Long-term performance of a geosynthetic clay liner exposed to hydrocarbons in the Arctic

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M. Hosney and R.K. Rowe
GeoEngineering Centre at Queen's-RMC, Queen's University, Kingston, ON, Canada
R.J. Bathurst
GeoEngineering Centre at Queen's-RMC, Royal Military College of Canada, Kingston, ON, Canada

ABSTRACT
For the last eight years, a geosynthetic clay liner (GCL) has been used as part of a subsurface barrier system to minimize the migration of a hydrocarbon spill in the Canadian Arctic. GCL samples exhumed from the site 1, 6 and 7 years after installation were examined to assess their hydraulic conductivity with respect to both water and jet fuel. Test results indicate that the GCL has performed well over 7 years. However, samples subjected to wet-drying cycles, freeze-thaw cycles, and exposed to jet fuel over the 7 year period showed an increase in the hydraulic conductivity by 1 to 3 orders of magnitude and a loss of swell and self-healing capacity.

RÉSUMÉ
Au cours des huit dernières années, un revêtement d'argile géosynthétique (GCL) a été utilisé dans le cadre d'un système de barrière souterraine pour minimiser la migration d'un déversement d'hydrocarbures dans l'Arctique canadien. Des échantillons GCL exhumés du site 1, 6 et 7 ans après l'installation ont été examinés pour évaluer leur conductivité hydraulique à l'égard de l'eau et du carburant. Les résultats indiquent que la GCL fonctionne bien jusqu'à 7 ans après l'installation. Cependant, les échantillons soumis à des cycles de lavage-séchage, des cycles de gel-dégel, et exposés à du kérosène ont augmenté leur conductivité hydraulique de 1 à 3 fois. Ces échantillons ont aussi démontré une perte de leur houle ainsi qu'une diminution dans leur capacité d'auto-guérison.

1 INTRODUCTION

In 2001, at the request of the North Warning System Office of the Department of National Defence, a subsurface geocomposite barrier system was installed at the Distant Early Warning (DEW) Line site called BAF-3 and located at a latitude of $63^{o}20'23''$ and a longitude of $64^{o}08'45''$ on Brevoort Island, approximately 225 km east of Iqaluit, the capital of Nunavut Territory. The barrier was installed as a short-term means of containing a subsurface hydrocarbon spill from two large tanks situated within a lined berm area approximately 5 m above the average sea level and 75 m north of the ocean (Bathurst et al., 2006). The barrier was initially intended to allow a few years for the clean-up of the contaminated soil. However, the clean-up has not yet occurred and the barrier is still the primary means of preventing hydrocarbon migration to the ocean.

A feature of the BAF-3 site is the presence of continuous shallow permafrost at depth 2 to 3 m (Li et al., 2002). This permafrost provides a natural barrier to the downward migration of hydrocarbons. Thus, the barrier system was required only down to the permafrost level. The geocomposite barrier system comprises (from bottom up) a needle-punched geosynthetic clay liner (GCL), fluorinated high density polyethylene (HDPE) geomembrane, a needle-punched geotextile protection layer, and backfill. Although the HDPE liner can provide a continuous containment system without significant degradation at low temperatures representative of the site (Richards and Foster, 1991), the GCL component in the geocomposite barrier plays an important role controlling leakage through any holes or imperfect seams. In addition to being exposed to hydrocarbons, the GCL at this site is subjected to freeze-thaw cycles under a low confining insitu stress (0-14 kPa). These freeze-thaw cycles have the potential to cause changes in the particle structure and the size of the macropores of the bentonite, while the jet fuel has the potential to reduce the thickness of the double layer and increase the free pore space in the bentonite (Rowe et al., 2006). Both effects may influence the hydraulic conductivity of the GCL; hence the performance of the GCL in such an environment needs to be examined

At the time of the geocomposite barrier design in 2001, there was a paucity of literature assessing the performance of GCLs after being subjected to freeze-thaw cycles. Moreover, the combined effect of freeze-thaw cycles and permeation of GCLs with hydrocarbons had received limited past attention. Hewitt and Daniel (1997) reported that the hydraulic conductivity of GCLs with respect to water did not change after 3 freeze-thaw cycles. The same finding was observed by Kraus et al. (1997) for GCLs subjected to up to 20 freeze-thaw cycles.

To ensure that the system will perform efficiently as a barrier, GCL and geomembrane sample coupons were buried at the site in the summer of 2001 for future retrieval to assess the long-term durability of barrier components. Since the GCL samples were installed vertically in the coupon frames, some gravity-induced movement of bentonite from the upper part to the lower part of the GCL was observed in some of the recovered samples. These samples were also subject to less confining stress than in the composite barrier where the GCL was installed on a 2H:1V slope and covered with soil. Thus, while the samples tested provide an indication of behaviour, the results of the hydraulic conductivity tests for the samples recovered from the coupon frames may over-estimate or under-estimate the actual performance of the GCL in the barrier. In order to overcome this problem, a trench was excavated at the site in the summer of 2007 to a depth 0.8 m and GCL samples were installed horizontally in the trench and the trench backfilled.

Visits to the site for sample recovery took place in 2002, 2004, 2007 and 2008; laboratory experiments on the geosynthetic components of the barrier have taken place throughout the project. The objective of this paper is to present the mechanical and chemical properties of GCL samples exhumed from the coupon frames after 6 and 7 years and from the trench after 1 year. Hence, the oldest samples have been subjected to natural freeze-thaw cycles and interaction with hydrocarbons and local soil pore water for up to 7 years.

2 PREVIOUS STUDIES

The construction of the temporary geocomposite barrier at Brevoort Island was the motivation for a series of studies conducted to assess the performance of GCLs in an extreme Arctic environment. Rowe et al. (2003) investigated the hydraulic conductivity of GCL specimens recovered from BAF-3 after 1 year of insitu freeze-thaw cycles at low confining stress (1 and 14 kPa). They found that the hydraulic conductivity of the recovered samples with respect to water was in the range of virgin GCL hydraulic conductivity ($2x10^{-11}$ – $5 x10^{-11}$ m/s). In addition, they found that there is no negative effect on the hydraulic conductivity with respect to water for GCL specimens subjected to up to 20 freeze-thaw cycles in the laboratory.

Rowe et al. (2004) reported results from a series of hydraulic conductivity tests conducted using a flexible wall permeameter (FWP) for GCL specimens subjected to 0, 5 and 13 freeze-thaw cycles and then permeated with water followed by permeation with jet fuel. It was observed that the hydraulic conductivity with respect to water decreased with increasing number of freeze-thaw cycles despite the increase in void ratio after up to 13 freeze-thaw cycles. This is due to the ability of the sodium bentonite to swell and seal the cracks introduced by freeze-thaw. Moreover, the hydraulic conductivity with respect to jet fuel was about one order of magnitude less than that with respect to water. This is because of the different viscosity of jet fuel. Hydraulic conductivity tests on GCL samples recovered from the BAF-3 site after 1 year showed no change in the hydraulic conductivity with respect to either water or jet fuel. However, it should be noted that the GCL specimens were permeated with jet fuel for an average outflow of 0.15 pore volumes which represents short- to medium-term conditions.

Rowe et al. (2006) used rigid wall permeameters (RWPs) to assess the performance of GCL specimens subjected to up to 12 freeze-thaw cycles and samples recovered from the BAF-3 site 1 and 3 years after installation. The advantage of using the RWP is that the hydraulic conductivity test can be conducted with the permeation of hydrocarbon (in this case jet fuel) for high pore volumes within a reasonable period of time. However, the higher hydraulic gradients associated with these high flows using the RWP could over-estimate the hydraulic conductivity. These hydraulic conductivity tests were carried out to an average outflow of 30 pore volumes. Based on the laboratory results, the effect of the freeze-thaw cycles on the hydraulic conductivity of GCLs with respect to water was negligible. The combined effect of freeze-thaw cycles and jet fuel permeation cause an increase in the hydraulic conductivity. However, the increase was modest and the maximum hydraulic conductivity was about $1.6x10^{-10}$ m/s for specimens subjected to 12 freeze-thaw cycles. The hydraulic conductivity with respect to jet fuel of GCL samples recovered from the field after 1 and 3 years was $6.2x10^{-11}$ m/s.

Podgorney and Bennett (2006) evaluated the hydraulic conductivity with respect to water of several commonly available GCLs exposed to repeated freeze-thaw cycling up to 150 cycles using a FWP at a low confining pressure (20 kPa). They concluded that the long-term susceptibility to increased hydraulic conductivity as a response to repeated freeze-thaw cycling is negligible due to the self-healing characteristics of the sodium bentonite.

Rowe et al. (2008) used a FWP to examine the hydraulic conductivity of GCLs with respect to water and jet fuel. They found that before freeze-thaw, the hydraulic conductivity of virgin GCL with respect to water was about $3.3x10^{-11}$ m/s, while the hydraulic conductivity to jet fuel was less than $1.4x10^{-12}$ m/s for an entry pressure of 27 to 55 kPa. For GCL specimens subjected to 5, 12 and 50 freeze-thaw cycles, the hydraulic conductivity with respect to jet fuel was less than $3x10^{-11}$ m/s with an entry pressure of 13.8-20.7 kPa. With 100 freeze-thaw cycles, the hydraulic conductivity with respect to jet fuel increased to $1x10^{-10}$ m/s and the entry pressure dropped to 0-13.8 kPa. The hydraulic conductivity of GCL samples recovered from BAF-3 after 3 years was found to be $0.3x10^{-11}$ m/s (20 times less than the value obtained from the RWP tests, Rowe et al. (2006)) at the low pressure heads expected in this field application.

Previous studies have examined the effect of hydrocarbon permeation on the bentonite structure and chemical properties of GCLs. Foreman and Daniel (1986) showed that organic fluids can cause compacted clay to shrink due to the change in the double layer thickness and at the same time the Atterberg limits can change significantly. Brown et al. (1984) performed hydraulic conductivity tests using a RWP on different soils with different hydrocarbons as a permeant. They found by using X-ray diffraction that the hydrocarbons destroyed the clay platelets.

Petrov et al. (1997a) showed that permeation of ethanol/water mixtures containing 25% and 50% ethanol through a water hydrated GCL resulted in a decrease in the GCL hydraulic conductivity due to the increased viscosity of the organic permeants. In contrast, 75% ethanol and pure ethanol mixtures increased the hydraulic conductivity due to contraction of the double layer and the increase in the volume of the free pores. The same observation regarding the reduction in the double layer thickness was reported by Mukunoki et al. (2003).

It may be concluded from these previous studies that:

a- The effect of up to 150 freeze-thaw cycles on the hydraulic conductivity of GCLs with respect to clean water is minimal based on RWP or FWP tests. However, the physical and chemical changes in the GCL resulting from repeated freeze-thaw cycles followed by permeation with jet fuel can cause an increase in GCL hydraulic conductivity to jet fuel and thus influence its function as a hydraulic barrier.
b- After 3 years of monitoring of the GCL used at the BAF-3 site, the containment system was still performing well with a maximum value of hydraulic conductivity with respect to jet fuel of 6.2×10^{-11} m/s (RWP) and 0.3×10^{-11} m/s (FWP).

3 MATERIALS

The GCL used at the BAF-3 site is Bentofix Thermal Lock "NWL". This is a needle-punched reinforced GCL comprised of a uniform layer of granular bentonite (3.66 kg/m^2, MARV) between a scrim-reinforced nonwoven carrier (200 g/m^2, MARV) and a virgin staple fibre nonwoven cover (200 g/m^2, MARV). The needle-punched fibres are thermally fused to the scrim-reinforced nonwoven geotextile to enhance the reinforcing bond.

The jet fuel A-1 is a colourless to pale yellow liquid with kerosene-like or petroleum odour. It is widely used in northern regions. Its freezing point is below -47^{o}C, the relative density and dynamic viscosity at 20^{o}C are 0.82 and 2.76 MPa.s, respectively (Rowe et al., 2007)

4 EXPERIMENTAL PROGRAM

A series of hydraulic conductivity tests was conducted to evaluate the performance of GCL specimens recovered from the site after 1, 6 and 7 years exposure to natural freeze-thaw cycles and interaction with the local pore liquid. The hydraulic conductivity was measured using a flexible wall permeameter (FWP) under falling head/rising tail conditions according to ASTM (D5084-03). The flexible wall permeameter was selected because it is considered reliable for measuring the hydraulic conductivity at low flow rates and to prevent the possibility of preferential sidewall flow (Petrov et al., 1997b). The average confining pressure was 15 kPa. The hydraulic conductivity was initially established with respect to water. When the hydraulic conductivity reached equilibrium, water was then replaced with jet fuel. The initial differential pressure across the GCL specimen for permeation with jet fuel was 7 kPa. In cases where there was no flow observed under this differential pressure, the differential pressure was increased in 7 kPa increments until the differential pressure exceeded the threshold pressure required to cause flow of jet fuel through the specimen.

Since the hydraulic conductivity of the GCL is influenced by the change in the electro-chemical activity of the bentonite, the chemical properties of the GCL were evaluated to assess the change in the physio-chemical properties of the GCL recovered from the site and to correlate this change with the change in the hydraulic conductivity, if any. To evaluate the chemical properties of the GCL, the following tests were conducted:

a- Cation exchange capacity according to ASTM (D7503-10);
b- Swell Index tests according to ASTM (D5890-06);
c- Atterberg limits according to ASTM (D4318-05).

5 INITIAL PROPERTIES OF RECOVERED SAMPLES

In 2007, 6 years after GCL installation, GCL samples were extracted from the coupon frames from depths between 1.1 to 2.3 m below the ground surface. In 2008, 7 years after installation, relatively shallow GCL samples were recovered from the coupon frames at depths 0 to 1.1 m below the ground surface. In addition, in 2008, GCL samples were extracted from the trench at depth of 0.8 m (1 year after installation). Details of the recovered samples are presented in Table 1. Samples 1 and 2 were recovered from the trench, while samples 3 to 6 were recovered from the coupon frames.

Table 1. Initial properties of recovered samples.

Sample	Depth (m)	Exhumed after (year)	Thickness (mm)[a]	Bentonite mass /unit area (g/m^2) [b]
Virgin sample	-	-	8.3	4076
1	0.8	1	7.9	4342
2	0.8	1	8.0	4288
3	1.70	6	13.0	4548
4	2.15	6	14.3	4917
5	0.15	7	12.8	3382
6	0.23	7	14.6	3937

[a] a laser was used to measure thickness, each data point is an average of at least 150 measurements
[b] average of three measurements

The average water content of recovered samples was 108% (range: 90% to 136%). It can be noted from Table 1 that the bentonite mass per unit area of recovered samples from the coupon frames at shallow depths (samples 5 and 6) is smaller than that for samples recovered from greater depths (3 and 4). This is due to the movement of bentonite by gravity. Also the bentonite mass per unit area of sample 5 is less than the minimum average roll value specified by the manufacturer (3660 g/m^2).

6 RESULTS AND DISCUSSION

During visual inspection, it was noted that there was a difference between the samples recovered from shallow depths (up to 1.1 m) and samples recovered from greater depths (1.1 to 2.3 m). A feature of the samples recovered from depths up to 1.1 m was the paste-like structure of the bentonite layer which is a typical for sodium bentonite that has undergone osmotic swell. An example is shown in Figure 1 for a GCL specimen recovered from the trench after 1 year. This is typical for the 1- and 7-year samples extracted from the coupon frames at 1.1m and above and from the trench. In contrast, Figure 2 shows the bentonite structure of a GCL specimen recovered from the coupon frame at a depth 2.15 m after 6 years. It can be seen from Figure 2 that the bentonite layer has a relatively high void ratio with flocculated bentonite particles.

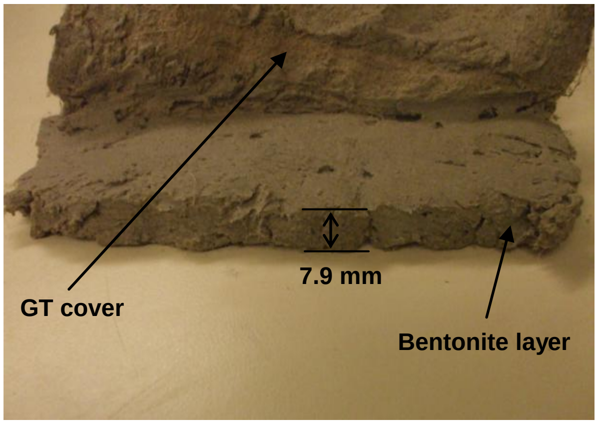

Figure 1. Specimen from sample 1 recovered from the trench after 1 year at a depth 0.8 m

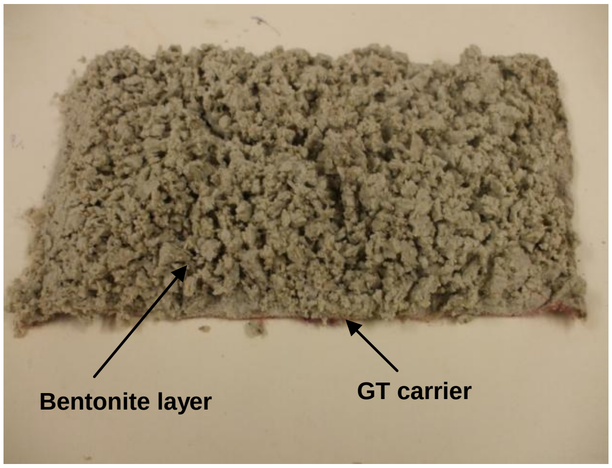

Figure 2. Specimen from sample 4 recovered from the coupon frame after 6 years at a depth 2.15 m

6.1 Hydraulic Conductivity

Figure 3 shows the hydraulic conductivity with respect to water and jet fuel for samples recovered from BAF-3 as a function of depth. The average of two hydraulic conductivity tests conducted on virgin GCL with respect to water was 3.9×10^{-11} m/s (the hydraulic conductivity values for the two specimens were 3.8×10^{-11} m/s and 4.1×10^{-11} m/s), while the hydraulic conductivity to jet fuel was 6.2×10^{-12} m/s at a differential pressure across the sample of 38 kPa. These values are within the range of hydraulic conductivity values presented by Rowe et al. (2008). Samples recovered in 2007 (samples 3 and 4, Table 1) from the coupon frames after 6 years showed an increase in hydraulic conductivity of about one order of magnitude for water and about two to three orders of magnitude for jet fuel compared to the values for virgin GCL. For example, Figure 3 shows that the hydraulic conductivity with respect to water increased to 3.1×10^{-10} m/s, while the hydraulic with respect to jet fuel increased to between 7.4×10^{-10} m/s and 2.0×10^{-9} m/s. Furthermore, the entry pressure required for the jet fuel to begin to permeate through the GCL was reduced from in excess of 27 kPa for virgin samples to a range of 9 kPa to 20 kPa. In order to eliminate the effect of sample thickness, the hydraulic gradient (i) required for the jet fuel to enter the GCL was calculated and is recorded in Figure 3. It is thought that these samples had been subjected to cycles of freeze-thaw as well as exposure to hydrocarbons.

In 2007 the water level was estimated to be about 1.2 m below the ground surface while during the 2008 visit the water level was estimated to be below 1.7 m. There is some evidence in the literature to suggest that wet-dry cycles together with the exchange of divalent cations in the local pore water for sodium in the original bentonite may increase GCL hydraulic conductivity since bentonite containing primarily divalent cations does not undergo osmotic swell and lose the ability for self-healing of desiccation cracks when rehydrated (Meer and Benson, 2007). This could be a reason for the difference in the bentonite structure for shallow and deep samples.

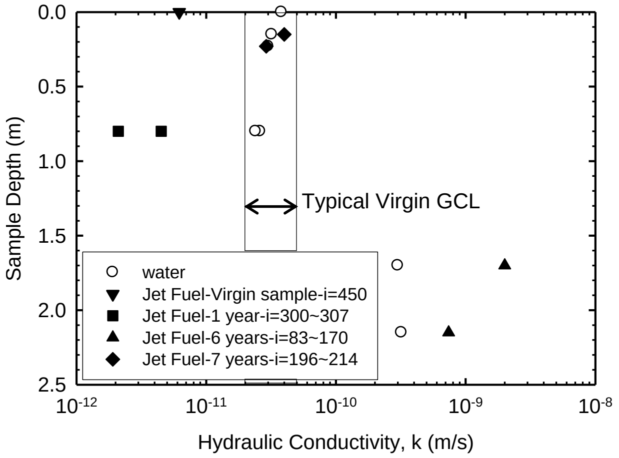

Figure 3. Hydraulic conductivity of recovered samples at different depths

Another factor that may contribute to a change in the bentonite structure and an increase in the hydraulic conductivity is exposure to jet fuel. Bathurst et al. (2006) showed that the original total petroleum hydrocarbon (TPH) concentration at the site increased with depth and reached a maximum value at the permafrost level. This is probably because the neat jet fuel is less dense than water and hence floats on top. Thus, since water levels are most commonly 1.2 to 1.7 m below the surface, the deeper GCL samples at the site have a higher probability of exposure to neat jet fuel that may affect the clay structure. The increase in the hydraulic conductivity of these samples is consistent with the findings from chemical analysis discussed later.

Unlike the deep samples recovered in 2007, the samples recovered from a relatively shallow depths (0 to 0.25 m) 7 years after installation experienced negligible change in the hydraulic conductivity to both water and jet fuel (Figure 3). The hydraulic conductivity with respect to water is about 3.1×10^{-11} m/s, while the hydraulic conductivity with respect to jet fuel is about 2.9×10^{-11} m/s to 4.0×10^{-11} m/s with an entry pressure of between 27 kPa to 35 kPa.

Samples recovered in 2008 from the trench at a depth of 0.8 m after 1 year showed no significant change in the hydraulic conductivity with respect to both water and jet fuel. The hydraulic conductivity with respect to water is about 2.6×10^{-11} m/s while the hydraulic conductivity decreased to a range of 2.1×10^{-12} m/s to 4.5×10^{-12} m/s with respect to jet fuel for differential (entry) pressures of 27.6 kPa to 34.5 kPa. The hydraulic conductivity with respect to water for GCL samples recovered from the coupon frames after one year from installation was about 3.9×10^{-11} m/s (Rowe et al., 2004). Thus the hydraulic conductivity with respect to water for samples recovered from the trench appear to be 30% lower than for samples recovered from the coupon frames one year after installation. This may be due to the more uniform confining stress on the samples in the trench. Thus, it is expected that the actual hydraulic conductivity for the subsurface composite barrier will be better (lower) than that observed for the samples from the coupon frames.

6.2 CEC, Swell Index, and Bentonite Activity

The exchangeable cations and cation exchange capacity (CEC) of bentonite in the recovered GCL samples are presented in Table 2. For the cation exchange capacity tests, a spike and blank samples were prepared as per ASTM (D7503-10). The variation of Swell Index and Bentonite Activity of the bentonite extracted from the exhumed GCL with depth are illustrated in Figures 4 and 5, respectively. It should be noted that each data point presented for Swell Index is an average of at least three measurements. The standard deviation in all Swell Index values is less than 1 mL/2g.

The Bentonite Activity was calculated using the following equation: (Holtz and Kovacs, 1981)

$$A = PI / \text{Clay Fraction} \qquad [1]$$

Where PI is the plasticity index (liquid limit - plastic limit), and clay fraction is taken as the percentage of the sample less than 2 µm. The clay fraction was calculated from hydrometer tests carried out on the recovered GCLs according to ASTM (D422-63).

Test results showed that the Swell Index and Bentonite Activity of samples recovered in 2007 (samples 3 and 4) from the coupon frames after 6 years at depths 1.5 to 2.3 m are approaching typical values for calcium bentonite as about 90% of the sodium in the bentonite was replaced by divalent cations. This is accompanied by a loss of swelling and self-healing capacity with the Swell Index reducing to 8 ml/2g and the Bentonite Activity reducing to 1.0. The values for the deeper samples are consistent with the bentonite structure shown in Figure 2 as the bentonite had lost much of its ability to self-heal the cracks after being rehydrated due to the change in ground water level. However, despite the very significant cation exchange it is noted that the deep GCL samples only experienced about one order of magnitude increase in hydraulic conductivity with respect to water. The effect was greater with respect to jet fuel due to an apparent change in the size of macrospores which reduce the jet fuel entry pressure.

On the other hand, there was negligible change in the chemical properties of samples recovered in 2008 (samples 5 and 6). Table 2 shows that for the sample recovered from the top 0.25 m only about 30% of the sodium was replaced by divalent cations in a 7-year period while the Swell Index and Bentonite Activity values suggest that the bentonite still behaves as a sodium bentonite.

Table 2. Exchangeable cations and cation exchange capacity.

Sample	Exchangeable cations (mole fraction)				CEC (cmol/kg)
	Na	K	Mg	Ca	
Virgin sample	0.67	0.01	0.08	0.24	78.6
1	0.32	0.02	0.21	0.45	60.0
2	0.35	0.02	0.19	0.42	62.5
3	0.10	0.06	0.28	0.56	54.9
4	0.07	0.06	0.36	0.50	57.2
5	0.58	0.02	0.14	0.26	72.0
6	0.53	0.04	0.14	0.29	61.2

The chemical properties of samples 1 and 2 recovered from the trench 1 year after installation showed that, although the hydraulic conductivity of these samples is still essentially the same as the virgin samples, about 60% of the sodium had been replaced by divalent cations within a 1-year period. Hence, it is expected that there may be an increase in hydraulic conductivity in the future if the cation exchange causing this change in chemical properties in the first year continues. It appears that for this specific site, location within the soil profile (and contact with groundwater and potentially jet fuel) rather than time has the greatest effect on the ageing of the GCL and its change in properties.

The chemical properties of the GCLs affect hydraulic conductivity as the replacement of sodium by divalent cations results in higher hydraulic conductivity as described by Jo et al. (2001).

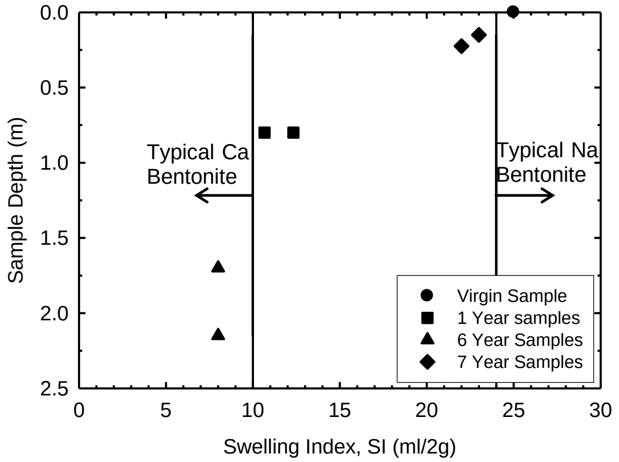

Figure 4. Variation in Swell Index with depth

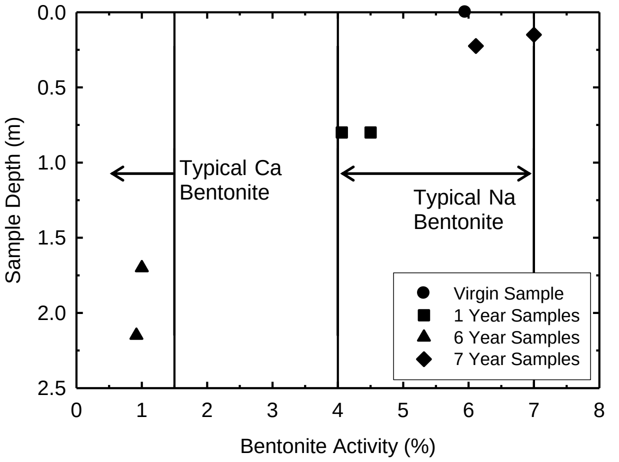

Figure 5.Bentonite Activity of recovered samples

Figure 5 shows the variation in Bentonite Activity with depth. The shallow samples above 1.1m had activity in the range normally expected of sodium bentonite while those form below were within the range for calcium bentonite. Figure 6 shows the hydraulic conductivity of recovered GCL samples with respect to water and jet fuel versus Swell Index. Figure 7 shows the hydraulic conductivity with respect to water and jet fuel versus Bentonite Activity. This data demonstrates that the hydraulic conductivity of GCLs recovered from shallow depth perform well with almost no change in the hydraulic conductivity and after 7 years the Swell Index and Bentonite Activity remained within the typical range of values for sodium bentonite. After one year, samples from a depth of 0.8 m were in the transition phase between sodium and calcium bentonite with Swell Index and Bentonite Activity at the low end of the typical sodium bentonite range but still with low hydraulic conductivity. The deep samples (1.7 and 2.1 m) had experienced significant physio-chemical changes after 6 years and plot in the zone of calcium bentonite. For these samples, the hydraulic conductivity increased by about one order of magnitude with respect to water and by about 2 to 3 orders of magnitude with respect to jet fuel. It is postulated that this is because these samples experienced the greatest variation in exposure to the water table and potential jet fuel above the water table. The greatest effect was observed for the sample at 1.7 m which is the sample most likely to be affected by changes in water level.

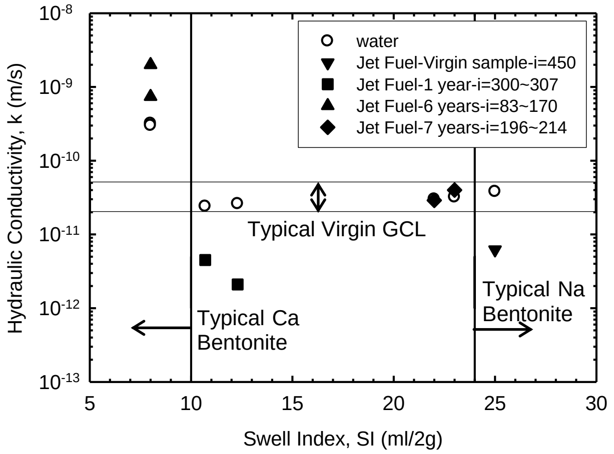

Figure 6. GCL hydraulic conductivity versus Swell Index

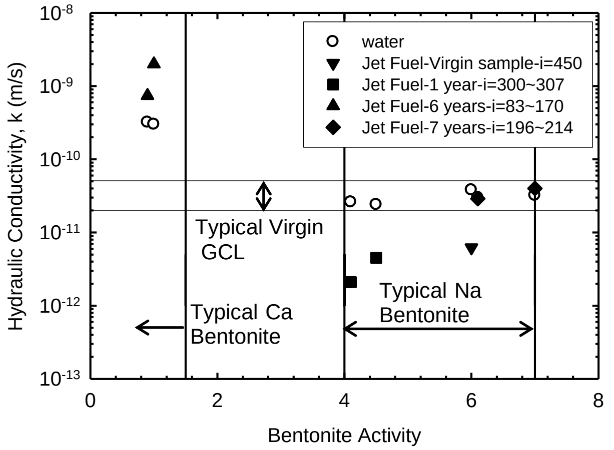

Figure 7. GCL hydraulic conductivity versus Bentonite Activity

7 CONCLUSIONS

The barrier system at Brevoort Island was initially installed as a temporary measure to control hydrocarbon migration for about 3 years while remediation measures were instituted. However, as the tenth anniversary of its construction approaches, it is still the primary barrier to the migration of hydrocarbons at the site. A series of hydraulic conductivity tests and chemical analysis tests were conducted to evaluate the performance of GCL specimens recovered from the site after 1, 6 and 7 years exposure to natural freeze-thaw cycles, and interaction with the local pore water. The results from the current tests indicate the following:

- The hydraulic conductivity of virgin GCL with respect to water was about 3.8×10^{-11} m/s, while the hydraulic conductivity to jet fuel was about 6.2×10^{-12} m/s for an entry pressure of 38 kPa.
- Samples recovered in 2007 from the coupon frames after 6 years at depths 1.7 and 2.1 m showed an increase in hydraulic conductivity of about one order of magnitude with respect to water and about two to three orders of magnitude for jet fuel compared to the values for virgin GCL. In addition, the threshold pressure required for the jet fuel to begin to permeate through the GCL was reduced to 9 kPa and 20 kPa, respectively.
- Freeze-thaw cycles together with cation exchange between the sodium bentonite and the local pore water, and exposure to relatively high TPH have led to an increase in high hydraulic conductivity by an order of magnitude or more, loss of swell capacity, and loss of the ability for self-healing.
- Samples recovered from relatively shallow depths (0 to 0.25 m) 7 years after installation experienced negligible change in the hydraulic conductivity to both water and jet fuel. The hydraulic conductivity with respect to water was about 3.1×10^{-11} m/s, while the hydraulic conductivity with respect to jet fuel was about 2.9×10^{-11} m/s to 4.0×10^{-11} m/s with an entry pressure of 27 kPa to 35 kPa.
- Samples recovered in 2008 from the trench at a depth of 0.8 m after 1 year showed no significant change in the hydraulic conductivity with respect to both water and jet fuel and the values of hydraulic conductivity were less than the values measured from the 1-year samples recovered from the coupon frames. This suggests that the subsurface composite barrier will perform better than what was observed for the samples from the coupon frames.
- The hydraulic conductivity of GCLs recovered from the site performed well as a hydraulic barrier provided that the chemical properties of GCLs remained within typical values of sodium bentonite or was in transition phase between sodium and calcium bentonite. Once the samples reach the zone of calcium bentonite, the hydraulic conductivity increased significantly.

The laboratory results suggest that while the GCL at the BAF-3 site will still offer some resistance to the migration of contaminated water up to 7 year, its ability to do so has been reduced to some extent as some samples showed a significant increase in hydraulic conductivity as a result of the combined effect of freeze-thaw/wet-dry cycles and exposure to jet fuel with the major effect considered to be due to the combination of significant cation exchange combined with freeze-thaw and possibly wet-dry cycles. It is therefore important to monitor this site carefully in the coming years since the GCL may, at least at some critical elevations, be approaching its service life in this barrier application.

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