PERMEABILITY OF JET FUEL THROUGH GCLS UNDER ARCTIC CLIMATIC CONDITIONS

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ABSTRACT
The permeability of a geosynthetic clay liner (GCL) with respect to jet fuel was evaluated using both a flexible wall and a rigid wall (fixed ring) permeameter. The GCL specimens were initially hydrated under the low confining pressures corresponding to a documented field application and then subjected to different numbers of freeze and thaw cycles before permeation with jet fuel. At the very high gradients characteristic of the fixed ring test, the intrinsic permeability of jet fuel after breakthrough (steady state) increased to about 1.5 times larger than that for water. In contrast, at the lower gradients used in the flexible wall permeameter test, there was no flow of jet fuel into or from the GCL specimen when the pressure head on the GCL specimen was 14 kPa (or less). The threshold pressure at which jet fuel did permeate through the GCL was found to be well above that anticipated in the field. Thus despite many freeze and thaw cycles it can be anticipated that the GCL would provide an excellent barrier to pure phase jet fuel at the pressure heads examined in these tests and anticipated in the field.

RÉSUMÉ
La perméabilité des recouvrements geosynthetic d'argile (GCLs) en ce qui concerne le carburant pour réacteurs a été évaluée à l'aide d'un mur flexible et d'un perméabilimètre rigide de mur (un anneau fixe). Les spécimens de GCL ont été au commencement hydratés sous les basses pressions d'emprisonnement correspondant à l'application de champ et alors soumis à différents nombres de gel et dégèlent des cycles avant la perméation avec le carburant pour réacteurs. Aux gradients très élevés caractéristiques du test de l'anneau fixe, la perméabilité intrinsèque du carburant pour réacteurs après percée (état d'équilibre) a grimpé jusqu'environ 1.5 fois plus grand que cela pour l'eau. En revanche, aux gradients inférieurs utilisés dans l'essai flexible de perméabilité à mur, il y avait de débit nul de carburant pour réacteurs dans ou du spécimen de GCL quand la tête de pression sur le spécimen de GCL était le kPa 14 (ou moins). La pression de seuil à laquelle le carburant pour réacteurs a imprégné par le GCL s'est avérée bien au-dessus de cela prévu dans le domaine. Ainsi en dépit des beaucoup de des cycles de gel et de dégel il peut prévoir que le GCL fournirait une excellente barrière au carburant pour réacteurs pur de phase aux têtes de pression examinées dans ces essais et prévues dans le domaine.

1. INTRODUCTION

A previous paper (Li *et al.* 2002) described the construction of a composite (geomembrane and geosynthetic clay liner (GCL)) wall intended to provide temporary containment (over a period of several years) of a spill of Arctic diesel (jet fuel A-1) at a remote site in the Canadian Arctic while a permanent cleanup plan is implemented. The present paper reports results from a study directed at assessing how long the GCL can be expected to provide this temporary containment function. Particular attention is directed at the effects of: a) interaction with the jet fuel; and (b) freeze-thaw on the long-term performance of the GCL. Since jet fuel is an organic immiscible liquid, consideration is given to: 1) the effect of the water-jet fuel interface between fluids in the soil pores; 2) the effect of interaction between jet fuel and the bentonite double layer; and 3) the changes in the pore structure of bentonite due to freeze-thaw and permeation by jet fuel. Consideration is also given to the effect of the choice of test method on the results.

Both rigid wall permeameter (RWP) and flexible wall permeameter (FWP) tests were performed. The FWP tests are still in progress. Thus, barrier performance of the GCL discussed in this paper is based on the published results (Rowe *et al*. 2004a and b) and the presently available data from the FWP tests

2. TEST METHODS

All specifications with respect to the single type of GCL (Bentofix NWL) used in the current investigation and permeants (de-aired water and jet fuel) tested are described by Mukunoki *et al.* (2003) and Rowe *et al.* (2004a). GCL specimens were prepared in the same way for both RWP and FWP tests, and in each case the specimens were:

1) hydrated for 5 days under a confining pressure of about 14 kPa and an hydraulic gradient of 20;
2) subjected to 0, 5 or 12 freeze and thaw cycles;
3) permeated with de-aired water to establish hydraulic conductivity (k) with respect to water; and then,
4) permeated with jet fuel to establish k following interaction.

2.1 Rigid wall permeameter (RWP) test

The fixed ring permeameter used here is the same type of apparatus used by Petrov and Rowe (1997). In this system, stress (12 – 18 kPa) is applied to the GCL specimen by springs acting on a porous plate. A dial gauge is attached to the plate and the thickness of GCL is monitored during hydration and permeation of the specimen. The inside diameter is 54 mm. The influent volume per day is 3.18 mL and effluent volume was monitored regularly. The influent pressure was measured during permeation and hydraulic conductivity was calculated using Darcy's Law.

2.2 Flexible wall permeameter (FWP) test

FWP tests were conducted on 70mm diameter specimens using a Tri-Flex 2 Permeability Test system (Hoskin Science). A pressure interface chamber (K-790A model) was used to control jet fuel inflow and outflow.

Mukunoki *et al.* (2003) examined the chemical resistance of the membrane sleeve and reported that both conventional latex and neoprene sleeves do not work well. In these tests, a viton membrane sleeve was used and found to perform well (i.e. no evident chemical interaction or wrinkling of the sleeve as reported for neoprene by Mukunoki *et al.* (2003)) over 6 months of jet fuel permeation. The hydraulic conductivity of GCL specimens was evaluated based on ASTM D5084-90 and D6766-02.

2.3 Freeze and thaw cycles test

After hydration, the entire RWP cell was placed in a freezer at –15°C. After about 24 hours, the cell was placed in a room with a regulated temperature of 22±1°C for about 24 hours (ASTM D6035-96). This procedure was repeated 5 and 12 times. There was no additional supply of water to the GCL specimen during the freeze-thaw cycles.

The standard FWP cell is too large to place the entire cell in the freezer. Thus a special chamber was developed to hydrate a GCL specimen and subject it to freeze-thaw cycles as shown in Figure 1. The freeze-thaw cycles were applied as described above for the RWP specimens. After completion of the last freezing, the GCL specimens were removed from the chamber and installed into the FWP, and the last thaw was completed in the FWP cell. This procedure minimized the effect of stress release when the specimen was transferred from the special chamber to the FWP because the frozen specimen did not experience any significant volume change.

3. RESULTS AND DISCUSSIONS

3.1 Permeability of GCL to jet fuel

Tables 1, 2 and 3 present the physical properties of the GCL specimens, geometric mean hydraulic conductivity values and hydraulic gradients in the RWP and FWP tests. In the following discussion, the subscripts 'w', 'j' and 'B' in Table 1 denote 'entire effluent is water', 'entire effluent is jet fuel', and 'bulk void ratio', respectively. The

Table 1 Properties of GCL used in the four test series

Test method	Number of F-T cycles	M_{GCL} (g/m^2)	e_{Bw}	e_{Bj}	Fluid content L*** (%)
RWP	0	4464	4.3*	3.6	133
RWP	5	4247	6.3*	5.8	192
FWP	0	4316	3.3**	tbd	tbd
FWP	12	4451	5.4**	tbd	tbd

tbd : to be determined
* At the end of water permeation; ** Before water permeation
*** $L=M_L/M_s$, where M_L is a mass of fluid in the bentonite and M_s is dry mass of bentonite

Table 2 Geometric mean hydraulic conductivity of GCLs at each stage

Test method	k_1 (m/s)	k_2 (m/s)	k_3 (m/s)	k_3/k_1
RWP (0)	2.0×10^{-11}	8.2×10^{-12}	2.0×10^{-11}	1
RWP (5)	2.0×10^{-11}	5.8×10^{-12}	8.0×10^{-11}	4
FWP (0)	3.3×10^{-11}	6.0×10^{-13}	tbd	tbd
FWP (12)	3.0×10^{-11}	1.7×10^{-12}	tbd	tbd

( ) : Number of freeze and thaw cycles
tbd : to be determined

Table 3 Hydraulic gradient across each GCL specimen at each stage

Test method	i_1	i_2	i_3	i_3/i_1
RWP (0)	730 (*71)	1153 (*75)	723 (*16)	1.0
RWP (5)	750 (*226)	790 (*170)	222 (*14)	0.3
FWP (0)	90	690**	tbd	tbd
FWP (12)	74	175**	tbd	tbd

tbd : to be determined ; * Standard deviation.
** Hydraulic gradients at the threshold pressure

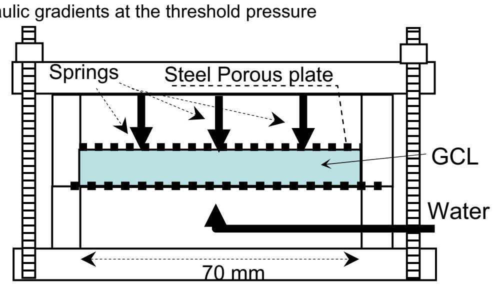

Figure 1 Schematic of the freeze-thaw test cell

progress of both types of permeability tests can be split into three stages. In stage 1, de-aired water was permeated through the GCL. In stage 2, jet fuel was permeated through the GCL but the effluent at this stage was a mixture of both pore water and jet fuel. In stage 3, the effluent was entirely jet fuel. The hydraulic conductivities (k_1, k_2, k_3), and hydraulic gradients (i_1, i_2, i_3), in each of the stages are summarized in Tables 2 and 3, respectively.

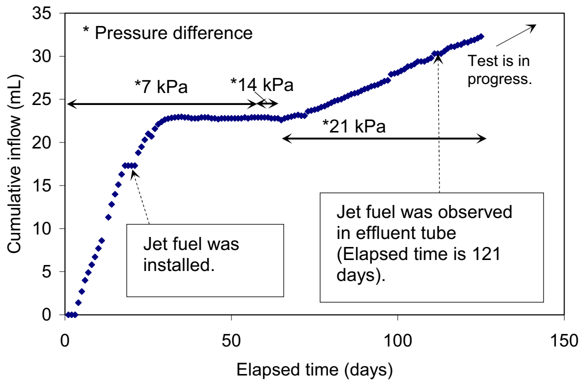

Figure 2 Cumulative inflow volumes through GCL specimen subjected to 12 freeze-thaw cycles in FWP test

Table 4 Intrinsic permeability

Test method	K_1* (m^2)	K_2 (m^2)	K_3 (m^2)	K_3/K_1
RWP (0)	2.1 x10^{-18}	2.9 x10^{-18}	6.9 x10^{-18}	3.3
RWP (5)	2.2 x10^{-18}	2.0 x10^{-18}	2.8 x10^{-17}	12.7
FWP (0)	3.3 x10^{-18}	2.0 x10^{-19}	tbd	tbd
FWP (12)	3.0 x10^{-18}	5.7 x10^{-19}	tbd	tbd

tbd: to be determined;
*$K_1=k_1\mu/g$: where k_1 is hydraulic conductivity [LT^{-1}], μ is kinematic viscosity [L^2T^{-1}] at 22°C, and g is gravitational acceleration [LT^{-2}].

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3.1.1 RWP test results

Four GCL specimens were prepared. Two were virgin specimens with no freeze and thaw cycles and two were specimens subjected to 5 freeze and thaw cycles. The bulk void ratio during water permeation and jet fuel permeation, was calculated when the hydraulic conductivity and GCL height had reached constant values (after at least one pore volume of flow). As shown in Table 1, the virgin GCLs had lower bulk void ratios than the GCLs subjected to freeze-thaw cycles. This indicates that the pore space in the bentonite increased due to the freeze-thaw cycles. After permeation to equilibrium, the average total liquid (pore water and jet fuel) content (L) of the virgin GCLs was about 133% and that of the GCLs after freeze-thaw cycles was about 192% (see Table 1).

The hydraulic conductivity (k_1) of the GCLs with respect to de-aired water averaged about 2.0 x 10^{-11} m/s for both the specimens with no freeze-thaw and those with 5 freeze-thaw cycles once the influent to effluent ratio became 1. (Table 2) Initial permeation by jet fuel (k_2) resulted in a reduction in the hydraulic conductivity of the GCL due to the difference between the density and viscosity of jet fuel compared to that of water. However, with time, interaction between the jet fuel and bentonite resulted in an increase in hydraulic conductivity (k_3). For the specimens with no freeze-thaw the final (equilibrium) hydraulic conductivity with respect to jet fuel was, within measurement accuracy, the same as the value with respect to water (≈ 2.0x10^{-11} m/s). For the specimens subjected to 5 freeze-thaw cycles, the average final equilibrium hydraulic conductivity with respect to jet fuel was about 8.0 x 10^{-11} m/s (i.e. about 4 times higher than the initial value with respect to water of 2.0 x 10^{-11} m/s) but still low.

The jet fuel broke through both of the GCL specimens quickly (Rowe *et al.* 2004b). However these tests were conducted at very high gradients (see Table 3) whereas in the field the gradients are much smaller. This behaviour is different from that observed in the corresponding FWP test.

3.1.2 FWP test results

Since FWP tests for both 0 and 12 freeze-thaw cycles are still in progress (after 6 months), the thickness of specimens after the termination of the tests is not yet known and so the thickness of each specimen used to calculate the hydraulic gradient is assumed to be the initial thickness in these results. The initial pressure difference across all specimens was 7 kPa (hydraulic gradient of 70 – 90) during the water permeation stage. Hydraulic conductivities for both 0 and 12 freeze and thaw cycle specimens were 3.0 – 3.3 x 10^{-11} m/s.

Figure 2 shows the cumulative inflow volumes of a GCL specimen subjected to 12 freeze and thaw cycles. At a fluid pressure of 7 kPa, the replacement of water by jet fuel as the permeant resulted in a reduction in the rate of cumulative inflow volume, eventually to zero. The jet fuel could not permeate the GCL specimen because the fluid pressure was less than the threshold pressure in the GCL specimen and so the hydraulic gradient was not sufficient to overcome the interfacial tension between water and jet fuel. To establish the magnitude of the threshold pressure, the pressure head was increased in steps (and the cumulative volume monitored for one week) until flow was restarted (see Figure 2). The threshold pressure was found to be between 14 and 21 kPa (depending on the specimen). Hydraulic gradients calculated using the maximum threshold pressure are given in Table 3. The threshold hydraulic gradient for the GCL specimen subjected to no freeze-thaw cycles is about 4 times greater than that for the GCL specimen subjected to 12 freeze and thaw cycles. However in both cases the threshold pressure is greater than the pressure differential likely to be encountered in the referenced field application and hence no flow is anticipated in the field case.

The hydraulic conductivity with respect to jet fuel for the GCL specimen with no freeze-thaw cycles is about one third of that of the GCL specimen with 12 freeze-thaw cycles (see Table 2). However, both values are very low and the GCL with 12 freeze-thaw cycles appears to be a suitable barrier to jet fuel in the short and medium term (certainly up to 4 years and potentially much longer). The hydraulic conductivity of jet fuel obtained to date in the FWP tests corresponds to stage 2 in the RWP test (see Table 2). However, the performance of the barrier in the long term is not expected to be worse than that implied by stage 3 of the RWP test.

3.2 Evaluation of long-term barrier performance

Table 4 presents the intrinsic permeability calculated using the Kozeny-Carman equation and data in Table 2. Rowe et al. (2004a) reported that the intrinsic permeability did not change significantly due to permeation by jet fuel in the short to medium term. However, in the present tests, many pore volumes of permeation by jet fuel resulted in a long term (equilibrium) intrinsic permeability about a factor of three higher than that for water and no freeze-thaw cycles, and a factor of 13 times higher for the specimens after 5 freeze-thaw cycles (see Table 4). Rowe et al. (2004b) reported that jet fuel permeation resulted in a decrease in bulk void ratio but an increase in intrinsic permeability. This increase is a result of a change in the structure of the bentonite. The increase in intrinsic permeability due to permeation by jet fuel is much greater than that in hydraulic conductivity due to the difference in density and viscosity of jet fuel relative to water.

3.3 Effect of test method on permeability results

In the FWP tests, the flow of jet fuel does not begin until the threshold pressure (gradient) is reached. In RWP tests, the pressure gradient was very high until the jet fuel broke through the GCL specimens at stage 2 and the maximum pressure gradient in stage 2 was greater than that in stage 1. However, after jet fuel broke through the GCL specimen subjected to freeze and thaw cycles (stage 3), the pressure gradient decreased. Thus, once the threshold pressure is exceeded and the jet fuel creates a path through the bentonite, the jet fuel can permeate more readily. Since the pressures applied in the RWP tests are much larger than are likely to be encountered in the field application described by Li *et al.* (2002), the RWP test likely overestimates the hydraulic conductivity of the GCL to jet fuel.

4. CONCLUSIONS

The effects of up to 5 freeze-thaw cycles (RWP test) and 12 freeze-thaw cycles (FWP test) permeation with de-aired water and jet fuel have been examined for a specific thermal locked, needle-punched GCL used to construct a trial subsurface barrier against groundwater contaminated by jet fuel at Brevoort Island in the Canadian Arctic (Li *et al.* 2002). RWP and FWP tests were conducted on both virgin GCL specimens before and after freeze-thaw cycles. The results of these tests conducted at low confining stress levels (12 ~ 18 kPa) using a fixed ring permeameter and flexible wall permeameter indicate that for the specific GCL and conditions examined:

- The hydraulic conductivity with respect to water was between 2.0×10^{-11} (RWP) and 3.3×10^{-11} m/s (FWP) before freeze-thaw, and 2.0×10^{-11} (RWP) and 3.0×10^{-11} m/s (FWP) after freeze-thaw.

- The hydraulic conductivity of the GCL after the freeze- thaw cycles with respect to jet fuel was about 4 times larger than that with respect to water in the long term. The intrinsic permeability of specimens permeated with water and then, jet fuel was 6.9×10^{-18} m^2 and 2.8×10^{-17} m^2 for specimens subjected to no freeze-thaw and 5 freeze-thaw cycles (RWP), respectively.

Based on these laboratory tests, it appears that the GCL subjected to up to 12 freeze-thaw cycles can be expected to perform well as a hydraulic barrier with respect to permeation by jet fuel. The threshold pressure for any flow of jet fuel also appears to be higher than the pressure differential likely to be encountered in field applications and consequently no flow is expected.

5. ACKNOWLEDGEMENTS

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