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Application of geosynthetic barrier wall to containment of hydrocarbons in the Arctic

L'application dans l'arctique des murs protecteurs faits d'argile geosynthetique pour retenir les hydrocarbures

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ABSTRACT
The effect of freeze-thaw cycles on the hydraulic conductivity of a geosynthetic clay liner (GCL) is assessed with respect to Jet Fuel A-1 (Arctic diesel). GCL specimens subjected to 0 and 5 freeze-thaw cycles and specimens recovered from a site on Brevoort Island in the Canadian Arctic after 3 years are examined. The GCL recovered from Brevoort Island had the lowest hydraulic conductivity with respect to de-aired water. Freeze-thaw cycles did not have a negative impact on hydraulic conductivity with respect to de-aired water. Freeze-thaw cycles did increase the hydraulic conductivity, k, with respect to Jet Fuel A-1. However, the hydraulic conductivity was still very low and the results suggest that the GCL can be expected to perform well as a hydraulic barrier in the medium term with respect to the effects of both freeze-thaw and permeation with Jet A-1. More testing is needed to assess long term performance.

RÉSUMÉ
On évalue l'effet des cycles de gel et dégel sur la conductivité hydraulique d'un revetement imperméable d'argile géosynthetique (RAG) vis-à-vis le carburant diesel arctique A-1 (combustible pour moteurs à réaction) . Les échantillons RAG soumis entre 0 et 5 cycles de gel et dégel, ainsi que les échantillons de RAG récuperés après un séjour de 3 ans à un site sur l'ile Brevoort dans la région arctique canadienne, sont examinés. L'échantillon recuperé de l'ile Brevoort a la plus basse conductivité hydraulique vis-à-vis l'eau de-aérée. Les cycles de gel et dégel n'avaient pas un impact négatif sur la conductivité hydraulique vis-à-vis l'eau de-aérée. Les cycles de gel et dégel augmentent nettement la conductivité hydraulique, k, vis-à-vis le carburant diesel arctique A-1 . Cependant, la conductivité hydraulique restait toujours très basse , et les résultats suggèrent qu'on peut attendre que le RAG agisse bien comme barrière hydraulique envers le gel et dégel et la perméation par le carburant diesel arctique A-1.

1 INTRODUCTION

Geosynthetic clay liners (GCLs) have become a well-established alternative to compacted clay liners in landfills and other waste containment facilities. GCLs typically consist of three components (i.e. a cover geotextile, bentonite and a carrier geotextile). The high swelling capacity of the bentonite clay produces a very low hydraulic conductivity that helps prevent migration of subsurface contamination. The applications for GCLs in environmental applications are rapidly growing in North America (Bélanger *et al.* 2004). This paper describes a case study in which the utility of GCLs is extended to containment of hydrocarbon spills to minimize the environmental impact in areas with difficult access and where cleanup may be delayed for several years (e.g. the Canadian Arctic).

Fuel spills and leaks have occurred at a Canadian radar site on Brevoort Island (located in northern Canada at the east end of Baffin Island). A subsurface geosynthetic composite barrier wall which included a geomembrane and a GCL as the key components was designed and constructed in the summer of 2001 (Li *et al.* 2002). The wall is intended to provide temporary containment of a hydrocarbon plume over a period of several years while a more permanent solution is investigated for this remote location. Field monitoring with respect to subsurface temperature profiles and ground water levels is ongoing at the site.

A key question in the field application is how long will the wall provide temporary containment and, in particular, what will be the effects of interaction with the Jet Fuel A-1 (also called Arctic diesel and referred to as Jet A-1 hereafter) and freeze-thaw on the capacity of the GCL to provide long-term containment? Thus, the objective of the present paper is to examine the hydraulic conductivity of a GCL with respect to Jet A-1 for specimens recovered from the field and virgin specimens 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 A-1 both following freeze-thaw and at different temperatures ranging between –20 and 20°C. The practical implications are then discussed.

2 OVERVIEW OF PREVIOUS RESEARCH RELATING TO THE BREVOORT ISLAND SITE

A feature of this site is the presence of shallow permafrost (2-3 m) that provides a natural barrier against significant downward contaminant migration. Thus, the primary mechanism for contaminant transport involves lateral migration above the permafrost. To control this migration, a barrier system was constructed on the down-gradient slope of a trench excavated to bedrock/permafrost. The barrier system comprised (from bottom up): a needle-punched GCL (Bentofix NWL, a nonwoven-nonwoven thermal treated, needle-punched, sodium bentonite GCL); a fluorinated high density polyethylene (HDPE) geomembrane; a needle-punched geotextile protection layer and; site backfill. The ground surface above the plume was graded and then covered with a geomembrane to minimize infiltration of rainwater or runoff into the contaminated zone. Coupons of geocomposite barrier system materials were also installed immediately upstream of the barrier so that samples could be removed from time to time to assess their performance under site conditions.

3 MATERIALS AND TEST METHODS

3.1 *Geosynthetic clay liner*

Table 1 shows the initial mass per unit area of the GCL. Specimens were hydrated (from the bottom) for 5 days under a confining pressure of about 14 kPa at a hydraulic gradient of 20.

3.2 *Permeant*

Jet A-1 is a colourless to pale yellow liquid with a kerosene-like or petroleum odour. The freezing point is below –47°C. The specific gravity at 15°C is 0.755-0.840. Its kinematic viscosity is 8.0 mm^2/s maximum at –20°C.

3.3 *Rigid wall permeability test*

The rigid wall permeameter (RWP) used in this investigation was similar to that 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 the GCL specimen is monitored during hydration and permeation. The inside diameter is 54 mm. The influent flow rate was 3.18 mL/day and effluent flow rate was monitored regularly. Unless otherwise noted, the test temperature was 20±1°C. The influent pressure was measured during permeation, and hydraulic conductivity was calculated using Darcy's Law.

To examine the effect of freeze-thaw, six GCL specimens were tested. Two were virgin specimens with no freeze-thaw cycles, two were subjected to 5 freeze-thaw cycles and one GCL specimen was recovered from the actual site after three years exposure to freeze-thaw in the field. The bulk void ratio during water permeation and jet fuel permeation was calculated when the hydraulic conductivity and GCL height had reached constant values.

3.4 *Freeze-thaw 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 D 6035-96). This procedure was repeated 5 times. There was no additional supply of water to the GCL specimen during the freeze-thaw cycles.

Table 1: Initial mass per unit area of GCL components

	Mass per unit area		
	Test method	Specified value	Measured value
Cover and carrier geotextile	ASTM D 5261	200 g/m^2 MARV[a]	250 g/m^2 (SD[b]: 26) 270 g/m^2 (SD[b]:13)
Bentonite	ASTM D 5993	3.66 kg/m^2 MARV[a]	3.8 kg/m^2 (SD[b]: 0.26)

[a]Minimum Average Roll Value; [b] standard deviation

Table 2: Properties of GCLs tested

Sample	Number FTC*	M_{GCL} (g/m^2)	e_{Bw}	e_{Bj}	Fluid content L^c (%)
Virgin GCL	0	4464	4.3[a]	3.6	133
Virgin GCL	5	4247	6.3[a]	5.8	192
Recovered GCL after 3 years	unknown	4904	7.2	tbd**	273[d]

*FTC: Freeze-thaw cycles, **tbd: to be determined; [a] at the end of water permeation; [b] before water permeation; [c] $L=M_L/M_s$, where M_L is mass of fluid in the bentonite, M is dry mass of bentonite, and; [d] moisture content after retrieval from Brevoort site

Table 3: Hydraulic conductivity of GCL at each stage (m/s)

Sample	k_1	k_2	k_3	k_3/k_1
Virgin GCL with 0-FTC*	2.0×10^{-11}	8.2×10^{-12}	2.0×10^{-11}	1
Virgin GCL with 5-FTC	2.0×10^{-11}	5.8×10^{-12}	8.0×10^{-11}	4
Recovered GCL after 3 years	7.1×10^{-12}	1.8×10^{-12}	3.6×10^{-11}	5

*FTC: Freeze-thaw cycles

4 RESULTS AND DISCUSSIONS

4.1 *Properties of the GCL tested*

Tables 2 and 3 summarize the physical properties of the GCL specimens and geometric mean hydraulic conductivities. In the following discussion, the subscripts 'w', 'j' and 'B' in Table 2, denote 'entire effluent is water', 'entire effluent is Jet A-1', and 'bulk void ratio', respectively. The behaviour can be characterized in three stages. In stage 1, de-aired water was permeated through the GCL. In stage 2, Jet A-1 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 A-1. The hydraulic conductivities (k_1, k_2, k_3), where the subscripts correspond to the 1st, 2nd or 3rd stage of the test, respectively, are given in Table 3. Note that the hydraulic conductivity test using the single GCL specimen recovered after 3 years is ongoing.

As shown in Table 2, 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 with Jet A-1, the average total liquid content (L) (pore water and jet fuel) of the virgin GCLs was about 133% and that of the GCLs after freeze-thaw cycles was about 192%. The GCL recovered from the site after 3 years had the greatest bulk void ratio and moisture content of 273%. A jet fuel extraction test was conducted on a sample of bentonite in the GCL recovered from the site and the concentration of jet fuel was found to be below the detection limit (i.e. 40μg/g) of the Gas Chromatography and Flame Ionization Detector (GC-FID) apparatus used. Thus it can be inferred that the GCL installed in the field was hydrated only by ground water.

4.2 *Hydraulic conductivity*

The hydraulic conductivity (k_1) of the GCLs with respect to de-aired water was 2.0×10^{-11} m/s for both the specimens with no freeze-thaw and with 5 freeze-thaw cycles (Figures 1 and 2, Table 3). Note that only one test result is shown for the virgin specimen but the replicate test gave essentially the same response. The hydraulic conductivity of the GCL recovered after 3 years was 7.1×10^{-12} m/s which was lower than that for both laboratory specimens. In all cases, initial permeation by Jet A-1 (k_2) resulted in a reduction in the hydraulic conductivity of the GCL due to the difference between the density and viscosity of Jet A-1 compared to water. In stage 2, the hydraulic conductivity with respect to Jet A-1 of all GCL specimens dropped to between 0.25 ~ 0.41 times that in stage 1 (i.e. to between 1.8×10^{-12} and 8.2×10^{-12} m/s). 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 A-1 was, within measurement accuracy, the same as the value with

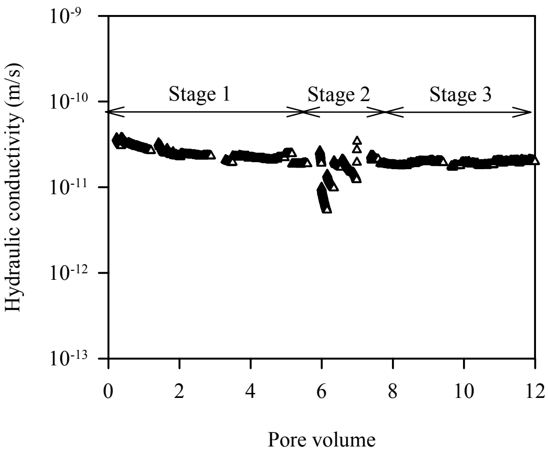

Figure 1: Hydraulic conductivity of a GCL with no freeze-thaw cycles versus pore volume

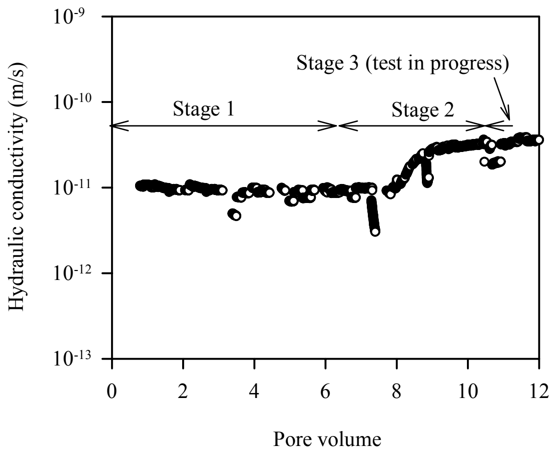

Figure 2: Hydraulic conductivity of GCL recovered from the site after 3 years versus pore volume

respect to water (~ 2.0×10^{-11} m/s). For the specimens subjected to 5 freeze-thaw cycles (Table 3), the average final equilibrium hydraulic conductivity with respect to Jet A-1 was about 8.0×10^{-11} m/s. The hydraulic conductivity of the recovered GCL was 3.6×10^{-11} m/s. Thus with increasing number of freeze-thaw cycles, the ratio of hydraulic conductivity for Jet A-1 to that for water (k_3/k_1) increased (see Table 3). The hydraulic conductivity (k_3) of the field-recovered sample was quite low at 3.6×10^{-11} m/s.

4.3 *Effect of freeze-thaw*

The hydraulic conductivity of the field-recovered GCL was smaller than that for the virgin specimens by about a factor of 3. However, the mass per unit area and bulk void ratio of the field-recovered GCL were larger and this raises the question whether the difference is just due to more bentonite and hence a thicker GCL. To assess this, Table 4 shows permittivity values for each GCL sample. Assuming that the number of freeze-thaw cycles at the field site exceeded 5 over a 3-year period, it appears that the permittivity of the GCL with respect to de-aired water decreased with an increasing number of freeze-thaw cycles. These results indicate that freeze-thaw cycles did not negatively impact on the GCL performance with respect to water permeation for the range of conditions considered. The permittivity with respect to Jet A-1 was low for the field-recovered specimen and a maximum for the virgin specimens with 5 freeze-thaw cycles. Permeation with Jet A-1 did increase

Table 4: Permittivity and of GCL at stages 1 and 3

	Permittivity (s^{-1})	
Sample	ϕ_1	ϕ_3
GCL with 0-FTC*	2.4×10^{-9}	2.8×10^{-9}
GCL with 5-FTC	1.9×10^{-9}	7.8×10^{-9}
Recovered GCL after 3 years	0.52×10^{-9}	2.8×10^{-9}

*FTC: Freeze-thaw cycles

Table 5: Intrinsic permeability of GCL at stages 1 and 3

	Intrinsic permeability (m^2)		
Sample	**K_1	K_3	K_3/K_1
GCL with 0-FTC*	2.0×10^{-18}	6.9×10^{-18}	3
GCL with 5-FTC	2.1×10^{-18}	2.8×10^{-17}	13
Recovered GCL after 3 years	7.2×10^{-19}	4.5×10^{-18}	6

*FTC: Freeze-thaw cycles; **$K=k\,\eta/\gamma$: where k is hydraulic conductivity [LT-1], η is dynamic viscosity [$ML^{-1}T^{-1}$] at 20°C and γ is unit weight [$ML^{-2}T^{-2}$]

permittivity with the greatest effect being on the virgin specimens subjected to 5 freeze-thaw cycles. The lowest hydraulic conductivity with respect to Jet A-1 was for the virgin GCL. In all cases, the hydraulic conductivity with respect to jet fuel was less than 10^{-10} m/s and hence still very small.

4.4 *Intrinsic permeability*

Table 5 presents the intrinsic permeability calculated using the Kozeny-Carman equation. Rowe *et al.* (2004a) reported that the intrinsic permeability did not change significantly due to permeation by Jet A-1 in the short to medium term. However, in the present tests permeation by many pore volumes (at least 6) of Jet A-1 resulted in an increase in the equilibrium intrinsic permeability by about a factor of 3 for no freeze-thaw cycles, and a factor of 13 times for the specimens subjected to 5 freeze-thaw cycles (Table 5). Rowe *et al*. (2004b) reported that permeation with jet fuel 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 the increase in hydraulic conductivity due to the effect of the difference in density and viscosity of Jet A-1 relative to water. Note that since the gradients applied in these tests are much larger than are likely to be encountered in the field application described by Li *et al*. (2002), the results obtained likely overestimate the hydraulic conductivity of the GCL to Jet A-1.

4.5 *Effect of hydrating fluid*

Figure 3 shows the swelling behaviour of two additional GCL specimens using de-ionised, de-aired water and groundwater retrieved from down-gradient of the barrier wall system at a depth of 2 m in summer 2004. The behaviour is very similar suggesting that the use of de-ionised, de-aired water had no effect on GCL hydration relative to groundwater. Chemical analyses indicated that total petroleum hydrocarbon (TPH) in the groundwater and was below the detection limit (1 mg/L).

4.6 *Effect of temperature and degree of saturation*

The hydraulic conductivities of virgin GCLs with respect to Jet A-1 were examined at 4 different temperatures (i.e. 20, 5, −5 and −20 °C). In the field, the GCL is likely to quickly achieve a degree of saturation, Sr, in excess of 60% and may be expected to have a degree of saturation in excess of 90% after 1-2 months.

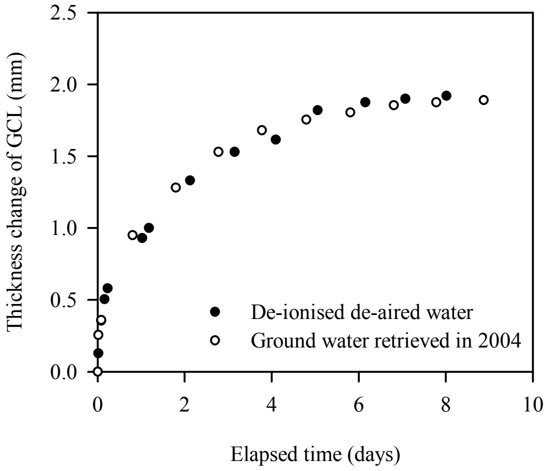

Figure 3: Intrinsic permeability versus temperature used in the rigid wall permeability test

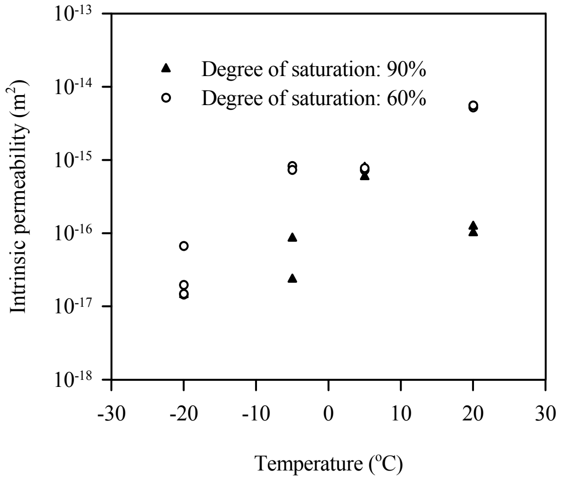

Figure 4: Intrinsic permeability versus temperature used in the rigid wall permeability test

Thus tests were performed for GCLs with a degree of saturation of about 60 and 90%. The dynamic viscosity of jet fuel at different temperatures was deduced using the data from Lewis and Squires (1934). The density of Jet A-1 was measured for temperature of 5, 20 and −20 °C and was deduced by interpolation at 5°C. The intrinsic permeability of GCL was then calculated and its variation with temperature is shown in Figure 4 for unsaturated GCLs. The intrinsic permeability at Sr = 90% is less than at 60% and it decreases due to a decrease in temperature for both cases. Thus, there appears to be an effect of a change in structure of the GCL with temperature, particularly below freezing. The latter change is attributed to a change in pore structure as the water freezes and expands. The decrease between −5 and −20°C is interesting since the effect of temperature on viscosity and density have both been considered in calculation of the intrinsic permeability and suggests that there is some change in structure of the GCL between −5 and −20°C. The decrease in intrinsic permeability with higher degree of saturation is to be expected. These results demonstrate that the degree of saturation of the GCL is an important factor to be considered in evaluating its likely performance as a barrier to jet fuel.

5 CONCLUSIONS

To assess the long-term performance of a GCL installed in an area subject to extreme climatic conditions, the hydraulic conductivity of saturated GCLs subjected to freeze-thaw cycles and unsaturated GCLs at different temperatures (including frozen conditions) was examined with respect to Jet A-1. Tests were performed using rigid wall permeameters. For the conditions examined (at 14 kPa), the results of these tests indicated:

- The hydraulic conductivity of the GCL with respect to Jet A-1 was 2.0×10^{-11} with no freeze-thaw cycles, 8.0×10^{-11} after 5 freeze-thaw cycles, and 3.6×10^{-11} m/s (after 4 pore volumes from jet fuel permeation) for the GCL recovered from the field site after 3 years.
- Freeze-thaw cycles did appear to cause an increase in the hydraulic conductivity of the GCL with respect to Jet A-1, although in all cases the hydraulic conductivity was still less that 10^{-10} m/s and these changes are unlikely to have a negative impact on the hydraulic performance of the GCL in the field system.
- GCLs with a low degree of saturation (Sr = 60%) did not perform as well as an hydraulic barrier against jet fuel as specimens with higher (90% and 100%) degrees of saturation either before or after freezing. However, when frozen, the intrinsic permeability of the unsaturated GCLs dropped, with a greater effect at lower temperature (−20°C) than at higher temperature (−5°C), suggesting that there is some difference in the effect of temperature even for sub-freezing temperatures.

Based on these laboratory tests, it appears that the GCL used in the trial geocomposite liner at Brevoort Island can be expected to perform well as an hydraulic barrier for at least up to 4 years (and potentially much longer) with respect to the effect of both freeze-thaw and permeation with jet fuel.

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