COMPATIBILITY OF A GCL WITH ARCTIC DIESEL BEFORE AND AFTER FREEZE AND THAW

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ABSTRACT: The hydraulic conductivity of a scrim-reinforced nonwoven thermal locked geosynthetic clay liner (GCL) with respect to both de-aired distilled water and Arctic diesel (jet fuel) are examined for five freeze-thaw cycles using a fixed ring permeameter. The hydraulic conductivity with respect to jet fuel is found to be about one order of magnitude smaller than that for de-aired water in the short to medium term. The hydraulic conductivity with respect to water did not change significantly after five freeze-thaw cycles. Long term permeation by jet fuel increased the intrinsic permeability of the GCL subject to freeze-thaw cycles, relative to virgin samples, despite the decrease of bulk void ratio of the GCL. However, there was only a modest (four fold) increase in hydraulic conductivity to a still quite low value of about 8×10^{-11} m/s. It appears that under the conditions examined, the GCL performed very well.

1 INTRODUCTION

Arctic diesel fuel spills and leaks have occurred on Brevoort Island (located in northern Canada at the east end of Baffin Island). The Canadian Department of National Defence has initiated a cleanup program at a number of contaminated military sites including Brevoort Island. As part of this program, during the summer of 2001 a subsurface geosynthetic composite barrier wall which included a geomembrane and a geosynthetic clay liner (GCL) as the key components was designed and constructed (Li *et al.* 2002). The wall is intended to provide temporary containment (over a period of several years) of a hydrocarbon plume while a more permanent solution is investigated for this remote location. A feature of this site is the presence of shallow permafrost that provides a natural barrier against significant downward contaminant migration. However, the shallow depth to permafrost also contributes to lateral spreading of the hydrocarbon plume, particularly following infiltration by rainwater and snow melt. The barrier system was laid directly on the down-gradient slope of a trench excavated to permafrost. The barrier system comprised (from bottom up): a needle-punched GCL; fluorinated high density polyethylene (HDPE) geomembrane; a needle-punched geotextile protection layer and; backfill. The surface area above the plume was graded and then covered with a geomembraneto minimize infiltration of rainwater or runoff into the contaminated zone.

Rowe *et al.* (2004) examined the hydraulic conductivity of GCLs subjected to several freeze-thaw cycles and the GCLs recovered from the Brevoort site after one year using de-aired water and jet fuel in the short-medium term. They concluded that good performance of the the GCL as a hydraulic barrier can be expected in the short to medium term (≈ 3 - 4 years, and possible more) with respect to the effect of both freeze-thaw and permeation with jet fuel. However, they also noted the need to assess the long-term performance of the GCL subjected to freeze-thaw cycles. Organic permeant with a low dielectric constant causes contraction of the double layers of water on the bentonite clay particles in a GCL during permeation (Rowe et al., 1995, Petrov and Rowe, 1997). At low stress conditions (as in this case) this has the potential to increase the hydraulic conductivity of a GCL.

In the field application under investigation, a key question is how long will the wall provide temporary containment and, in particular, what will be the effects of interaction with the Arctic diesel and freeze-thaw on the ability of the wall to provide long-term containment? Thus, the objective of the present study is to examine the hydraulic conductivity of a GCL with respect to Arctic diesel (jet fuel) for both virgin specimens and for specimens subject to freeze-thaw cycles using the same material that was used to construct the hydraulic barrier wall at Brevoort Island. As a reference, consideration is initially given to the hydraulic behaviour with respect to de-aired water both before and after freeze-thaw cycles. The behaviour is then examined with respect to jet fuel. The study was conducted using fixed ring permeameters that allowed monitoring of the change of void ratio during permeation.

2 MATERIALS & TEST METHODS

2.1 *GCL properties*

A needle-punched reinforced GCL was examined. This product is comprised of a uniform layer (3.66 kg/m^2 Minimum Average Roll Value (MARV)) of granular sodium bentonite encapsulated between a scrim-reinforced nonwoven (200 g/m^2 MARV) carrier and a virgin staple fibre nonwoven (200 g/m^2 MARV) cover geotextile. The needle-punched fibres are thermally fused to the scrim-reinforced nonwoven geotextile to enhance the reinforcing bond. Other properties of the GCL are given by Rowe *et al.* (2004).

Table 1 Properties of GCL specimens at the end of water/jet fuel permeation

Test case	Number of F-T cycles	M_{GCL} (g/m^2)	e_{Bw}	e_{Bj}	w_{wf} (%)
L1	0	4544	4.3	3.4	134
L2		4384	4.3	3.7	131
L3	5	4384	6.0	5.6	193
L4		4111	6.6	5.9	191

Table 2 Hydraulic conductivity of GCLs with respect to both water/jet fuel

Test case	k_1 (m/s)	k_2 (m/s)	k_3 (m/s)	k_3/k_1
L1	2.1E-11	1.1E-11	2.0E-11	0.93
L2	1.9E-11	5.4E-12	2.0E-11	1.07
L3	1.6E-11	6.7E-12	7.0E-11	4.29
L4	2.5E-11	4.9E-12	8.9E-11	3.53

Specimens were subjected to freeze-thaw cycles by placing the hydrated specimen and fixed ring cell, in a freezer at – 15° C for 24 hours and then thawing the specimen at 22°C. There was no water flow in or out of the hydration cell during freezing or thawing (closed condition). This process was repeated five times for each freeze-thaw specimen.

2.2 *Arctic diesel*

The permeants examined were de-aired distilled water and jet fuel A-1. Jet fuel A-1 (also called Arctic diesel), is a colorless to pale yellow liquid with kerosene-like or petroleum odor that is widely used in northern regions. Its freezing point is below – 47°C and specific gravity at 15°C is 0.755-0.840. Jet fuel A-1 is practically insoluble in water with a solubility of approximately 5 mg/L. Its kinematic viscosity is 8.0 mm^2/s maxmum at – 20°C. In the following discussion, permeants are referred to as "de-aired water" or simply "water", and "jet fuel".

2.3 *Fixed Ring Permeability test*

The fixed ring permeameter used in this test is the same type of apparatus used by Petrove and Rowe (1997). In this system, stress is applied to the GCL by springs acting on a porous plate. A dial gage is attached to the plate and the thickness of GCL is monitored during hydration and permeation of the specimen.

3 RESULTS AND DISCUSSION

3.1 *Physical properties of the GCL after jet fuel permeation*

Four GCL specimens were prepared. Two were virgin GCLs (L1, L2) with no freeze-thaw cycles and two GCLs were subjected to five freeze-thaw cycles (L3, L4). Confining pressures of 12.0 - 18.0 kPa were applied to the specimens which were first permeated with de-aired water and then with jet fuel. The physical properties of the GCLs are summarized in Table 1. The subscripts "w", "j", "B" and "f" respectively denote "entire effluent is water", "entire effluent is jet fuel", "bulk void ratio" and "final condition". 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 (F-T) cycles. This indicates that the pore space in the bentonite increased due to freeze-thaw cycles. After permeation to equilibrium, the average total moisture content of the virgin GCLs was about 133% and that of the GCLs after freeze-thaw cycles was about 192% (Table 1). Note that these moisture contents include both jet fuel in the free pore space and water that remains attached to the clay.

3.2 *Hydraulic conductivities*

The results of the fixed ring permeameter tests are presented in Figures 1 and 2 with hydraulic conductivity plotted against pore volumes of flow through each GCL specimen. Figures 3 and 4 show the ratio of the volume of jet fuel versus the total volume of the effluent in pore volumes. The behaviour during permeation can be split into three stages as shown in each figure. 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.

The hydraulic conductivity (k_1) of the GCLs with respect to de-aired water averaged about 2.0 x 10^{-11} for both the specimens with no freeze-thaw and those with five freeze-thaw cycles. 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 (≈ 2x10^{-11} m/s). For the specimens subjected to five freeze-thaw cycles, the average final equilibrium hydraulic conductivity with respect to jet fuel was about 8 x 10^{-11} m/s (i.e. about 4 times higher than the initial value with respect to water of 2 x 10^{-11} m/s).

As shown in Figures 3 and 4, the jet fuel broke through both of the GCL specimens quickly. However these tests were conducted at very high gradients whereas in the field the gradients are less than unity. At lower gradients the time required for interaction and the level of interaction may be different. Tests designed to examine behaviour under low hydraulic gradients and diffusion are presently in progress.

3.3 *Intrinsic permeability*

The intrinsic permeability, K_L, at each stage is calculated from:

$$K_L = \frac{k_L \cdot \eta_L}{\gamma_L} \qquad [1]$$

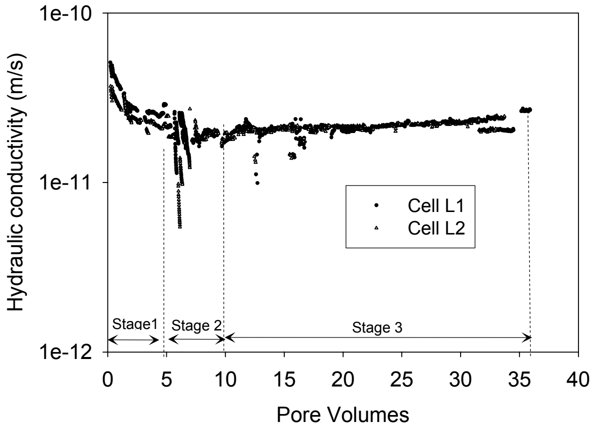

Figure 1 Hydraulic conductivity of GCLs with

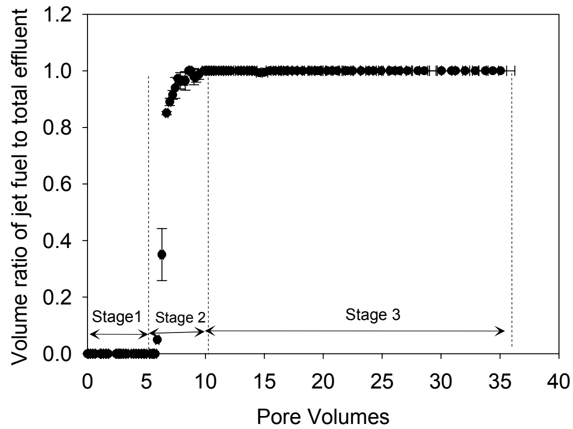

Figure 3 Volume ratio of jet fuel to total effluent for GCL

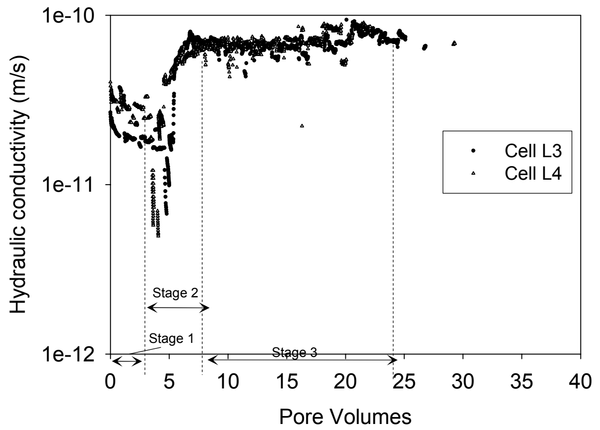

Figure 2 Hydraulic conductivity of GCLs with five free-ze-thaw cycles

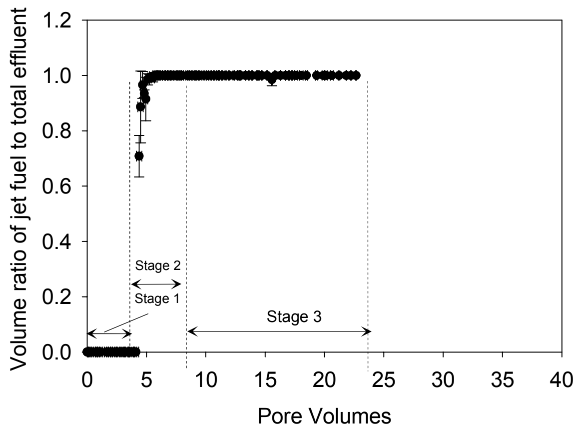

Figure 4 Volume ratio of jet fuel to total effluent for

where k_L is a hydraulic conductivity [LT^{-1}], η_L is dynamic viscosity [$ML^{-1}T^{-1}$], γ_L is unit weight of the permeant [$ML^{-2}T^{-2}$]. The values of K is calculated using the density, viscosity (at 22°C) and hydraulic conductivities (k_1, k_2, k_3) obtained from each stage, are given in Table 4. The intrinsic permeability, K_2, was calculated using the viscosity of jet fuel and the lowest hydraulic conductivity obtained during stage 2.

Rowe *et al*.(2004) reported that the intrinsic permeability did not change significantly due to permeation by jet fuel in the short to medium term (3-10 years at a unit gradient). However, in the present tests, after many pore volumes of permeation, the equilibrium intrinsic permeability of both GCL specimens increased by about a factor of three for the no freeze-thaw specimens and a factor or 12-14 for the specimens with 5 cycles of freeze thaw (Table 4).

Figure 5 shows a plot of intrinsic permeability versus bulk void ratio at each stage during permation. Jet fuel permeation resulted in a decrease in bulk void ratio but an increase in intrinsic permeability. This clearly highlights the fact that the change in intrinsic permeability is a result of a change in the structure of the bentonite. The fact that the change in intrinsic permeability due to permeation by jet fuel is much greater than the change in hydraulic conductivity is a result of the beneficial difference in density and viscosity of jet fuel relative to water.

3.4 *Practical Implications*

Based on the mean hydraulic conductivity values for the virgin GCL specimens during stage 2 and assuming a unit gradient in the field, the permeation of between 5.4 – 7.9 (no freeze thaw) and 3.5 – 7.1 (5 freeze-thaw cycles) pore volumes in stage 2, corresponds to between 66 years and 186 years. Recognising that after equilibrium is reached the hydraulic conductivity was still less than 9×10^{-11} m/s at a low confining stress (20 kPa), it can be concluded that at least for the conditions examined (up to five freeze-thaw cycles) the GCL performed very well. Tests are in progress to assess performance after more freeze-thaw cycles.

4 CONCLUSIONS

The effects of up to five freeze-thaw cycles and permeation with 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. Tests were conducted on both virgin GCL specimens before and after freeze-thaw cycles. The results of these tests conducted at low confining stress

Table 3 Hydraulic gradient across each GCL specimen at each stage

Test case	i_1	i_2	i_3	i_3/i_1
L1	677	1100	712	1.1
L2	778	1206	734	0.9
L3	910	911	232	0.3
L4	590	670	212	0.4

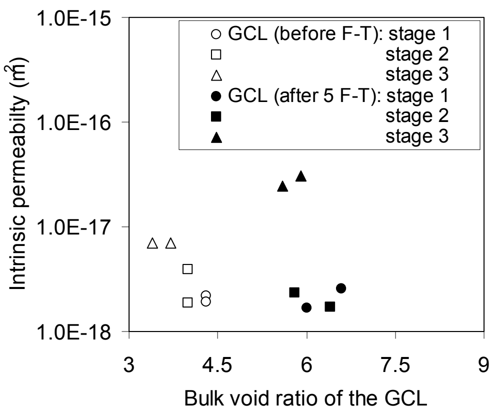

Figure 5 Intrinsic permeability vs bulk void ratio of

levels (12 ~ 18 kPa) using a fixed ring permeameter indicate that for the specific GCL and conditions examined:

- The hydraulic conductivity with respect to water was between 1.9 x 10^{-11} and 2.1 x 10^{-11} m/s at 14 kPa before freeze-thaw, and 1.6 x 10^{-11} and 2.5 x 10^{-11} m/s at 14 kPa after freeze-thaw.
- The hydraulic conductivity with respect to jet fuel was lower than that with respect to water in the short–medium term. This was in large part because of the difference in viscosity and density of jet fuel and water.
- The hydraulic conductivity of the GCL after the freeze-thaw cycles with respect to jet fuel was about 4 times magnitude larger than that with respect to water in the long-terms.
- The intrinsic permeability of specimens permeated with water and then, jet fuel was 6.9 x 10^{-18} m^2 and 2.8 x 10^{-17} m^2 for water and jet fuel, respectively.

Table 4 Intrinsic permeability at each stage

Test case	K_1 (m^2)	K_2 (m^2)	K_3 (m^2)	K_3/K_1
L1	2.2E-18	3.9E-18	6.9E-18	3.2
L2	1.9E-18	1.9E-18	6.9E-18	3.6
L3	1.7E-18	2.3E-18	2.4E-17	14.6
L4	2.6E-18	1.7E-18	3.1E-17	12.0

Based on these laboratory tests, it appears that the GCL subjected to up to 5 freeze thaw cycles can be expected to perform well as a hydraulic barrier in the long term with respect to permeation with jet fuel.

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