GeoVirtual 2020 September 14-16
Resilience and Innovation

A preliminary study of the effect of freeze-thaw cycles on GCL/Geomembrane interface transmissivity

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ABSTRACT

Recently, there has been increased interest in the use of geosynthetic clay liners (GCL) in composite liners in harsh environments like the Arctic and Antarctic regions. The primary role of a GCL in the composite liner is to minimize the advective flow of contaminants if there are any holes in the geomembrane (GMB). The two parameters controlling the effectiveness of this composite system are the hydraulic conductivity, *k,* of the GCL and interface transmissivity, *θ,* between the GMB and GCL. This paper reports results from a preliminary study of a "closed system" approach to subjecting specimens to freeze-thaw cycles by putting them in and out of a freezer and an "open system" where the specimen remains in contact with the subgrade under an applied stress during 5-freeze-thaw cycles. Attention is focused on the effect of these two methods on interface transmissivity for a range of stresses typical for cover applications. The preliminary results shows that the "open system" during freeze-thaw cycles allowed the formation of an ice lens at the GMB-GCL interface due to cryosuction, and this increased *θ* at a low stress of 10 kPa compared to using the "closed system."

RÉSUMÉ

Récemment, il y a eu un intérêt accru pour l'utilisation de revêtements en argile géosynthétique (GCL) dans des revêtements composites dans des environnements difficiles comme les régions arctiques et antarctiques. Le rôle principal d'un GCL dans le revêtement composite est de minimiser le flux advectif des contaminants s'il y a des trous dans la géomembrane (GMB). Les deux paramètres contrôlant l'efficacité de ce système composite sont la conductivité hydraulique, k, du GCL et la transmissivité d'interface, θ, entre le GMB et le GCL. Cet article rend compte des résultats d'une étude préliminaire d'une approche en 'système fermé' pour soumettre les échantillons à des cycles de gel-dégel en les mettant dans et hors d'un congélateur et d'un 'système ouvert' où l'échantillon reste en contact avec le sous-sol sous une couche appliquée. stress pendant les cycles de 5 gel-dégel. L'attention est concentrée sur l'effet de ces deux méthodes sur la transmissivité de l'interface pour une gamme de contraintes typiques pour les applications de couverture. Les résultats préliminaires montrent que le 'système ouvert' pendant les cycles de gel-dégel a permis la formation d'une lentille de glace à l'interface GMB-GCL en raison de la cryosuccion, et cela a augmenté θ à une faible contrainte de 10 kPa par rapport à l'utilisation du 'système fermé'.
Keywords: Geosynthetic clay liners, Interface transmissivity, Freeze-thaw Cycle, Ice lens, Simulated Godfrey Silty Sand Pore water.

1 INTRODUCTION

Geosynthetic clay liners (GCLs) are typically comprised of a thin layer of sodium bentonite sandwiched between two geotextiles and bonded together by needle punching. Over the last two decades, GCLs have been extensively used due to their excellent performance in reducing the advective flow of both liquid and gas in geotechnical and geoenvironmental engineering applications (Rowe 1998, 2005, 2007, 2020; Shackelford et al. 2000; Jo et al. 2001; Bouazza 2002) before being subjected to a freeze-thaw cycle (Karus et al. 1997; Rowe et al. 2006; Rowe et al. 2008; Makusa et al. 2014).

Composite liners (e.g., a geomembrane over a GCL) are widely used in a wide variety of waste containment systems like municipal solid waste landfill (Bouazza 2002; Rowe 2005, 2007; Rentz et al. 2016; AbdelRazek and Rowe 2019a), and also in resource recovery system (Benson et al. 2010; Shackelford et al. 2010; Touze-Foltz et al. 2016; Bouazza et al. 2017; Rowe 2020). The performance of the geosynthetic clay liners in the composite line primarily depends on the hydraulic conductivity (*k*) and the interface transmissivity (*θ*) between the geomembrane (GMB) and the geosynthetic clay liner (GCL). It has been long recognized that the leakage through composite liners related to the number of holes in the geomembrane (e.g., Giroud and Bonaparte 1989) and a decade later there was a recognition that holes in wrinkles play a crucial role in leakage (e.g., Rowe 1998, 2005, 2007, 2012, 2020; Chappell et al. 2012a; Chappell et al. 2012b). Leakage is related to the head difference across the liner, number and size of the holes, hydraulic conductivity of the GCL, and interface transmissivity between the GMB and clay liner/GCL (Fukuoka 1986; Brown et al. 1987; Giroud and Bonaparte 1989; Harpur et al. 1993; Rowe 1998; Touze-Foltz et al. 2002; Needham et al. 2004; Rowe and Abdelatty 2007; Mendes et al. 2010; Rowe and Abdelatty 2013; Rowe and Hosney 2015; AbdelRazek et al. 2016a; AbdelRazek and Rowe 2016b;; AbdelRazek and Rowe 2017; AbdelRazek and Rowe 2019a; AbdelRazek and Rowe 2019b).

The effect of freeze-thaw cycles on the hydraulic conductivity of GCLs has been investigated over the last two decades. Kraus et al. (1997) reported no significant change in hydraulic conductivity between 5 and 20 freeze-thaw cycles when permeated with water. Rowe et al. (2006) investigated 0, 5, 12, 50, 100 freeze-thaw cycles and reported that after applying 12 cycles there was a slightly (30%) increase in hydraulic conductivity (using a Rigid Wall Permeameter) of the GCL when permeated with water. They also found up to a 4-fold increase in *k* when permeated with Jet A-1 fuel from freeze-thaw cycles. Rowe et al. (2008) used a flexible wall permeameter but reached findings consistent with those of the Rowe et al. (2006). Makusa et al. (2014) investigated 0, 1, 3, 5, 15, 20 freeze-thaw cycles. They reported that there was no change of hydraulic conductivity until 5 freeze-thaw cycles when permeated with both DI water and a subgrade solution; from 5-15 to cycles, there was a small decrease in *k;* and from 15-20 cycles there was a small increase in *k* for both permeants. The effect of a different number of freeze-thaw cycles on *k* raises the question of how freeze-thaw cycles might affect the interface transmissivity? However, to date, no one has examined the effect of GCL prehydration method during freeze-thaw cycles on GMB/GCL interface transmissivity.

The objective of this paper is to report on a preliminary investigation to investigate the effect of 5 freeze-thaw cycles and the method of GCL prehydration during freeze-thaw cycles under a range of applied stress (10-25 kPa) typical for cover applications on GMB/GCL interface transmissivity.

2 MATERIALS AND TEST METHOD

2.1 Properties of materials

2.1.1 GCL and GMB

A needle-punched GCL with a nonwoven cover geotextile was examined which had 5294±195 g/m^2 of fine granular sodium bentonite on a scrim-reinforced nonwoven carrier geotextile (260 g/m^2). This GCL was thermally treated to melt and bond the needle-punched fibres with the carrier geotextile. The geomembrane (GMB) used was smooth, 1.5 mm thick, and made of high-density polyethylene (HDPE), denoted as MxC15 by Ewais and Rowe (2014).

2.1.2 Prehydration solutions

A simulated Godfrey silty-sand pore water solution reported by Hosney et al. (2016) and Rowe et al. (2019) was used in this study. It is dominated by calcium (RMD~0.02 (mol/l)$^{0.5}$),but has low cationic strength (8.6 mmol/L). Chemical composition of this solution was Ca^{2+}≈ 230 mg/l, Na^{+}≈ 30 mg/l, K^{+}≈ 6 mg/l, and Mg^{2+}≈ 33 mg/l.

2.1.3 Freeze-thawed sample preparation

2.1.3.1 Closed system

To simulate initial GCL hydration when on top of Godfrey silty sand at about 16% gravimetric water content, the samples of GCLs were immersed in a simulated Godfrey silty sand pore water solution under applied stress of 2 kPa for three days until it reached a gravimetric water content of 106±9% (a degree of saturation of about 90%). After finishing pre-hydration, the GCLs were instrumented with thermocouples (HOBO 4-channel thermocouple data logger connected with T type thermocouples cable) to monitor GCL temperature in the freezer (one thermocouple cable attached to the nonwoven geotextile and another attached to the scrim reinforced nonwoven carrier geotextile of the GCL. A GMB was then placed on top of the GCL and they were placed in two Ziploc bags and then placed in the freezer under 2 kPa stress. Data collected from the thermocouples showed that after 24 hours of freezing, the temperature of the scrim reinforced nonwoven carrier geotextile reached at -18.7˚C and the nonwoven geotextile reached -17.7˚C. After 24 hours of freezing, the GCL specimen was allowed to thaw at 28˚C for 24 hours. The process of placing the GMB/GCL composite pair into the freezer for 24 hours and thawing for 24 hours was repeated until the desired number of freeze-thaw cycles had been attained. For the purposes of this paper, after applying 5 freeze-thaw cycles, the thawed composite liner was installed into a transmissivity cell (AbdelRazek et al. 2016a), and a stress of 10 kPa was applied.

2.1.3.2 Open system

In this open system of freeze and thaw cycle application, a test set-up was developed to simulate field conditions of a was cover, e.g., like those at the Queen's University Environmental Liner Test Site (QUELTS) (Brachman et al. 2007). The GCL was placed directly on the top of the subgrade and was allowed to hydrate with pore water from the subgrade. The GCL remained in contact with the both the geomembrane and soil throughout initial hydration and during the subsequent freeze-thaw cycles. The target temperature of the GMB/GCL interface was chosen to be -5˚C in the freezing stage and +5˚C in the thawing stage in this preliminary study.

2.1.3.2.1 Hydration test in the open system

A polyvinyl chloride (PVC) column (internal diameter of the column was 280 mm, and height 300 mm) was used in this study (Figure 1a). A virgin GCL (initial water content of the GCL was 7%, and thickness was 7.6 mm) was instrumented with two thermocouples at the GMB/GCL interface (one of at the centre and one at the edge) and two more at the GCL/subgrade interface (one of at the centre and one at the edge; Figure 1a). Before putting the soil inside the PVC cell, the cell was instrumented with two thermocouples at the bottom of the cell (one was at the centre, and the other was at the edge). After instrumented with thermocouples, the PVC cell was filled with subgrade soil with a thickness of 180 mm. The GCL was placed on the top of the subgrade (nonwoven cover geotextile of the GCL was placed towards the subgrade), and the geomembrane was then placed on the top of the GCL.

Freezing was achieved by placing a chiller plate on top of the geomembrane. It consisted of copper tube formed into a circular shape and was kept on the top of the GMB and a steel block which applied 2 kPa stress was placed on the top of the copper tube plate. The copper tube was connected to a circulation loop that passed through a cooling bath (set to -31°C) to achieve the desired freezing temperature of the GMB/GCL interface. Freezing was intended to be one-dimensional and in the direction from the top of the GMB down to the subgrade. The top of the cell was filled with fiberglass insulation and covered with a PVC lid to keep 0 closed system. The outer wall and top of the cell were wrapped with fiberglass insulation with Reflectix duct wrap and foil tape to eliminate unnecessary heat loss/gain except for the bottom of the cell. The bottom of the cell was kept at room temperature to create the thermal gradient. The test was conducted at a room temperature of 5˚C inside a temperature-controlled environmental chamber.

A cold bath containing a propylene glycol solution chilled to the temperature of -31˚C was circulated through Soft ND-100-65 Tygon PVC Tubing connected to the circular copper tube plate placed on the top of the GMB to apply the source of freezing (Figure 1b). After circulating the chilled solution for 18 days on the top of the GMB, the GMB-GCL interface reached a temperature of -7˚C.

After this first freezing cycle, the GCL had a water content of 46%. After applying the fifth freezing cycle, the GMB and GCL were removed, without disturbing the GMB-GCL interface and was photographed. Figure 2 shows that ice lenses developed both within the bentonite component of the GCL and also within the GMB/GCL interface. The final gravimetric water content of the GCL specimen after the fifth freezing cycle was 94%.

After the fifth cycle of freezing, the frozen composite liner was transferred to the transmissivity test cell, and a stress of 10 kPa was applied while the GCL was allowed to warm up inside the transmissivity test cell. This approach minimized any disturbance of the geomembrane-GCL interface between the end of the last freezing cycle and the interface transmissivity test.

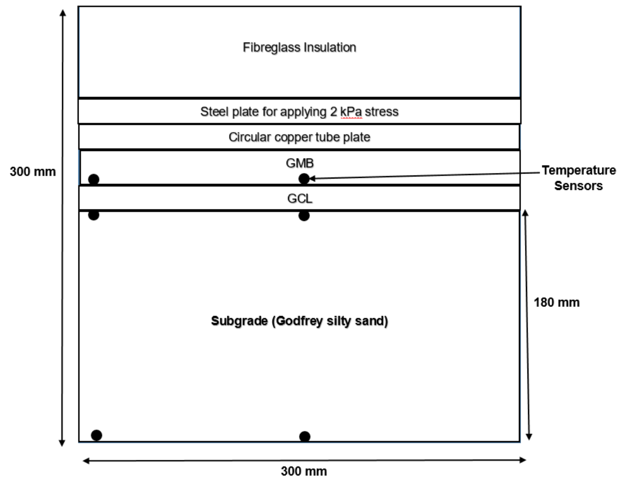


Figure 1a. Configuration of the hydration cell where freeze-thaw cycles were applied in the open system. Moisture could be attracted to the GCL and GMB/GCL interface from the subsoil by cryosuction as the freezing front advanced.

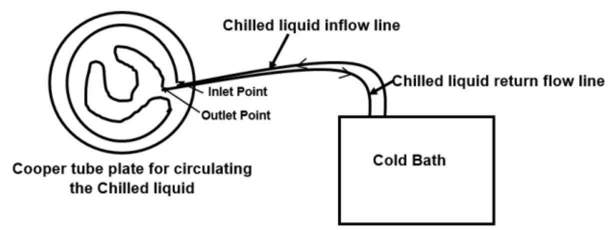


Figure 1b. Freezing system for the open system

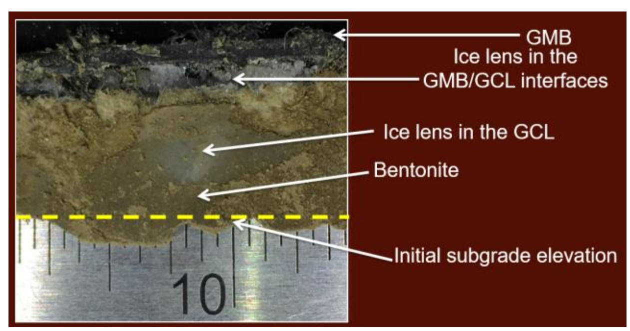


Figure 2. Ice lenses formed in the GCL and within the GMB-GCL interface in the open system. Note the variable thickness of both the ice lenses in the GCL and at the GMB-GCL interface. For scale, the smallest division of the ruler are 1.0 mm.

2.2 Interface transmissivity test cell and test setup

The interface transmissivity test cells used in this study were the same as used in previous studies (AbdelRazek et al. 2016a, AbdelRazek and Rowe 2016b, AbdelRazek and Rowe 2019a; AbdelRazek and Rowe 2019b). The polyvinyl chloride (PVC) calls had an internal diameter of 0.2 m, height 0.11 m, and 15 mm thick walls. All interface transmissivity tests were conducted at 28˚C following the same procedure previously reported by others (AbdelRazek et al. 2016a; AbdelRazek and Rowe 2016b; AbdelRazek and Rowe 2019a; AbdelRazek and Rowe 2019b) and as briefly summarized below.

A smooth 1.5 mm-thick HDPE GMB with a central 12.5 mm hole was sealed in the bottom of the cell and tested to ensure there were no leaks. Before placement of the GCL sample, the permeant of interest was allowed to flow through the inlet valve to release any trapped air through the purge valve.

The GCL sample was cut to a 200 mm-diameter test specimen. The bentonite and geotextile to be in contact with the GMB were removed from an annular ring located 75 mm from the centre of the specimen to make space for the drainage layer surrounding the GCL and a geotextile strip having equal thickness to the bentonite was placed around the perimeter of bentonite, to contain the bentonite. The 150 mm-diameter scrim-reinforced nonwoven carrier geotextile was then placed in direct contact with the GMB. To transmit the interface flow through to the effluent valve, fine gravel (with grain sizes between 4.75 to 5.6 mm) was placed in the annular region around the edge of the bentonite in the GCL. A rubber bladder was placed over the nonwoven cover geotextile, and silicone gel was applied at the edge of the rubber bladder and allowed 24 hours to dry before bentonite paste was applied on the edge of the rubber bladder as an extra seal between the edge of the bladder edge and walls of the PVC cell (to force flow laterally in the interface and GCL).

To ensure maximum transfer of the applied pressure through the sand to the bottom of the cell, friction treatment was placed surrounding the entire inside sidewalls of the cell and the remainder of the cell was filled with fine sand. A geotextile was placed on the top of the sand layer and a rubber bladder placed on the geotextile was used to transmit the applied pressure which was controlled by a regulator connected on the top of the cell.

The influent head and flow was monitored with a graduated cylinder which was connected to an influent valve at the bottom of the cell. The effluent was collected in a 250 ml HDPE capped bottle (with a thin air pressure equilibration tube) that connected to the side of the cell and fine gravel.

2.2.1 Interpretation of the transmissivity test result

The inflow (θ_{inflow}) transmissivity was measured by monitoring the change of permeant head in the graduated cylinder after discrete intervals and calculated using the falling head test method and Equation 1. The outflow transmissivity ($\theta_{outflow}$) was obtained by collecting the effluent from the cell over discrete time intervals and using the measured mass of effluent to obtain a volume and then calculating θ_{inflow} based on the constant head method and Equation 2.

$$\theta_{inflow} = -a.\frac{\ln(\frac{R_2}{R_1})\,x\,\ln(\frac{h_2}{h_1})}{2\pi t} \qquad [1]$$

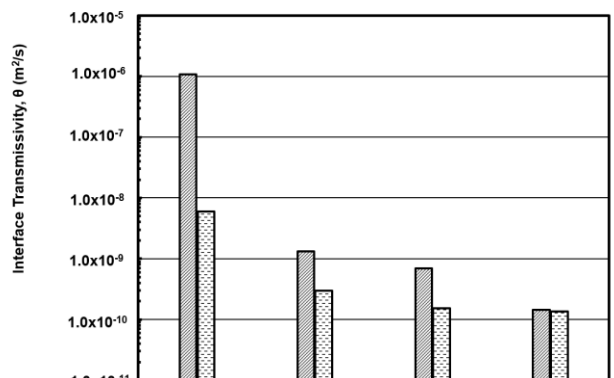
$$\theta_{outflow} = \frac{Q}{t}\cdot\frac{\ln(\frac{R_2}{R_1})}{2\pi havg} \qquad [2]$$

where, a is the cross-sectional area of the graduated cylinder (m^2), R_1 is the radius of the GCL specimen (0.075 m), R_2 is the radius of the hole in the GMB (0.00625 m), h_1 is the initial head of permeant in the graduated cylinder (m), h_2 is the final head of permeant in the graduated cylinder after a certain time interval (m), Q is the volume of effluent (m^3), t is the time interval (s), and h_{avg} is the average head on the GCL (m).

In any test, steady-state was deemed to have been reached when the following two conditions were met: (i) the rate of inflow and outflow remained the same with time for a duration of 15 days; and (ii) the electrical conductivity of the influent and effluent was same.

3 RESULTS AND DISCUSSION

The interface transmissivity results obtained after 5 freeze-thaw cycles at 10, 15, 20, and 25 kPa are reported for both the open and closed system in Figure 3. In both tests, the scrim reinforced nonwoven carrier geotextile of the GCL was in contact with the GMB.



	10 kPa	15 kPa	20 kPa	25 kPa
Open system	$1.1x10^{-6}$	$1.3x10^{-9}$	$6.9x10^{-10}$	$1.4x10^{-10}$
closed system	$6.0x10^{-9}$	$2.9x10^{-10}$	$1.5x10^{-10}$	$1.4x10^{-10}$

Figure 3. GMB/GCL transmissivity, θ, for GCL subjected to five freeze-thaw cycles in an open system and closed system

The transmissivity tests on the specimen subjected to freeze-thaw in the closed system had an equilibrium transmissivity of 6.0x10^{-9} m^2/s at 10 kPa. This reduced 20-fold to 2.9x10^{-10} m^2/s at 15 kPa. Subsequent increases in stress reduced the transmissivity another 2-fold to 1.5x10^{-10} m^2/s at 20 kPa, and then to 1.4x10^{-10} m^2/s at 25 kPa.

The transmissivity tests on the specimen subjected to freeze-thaw in the open system had an equilibrium transmissivity θ = 1.1x10^{-6} m^2/s at 10 kPa. Increasing the stress to 15 kPa resulted in an 800-fold decrease in θ to 1.3x10^{-9} m^2/s. A further increase in stress from 15 to 20 kPa, reduced θ by 2-fold to 6.9x10^{-10} m^2/s and there was a 5-fold decrease to 1.4x10^{-10} m^2/s going from 20 to 25 kPa.

Comparing the results for the open and closed system, it is apparent that at 25 kPa they were essentially the same. However, at 10 kPa, there was an almost 200-fold higher transmissivity in the open system and in the closed system. This reduced to a 5-fold difference at 15 and 20 kPa, and no difference at 25 kPa. This begs the question as to why there was so much difference at 10 kPa and no effect at 25 kPa. The explanation lies in what happened differently at the interface between the GMB and GCL in the two tests.

In the closed system, GCL was placed into the freezer and there was no opportunity for any additional water to be transferred to the composite liner during the freeze-thaw cycles. In contrast, in the open system the composite liner froze at a faster rate than the underlying soil by 1D cooling from the top and this allowed the upward movement of moisture to the GMB/GCL interface and the GCL due to cryosuction.

At the end of the fifth freeze cycle, the frozen composite liner was carefully inspected and photographed in profile without disturbing the GMB-GCL interface. Ice lenses had formed in the GCL and at the GMB-GCL interface (Figure 2).

The high transmissivity data suggests that the ice lenses at the GMB interface left a local, more open transmissive zone area at the interface between the GMB and GCL even after it thawed under 10 kPa and that this provided a preferential flow path resulting in high transmissivity at 10 kPa. Increasing the applied stress appeared to progressively close up this preferential path, decreasing θ by almost three orders of magnitude at 15 kPa stress and almost 4 orders of magnitude by the time the stress reached 25 kPa.

4 CONCLUSION

Preliminary results of interface transmissivity between the GMB and GCL after being subjected to five freeze-thaw cycles and when permeated with a solution intended to simulate pore fluid from a silty-sand suggest the following:

i. In the open system that allows moisture migration to the freezing front allows the ice lens formation at or near the GMB/GCL interface and provides a more representative situation for evaluating interface transmissivity at stresses less than 25 kPa relative to a more conventional closed system without additional supply of water during freezing.
ii. At least in this preliminary study, the effect of the method of applying five freeze-thaw cycles (i.e. open vs. closed systems) did not appear to have any significant effect at 25 kPa.

Thispreliminary study raises more questions than it answers and needs to be supplemented by more detailed and extensive study. However, it does highlight that there is an issue requiring investigation since many covers have stresses of 15 kPa or less.

5 ACKNOWLEDGMENTS

Funding for the development of the research infrastructure was provided by the Canada Foundation for Innovation, the Ontario Innovation Trust, the Ontario Research Fund Award, and Queen's University under project 36663. The research was funded by a strategic grant from the Natural Sciences and Engineering Research Council of Canada The support of all those listed above is much appreciated; however, the opinions expressed in the paper are solely those of the authors.

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