EFFECT OF JET FUEL ON THE BEHAVIOUR OF UNSATURATED AND SATURATED FROZEN GCLS

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ABSTRACT
This paper examines the hydraulic conductivity of partially hydrated and frozen GCLs with respect to hydrocarbons (i.e. to examine how readily these hydrocarbons will permeate through the GCL in a frozen state). Jet fuel-A1 (arctic diesel fuel) was used as the permeant due to the fact that it is often used as the primary fuel source in very cold climates. A constant flow rate apparatus was constructed for use in a cold room that would allow testing to be preformed at sub zero temperatures. Methods developed to hydrate GCLs to controlled water contents (dry, 60%, 90%, and 120%) and then to freeze them without additional uptake of water are described. Once frozen, samples were permeated and the hydraulic conductivity monitored. The paper presents results from the hydraulic conductivity testing of both saturated and unsaturated GCLs at room temperature (20°C) and –5°C. The effects Jet Fuel-A1 has on the mechanical properties of GCLs are also examined. The GCLs were exposed to Jet-Fuel A1 and the peel strength (ASTM D6496) of the GCL was then evaluated at different prescribed times.

Keywords: mechanical properties, hydraulic conductivity, GCL, jet fuel, unsaturated

RÉSUMÉ
Cet article examine la conductivité hydraulique des GCLs partiellements hydraté et congelé en ce qui concerne des hydrocarbures (c.-à-d. pour examiner comment facilement ces hydrocarbures peuvent pénétrer par le GCL dans un état gelé). Le carburant gicleur-A1 (carburant diesel arctique) a été utilisé pour pénétrer le GCL, car il qu'il est souvent employé comme source primaire de carburant dans des climats très froids. Un appareille de flux a été construit pour l'usage dans une chambre froide qui permet des analyses a être préformée aux températures du sous-marin zéro. Des méthodes développées pour l'hydrate les GCLs aux teneurs en eau commandées (séchez, 60%, 90%, et 120%) et les geler alors sans prise additionnelle de l'eau sont décrites. Une fois que congelés, des échantillons ont été pénétrer et la conductivité hydraulique ont été surveillées. Le papier présente des résultats de l'essai hydraulique de conductivité de GCLs saturé et insaturé à la température ambiante (20°C) et au -5°C. Les effets que le carburant gicleur-A1 a sur les propriétés mécaniques de GCLs sont également examinés. Les GCLs ont été exposés au carburant gicleur-A1 et la force de peau (ASTM D6496) du GCL a été alors évaluée à différentes heures prescrites.

Mots-clés : propriétés mécaniques, conductivité hydraulique, GCL, carburant gicleur, insaturé

1. INTRODUCTION

The applications of Geosynthetic Clay Liners (GCLs) in environmental applications are rapidly growing. Of particular interest is their use for containment of hydrocarbon spills and minimizing the environmental impact of mining in climates where the GCL may be frozen. In order to safely use GCLs in cold climates, it is necessary to determine how both saturated and unsaturated GCLs will behave when permeated with hydrocarbons at frozen and unfrozen temperatures.

1.1 Geosynthetic clay liner (GCL)

The GCL used in this work is a nonwoven nonwoven thermally treated product. It is a needle punched reinforced GCL comprised of a uniform 3.66 kg / m^2 (Minimum Average Roll Value – MARV) granular sodium bentonite layer encapsulated between a scrim reinforced non-woven and a virgin staple fibre nonwoven geotextile. The needle-punched fibres are thermally fused to the scrim reinforced nonwoven geotextile to enhance the reinforcing bond. Table 1 gives the mass per unit area of each component of the GCL. Other significant properties listed by the manufacturer are: a hydraulic conductivity of 5x10^{-11} m/s, internal shear strength of 24 kPa (ASTM D5321), a minimum bentonite swell index of 24 ml/2g (ASTM D5890), and a peel strength of 66N (ASTM D 4632). The GCL used in this work is supplied by BENTOFIX®, product name FIX-501NWL.

Table 1. Mass per unit area of GCL components

Mass per unit area^	Specified values (g/m^2)	Measured values (g/m^2)
Cover geotextile	200 MARV*	237 (SD**; 33.3)
Bentonite layer	3660 MARV*	4808 (SD**; 406)
Carrier geotextile	200 MARV*	245 (SD**; 6.8)

^ ASTM D 5261
* Minimum Average Roll Value
** Standard Deviation

1.2 Jet Fuel A-1 (Arctic diesel)

Jet fuel A-1 (also called arctic diesel) is a colourless to pale yellow liquid with a kerosene-like or petroleum odour that is widely distributed in the northern regions. According to its Material Safety Data Sheet (MSDS), 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 max at - 20°C.

2. FIXED WALL APPARATUS

Hydraulic conductivity testing was completed in a rigid wall constant flow apparatus (called a fixed wall apparatus), similar to the apparatus described by Petrov et al. (1997). In order to maintain a tight control on temperature, the cells of the fixed wall apparatus were placed inside a freezer retrofitted with a more accurate thermostat, which in turn was placed in a cold room. With this double buffer setup, it was possible to maintain a temperature control of +/- 0.5 °C.

A constant head apparatus was constructed out of glass to help evaluate the hydraulic conductivity of GCL's at lower saturation values. This is needed because at low saturations, there isn't enough water in the GCL to create a seal between the fixed wall cell and the sample. Using the glass cell, and a layer of grease between the sample and the cell wall, sidewall leaks can be eliminated, and a visual examination is permitted.

3. SAMPLE PREPARATION

In order to achieve specific water contents for each sample, a sample preparation procedure was developed. First, the GCL was carefully cut using a 54mm diameter steel cutting shoe. The mass of the GCL and cutter was measured, and by knowing the mass of the cutter, the GCL sample mass was determined. This mass was checked against the calculated average to ensure a high degree of quality control. Any samples falling outside a specified range were discarded. To remove the GCL from the cutter without the loss of any powdered bentonite, a small bead of water was spread around the outside diameter of the cutter. As the sample was slowly removed, the bentonite at the edges absorbed the water and created a seal around the edges of the sample. Finally, the GCL sample was placed in the fixed wall cell, with a saturated stone porous disk and a dry porous Teflon disk on the bottom and top of the GCL respectively. One large central spring was inserted into the cell to provide a confining stress of approximately 14 kPa. By knowing the mass of the GCL sample and the mass of water used in sample preparation, the amount of water needed to reach a target water content was calculated and added. After a prescribed time of 24 hours, the cell was opened, and the stone porous disk replaced with another Teflon porous disk. This was done to stop the further uptake of water from the porous disk into the GCL. The cell was resealed and the sample allowed to equilibrate for 7 days or longer at either 5 °C or 20 °C before testing began. Sample preparation and hydration was done using de-ionised distilled water.

4. JET A-1 PERMEATION

In order to understand the behaviour of GCLs permeated with Jet A1, a variety of tests were completed using a fixed wall apparatus. The hydraulic conductivity of GCLs permeated with Jet A1 was evaluated at four temperatures; -5°C, +5°C, -20°C, and +20°C, using different controlled water contents. In addition a test was run where the samples were first permeated with Jet A1 at +5°C and then frozen to –5°C and permeated again with Jet A1.

4.1 Hydrocarbon permeation at sub zero temperatures: previous studies

Very little data exist on the permeation of hydrocarbons through frozen bentonite exists. Using Decane (a nonaqueous phase liquid) Wiggert et al. (1997) found intrinsic permeability correlated linearly with saturation for granular soils, and with the addition of bentonite prior to freezing, intrinsic permeability was reduced to negligible levels. Using a Jet A-50 fuel mixture, McCauley et al. (2000) also found that hydraulic conductivities decreased at ice saturation increased for organic rich silty sand.

4.2 Hydrocarbon permeation at non freezing temperatures: previous studies

Brown et al. (1984), and Foreman and Daniel. (1986), performed tests on natural soils and concluded that permeation by organic fluids cause a change in the soil structure. Brown et al. (1984) used a fixed wall permeameter to evaluate the hydraulic conductivity of kaolinite, mica, and bentonite. Using several different hydrocarbons (kerosene, paraffin oil, diesel oil, gasoline, and motor oil) and x-ray diffraction, it was determined that the organic fluids destroyed the clay platelets. Foreman and Daniel (1986) investigated the effect of hydraulic gradient and type of permeameter (fixed or flexible wall) on the hydraulic conductivity of compacted clay to methanol and heptane. They found that the organic fluids caused the compacted clay to shrink and produce cracks or microspores. They also found at low confining pressures, the rigid wall permeameter developed sidewall leakage due to the organic fluid permeant. Fernandez and Quigley (1985, 1988a,b) performed a detailed study of hydrocarbon clay interaction and identified the potential for an increase in hydraulic conductivity of samples permeated by hydrocarbons at low confining stress.

Daniel et al. (1993) found that for a partially wetted GCL (water content < 50%) the bentonite part of the GCL was very permeable to hydrocarbons (~ 10^{-7} m/s) and for water contents greater then 100% the hydraulic conductivity was very low (< 10^{-11} m/s). Petrov et al. (1997) performed hydraulic conductivity tests on GCL samples hydrated with water and permeated with water, salt water, and ethanol using a fixed wall permeameter. It was found that at low concentrations of ethanol (< 50%) the hydraulic conductivity was less then that of water due to viscosity effects. At high concentrations (> 75%) the hydraulic conductivity was higher then that of water due to the diffuse double layer contraction from the ethanol. Shan and Lai (2002) found that gasoline couldn't permeate a saturated GCL at gradients less then 150.

4.3 Hydraulic conductivity of Jet A-1 at 20°C

As part of the current research, the hydraulic conductivity of GCLs permeated with Jet A1 at 20 °C is being investigated. For this test, samples were hydrated to water contents of 60%, 90%, around 120%. This resulted in saturations ranging from approximately 55% to 100%. After hydration, samples were allowed to equilibrate for 1 week under stress, and then permeated with Jet A1. Preliminary results show that there may be a decrease of hydraulic conductivity as saturation increases. Figure 1 shows the results from one round of testing.

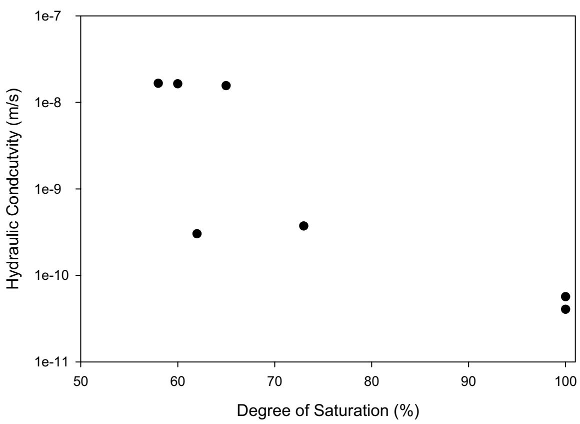

Figure 1. Hydraulic conductivity of GCLs at 20 °C vs. degree of saturation

At the end of this test, the flow rate of the fixed wall apparatus was increased twice, allowing time in between each increase for the samples to come to equilibrium. For the saturated samples, it appears that the hydraulic conductivity of Jet A1 depends on the applied gradient. Figure 2 shows the trend observed during this stage of the test. It is hypothesized that the trend seen in Figure 2 arises from the opening of an increases number of flow paths through the GCL due to the increase in pressure associated with the increased flow rate. Tests are ongoing to examine this hypothesis.

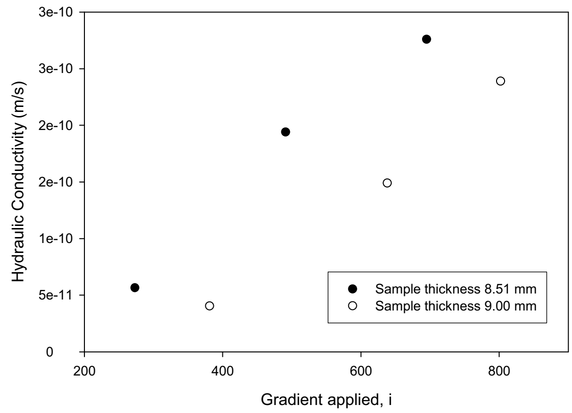

Figure 2. Hydraulic conductivity vs. gradient for unfrozen saturated GCLs

4.4 Hydraulic conductivity of Jet A-1 at -5°C and -20°C

In addition to hydraulic conductivity testing of unfrozen samples, testing was also completed on frozen samples. Because of the varying mass of bentonite per unit area in each sample, and an apparent localization of ice in frozen samples, there is a high variability of hydraulic properties.

Using the constant head apparatus in a cold room at -5°C, with a dry sample (water content ~ 8%) consolidated under 14 kPa for 24 hours, but tested under zero stress, a preliminary upper bound of hydraulic conductivity was found to be 2 x 10^{-6} m/s.

For samples with a degree of saturation greater then 80%, the hydraulic conductivity was very small (<10^{-12} m/s). For these samples, the pressure in the test cells quickly escalated to the maximum permissible pressure (~1240 kPa) and test had to be discontinued.

Figure 3 shows the trend observed for samples with a degree of saturation less than 80%. While it appears hydraulic conductivity decreases as the bulk void ratio of the GCL decreases, more tests are needed to confirm this.

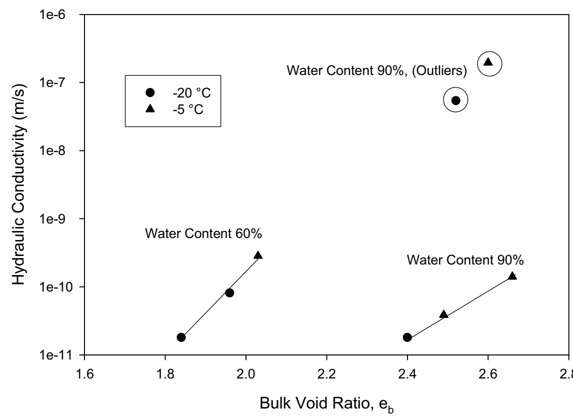

Figure 3. Hydraulic conductivity of frozenGCLsvs. bulkvoid ratio

4.5 Effect of permeating first with Jet A-1 before freezing and permeating

When samples were first permeated with Jet A1 at 5°C and then frozen to -5°C and permeated again with Jet A1, the hydraulic conductivity decreases. It appears that the more saturated the sample (i.e. the more water in the sample) the larger the decrease of hydraulic conductivity. (Table 2).

The negligible flow noted from previous tests with highly saturated frozen samples didn't occur in this test and no samples had hydraulic conductivities less then 9.6×10^{-10} m/s.

Table 2. Hydraulic Conductivity of GCLs permeated with Jet A1 before and after freezing

Degree of Saturation (%)	Hydraulic Conductivity at +5 °C (m/s)	Hydraulic Conductivity at -5 °C (m/s)
58	1.5×10^{-9}	1.4×10^{-9}
65	1.6×10^{-9}	1.2×10^{-9}
86	1.7×10^{-9}	9.6×10^{-10}
91	1.1×10^{-9}	1.7×10^{-10}
94	2.3×10^{-9}	1.4×10^{-10}
94	1.2×10^{-9}	4.3×10^{-10}

5. EFFECT OF JET A-1 EXPOSURE ON AVERAGE BONDING PEEL STRENGTH

In addition to examining the hydraulic behaviour of Jet A1 through GCLs, the mechanical properties are also being examined. The average bonding peel strength (ASTM D6496) is an index used for GCLs. For this preliminary test, GCL samples were aged in a Jet A1 bath under zero stress for a prescribed time and then tested to determine the average bonding peel strength. Figure 4 shows the trend observed in this test, with each point being the average of 5 samples tested. Preliminary results show that there is an immediate decrease in strength, followed by a tapering decrease as exposure time increases. Further tests are ongoing.

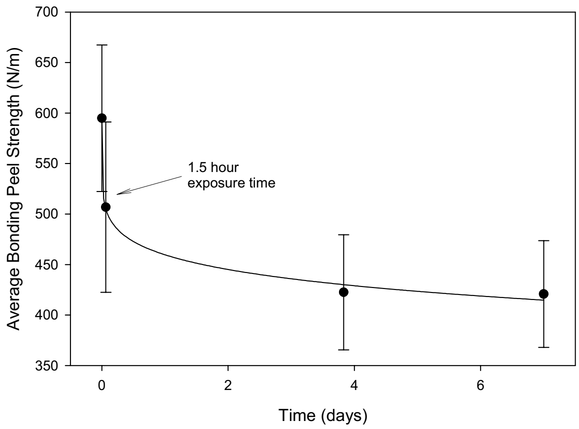

Figure 4. Average bonding peel strength of GCLs exposed to Jet A1 at zero stress

6. CONCLUSIONS

There are five preliminary conclusions arising from this research:

1. The hydraulic conductivity of highly saturated (degrees of saturation ≥ 80%) samples, frozen and permeated with Jet A1 is essentially zero (< 10^{-12} m/s). If samples are first permeated with Jet A1 at 5°C and then frozen to -5°C, the hydraulic conductivity drops, but some degree of the flow paths remain open. Samples with more water present (i.e. higher saturation), experience a greater decrease in hydraulic conductivity than samples with less water.

2. The hydraulic conductivity of frozen samples permeated with Jet A1 decreases as the bulk void ratio decreases, and as water content increases.

3. Hydraulic conductivity depends on the applied hydraulic gradient for saturated unfrozen samples. It is hypothesised is that higher pressures open up flow paths that were previously unavailable at lower pressures.

4. Initial tests showed that for unfrozen samples, as degree of saturation increased, the hydraulic conductivity decreased.

5. There is a high variability in the hydraulic properties for frozen samples due to different mass per unit area of bentonite and localization of ice masses in frozen samples.

6. For dry GCLs immersed in jet A1 with no stress, there is an early decrease in the average bonding peel strength, but the loss tapers off with time.

Additional testing is in progress to confirm these preliminary conclusions.

7. ACKNOWLEDGEMENTS

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