeation of 0.1 M NaCl. The effect of the degree of bentonite hydration at the time of the application of the confining stress was also found to be significant, highlighting the hydraulic benefits of maximizing overburden stress prior to GCL hydration. Tests performed using a synthetic MSW leachate gave results comparable to those obtained for aqueous salt solutions between 0.2 and 0.8 M NaCl. Practical implications are discussed.

Key words: geosynthetic clay liner (GCL), hydraulic conductivity, compatibility, hydrating medium, confinement, leachate.

Résumé :

On rapporte ici les résultats d’essais de gonflement sous confinement, d’essais de consolidation et de conductivité hydraulique effectués sur une membrane argile-géosynthétique (MAG) aiguilletée. On a examiné les effets du liquide de percolation (eau distillée, solutions aqueuses salines avec des concentrations en NaCl de 0,01 et 2,0 M, lixiviat synthétique de type déchets municipaux), ainsi que les effets de la contrainte statique, du liquide hydratant et du degré d’hydratation de la bentonite à l’instant de l’application de la pression de confinement. L’augmentation de la concentration en sel de la solution et la diminution de la pression de confinement ont entrainé une augmentation de la conductivité hydraulique. On a aussi montré que des concentrations en sel élevées dans le liquide hydratant augmentent la conductivité hydraulique. Les MAG soumises à des solutions de NaCl à des concentrations de 0,6 et 2,0 M étaient plus perméables que les MAG initialement hydratées à l’eau. Le liquide hydratant n’était pas un facteur aussi critique pour des circulations de fluide à 0,1 M NaCl. On a également constaté l’importance du degré d’hydratation de la bentonite lors de l’application de la pression de confinement, ce qui souligne les avantages hydrauliques qu’il y a à maximiser la contrainte verticale avant l’hydratation de la membrane. Les essais effectués avec le lixiviat synthétique ont donné des résultats comparables à ceux obtenus avec les solutions salines entre 0,2 et 0,8 M NaCl. On discute finalement les conséquences pratiques de ces essais.

Mots clés : membrane argile-géosynthétique (MAG), conductivité hydraulique, compatibilité, milieu hydratant, confinement, lixiviat.
[Traduit par la rédaction]

Introduction

Geosynthetic clay liners (GCLs) are bentonite-based liners that are gaining acceptance for use as hydraulic barriers in containment and sealing applications. In certain situations, GCLs may have advantages over compacted clay liners (see Koerner and Daniel 1995); however, there is a need to evaluate both the potential susceptibility of GCLs to increases in hydraulic conductivity when exposed to some organic and inorganic “leachates” (see Shan and Daniel 1991; Petrov et al. 1997*a*, 1997*b*) and their effectiveness as a diffusion barrier, prior to their application in base sealing (liner) systems. Diffusive transport of chemical species through GCLs is beyond the scope of this paper; however, it should be recognized that diffusion will in some circumstances dominate over advective transport. For example, premature arrival of the contaminant front in the effluent during hydraulic conductivity testing was primarily attributed by Petrov et al. (1997*a*) to a diffusion-dominated transport mechanism through the relatively thin GCL samples. Similarly, Rowe et al. (1997) found that, as a result of diffusion, “breakthrough” could be expected in less than 1 day.

Even at relatively high void ratios, the natural sodium (Na^+) bentonite used in North American manufactured GCLs typically maintains reasonably low hydraulic conductivity values

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when permeated with potable water. However, it is well known that smectite-rich soils can undergo significant increases in hydraulic conductivity when exposed to some leachates (see Mesri and Olson 1971; D'Appolonia 1980; Anderson et al. 1985). Although important work on clay–leachate compatibility has been conducted on a number of soil types by several investigators (see Mitchell and Madsen 1987; Mitchell 1993; Rowe et al. 1995), Quigley (1993) states that "since they (bentonites) are very susceptible to double layer and c-axis contraction, bentonites are the most temperamental of the barrier clays and have not received nearly enough laboratory and field study." Mitchell et al. (1995) also identify the need to consider the potential change in the hydraulic properties of bentonite in GCLs due to interaction. For liner components such as GCLs to adequately perform their design function, it is important to identify through appropriate laboratory hydraulic conductivity tests the potential hydraulic conductivity that would be expected when exposed to the intended leachate under simulated field conditions. In addition, there has been a paucity of information specifically addressing the long-term compatibility characteristics (i.e., specifically tests run to chemical equilibrium) of GCLs. Previous studies investigating the effect of some inorganic and organic permeants on the hydraulic conductivity of GCLs include Shan and Daniel (1991), Daniel et al. (1993), Rad et al. (1994), Heyer (1995), and Petrov et al. (1997*a*, 1997*b*).

This paper examines a number of factors that can potentially influence the hydraulic conductivity of a needle-punched geosynthetic clay liner. Specifically, the objectives of this paper are threefold: (1) examine the effect of prehydration versus posthydration confinement on the bulk void ratio; (2) discuss the effects of varying concentrations of NaCl solutions and a synthetic municipal solid waste (MSW) leachate on some bentonite index properties and the implications with respect to clay–chemical interaction; and (3) investigate the effect, on the hydraulic conductivity of the GCL, of the concentration of a single salt solution (NaCl), the static confining stress, the hydrating medium, prehydration versus posthydration confinement, and a synthetic MSW leachate.

Bulk GCL void ratio

It is important to recognize that the manufacturing process usually produces some spatial variability in the mass of bentonite throughout any given GCL roll. This variability influences some test results, hence it is useful to be able to separate the effects of variability in bentonite mass from those due to other factors. Both the hydrated GCL height, H_{GCL}, and the height of solids in the GCL (bentonite and geotextile), H_{s}, will vary from one GCL sample to the next because of changes in the mass of bentonite per unit area (M_{BENT}). Petrov et al. (1997*b*) demonstrated that, although the hydraulic conductivity of the GCL is related to both the bulk GCL void ratio, e_{B}, and H_{GCL}, a better correlation is observed with respect to e_{B}, which is defined as the ratio of the volume of voids to the volume of solids in the GCL (including both the bentonite and geotextiles) and is calculated as follows:

$$[1] \qquad e_{\mathrm{B}} = \frac{H_{\mathrm{GCL}} - H_{\mathrm{s}}}{H_{\mathrm{s}}}$$

$$[2] \qquad H_{\mathrm{s}} = \frac{M_{\mathrm{BENT}}}{\rho_{\mathrm{s}}(1 + w_{\mathrm{o}})} + \frac{M_{\mathrm{GEO}}}{\rho_{\mathrm{sg}}}$$

where M_{BENT} and M_{GEO} are the mass per unit area of the bentonite and geotextiles, respectively, prior to testing; ρ_{s} and ρ_{sg} are the densities of the bentonite solids and geotextile polymer solids (polypropylene here), respectively; and w_{o} is the initial bentonite moisture content. In the following discussion, the term bulk GCL void ratio will be abbreviated to void ratio for simplicity of presentation.

Materials and methods

All laboratory tests described in this paper were conducted on a GCL specified to contain a minimum of 3500 g/m^2 of essentially dry, natural, Na$^+$ bentonite sandwiched between nonwoven polypropylene geotextiles and held together by needle-punching. The initial unconfined height of the GCL ranged from about 5 to 7 mm, and the initial bentonite moisture content averaged 8%. The buff-coloured powder bentonite taken from the GCL had a high activity ($A_{\mathrm{c}} = 5.3$) and contained mostly smectite (91%) with small amounts of quartz (5%), feldspar (3%), and carbonate (1%). About 70% of the measured cation exchange capacity of 86 mequiv./100 g consisted of Na$^+$.

Additional information about the GCL and complete details pertaining to specimen preparation, installation and test procedures employed for one-dimensional (1D) confined swell, consolidation, and hydraulic conductivity tests, and descriptions of the apparatus are given elsewhere (see Petrov 1995; Petrov et al. 1997*a*, 1997*b*). Briefly, the 1D confined swell and consolidation tests were conducted in a standard oedometer with distilled water as the hydrating medium. Prehydration confinement (confined swell tests) involved loading the GCL to the desired confining stress prior to bentonite hydration and GCL swell. Posthydration confinement (consolidation tests) involved allowing the essentially dry GCL to hydrate and swell under a low confining stress of 6 kPa until its height was constant with time, after which the confining stress was increased incrementally (i.e., the confining stress was doubled every 48 h). Sample consolidation was monitored with time. The 6 kPa confining stress represents 30 cm of overburden normally recommended by manufacturers prior to hydrating the GCL. For a given overburden stress, the results from the prehydration and posthydration confinement tests are considered in many practical applications to provide upper and lower bound GCL properties as discussed later in this paper.

The majority of hydraulic conductivity tests reported in this paper were conducted in the constant flow rate, fixed-ring (FR) permeameter designed by Fernandez (1989) for testing inactive compacted soils. For comparison purposes, the results from hydraulic conductivity tests conducted in both a double-ring (DR) and flexible-wall (FW) permeameter which were described by Petrov et al. (1997*a*) are also shown. Petrov et al. examined the effect of permeameter type and the potential for preferential sidewall flow in the fixed-ring apparatus and found that hydraulic conductivity values obtained in the fixed-ring apparatus were consistent with similar tests conducted in the double-ring and flexible-wall permeameters for the static confining stresses, hydrating mediums, and concentration of aqueous NaCl solutions considered. Thus for the range of confining stresses and permeants considered in this paper, the fixed-ring apparatus was regarded as an appropriate apparatus to obtain representative GCL hydraulic conductivity values. It has advantages over the other permeameters in terms of the ability to monitor the GCL thickness (and hence void ratio) during the test.

The fixed-ring apparatus that was used (Fernandez and Quigley 1991) is a consolidation-type permeameter. The GCL was cut using a specially fabricated steel cutting shoe with a sharp circumferential edge, having the same inner diameter as the fixed-ring cell (54 mm), and placed into the cell where it was sandwiched between upper and lower porous stones. The desired static confining stress (hereafter called the confining stress) was applied by a system of springs, and the GCL was hydrated with the reference (or initial) permeant under a hydrating reservoir head of 2–4 cm for a specified period until the GCL height was constant with time. The degree of saturation was not measured in these tests; however, in other similar tests on the same GCL, the degree of saturation exceeded 95% in all cases where measurements were made. For the tests described in this paper, the hydrating medium and reference permeant were distilled water, varying concentrations of NaCl solutions, or the synthetic MSW leachate. The apparatus was equipped with dial gauges that monitored the GCL height prior to, during, and at termination of the tests. Under a constant flow rate, the reference permeant was forced through the GCL, the induced head drop was measured by an in-line pressure transducer, and the GCL hydraulic conductivity was calculated using Darcy’s law.

As previously discussed in detail by Fernandez and Quigley (1991) and Petrov et al. (1997*a*), testing in the constant flow rate fixed-ring apparatus may result in high and variable seepage-induced stresses and small changes in the confining stresses (due to changes in GCL height) from a value of σ_w' when permeated with water to a final value of σ_f' after permeation with the NaCl solutions or the synthetic MSW leachate. For the tests reported herein, the final confining stresses, σ_f', were within 14% of the confining stress for the reference permeant (i.e., distilled water), σ_w'. Most of the test results for water permeation are reported by Petrov et al. (1997*b*).

Petrov (1995) examined the effects of increasing seepage-induced stresses due to increasing flow rates by a factor ranging from 2 to 11 and found that the effect on the hydraulic conductivity was not significant despite some small consolidation. Based on this, high hydraulic gradients and hence high seepage-induced stresses often were used to expedite tests so that chemical equilibrium or near-chemical equilibrium could be achieved within reasonable time periods.

The applied confining stresses for both water permeation, σ_w', and salt water permeation, σ_f', were about 3, 35, and 110 kPa. The NaCl concentrations, *C*, in aqueous single salt solutions were 0.01, 0.1, 0.6, and 2.0 M. A NaCl concentration of 0.1 M (5.84 g/L) corresponds to the total dissolved salt content in some MSW leachates, 0.6 M NaCl (35.1 g/L) has roughly the salinity of seawater, and 2.0 M NaCl (116.9 g/L) represents a brine solution. A synthetic MSW leachate was selected to chemically simulate cation concentrations at the upper end of the typical range for MSW leachate in Ontario (see Rowe 1995) and hence provide insight into clay – MSW leachate compatibility without the complicating influence of potentially beneficial microbial clogging of soil pores during laboratory hydraulic conductivity testing. The chemical composition of the synthetic MSW leachate is given in Table 1.

Table 1. Composition of the synthetic MSW leachate.

Component	Concentration
Acetic acid	4000
Propionic acid	3000
Butyric acid	500
Na^+	1615
K^+	354
NH_4^+	618
Ca^{2+}	1224
Mg^{2+}	473
Cl^-	4414
HCO_3^-	4876
NO_3^{2-}	40
SO_4^{2-}	137
HPO_4^{2-}	18
CO_3^{2-}	156
$CO(NH_2)_2$	772
E_h (adjusted by $Na_2S{\cdot}9H_2O$)	–328 mV
pH (adjusted by NaOH)	6.23
Trace metal solution (2 mL added per 1 L synthetic MSW leachate)	
$FeSO_4{\cdot}7H_2O$	2000
H_3BO_3	50
$ZnSO_4{\cdot}7H_2O$	50
$CuSO_4{\cdot}5H_2O$	40
$MnSO_4{\cdot}H_2O$	500
$(NH_4)_6Mo_7O_{24}{\cdot}4H_2O$	50
$Al_2(SO_4)_3{\cdot}16H_2O$	30
$CoSO_4{\cdot}7H_2O$	150

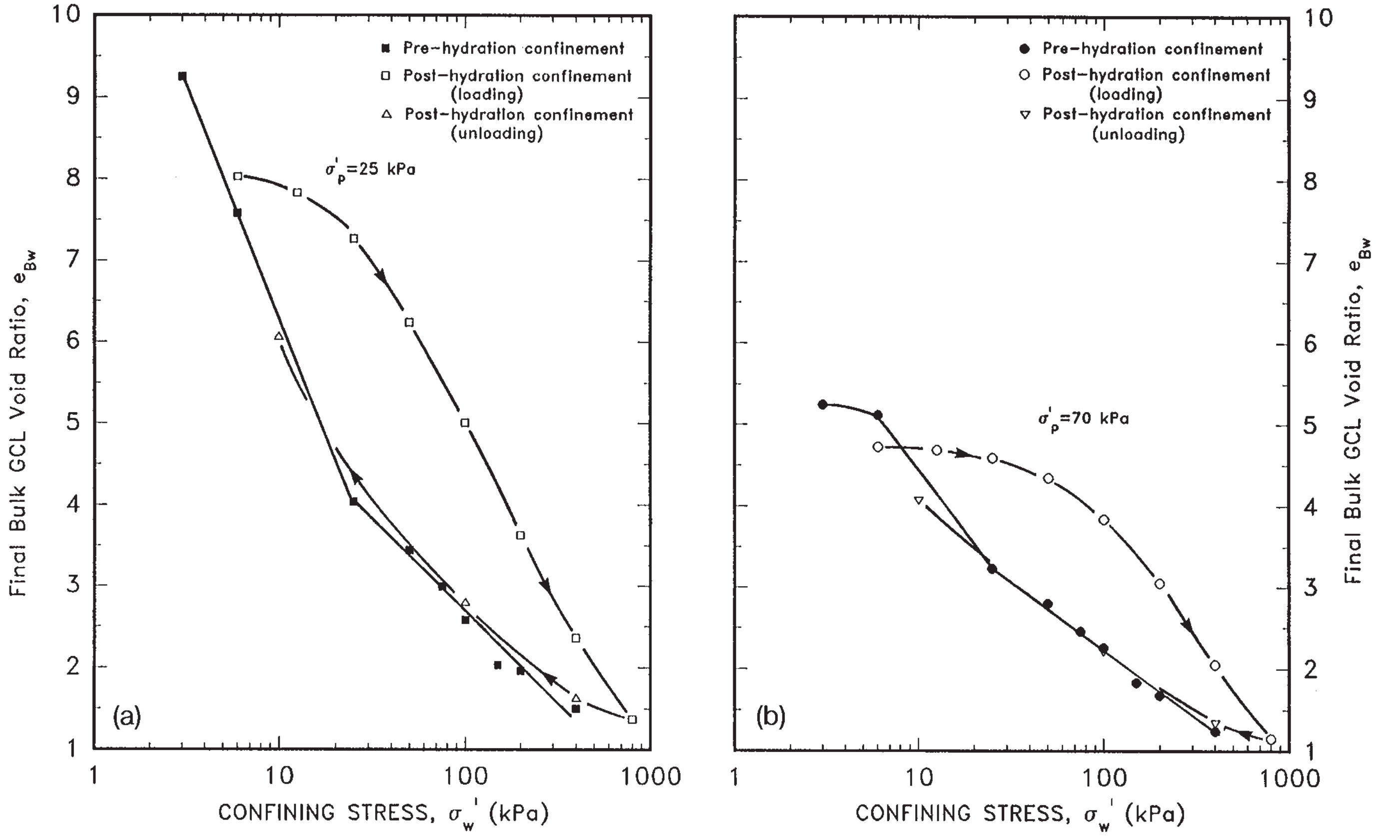
Note: All concentrations are in mg/L except for pH and E_h and are from L. Hrapovic (personal communication).

Prehydration confinement versus posthydration confinement

Petrov et al. (1997*b*) demonstrated that the void ratio, e_{Bw}, for GCLs hydrated and permeated with water was dependent on factors such as the confining stress, σ_w', and the presence (or absence) of needle-punching. To examine the effect of the level of bentonite hydration at the time of application of the confining stress, a series of confined swell (prehydration confinement) and consolidation (posthydration confinement) tests were performed and compared for both standard needle-punched GCLs (called fibre samples herein) and GCLs where the needle-punched fibres had been intentionally removed (called fibre-free samples herein).

In practice, GCLs may be intentionally prehydrated, they may be hydrated by precipitation, or they may hydrate by removing water from adjacent soils (e.g., for GCLs underlying geomembranes). As noted by Daniel et al. (1993), the level of bentonite hydration can significantly affect the hydraulic conductivity when permeated with some pure organics. Because GCLs are often hydrated prior to application of high overburden stresses, the void ratios obtained from confined swell tests may not be representative of field values at these high stresses. However, the confined swell (prehydration confinement) tests

Fig. 1. The effect of prehydration versus posthydration confinement on the bulk void ratio for (*a*) fibre-free and (*b*) fibre samples.



are valuable because the void ratios corresponding to a given confining stress likely represent lower bound void ratios (and hence hydraulic conductivities) representative of the GCL. An upper bound of void ratios at a given confining stress may be obtained from the laboratory consolidation (posthydration confinement) tests.

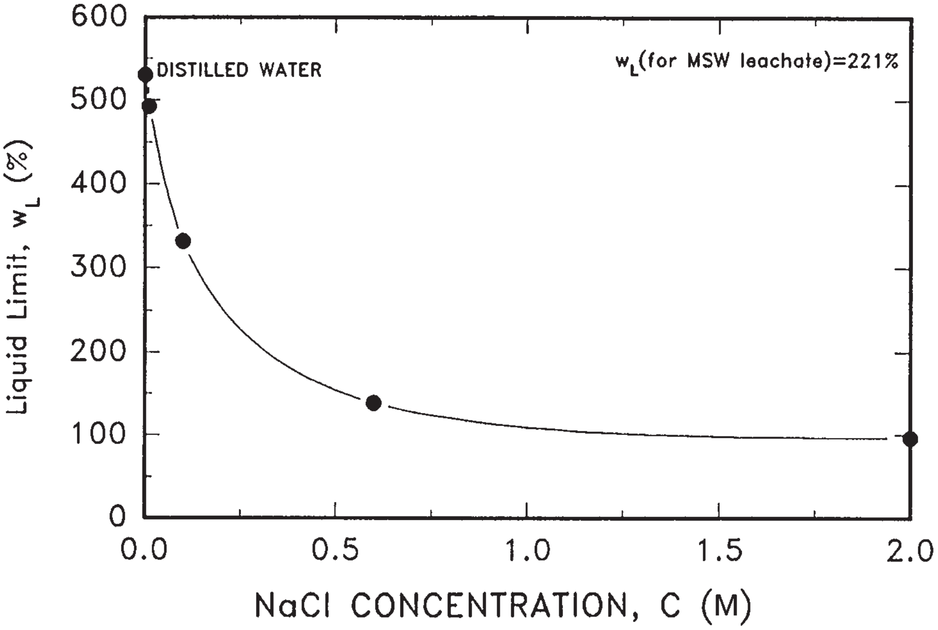
The effect of prehydration versus posthydration confinement on the final void ratio of fibre-free samples is illustrated in Fig. 1*a*. Prehydration confinement tests for both sample types were discussed by Petrov et al. (1997*b*). Referring to results for posthydration confinement, the GCL swelled under the 6 kPa confining stress to a final constant void ratio of 8.03 (after 47 days hydration), and had an apparent preconsolidation pressure, σ_p', of 25 kPa and a compression index, C_c, of 2.15. The void ratio of 1.37 was obtained at the 800 kPa confining stress. The results obtained in the unloading portion of the consolidation tests agreed well with those obtained from the confined swell tests.

The results indicate that for the range of confining stresses considered, the final void ratio at a given stress was highly dependent on the degree of bentonite hydration prior to confinement, with the differences in void ratio between the test types reaching a maximum at about 25 kPa. The differences in void ratio decreased for both stresses greater than and less than 25 kPa. At a 25 kPa confining stress, the void ratio ranged from about 4.0 for confinement prior to hydration to about 7.3 for confinement after hydration. Based on Petrov et al. (1997*b*), this range in void ratio corresponds to a range in projected hydraulic conductivity values of about an order of magnitude, from about 3×10^{-9} to 3×10^{-8} cm/s. This illustrates the considerable impact that significant swell prior to confinement can have on void ratio and, hence, hydraulic conductivity, even at the relatively low overburden stress of 25 kPa.

Figure 1*b* shows results similar to those of Fig. 1*a* but for the normal unaltered (fibre samples) GCL. This plot is similar to that for the fibre-free sample but the void ratios are lower at any given confining stress level. This difference is attributed to the additional confinement during swell applied to the bentonite core by the needle-punching. The impact of the needle-punching is greatest at the low stresses. The unaltered GCL fibre sample swelled to a void ratio of 4.7 prior to the application of the incremental confining stresses and had an apparent preconsolidation pressure of about 70 kPa and a compression index of 1.46. The largest difference in void ratios obtained between the confined swell and consolidation tests occurred at confining stresses between about 50 and 100 kPa. Based on Petrov et al. (1997*b*), this difference in void ratio corresponds to an approximately threefold difference in projected hydraulic conductivity values from about 1.8×10^{-9} cm/s at a void ratio of 3.2 in the confined swell test to about 4.7×10^{-9} cm/s at a void ratio of 4.6 in the consolidation test (for a confining stress of about 50 kPa).

In summary, the lower void ratios associated with prehydration confinement in contrast to posthydration confinement for the needle-punched GCL are primarily the result of two factors. First, significantly larger confining stresses are required to produce a given void ratio if the bentonite is initially allowed to hydrate and swell under low stresses (i.e., essentially

Fig. 2. The effect of varying NaCl concentrations on the liquid limit of bentonite.



free swell conditions) prior to sample consolidation in contrast to bentonite that is allowed to hydrate while confined. Second, the sum of the applied stresses (confining and fibre-induced stresses) varies depending on the level of hydration when external confinement is applied. Increases in the confining stress and the needle-punching as well as confining the GCL prior to hydration (in contrast to posthydration confinement) all contribute to decreasing the final void ratio. Since the hydraulic conductivity of the geosynthetic clay liner is related to the void ratio (Petrov et al. 1997*b*), it is advantageous to control the void ratio if the purpose of the GCL is to perform as a hydraulic barrier and, hence, minimize the advective flow. These results also suggest that for a given GCL, both the overburden stress in the field and the level of GCL hydration when confinement is applied must be taken into account in any laboratory test program if values representative of field conditions are to be obtained. The results of a test program examining the effects of confining stress and prehydration versus posthydration confinement on the hydraulic conductivity of the GCL for a number of permeants are presented in a subsequent section.

Index tests

Index tests were conducted to examine the potential effects of the synthetic MSW leachate and the range of aqueous NaCl solutions on the bulk bentonite taken from the GCL and to provide insight into their potential impact on the hydraulic conductivity. The synthetic MSW leachate and aqueous NaCl solutions (0.01, 0.1, 0.6, and 2.0 M) were identical to those used in hydraulic conductivity tests described later in this paper. The index tests included X-ray diffraction (XRD) traces on the clay-sized minerals (<2 μm), test tube flocculation, and liquid limits.

The effects of both leachate types on the c-axis of the smectite minerals in the bentonite were investigated by preparing water-wet preferred oriented slides on the <2 μm fraction of the bulk soil, after which the desired leachate was forced through by a suction applied to the underside of the slides. The smectite minerals remained well dispersed for the distilled water and 0.01 and 0.1 M NaCl solutions; however, the c-axis contracted to 1.96 nm for both 0.6 M NaCl and the synthetic MSW leachate, and 1.70 nm for 2.0 M NaCl. The data are consistent with those presented by Norrish (1954) and suggest that highly concentrated inorganic salt solutions have the potential to promote face-to-face flocculation and domain formation.

Test tube flocculation tests were prepared by mixing air-dried bulk powdered bentonite with 20 mL of distilled water, the varying concentrations of NaCl solutions, or the synthetic MSW leachate. The slurries were dispersed in a plastic vial for a few minutes using an ultrasonic probe, poured into test tubes which were stoppered to prevent evaporation, and then manually shaken prior to the commencement of testing. The distilled water and 0.01 and 0.1 M NaCl hydrated bentonite remained a well-dispersed homogenous gel throughout the 5 day test period. However, 0.6 and 2.0 M NaCl and the synthetic MSW leachate produced severe bentonite flocculation, and floccs settled to the bottom of the test tube in a few minutes (for 0.6 M NaCl and MSW leachate) and few seconds (for 2.0 M NaCl).

Using standard procedures in accordance with ASTM D4318 (ASTM 1993), the liquid limit was obtained for the bulk bentonite taken from the GCL. The powdered bentonite was air-dried for about 48 h and then wetted up to its respective saturation moisture content (the moisture content at which a wet sheen covers the surface of a remoulded soil) with the desired solution. The mixtures were allowed to equilibrate for about 24 h prior to testing. The measured moisture content (i.e., the mass ratio of water to total solids, which includes soil solids and salt precipitate), w_f, was corrected for salt precipitate using the relationship

$$[3] \qquad w_c = \frac{1}{\frac{1}{w_f} - C_1}$$

Table 2. Summary of prehydration confinement hydraulic conductivity tests.

Test	Final permeant	H_f (mm)	e_{Bf}	σ_f' (kPa)	i_f [a]	J_{Bf} (kPa)	k_f(cm/s)	w_f (%)	w_c (%)
Distilled water hydrated									
Suite 1									
C1	0.01 M NaCl	12.37	4.89	3.6	386	47	6.7×10^{-9}	244	244
C2	0.1 M NaCl	11.82	4.60	3.4	199	23	1.3×10^{-8}	222	225
C3	0.6 M NaCl	11.81	4.85	3.5	32	3.7	8×10^{-8}	219	237
C4	2.0 M NaCl	12.25	4.89	3.7	nd	nd	nd	177	226
Suite 2									
C1	0.01 M NaCl	8.47	2.81	35	700	58	1.5×10^{-9}	132	132
C2	0.1 M NaCl	8.24	2.63	36	521	42	2.0×10^{-9}	123	124
C3	0.6 M NaCl	7.75	2.66	35	111	8	9.3×10^{-9}	113	118
C4	2.0 M NaCl	7.37	2.43	33	55	4	4.7×10^{-8}	99	113
Suite 3									
C1	0.01 M NaCl	5.79	1.98	107	2142	122	4.8×10^{-10}	98	98
C2	0.1 M NaCl	5.80	1.91	108	1426	81	7.3×10^{-10}	89	89
C3	0.6 M NaCl	5.28	1.68	105	496	26	2.1×10^{-9}	80	82
C4	2.0 M NaCl	5.43	1.60	101	166	9	6.2×10^{-9}	66	72
Suite 4									
C3	2.0 M NaCl	10.67	4.59	4.0	23	2.4	2.3×10^{-7}	—	—
C4	2.0 M NaCl	10.48	4.66	4.0	18	2.0	2.9×10^{-7}	176	224
Salt water hydrated									
Suite 5									
C1	0.1 M NaCl	8.18	3.15	4.3	203	16	6.4×10^{-9}	128	129
C2	0.1 M NaCl	6.02	2.19	35	625	37	2.1×10^{-9}	99	100
C3	0.1 M NaCl	5.09	1.60	113	1477	74	9.2×10^{-10}	78	78
Suite 6									
C1	0.6 M NaCl	6.77	2.62	3.8	162	11	4.0×10^{-7}	88	91
C2	2.0 M NaCl	6.77	2.54	3.7	80	5	2.7×10^{-6}	75	83
C3	0.6 M NaCl	5.78	1.95	35	270	15	7.6×10^{-8}	73	75
C4	2.0 M NaCl	5.06	1.71	34	184	9	1.2×10^{-6}	66	72
Suite 7									
C1	0.6 M NaCl	4.82	1.52	111	280	13	2.3×10^{-8}	67	69
C2	2.0 M NaCl	4.47	1.34	107	125	5.5	2.6×10^{-7}	58	62

Note: All tests were conducted in a fixed-ring apparatus. nd, values not determined because of a failure to measure consistent positive head drop across the sample.

[a] Final hydraulic gradient.

Table 3. Summary of posthydration confinement hydraulic conductivity tests of distilled water hydrated GCLs in suite 8.

Test	Final permeant	σ_f' (kPa)	H_f (mm)	e_{Bf}	i_f	J_{Bf} (kPa)	k_f (cm/s)	w_f [a] (%)
C1	0.01 M NaCl	3.9	10.79	4.68	488	52	5.3×10^{-9}	
		14	10.54	4.55	507	52	5.1×10^{-9}	
		37	9.76	4.14	697	67	3.8×10^{-9}	
		69	8.62	3.54	1249	106	2.1×10^{-9}	
		114	8.15	3.29	160	129	1.6×10^{-9}	175 (175)
C2	0.1 M NaCl	3.5	10.45	4.36	342	35	7.6×10^{-9}	
		12	10.23	4.25	342	34	7.6×10^{-9}	
		34	9.32	3.78	496	45	5.3×10^{-9}	
		73	8.22	3.22	968	78	2.7×10^{-9}	
		112	7.34	2.76	1734	125	1.5×10^{-9}	140 (141)
C3	0.6 M NaCl	3.6	10.03	4.39	57	5.6	4.6×10^{-8}	
		12	9.53	4.12	48	4.5	5.5×10^{-8}	
		37	8.07	3.34	121	10	2.2×10^{-8}	
		74	6.82	2.67	378	25	6.8×10^{-9}	
		109	5.87	2.16	988	57	2.7×10^{-9}	107 (111)
C4	2.0 M NaCl	3.6	10.08	4.45	10–20	1–2	2×10^{-7} [b]	
		12	9.61	4.19	10–20	1–2	2×10^{-7} [b]	
		35	8.32	3.50	10–20	1–2	2×10^{-7} [b]	
		75	6.90	2.73	71	4.8	3.6×10^{-8}	
		114	6.11	2.30	165	10	1.6×10^{-8}	90 (101)

Note: All tests were conducted in a fixed-ring apparatus.

[a] Corrected bentonite moisture content, w_c, is given in parentheses.

[b] The approximate values given are estimated and not accurately measured.

$$C_1 = \frac{C}{\rho_{sol} - C} \quad [4]$$

where w_c is the corrected bentonite moisture content (mass ratio of water to soil solids), C is the salt concentration in the pore fluid (g/L), C_1 is a constant for a given pore fluid salt concentration and density, and ρ_{sol} is the density of the pore fluid (g/L). This correction is significant for soils at high measured moisture contents, w_f, containing highly concentrated saline pore water. The liquid limits, w_L, reported are corrected moisture contents and are plotted as a function of NaCl concentration in Fig. 2. The NaCl concentration had a significant effect on the liquid limit of the bentonite, as the liquid limit decreased from 530% for water to 139 and 96% for 0.6 and 2.0 M NaCl, respectively. The decreases in w_L for increasing salt concentration is attributed to double-layer and c-axis contraction. The liquid limit of 221% obtained for the synthetic MSW leachate was essentially equivalent to a concentration of NaCl ranging between 0.1 and 0.6 M; this is consistent with the total salt concentration in the synthetic leachate.

This investigation shows that high NaCl concentrations can impact the bentonite index properties, with the higher NaCl concentrations causing both c-axis and double-layer contraction and a more open structured, flocculated clay fabric. Similarly, the synthetic MSW leachate also changed the index properties of the bentonite. These index tests are simple to conduct, relatively inexpensive, and valuable in that they can be used to identify deleterious effects on the bentonite; however, as will become evident later in this paper, they should not be used as an alternative to hydraulic conductivity testing. The results from these tests can potentially be used to qualitatively estimate the relative impact of the solutions on the hydraulic conductivity of the GCL. For example, the results qualitatively suggest increases in hydraulic conductivity for permeation of salt water or MSW leachate at constant void ratio. A series of hydraulic conductivity tests was conducted to examine the impact of the solutions and the results are described below.

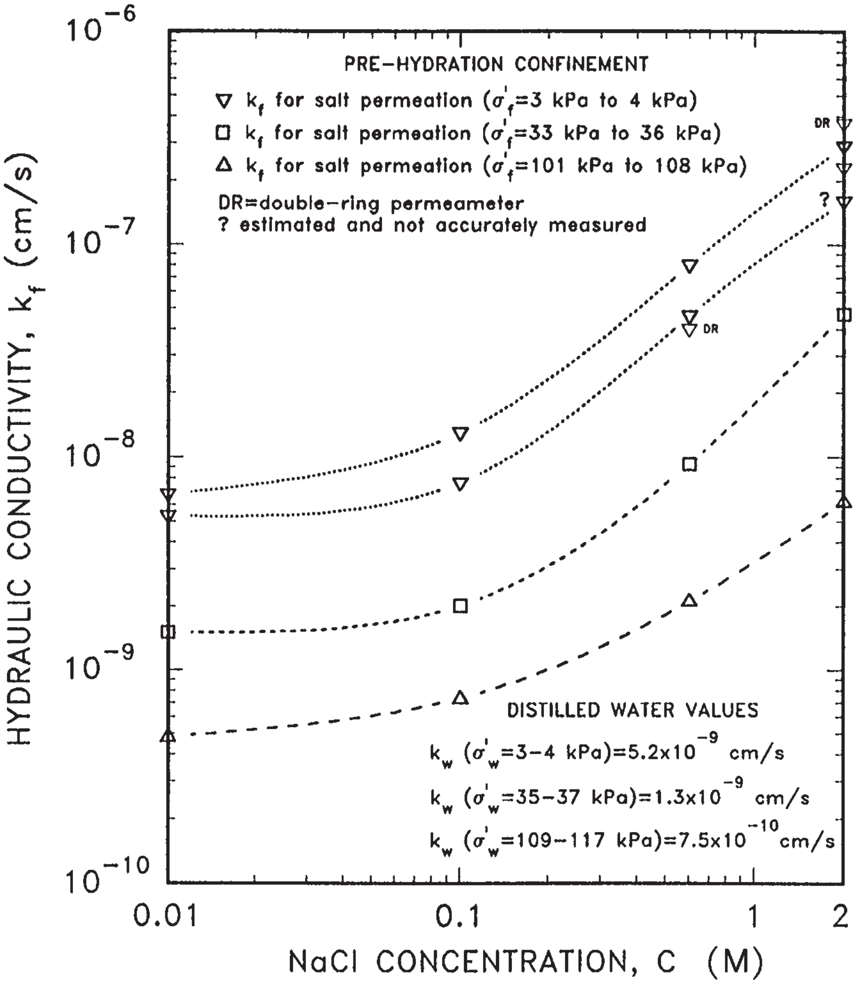
GCL hydraulic conductivity for permeation of aqueous NaCl solutions

The results of 27 hydraulic conductivity tests are summarized in Tables 2 and 3 for permeation of 0.01, 0.1, 0.6, and 2.0 M NaCl. The tests included both distilled water hydrated and salt water hydrated GCLs subjected to both prehydration and posthydration confinement. The number of pore volumes of sequential salt water permeants passed through the GCLs ranged from about 3.5 to 9.5. The final effluent salinities at test termination were greater than 90% of the initial reservoir values. For convenience, the confining stresses of 3–4 kPa are referred to as low confining stresses, confining stresses of 33–37 kPa are referred to as intermediate confining stresses, and confining stresses slightly greater than about 100 kPa are referred to as high confining stresses. The results of these tests will be described below and will be explained in a subsequent section.

Distilled water hydrated GCLs subjected to prehydration confinement

The final hydraulic conductivity, k_f, is shown as a function of the permeant NaCl concentration in Fig. 3 for the three confining stresses considered. The average reference hydraulic conductivity values for the GCLs initially hydrated and permeated with water ranged from 5.2×10^{-9} cm/s for low confining stresses to 7.5×10^{-10} cm/s for high confining stresses. As shown in Fig. 3, the shapes of the hydraulic conductivity – NaCl concentration (k_f–C) curves for permeation of the salt solutions are similar; however, they are shifted vertically contingent on the

Fig. 3. Hydraulic conductivity versus NaCl concentration for sequential permeation of varying concentrations of aqueous NaCl solutions at three confining stresses.



magnitude of the confining stress. At a given salt concentration, the hydraulic conductivity varied by about one to one and a half orders of magnitude and increased with corresponding decreases in the confining stress.

Permeation of the aqueous NaCl solutions produced either similar (i.e., within a factor of 2) or significantly larger (i.e., greater than a factor of 2) hydraulic conductivity values than for the reference permeant (i.e., distilled water). The similar hydraulic conductivities demonstrate adequate compatibility of the low concentrated salt solutions with the initially water hydrated bentonite core and suggest that GCLs can maintain their characteristically low hydraulic conductivity values for these permeants if effectively prehydrated with potable water. On the other hand, the significant increases in hydraulic conductivity, which occurred independent of the confining stresses, demonstrate poor chemical compatibility of the initially water hydrated bentonite with the concentrated salt solutions (0.6 and 2.0 M NaCl). This suggests that highly concentrated salt solutions have the ability to degrade the hydraulic performance of GCLs. Increases in the salt concentration increased the hydraulic conductivity for all confining stresses considered. For example, the hydraulic conductivity ranged by a factor of about 30, from 1.5×10^{-9} cm/s for 0.01 M NaCl to 4.7×10^{-7} cm/s for 2.0 M NaCl at the intermediate confining stress (suite 2).

The change in GCL height, ΔH_{GCL}, is shown as a function of pore volumes of salt solution flow in Fig. 4*a* (suite 3) for water-hydrated GCLs. The change in GCL height is defined as the difference in height measured at a given pore volume of flow, H_{GCL}, and the height measured at the completion of water permeation, H_{w}. Also noted are the range of void ratios prior to salt water permeation, e_{Bw}, the final void ratios at test termination, e_{Bf}, and the final volumentric strains at test termination, ε_{v} ($\Delta H_{\mathrm{GCL}}/H_{\mathrm{w}}$). All four samples were subjected to identical flow rates.

As the concentration of NaCl was increased from 0.01 to 2.0 M NaCl, the sample consolidation increased from about 0.1 to 0.88 mm and the final maximum seepage stresses (see Table 2), J_{Bf}, decreased from 122 to 9 kPa. The decrease in GCL height (relative to H_{w}) for sequential permeation of the less concentrated solutions (0.01 and 0.1 M NaCl) may in part be attributed to both osmotic consolidation and the effects of an increase in seepage stress (due to an increase in applied flow rate) relative to the maximum seepage stress of about 40 kPa for the reference permeant. However, for the higher salt solutions (0.6 and 2.0 M NaCl) the final seepage stresses decreased

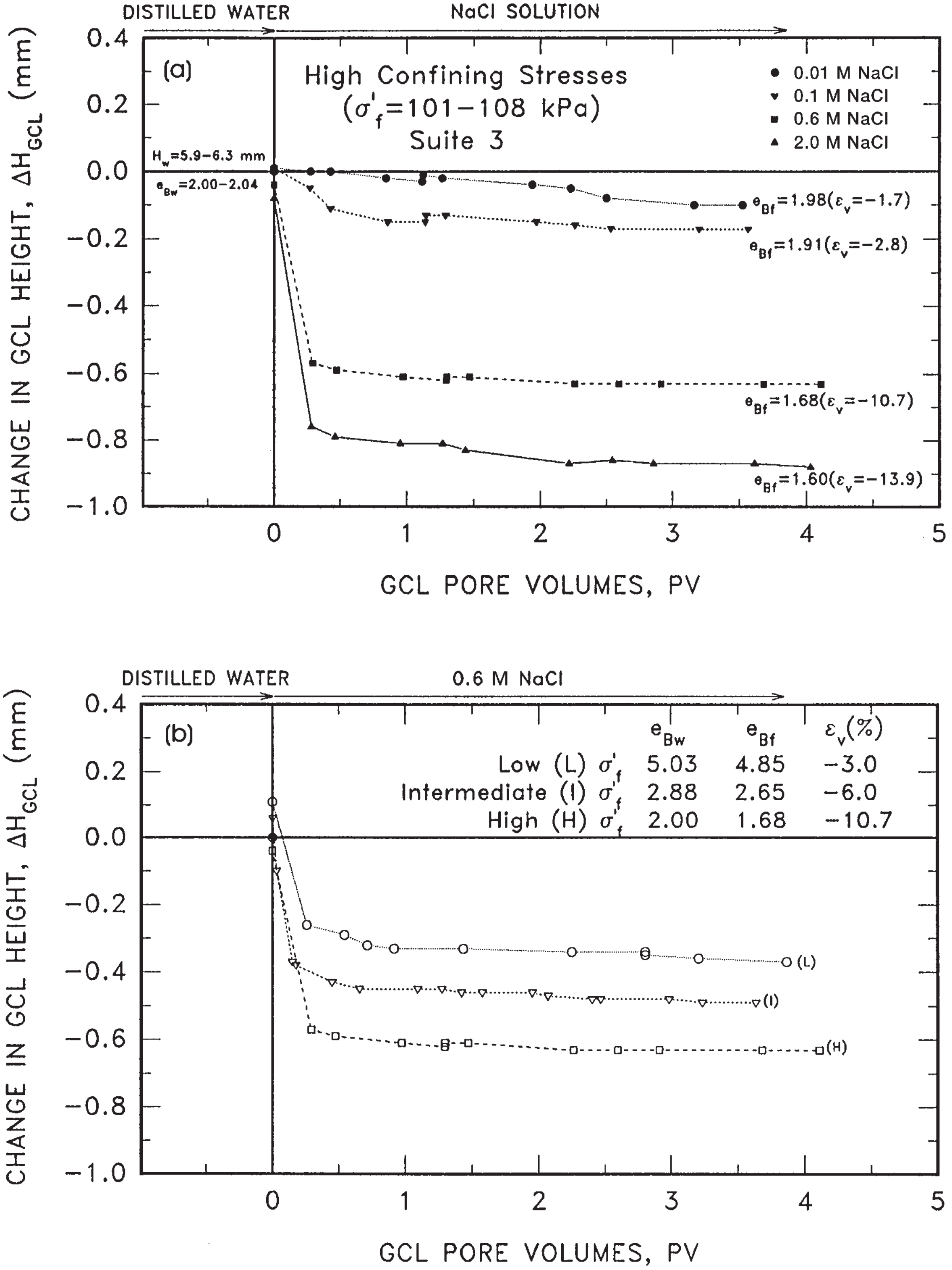
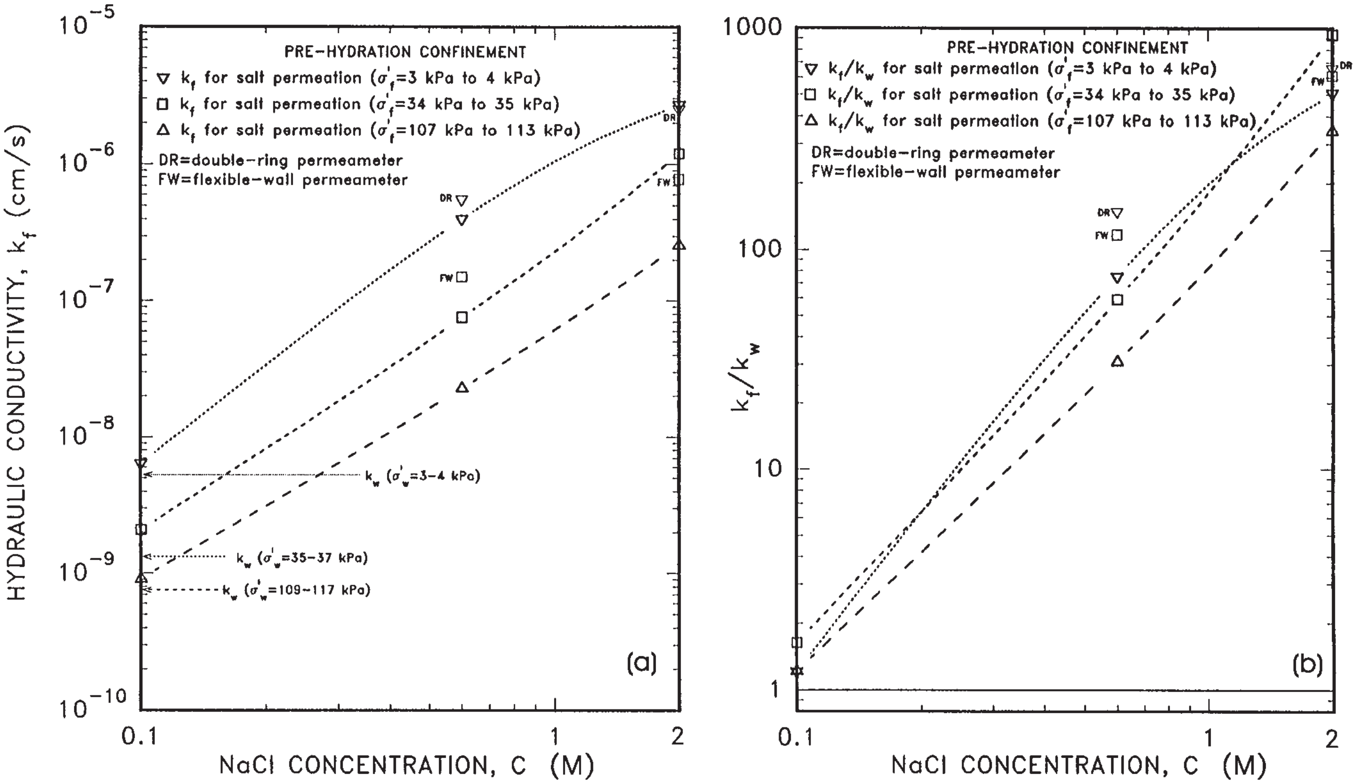


Fig. 4. Change in GCL height (H_{GCL}–H_w) versus pore volumes of flow for sequential permeation of aqueous NaCl solutions for (*a*) varying concentrations of NaCl solutions and (*b*) varying confining stresses.

(to 26 and 9 kPa, respectively) and thus cannot explain the considerable decreases in GCL height. The higher compressive strains associated with the higher salt concentrations are primarily attributed to physicochemical effects as will be discussed subsequently.

Figure 3 shows results for two suites of GCLs confined to low stresses and sequentially permeated with the range of salt concentrations. The curves are similar in shape, however, they are shifted relative to one another. The differences in observed hydraulic conductivity values can be explained by differences

Fig. 5. (*a*) Hydraulic conductivity and (*b*) relative hydraulic conductivity ratio versus NaCl concentration for hydration and permeation of varying concentrations of aqueous NaCl solutions at three confining stresses.



in void ratios observed between the suites. For example, final void ratios in the suite having slightly higher hydraulic conductivity values (suite 1) averaged 4.81 and were greater than those of the other suite (suite 8), which averaged 4.47. Both test suites were conducted under essentially identical applied confining and seepage-induced stresses; however, reservoirs were recharged more frequently in suite 1 (i.e., release of seepage-induced stresses), causing the GCL to rebound to greater heights (and hence void ratios) and thus the higher hydraulic conductivity values. This suggests that significant fluctuations in reservoir heads applied to GCLs used as pond liners may lead to increased rates of seepage with time in certain applications.

Generally, the GCL appears to be less susceptible to increases in hydraulic conductivity for sequential permeation (i.e., after permeation with distilled water) of these inorganic solutions if high confining stresses are applied. This trend appears to be related to both the lower initial void ratio prior to sequential permeation and the higher volumetric compressive strain for sequential permeation, for the higher confining stresses. This is illustrated, for example, in Fig. 4*b* for permeation of 0.6 M NaCl. The initial void ratio decreased from 5.03 at low stresses to 2.00 at high stresses while the shrinkage increased from 3.0% at low stresses to 10.7% at high stresses.

Salt water hydrated GCLs subjected to prehydration confinement

A series of hydraulic conductivity tests for GCLs hydrated and permeated with 0.1, 0.6, and 2.0 M NaCl was conducted. Confining stresses were applied prior to hydration (prehydration confinement). The results are plotted in Fig. 5, where the final hydraulic conductivity, k_f, and the relative hydraulic conductivity ratio, k_f/k_w, where k_w is the hydraulic conductivity at the completion of water permeation, are shown against the concentration of NaCl, *C*. Average hydraulic conductivity values for distilled water permeation, taken from Fig. 3, are shown for comparison in Fig. 5. The final GCL height, H_f, is plotted against the confining stress, σ_f', in Fig. 6. At a given confining stress, GCLs hydrated and permeated with the lower salt concentrations generally reached larger GCL heights and hence larger void ratios than those of the higher salt concentrations.

For all confining stresses considered, the hydraulic conductivity of the GCL was linearly related to the NaCl concentration (on a log–log scale), with increases in salt concentration causing a more permeable GCL (see Fig. 5*a*). The hydraulic conductivities were highly dependent on the salt concentration, as hydraulic conductivity values varied by a factor ranging from about 280 to 570 as the concentration was increased 20-fold from 0.1 to 2.0 M NaCl. This was despite the fact that void ratios at a given confining stress varied significantly and tended to decrease for permeation of the more concentrated aqueous NaCl solutions. For all salt concentrations considered the final hydraulic conductivity values were greater than average values obtained for permeation of distilled water at a similar confining stress. This was despite the fact that the void ratios tended to be smaller for samples hydrated and permeated with the salt solutions than for samples hydrated and permeated with distilled water. For example, even though the void ratios for permeation of 0.1 M NaCl were significantly smaller and ranged from 67 to 80% of the average void ratios for distilled water permeation, the relative hydraulic

Fig. 6. Final GCL height versus final confining stress for hydration and permeation of varying concentrations of NaCl solutions and distilled water; fixed-ring apparatus.

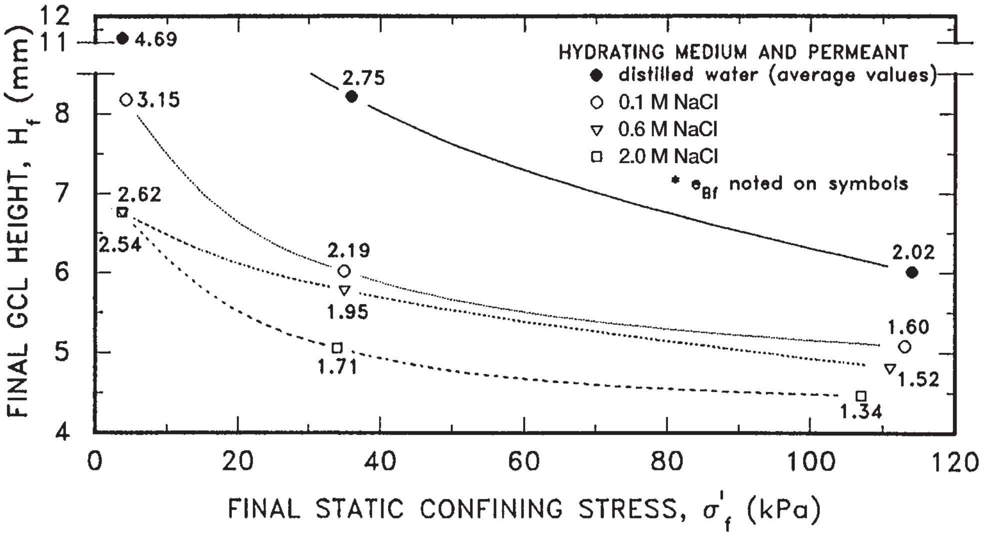
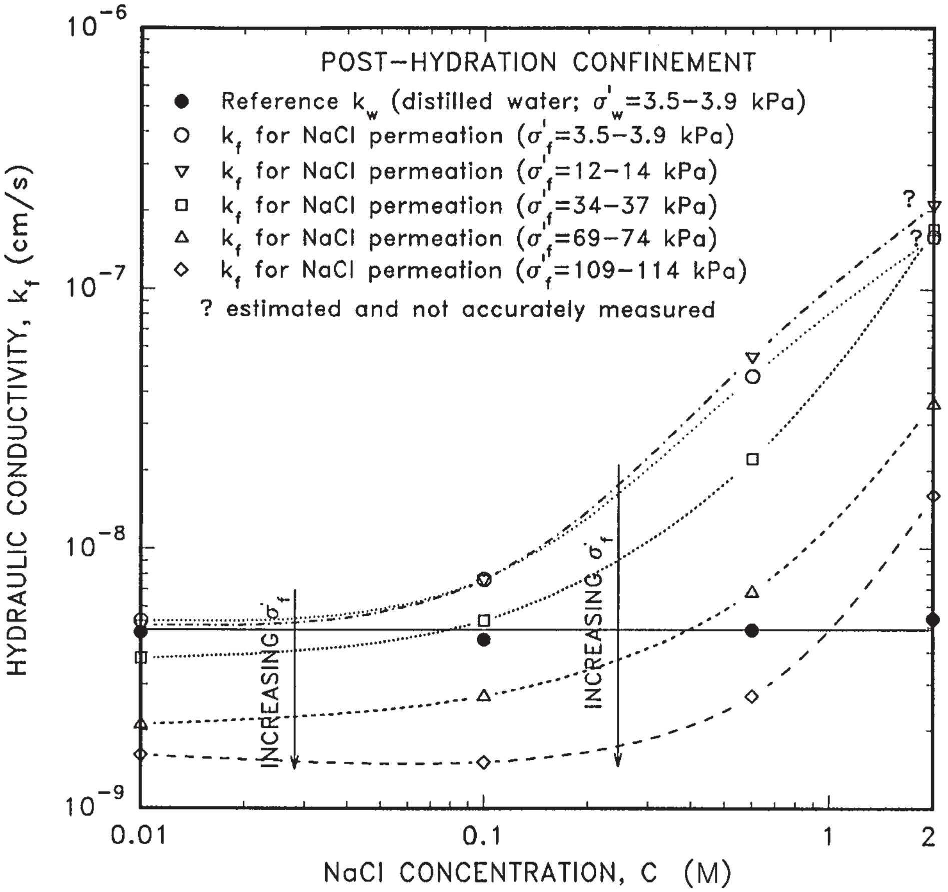
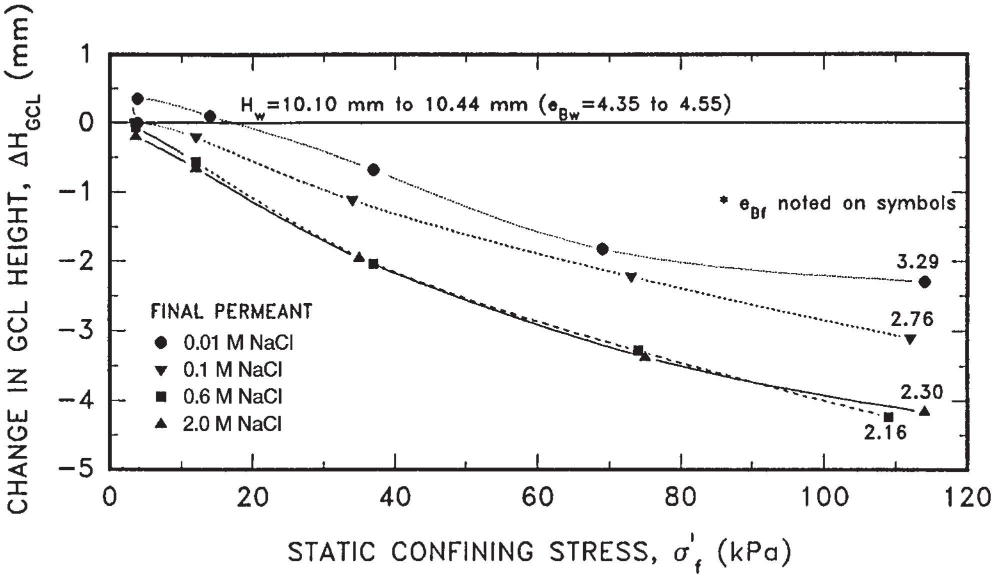


Fig. 7. The effect of posthydration confinement on the hydraulic conductivity for sequential permeation of varying concentrations of NaCl solutions.



conductivity ratios, k_f/k_w, were greater than unity and ranged from 1.2 to 1.6 (see Fig. 5*b*). Permeation of 2.0 M NaCl resulted in hydraulic conductivities that were 340–940 times greater than those obtained for distilled water permeation despite the fact that the void ratios after permeation were smaller and ranged from 54 to 66% of the average void ratios for distilled water permeation. This is discussed in a subsequent section. For a given NaCl concentration, the hydraulic conductivity did decrease for increasing confining stress, and this is attributed to a decrease in void ratios by as much as a factor

Fig. 8. Change in GCL height ($H_f - H_w$) versus confining stress for sequential permeation of varying concentrations of NaCl solutions; fixed-ring apparatus.



of 2 as the confining stress was increased from about 3 to about 110 kPa.

Distilled water hydrated GCLs subjected to posthydration confinement

The results of posthydration confinement on distilled water hydrated GCLs permeated with varying concentrations of aqueous NaCl solutions are shown in Fig. 7, where the hydraulic conductivity, k_f, is plotted against the NaCl concentration, C, and in Fig. 8 where the change in GCL height, ΔH_{GCL}, is plotted against the confining stress, σ_f'. The GCLs were hydrated and initially permeated with distilled water while confined to low (3–4 kPa) stresses and then permeated with one of the four different salt solutions. Confining stresses were incrementally increased to simulate the effect of increasing overburden and to assess its impact on the hydraulic conductivity. The final confining stresses at each stage, σ_f', were 12–14, 34–37, 69–74, and 109–114 kPa. The horizontal solid line in Fig. 7 represents the average reference hydraulic conductivity value of 4.9×10^{-9} cm/s for distilled water permeation at low stresses ($\sigma_w' = 3$–4 kPa). The curves representing hydraulic conductivity values for sequential permeation of varying salt concentrations are similar in shape; however, they are shifted vertically contingent on the magnitude of the confining stress and generally indicate decreasing hydraulic conductivity for increasing confining stress.

Results indicate very little effect of increasing the confining stress from 3–4 to 12–14 kPa on both the hydraulic conductivity (Fig. 7) and the thickness of the GCL (Fig. 8), irrespective of the concentration of NaCl in solution. However, incrementally increasing the confining stress from low- to high-stress conditions caused a significant reduction in hydraulic conductivity by about a half order of magnitude for 0.01 and 0.1 M NaCl and by about an order of magnitude for 0.6 and 2.0 M NaCl. These results are encouraging and suggest that due to the high compressibility of bentonite, GCLs are able to heal themselves by undergoing a significant reduction in void ratio when subjected to greater confinement, even if partially damaged due to early exposure with an incompatible liquid. This has practical implications with respect to the possible use of GCLs as part of a liner system in MSW landfills. As overburden (i.e., waste and cover liners) is increased, significant reductions in void ratio and hence reductions in the hydraulic conductivity are likely to occur, everything else remaining constant. King et al. (1993) attributed an order of magnitude decrease in the hydraulic conductivity of an inactive compacted clay liner, in part, to consolidation resulting from the placement of overburden.

Distilled water versus salt water hydration

Figure 9 shows the hydraulic conductivity, k_f, and the relative hydraulic conductivity ratio, k_f/k_w, for (1) GCLs initially hydrated and permeated with distilled water and sequentially permeated with aqueous NaCl solutions, (2) GCLs hydrated and permeated with aqueous NaCl solutions, and (3) reference values obtained using distilled water as the permeant. The results for posthydration confinement tests, where GCLs were hydrated and initially permeated with distilled water and sequentially permeated with aqueous NaCl solutions while subjected to incremental loads, are also shown but will be discussed in the next section.

Figures 9*a*–9*c* will be discussed simultaneously, as similar trends were observed; however, as discussed previously, they differed in the magnitude of hydraulic conductivities resulting from differences in void ratios. For permeants such as 0.6 and 2.0 M NaCl, hydraulic conductivity values can be minimized by prehydrating the GCL with potable water prior to subsequent exposure to these concentrated saline solutions. This observation is valid for all confining stresses and both prehydration and posthydration confinement tests; however, the significant differences observed in final hydraulic conductivity values at a given confining stress cannot be explained in terms of void ratios because void ratios were noticeably lower for the salt water hydrated specimens relative to the distilled water

Fig. 9. Hydraulic conductivity (k_f) and relative hydraulic conductivity ratios (k_f/k_w) versus NaCl concentration for (*a*) low, (*b*) intermediate, and (*c*) high confining stresses. ○, GCLs initially hydrated and permeated with distilled water and sequentially permeated with aqueous NaCl solutions (prehydration confinement); △, GCLs hydrated and permeated with aqueous NaCl solutions (prehydration confinement); ●, reference values obtained using distilled water as the permeant (prehydration confinement); ◇, GCLs hydrated and initially permeated with distilled water and sequentially permeated with aqueous NaCl solutions while subjected to incremental loads (posthydration confinement).

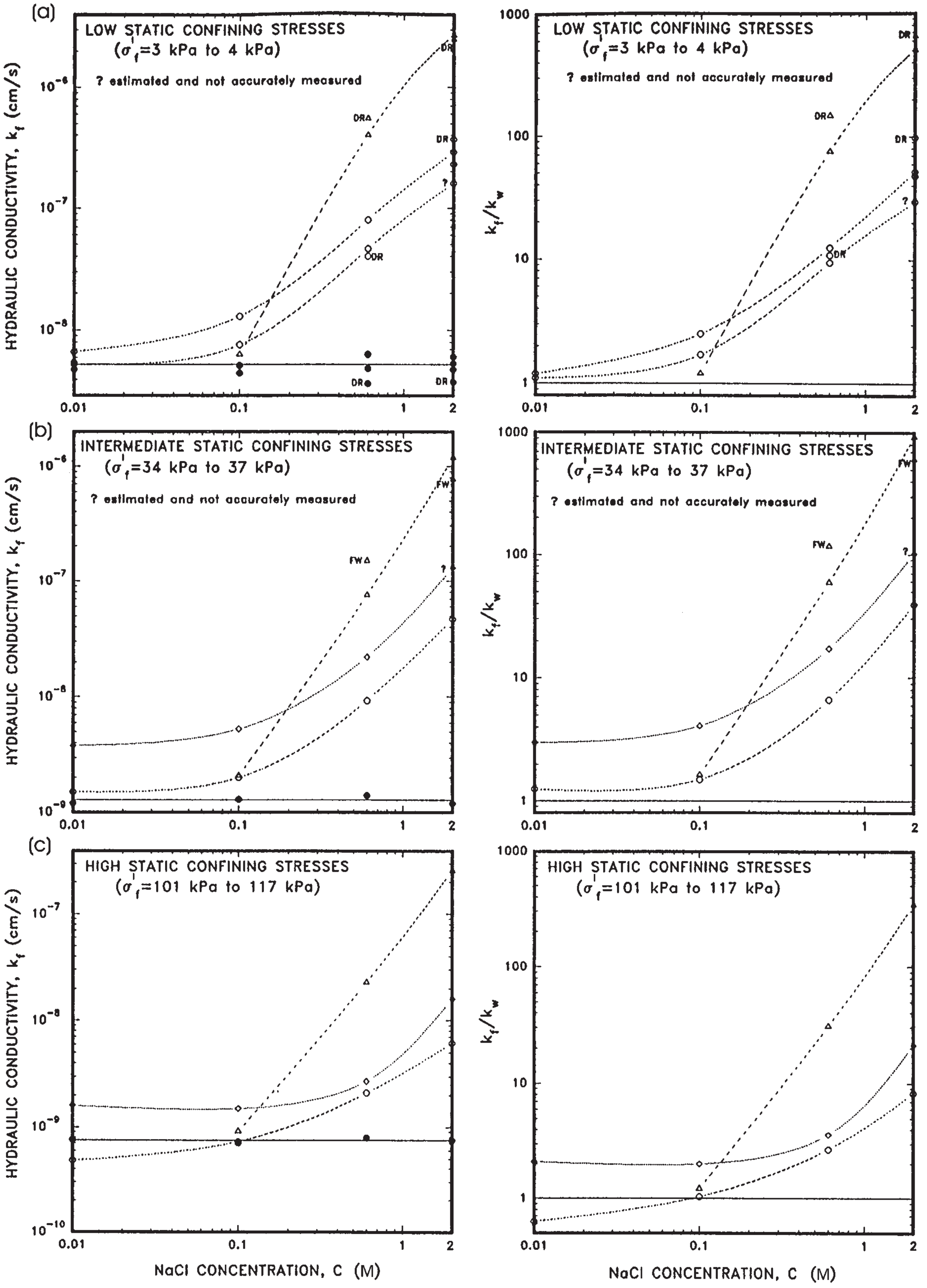
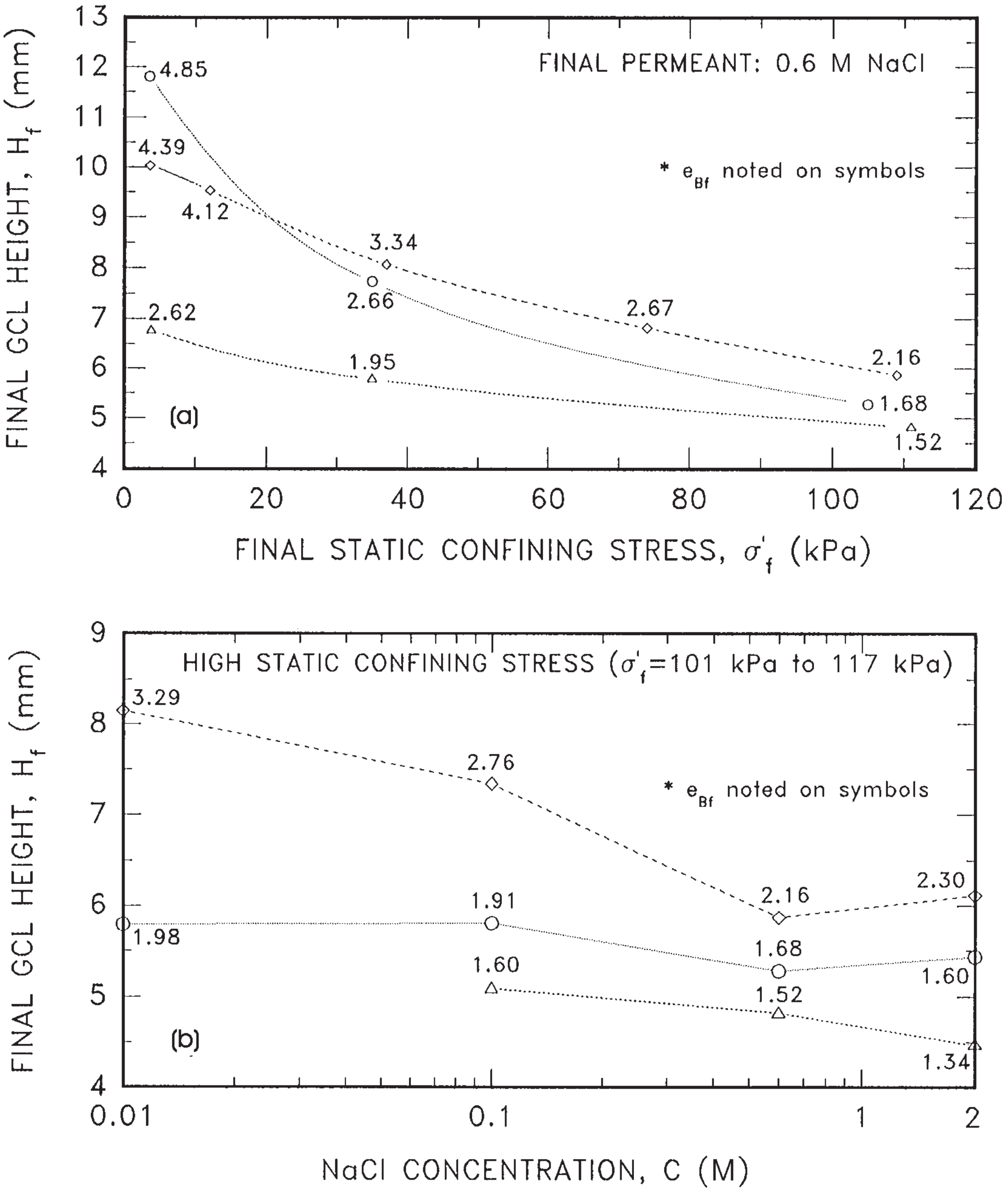


Fig. 10. Final GCL height versus (*a*) final confining stress and (*b*) NaCl concentration for permeation of aqueous salt solutions. ○, GCLs initially hydrated and permeated with distilled water and sequentially permeated with aqueous NaCl solutions (prehydration confinement); △, GCLs hydrated and permeated with aqueous NaCl solutions (prehydration confinement); ◇, GCLs hydrated and initially permeated with distilled water and sequentially permeated with aqueous NaCl solutions while subjected to incremental loads (posthydration confinement).



hydrated specimens. For 0.1 M NaCl, the hydraulic conductivity of the salt water hydrated and permeated GCL was similar to values obtained for the GCL when hydrated with distilled water and sequentially permeated with the salt solution.

Figure 10 shows the final GCL height, H_f (with the void ratios also noted), as a function of (1) the confining stress, σ_f', for 0.6 M NaCl; and (2) the NaCl concentration, C, for high confining stresses. The patterns in this figure were also observed for the other salt concentrations (see Fig. 10*a*) and static confining stresses (see Fig. 10*b*) considered in this paper. Final heights and void ratios were lower when the GCL was hydrated with salt water as opposed to distilled water, even when the final permeant (salt water) was the same, as is illustrated in both Figs. 10*a* and 10*b*. This demonstrates that the hydrating medium impacts the final void ratio.

Prehydration versus posthydration confinement of distilled water hydrated GCLs

Consistent with previous observations, final GCL heights and void ratios in prehydration confinement tests were less than values obtained in posthydration confinement tests at both the intermediate and high confining stresses (see Fig. 10*b*). Final void ratios for prehydration confinement tests were 60–78% (and 67–80% for intermediate confining stresses) of values obtained in posthydration confinement tests for high confining stresses which explains the variation in hydraulic conductivity values between the two test types. Thus, to minimize the hydraulic conductivity of GCLs, it is advantageous, for all salt solutions considered, to control the void ratio and maximize the overburden prior to hydration as opposed to allowing hydration and swell at low overburden and subsequently increasing the overburden.

Interpretation of test results

The hydraulic behaviour of the needle-punched GCL in this study is dominated by the bulk void ratio, the type of permeant, and the medium used to hydrate the bentonite core in the GCL. This is consistent with what might be expected of saturated soils without the presence of geosynthetics. The hydraulic conductivity of saturated soils (e.g., bentonite) is mainly determined by the size of individual pores, the total volume of pores (void ratio), and the shape of pores in the direction of flow. Any process that leads to smaller individual pores and smaller void ratios causes the soil permeability to decrease.

All other things being equal, there were two primary mechanical factors shown to impact the void ratio of this GCL, namely the magnitude of the confining stress (both the applied static confining stress and the stresses applied by the needle-punching during bentonite swell) and the level of bentonite hydration at the time of application of the confining stress. Petrov et al. (1997*b*) previously demonstrated the significant impact of the confining stress on the void ratio, and similar observations were found in this investigation. In Fig. 3, the hydraulic conductivity versus concentration curves were shifted vertically upward with decreasing confining stress, with the differences in hydraulic conductivity values being the result of higher void ratios (see Fig. 4*b*) and hence the effective void space for permeant flow at lower stress levels. Similar observations were found for the salt water hydrated GCLs in Figs. 5 and 6.

The significant decrease in hydraulic conductivity for posthydration confinement (i.e., consolidation test) tests shown in Figs. 7 and 8 is the result of reductions in void ratio due to sample consolidation. The reduction in void ratio for increasing confining stress is the result of consolidation due to application of both the confining stress and increasing seepage-induced stresses with increasing confining stresses; creep consolidation was found to be minimal. Sample consolidation was dominated by increasing confining stress for all tests except for permeation of 0.01 and 0.1 M NaCl at high confining stresses where seepage-induced consolidation contributed to a measurable part in the reduction in void ratio.

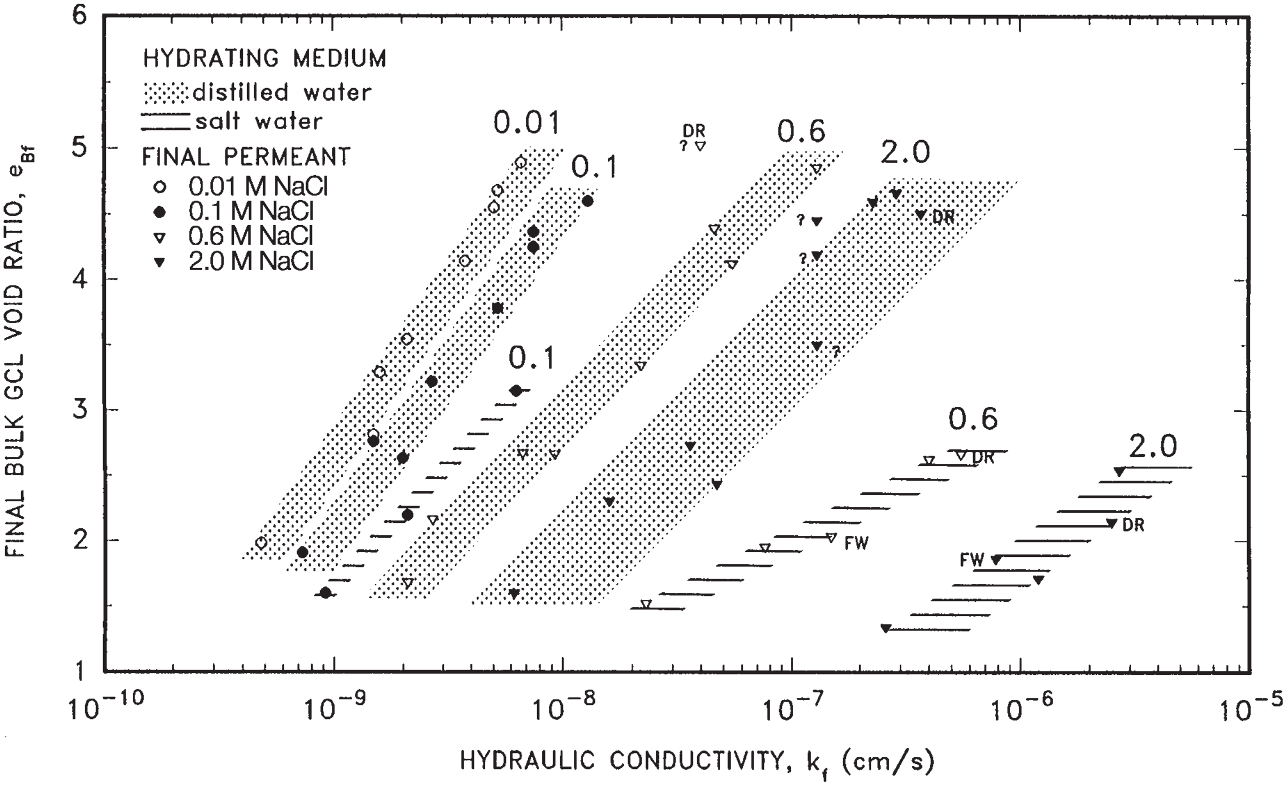
The level of bentonite hydration at the time of application of the confining stress was shown to have significant effects on the void ratio and hydraulic conductivity. Allowing the GCL to hydrate under low overburden prior to loading to a given stress (posthydration confinement) consistently resulted in a more permeable liner with a higher void ratio (see Figs. 9 and 10). Prehydration confinement is likely to represent a minimum void ratio that could be achieved at a given confining stress in a field application, whereas posthydration confinement is likely to represent a maximum void ratio at the same confining stress. In many practical field applications it is difficult to estimate both the time required for the GCL to fully hydrate and the overburden pressures during hydration. As a result, it is difficult to reproduce actual field conditions in controlled laboratory tests. However, because field void ratios would likely fall in between the upper and lower bound void ratios obtained from prehydration and posthydration confinement, for a given overburden pressure and permeant (which can often be reasonably estimated in field applications), two hydraulic conductivity tests, specifically prehydration and posthydration confinement, are required to estimate the likely range of hydraulic conductivity values.

Diffuse double layer theory (see van Olphen 1977; Mitchell 1993; Shang et al. 1994) has commonly been used to explain changes in the hydraulic properties of clayey soils arising from permeant effects. In this paper, it was repeatedly shown that, independent of both the level of bentonite hydration when the confining stresses were applied (i.e., prehydration versus posthydration confinement) and the hydrating medium, higher salt concentrations caused a more permeable GCL at a given confining stress (see Figs. 3, 5, 7, and 9). Higher salt concentrations lead to double-layer and c-axis contraction (i.e., domain formation, face-to-face flocculation) with a resulting more open structured, flocculated clay fabric which has larger pores and a greater effective pore space for permeant flow. In particular, the higher salt concentrations of 0.6 and 2.0 M NaCl produced rather high hydraulic conductivity values that were dominated by domain formation and face-to-face flocculation. The impact of these solutions is consistent with the index tests previously described and X-ray diffraction results reported by Norrish (1954). The trends described above are expected at constant void ratio; however, these tests were performed at constant stress and the samples were able to undergo 1D deformations. The subsequent decrease in GCL height after permeation of the salt solutions through the water-hydrated GCLs (see Fig. 4*a*) is attributed primarily to osmotic consolidation and was greatest for the higher salt concentrations. Haug et al. (1988) also observed similar phenomena for increases in permeant salt concentration. Final void ratios followed expected trends and were smallest for the more concentrated solutions. Even though the greatest decrease in void ratio and highest compressive strains at a given confining stress were observed for the highest salt concentrations, it is apparent that the lower void ratios (relative to the values for water and less concentrated salts) were insufficient to counter the change in clay fabric and increase in the size of individual pores, causing relative increases in the hydraulic conductivity of the GCL (see Fig. 3).

Not only was it shown that the concentration of salt impacted the amount of clay shrinkage, it was also shown that the swelling characteristics of the highly active bentonite core were affected by the same factors impacting the double layer and c-axis (see Fig. 6). Clearly, the bentonite swelling properties are highly degraded by concentrated salt solutions, higher concentrations producing lower void ratios and a more flocculated clay fabric. Of particular interest is the fact that even though void ratios tended to be lower for the higher concentrations, hydraulic conductivity values tended to increase with these decreases in void ratio at a given confining stress. The dominating influence of clay fabric over void ratio control on the permeability characteristics of the bentonite in the GCL is clearly illustrated.

The initial clay fabric is known to impact the hydraulic properties of cohesive soils such that soils with a flocculated

Fig. 11. Final bulk void ratio versus hydraulic conductivity for permeation of varying concentrations of aqueous NaCl solutions.



fabric exhibit significantly higher hydraulic conductivities than soils with a dispersed fabric at a given void ratio because of the larger effective pore space for permeant migration (Mesri and Olson 1971; Fernandez and Quigley 1985; Kenney et al. 1992). For example, extrapolation of data presented by Kenney et al. (1992) showed about two orders of magnitude difference in hydraulic conductivity values for salt water hydrated and fresh water hydrated bentonite permeated with a 40 g/L NaCl solution at constant void ratio. Similar observations were made by Fernandez and Quigley (1985) for a Sarnia (Ontario) clay moulded and permeated with water and a number of pure organic chemicals.

The hydrating medium and its potential impact on the hydraulic behaviour of GCLs is an issue of great interest. The question of whether to hydrate with potable water or the intended permeant was found to be dependent on the concentration of the salt permeant.

It is illustrated in Fig. 10 that the hydrating medium (distilled water versus salt water) significantly impacts the void ratio for GCLs permeated with the salt solution. The initially well dispersed clay fabric of the distilled water hydrated bentonite appears to limit the osmotic consolidation of the sample such that the final void ratio does not reach a value equivalent to a sample hydrated with the salt water. Even though void ratios were lower for salt water hydration, hydraulic conductivity values were significantly higher for the saltier permeants (0.6 and 2.0 M NaCl), suggesting again the dominating influence of clay fabric over void ratio control. Thus the samples hydrated with these high salt concentrations have a more open and flocculated structure, which in turn gives rise to higher hydraulic conductivities. The lower void ratios at a given confining stress did not compensate for the apparent large differences in the initial clay fabric caused by the different hydrating mediums producing a larger effective pore space for permeant flow. It appears that a water-hydrated bentonite core will not become as flocculated as a salt water hydrated core. This highlights the desirability of adequately prehydrating the GCL with potable water prior to exposure to highly concentrated salt solutions (0.6 and 2.0 M NaCl). Similar observations have been made by Shan and Daniel (1991), Daniel et al. (1993), and Heyer (1995) for hydrating mediums consisting of both organic and inorganic solutions. Since higher void ratio swelling soils are more susceptible to flocculation than lower void ratio soils (Kenney et al. 1992; Mitchell 1993), it is desirable from a hydraulic perspective to hydrate the GCL with potable water (i.e., disperse smectite) and minimize the void ratio before it is exposed to potentially flocculating or aggregating environments.

Notwithstanding the observations of the previous paragraph, the hydrating medium for the lower salt concentration (0.1 M NaCl) did not produce significant differences in the permeability of the GCL, even though void ratios for salt water hydration were lower and within 68–84% of values for the water-hydrated samples. The lower void ratios for salt water hydrated GCLs balanced the more open structured, flocculated fabric produced by salt water hydration. Prehydration with potable water may not be as essential when the GCL is to be exposed to low-concentration solutions (0.1 M in these experiments); however, prehydration with potable water prior to exposure with relatively low concentration NaCl solutions would still be preferred.

Summary of GCL hydraulic conductivity results

The results of all hydraulic conductivity tests reported in this paper for permeation of aqueous NaCl solutions, including

Fig. 12. (*a*) Final GCL height and (*b*) final corrected bentonite moisture content versus hydraulic conductivity for permeation of varying concentrations of aqueous NaCl solutions.

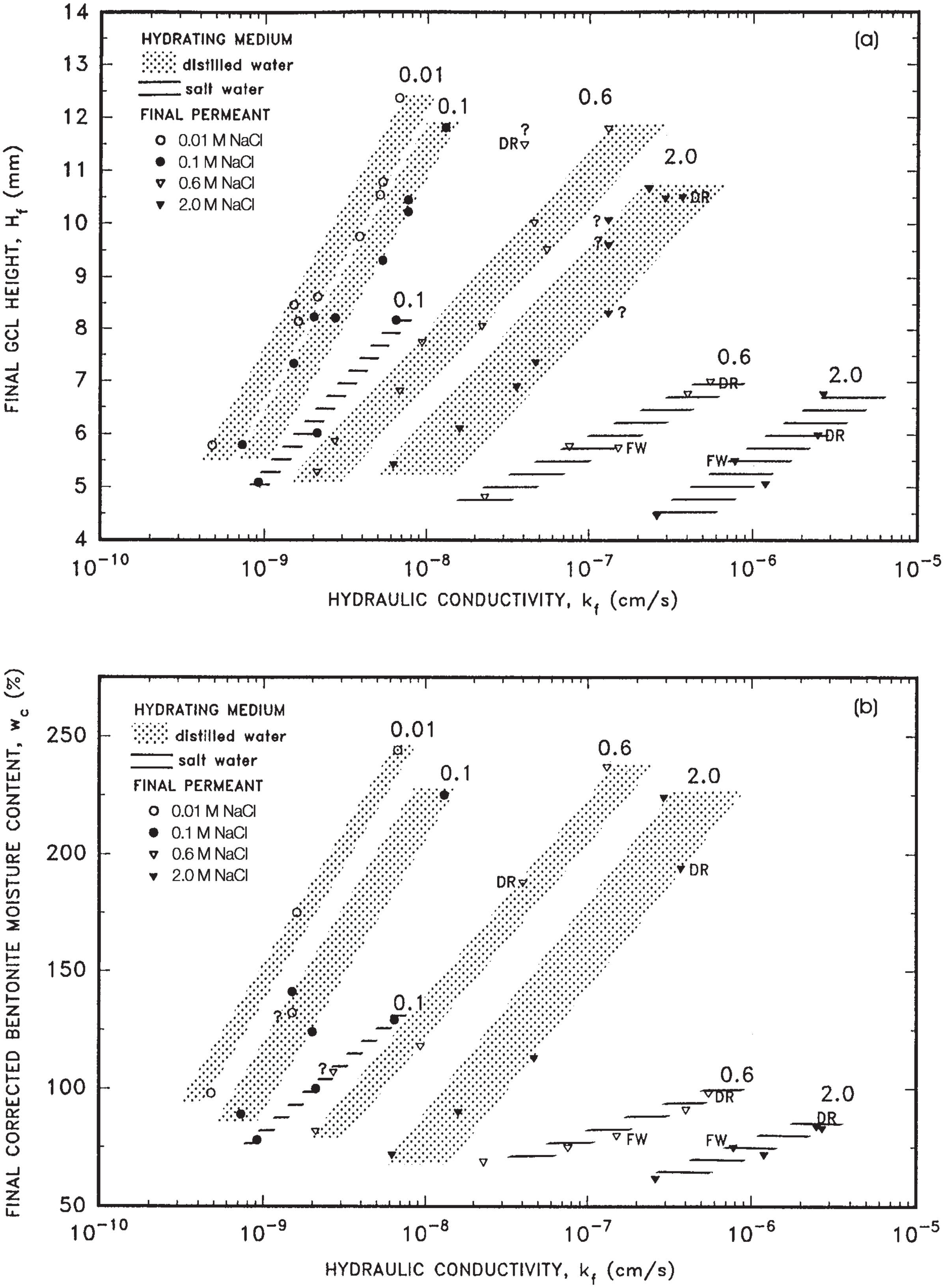


Table 4. Summary of prehydration and posthydration confinement hydraulic conductivity tests for permeation of synthetic MSW leachate.

Test	Permeant[a]	σ'_f (kPa)	H_f(mm)	e_{Bf}	i_f	J_{Bf} (kPa)	k_f (cm/s)	w_f (%)	Equivalent NaCl[b] (molar)
Distilled water hydrated									
C1	DW[c]	3.1	11.15	5.25	169	18	6.2×10^{-9}		
	SL[c]	3.0	10.82	5.06	31	3.3	5.5×10^{-8}		
	SL[d]	15	9.99	4.60	48	4.7	3.6×10^{-8}		
	SL[d]	34	8.22	3.61	80	6.5	2.1×10^{-8}		
	SL[d]	72	6.95	2.89	197	13.4	8.8×10^{-9}		
	SL[d]	124	5.90	2.31	569	33	3.1×10^{-9}	104	~ 0.45 to ~ 0.8
C2	DW[c]	33	7.69	3.25	673	51	1.6×10^{-9}		
	SL[c]	31	6.96	2.85	201	14	8.7×10^{-9}	122	~ 0.6
Synthetic MSW leachate hydrated									
C3	SL[c]	33	5.71	2.15	140	8	7.3×10^{-9}	74	~ 0.2

Note: All tests were conducted in a fixed-ring apparatus. Reference mass per unit area of GCLs ranged from 3.89 to 3.97 kg/m^2.

[a] DW, distilled water; SL, synthetic MSW leachate.

[b] NaCl concentration having equivalent k_f values as SL at the given static confining stress.

[c] Prehydration confinement.

[d] Posthydration confinement.

results of tests conducted in the double-ring and flexible-wall permeameter, are shown in Fig. 11 (linear–log scale) where the final GCL void ratio, e_{Bf}, is plotted against the final hydraulic conductivity, k_f. Similarly, the final GCL height, H_f, and the final corrected bentonite moisture content, w_c, are plotted against the final hydraulic conductivity, k_f, in Figs. 12*a* and 12*b*, respectively. Since increases in the void ratio generally correspond to increases in height and bentonite moisture content, for the tests described herein, the hydraulic properties of the GCL can be characterized by any of these three variables, as similar trends were observed. Included in each figure are the effects of both the salt concentration and the hydrating medium. In these tests (1) the final (bulk) void ratios ranged from about 1.5 to 5; (2) the final GCL heights ranged from about 4.5 to 12.5 mm; (3) the final corrected bentonite moisture contents ranged from about 60 to 250%; and (4) the hydraulic conductivity of the GCL ranged from about 2.5×10^{-6} to 5×10^{-10} cm/s.

As illustrated in Fig. 11, the hydraulic conductivity for permeation of aqueous NaCl solutions is clearly impacted by the final void ratio, the concentration of NaCl, and the hydrating medium, which impacted the initial clay fabric. Independent of both the salt concentration and the hydrating medium, the hydraulic conductivity is related to the final void ratio, with increases in void ratio corresponding to higher hydraulic conductivity values. For example, an increase in void ratio from 2 to 5 caused the hydraulic conductivity to increase by about one to one and a half orders of magnitude for the distilled water hydrated samples. Similarly, an increase in void ratio from 2 to 3 for the salt water hydrated specimens produced an increase in hydraulic conductivity by about a half to one order of magnitude.

Independent of the hydrating medium, the permeant salt concentration was shown to significantly influence the hydraulic conductivity at a given void ratio. For example, an increase in NaCl concentration from 0.01 to 2.0 M NaCl resulted in about one to one and a half orders of magnitude increase in the hydraulic conductivity for the distilled water hydrated GCLs, and about three orders of magnitude for the salt water hydrated GCLs as the concentration was increased from 0.1 to 2.0 M NaCl. The simple index tests previously discussed qualitatively demonstrated the relative impact of increasing NaCl concentrations on the hydraulic properties of this GCL. The hydrating medium was shown to significantly impact the hydraulic conductivity, with distilled water hydrated GCLs consistently exhibiting lower values than salt water hydrated GCLs for a given salt concentration at a given void ratio.

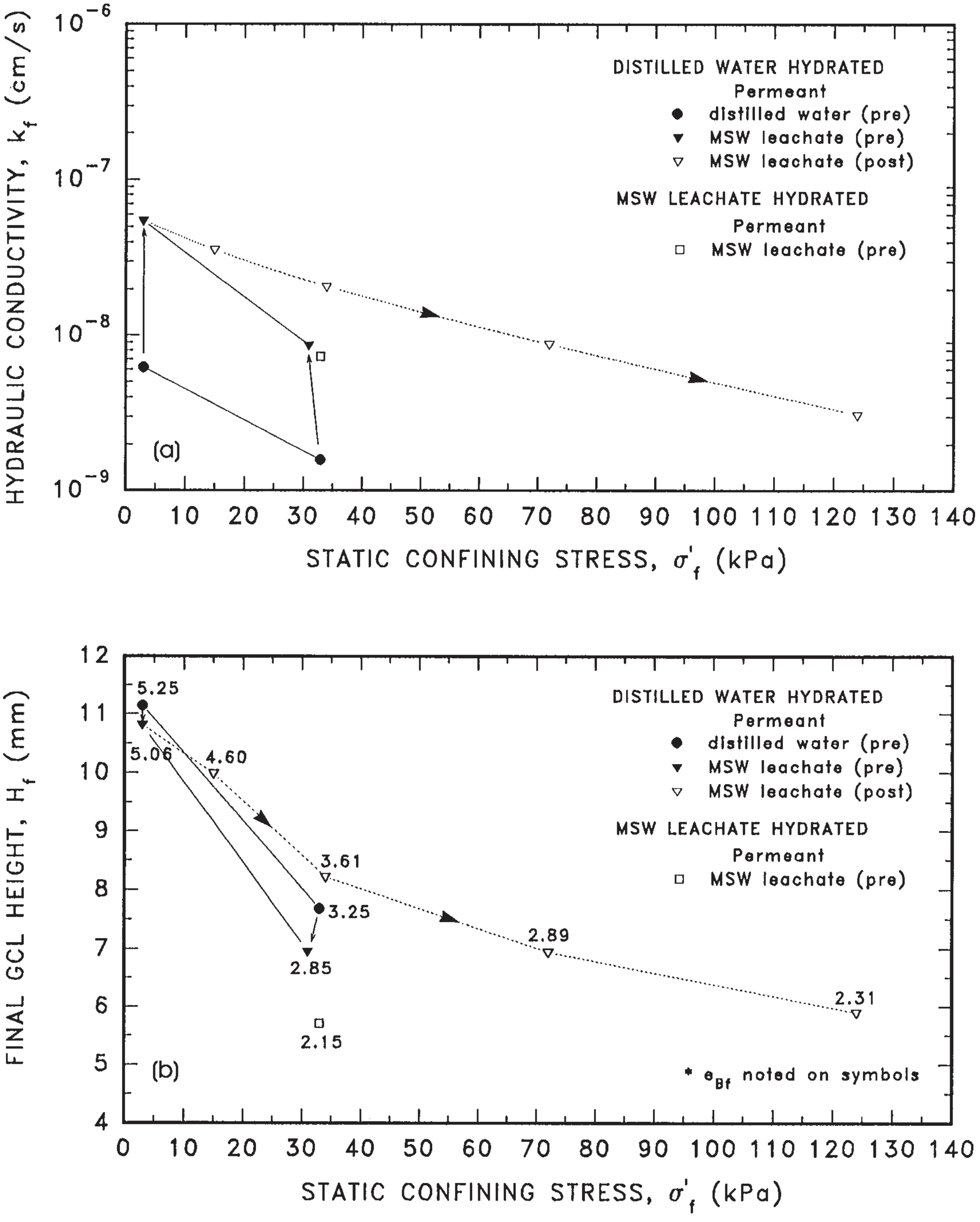
GCL hydraulic conductivity for permeation of synthetic MSW leachate

Effect of hydrating medium and prehydration versus posthydration confinement

A few tests were conducted with the synthetic MSW leachate and the results are summarized in Table 4. The final hydraulic conductivity, k_f, and the final GCL height, H_f, are plotted against the confining stress in Fig. 13 for the synthetic MSW leachate (hereafter referred to as leachate) and distilled water permeants. The final void ratio is plotted against the hydraulic conductivity in Fig. 14.

Prehydration confinement tests included hydration and initial permeation with distilled water and subsequent permeation of the leachate for low ($\sigma_f' \approx 3$ kPa) and intermediate ($\sigma_f' \approx 32$ kPa) confining stresses, and hydration and permeation with the leachate for an intermediate confining stress ($\sigma_f' =$ 33 kPa). The GCL hydrated with water at the low confining stress was then subjected to increases in stress after permeation of the leachate (i.e., posthydration confinement test) to simulate increasing overburden (i.e., in MSW landfills). Approximately 4.5, 9, and 18 pore volumes of the leachate were passed through C1, C2, and C3, respectively, and chemical equilibrium was considered reached as effluent concentrations of selected chemical species (Na^+, Mg^{2+}, K^+ and Cl^-) were comparable to initial reservoir values. Effluent Ca^{2+} concentrations were roughly one half of reservoir values during the test and were the result of precipitation (likely calcite) observed in the effluent bottles. The hydraulic conductivity values for permeation of the leachate were relatively constant with pore volumes of flow for a given confining stress suggesting negligible long-term impact

Fig. 13. (*a*) Hydraulic conductivity and (*b*) final GCL height versus confining stress for permeation of synthetic MSW leachate.

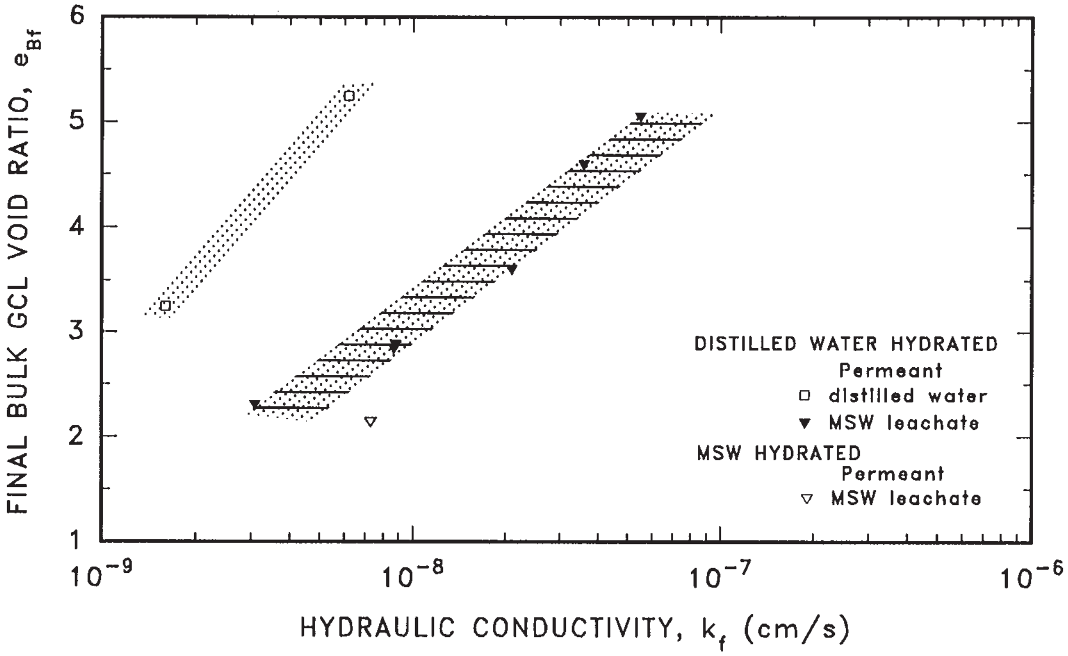


(over the 59 days of permeation) on the hydraulic properties of this GCL.

Reference hydraulic conductivities for permeation with distilled water (see Fig. 13*a*) decreased from 6.2×10^{-9} cm/s at the low confining stress to 1.6×10^{-9} cm/s at the intermediate confining stress. Both specimens were confined prior to hydration. Sequential permeation of the leachate caused an approximately ninefold increase in hydraulic conductivity to 5.5×10^{-8} cm/s and an approximately fivefold increase to 8.7×10^{-9} cm/s at the low and intermediate confining stresses, respectively, despite a small reduction in void ratio as shown in Fig. 13*b*. The decrease in void ratio (from 5.25 to 5.06 and from 3.25 to 2.85 at the low and intermediate confining stresses, respectively) for permeation of the leachate is similar to that observed for permeation of the 0.6 and 2.0 M NaCl solution. Increasing the confining stress from 3 to 124 kPa for posthydration confinement produced an 18-fold decrease in the hydraulic conductivity (to 3×10^{-9} cm/s) for sequentional permeation of the leachate and the void ratio was reduced from 5.01 to 2.31. Similarly, the leachate impacted the double layer and c-axis as previously discussed for the single salt solution.

Although details with respect to effluent chemistry, and hence chemical interaction of the leachate with the initially water hydrated bentonite, are beyond the scope of this paper,

Fig. 14. Final bulk void ratio versus hydraulic conductivity for permeation of synthetic MSW leachate.



there were some important and relevant observations which warrant mention.

Monitoring of the effluent chemistry throughout the duration of the test indicated premature arrival of chloride (i.e., the ratio of the concentration of effluent to initial reservoir concentration, C/C_0, reached 0.5 at significantly less than one pore volume of flow). This can be explained as a probable diffusion-dominated transport mechanism through the relatively thin GCL samples (see Petrov et al. 1997*a*; Rowe et al. 1997). Sodium (Na^+) appeared to arrive earlier than the assumed conservative species, chloride, while calcium (Ca^{2+}), magnesium (Mg^{2+}), and potassium (K^+) were retarded and arrived later than chloride. This suggests chemical interaction of the leachate with the bentonite, with probable desorption of Na^+ from the clay exchange sites and adsorption of competing species, Ca^{2+}, Mg^{2+}, and K^+. Thus double-layer contraction likely resulted from both increases in the pore fluid concentration and some replacement of the monovalent cation, Na^+, with divalent cations, Ca^{2+} and Mg^{2+}.

Hydrating the GCL with the leachate did not appear to produce significant differences in the hydraulic conductivity, as values of 8.7×10^{-9} and 7.3×10^{-9} cm/s, respectively, were obtained for the distilled water hydrated and leachate hydrated GCLs at the intermediate confining stress. This observation was similar to that from prehydration confinement tests presented for permeation of 0.1 M NaCl and also suggests that for the particular GCL examined it may not be critical for the GCL to be well hydrated with potable water prior to potential exposure with a leachate of similar chemical composition; nevertheless, hydration with water would still be preferred. Since actual MSW leachates are biologically active, microbial clogging of soil pores could decrease the hydraulic conductivity relative to a non-biologically active leachate, all else remaining constant; however, more research is required to test this hypothesis.

As in the case for permeation of the aqueous NaCl solutions, there are substantial benefits with regard to the GCL hydraulic properties to confinement prior to hydration (for both distilled water hydrated and leachate hydrated samples) as shown in Fig. 13. At the intermediate confining stress, prehydration confinement produced a hydraulic conductivity value that was about 40% of the value for posthydration confinement for distilled water hydrated GCLs. The significantly lower hydraulic conductivity value can be attributed to differences in void ratios, which were 2.85 and 3.61, respectively, for the prehydration and posthydration confinement tests. A similar observation can be made for the leachate hydrated GCL. At a constant void ratio (see Fig. 14), differences in hydraulic conductivity exist dependent on the hydrating medium, which confirms previous observations that the hydrating medium can impact the initial clay fabric and hence can influence the hydraulic properties of the GCL.

Equivalent NaCl concentration

Based on the results presented in this paper, the leachate produced hydraulic conductivity values similar to concentrations of NaCl solutions ranging from 0.2 to 0.8 M NaCl as reported in Table 4 for the three confining stresses. Also, at a constant void ratio (and GCL height and final bentonite moisture content), the GCL behaved similar to concentrations of NaCl solutions between 0.1 and 0.6 M NaCl; however, results were skewed towards 0.6 M NaCl. This suggests, based on the series of hydraulic conductivity tests, that the behaviour of the leachate with the bentonite in the GCL was similar to that of aqueous NaCl solutions ranging in concentration from 0.2 to 0.8 M NaCl. These observations generally agree with earlier observations for some index tests where it was found that the leachate was able to impact the index properties of the bentonite with a degree comparable to that of an aqueous NaCl solution between 0.1 and 0.6 M NaCl. This confirms that for the permeants considered in this investigation, index tests are valuable in that they could be used to qualitatively estimate the relative impact of such solutions on the hydraulic properties of the bentonite and hence the GCL; however, the index tests do not provide actual hydraulic conductivity values and void ratios, and they cannot adequately simulate field conditions. Therefore, they are not a viable alternative to laboratory hydraulic conductivity testing. It is emphasized that all tests reported in this paper were conducted on a natural Na^+ bentonite, and observations may differ from those of similar tests conducted on a chemically treated bentonite. Further investigation into factors impacting the hydraulic properties of GCLs containing treated bentonites is recommended so that any potential benefits can be addressed.

Conclusions

An extensive series of laboratory tests was performed on a needle-punched geosynthetic clay liner (GCL). The tests included 1D confined swell and consolidation tests, index tests (X-ray diffraction, test tube flocculation, and liquid limits), and hydraulic conductivity tests in a constant flow rate, fixed-ring apparatus. Permeants included distilled water, a range of concentrations (0.01, 0.1, 0.6, and 2.0 M) of a single salt solution (NaCl), and a synthetic municipal solid waste (MSW) leachate chemically similar to an actual MSW leachate. The confining stresses ranged from a low of 3 kPa to a high of 124 kPa. The hydraulic conductivity ranged over about 3.5 orders of magnitude, from a high of about 2.5×10^{-6} cm/s to a low of about 5×10^{-10} cm/s. Final GCL void ratios ranged from about 1.5 to 5, final hydrated GCL heights from about 4.5 to 12.5 mm, and final bentonite moisture contents from about 60 to 250%.

For the GCL and conditions examined, the following conclusions can be drawn from the laboratory investigation reported herein:

(1) At a given static confining stress, water-hydrated GCLs (hydrated under confinement) were susceptible to increases in hydraulic conductivity (relative to the hydraulic conductivity for reference water permeation) when exposed to aqueous saline (NaCl) solutions, with the relative increases ranging from small (for concentrations of 0.1 M or less) to significant (for concentrations of 0.6 M and greater). As the salt concentration increased from 0.01 to 2.0 M NaCl, the hydraulic conductivity increased, from a value similar to that obtained for distilled water, by a factor ranging from about 13 to 43. Greater double-layer and c-axis contraction and a resulting more open structured, flocculated soil fabric for the higher salt concentrations were considered responsible for the increase in effective pore space, and hence the increase in hydraulic conductivity.

(2) The observations described above were valid independent of the magnitude of the confining stress; however, for a given salt concentration, the hydraulic conductivity ranged by about an order to one and a half orders of magnitude, and decreased with corresponding increases in the confining stress. The significant difference in hydraulic conductivity values resulted from differences in void ratios, with lower void ratio GCLs exhibiting a smaller effective pore space for permeant migration.

(3) Hydrating the GCL with the higher concentrations of NaCl solutions caused smaller final void ratios at a given confining stress. The smaller void ratios associated with the higher salt concentrations did not compensate for the increased double-layer and c-axis contraction and resulting difference in clay fabric causing the hydraulic conductivity to increase by a factor ranging from about 280 to 420 as the salt concentration was increased from 0.1 to 2.0 m NaCl. An increase in the confining stress from about 3 to 110 kPa decreased the hydraulic conductivity by an order of magnitude for a given salt solution because of the substantial reduction in void ratio.

(4) The increases in hydraulic conductivity for an initially water hydrated GCL sequentially permeated with NaCl solutions can be reduced or eliminated by inducing sample consolidation through application of incremental confining stresses to decrease the void ratio. Incrementally increasing the confining stress from 3–4 to 109–114 kPa reduced the hydraulic conductivity by between about one half and one order of magnitude. Higher confining stresses were required for higher salt concentrations to effectively heal the GCL and produce a hydraulic conductivity value similar to that obtained for distilled water at a 3–4 kPa confining stress.

(5) At a given confining stress, the degree of impact of the hydrating medium on the hydraulic conductivity was shown to be dependent on the concentration of NaCl in solution. For anticipated exposure to highly concentrated NaCl concentrations (0.6 and 2.0 M NaCl), it is critical, if the hydraulic properties are to be optimized, that GCLs be well hydrated with fresh, potable water prior to potential exposure. The highly flocculated clay fabric for bentonite hydration with the salt solutions was responsible for the significantly larger hydraulic conductivity values relative to the values obtained for GCLs hydrated with distilled water and sequentially permeated with the salt solutions. However, there was little effect of the hydrating medium for permeation of a lower concentration of NaCl in solution (0.1 M NaCl), suggesting the hydrating fluid is not as critical. The lower void ratio associated with the salt water hydrated GCL balanced initial fabric effects and hence produced similar hydraulic conductivities for permeation of the 0.1 M NaCl independent of whether the GCL was salt water hydrated or distilled water hydrated. This observation was independent of the magnitude of static confining stresses considered.

(6) Applying static confining stresses prior to bentonite hydration (i.e., prehydration confinement) produced significantly lower void ratios at a given confining stress than applying increasing confining stresses after allowing the GCL to fully hydrate under a low confining stress of 6 kPa (posthydration confinement). For GCLs initially hydrated with water and sequentially permeated with the range of NaCl concentrations considered, prehydration confinement produced hydraulic conductivity values that were as much as 3.3 times smaller than those obtained for posthydration confinement, suggesting the significant hydraulic benefits of maximizing overburden prior to bentonite hydration.

(7) The hydraulic conductivity is significantly dependent on three main factors, specifically, the GCL void ratio, the concentration of the permeant salt solution, and the initial clay fabric (which depends on the hydrating medium). Void ratios were dependent on both the magnitude of the confining stress and the level of bentonite hydration at the time of the application of the confining stresses, all else remaining constant. At a given void ratio, increases in hydraulic conductivity result for GCLs hydrated with the salt solutions (relative to GCLs hydrated with distilled water) and for relative increases in the salt concentration. The index tests conducted on the bentonite taken from the GCL qualitatively predicted relative hydraulic conductivity differences, suggesting that index tests can be used to provide a reasonably quick estimate of the compatibility of

a selected permeant with the smectitic-rich soil; however, they should not be used exclusively as an alternative to hydraulic conductivity testing.

(8) Based on tests similar to those conducted for permeation of salt solutions, a synthetic MSW leachate produced hydraulic conductivity values similar to concentrations of NaCl ranging from about 0.2 to 0.8 M at both constant confining stress and constant void ratio. The index tests conducted also qualitatively suggested a degree of impact similar to the concentration of NaCl found in the hydraulic conductivity testing program, which again suggests the usefulness of such tests. For permeation of the leachate, the initial hydrating medium (for prehydration confinement) did not appear to influence hydraulic conductivity values at a confining stress of about 33 kPa, suggesting no potential hydraulic benefits of a water-hydrated bentonite core; however, hydration with water would still be preferred. More work is required to evaluate leachates with significantly different chemical constituents and concentrations as well as the potential benefits of an actual biologically active MSW leachate.

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List of symbols

A_c	activity
C	concentration

C_c	compression index
C_o	initial reservoir concentration
e_{Bw}	void ratio at completion of water permeation
e_{Bf}	final void ratio
H_f	final height of GCL
H_{GCL}	height (thickness) of the GCL
ΔH_{GCL}	change in GCL height
H_s	height of solids in the GCL (bentonite and geotextiles)
H_w	height of GCL at completion of water permeation
i_f	final hydraulic gradient
J_{Bf}	final maximum seepage stress
k_f	final hydraulic conductivity
k_w	hydraulic conductivity at completion of water permeation
M_{BENT}	mass of bentonite per unit area
M_{GEO}	mass of geotextiles per unit area
PV	pore volumes
w_c	corrected bentonite moisture content (mass ratio of water to soil solids)
w_f	measured bentonite moisture content (mass ratio of water to total solids)
w_L	liquid limit
w_o	initial bentonite moisture content (prior to hydration)
ε_v	final volumetric strain ($\varepsilon_v = \Delta H_{GCL}/H_w$)
ρ_s	density of bentonite solids
ρ_{sol}	density of pore fluid
ρ_{sg}	density of geotextile polymer solids
σ_w'	static confining stress when permeated with water
σ_f'	static confining stress after permeation with NaCl solution or leachate
σ_p'	apparent preconsolidation pressure