HYDRAULIC CONDUCTIVITY OF GEOSYNTHETIC CLAY LINERS AFTER FREEZE-THAW

By Robert D. Hewitt[1] and David E. Daniel[2]

ABSTRACT: Hydraulic conductivity tests were performed in large tanks on intact (single panel) and overlapped samples of three geosynthetic clay liners (GCLs) that had been subjected to freeze-thaw cycles. The compressive stress applied to the GCLs (7.6–12.4 kPa) was selected to simulate final cover systems for landfills. Laboratory flexible-wall permeameter tests were also performed. With the exception of one overlapped GCL, all three GCLs withstood three freeze-thaw cycles without a significant change in hydraulic conductivity. An overlapped, geotextile-encased, stitch-bonded GCL did undergo a 1,000-fold increase in hydraulic conductivity after one freeze-thaw cycle, but the overlapped area contained stitches, which are left off the edges of the full-sized material that is deployed in the field. In general, the tests showed that GCLs can withstand at least three freeze-thaw cycles without significant changes in hydraulic conductivity.

INTRODUCTION

Geosynthetic clay liners (GCLs) are thin hydraulic barriers containing 5 kg/m^2 (1 lb/ft^2) of sodium bentonite, sandwiched between two geotextiles or attached with an adhesive to a geomembrane (Daniel and Estornell 1991; Daniel 1991, 1993; Daniel and Boardman 1993; Koerner 1994). GCLs are manufactured in panels and are installed by unrolling and overlapping the panels. Overlaps self-seal when the bentonite hydrates (Estornell and Daniel 1992). Geosynthetic clay liners are receiving increased use in bottom liners for landfills and impoundments (Schubert 1987; Daniel and Koerner 1991; Trauger 1991, 1992; Clem 1992), in final covers for landfills and remediation projects (Koerner and Daniel 1992; Daniel and Richardson 1995; Woodward and Well 1995), and as a liner for secondary containment around liquid storage tanks (Brunton 1991).

An important issue on some projects is whether freeze-thaw affects GCLs, either during or after construction. Freeze-thaw causes moisture migration, cracking, and increased hydraulic conductivity in natural clays and silts (Chamberlain and Gow 1979; Konard 1989). As discussed by Othman et al. (1994), compacted clay liners are vulnerable to damage from freeze-thaw (Chamberlain et al. 1990; Zimmie and LaPlante 1990; Zimmie 1992; Chamberlain 1992; Othman and Benson 1992, 1993; Kim and Daniel 1992; Benson and Othman 1993; Bowders and McClelland 1994).

Bentonite appears to be less vulnerable to freeze-thaw damage than other types of soil. Wong and Haug (1991) found that the hydraulic conductivity of compacted sand-bentonite mixtures did not increase after five freeze-thaw cycles. Published information on the effects of freeze-thaw on GCLs are summarized in Table 1. All tests summarized in Table 1 were performed on small ($\approx$100 mm diameter) test specimens without overlaps. The hydraulic conductivity after freeze-thaw has been found to be approximately the same as before freeze-thaw (Table 1). The ability of GCLs to withstand freeze-thaw is apparently the result of the swelling and self-sealing characteristics of bentonite.

Only one published case involving field performance of GCLs could be found in the literature. At a location near Milwaukee, Wisconsin, Erickson et al. (1994) placed three GCLs (with and without overlaps) over an underdrain system and covered them with 250 mm of gravel. The GCLs went through one winter of freeze-thaw. In general, the hydraulic conductivity of the GCLs underwent little or no change. Of the nine tests, the one that produced the greatest seepage was beneath an overlap of a geotextile-encased, stitch-bonded GCL; before freeze-thaw, the average hydraulic conductivity was 3×10^{-10} m/s, and after freeze-thaw, the hydraulic conductivity was 4×10^{-9} m/s.

The purpose of this study was to perform carefully controlled tests to evaluate the effect of several freeze-thaw cycles on the hydraulic conductivity of GCLs. Tests were performed on small-scale samples of the parent GCL materials in the laboratory, and large-scale tests were performed on the parent materials and on overlapped panels of GCLs. Conclusions are drawn concerning the hydraulic integrity of GCLs subjected to freeze-thaw cycles.

EFFECTS OF FREEZE-THAW ON SOILS

Mechanisms

As the temperature drops below 0°C, soil begins to freeze and ice crystals nucleate in the center of the largest pores of the soil. Water outside the larger pore spaces freezes at lower temperatures; capillary forces acting on the surface of the soil particles and electrolytes in the pore water depress the freezing point of the pore water. Konrad (1989) found that free water in the pore space froze at -0.4°C to -0.7°C; this zone where freezing is actively occurring consists of soil particles, ice, and water. As water changes to ice, it increases in volume by about 9% due to the expansion of the hexagonal ice crystals. Ice crystals exert pressure on each other and the surrounding soil (Andersland and Anderson 1978), inducing structural changes within the soil.

If the temperature remains below 0°C, the freezing front advances into the soil. Water is drawn to the freezing zone from the unfrozen soil (Tsytovich 1975). As water moves to the freezing front, it crystallizes onto existing ice, forming ice lenses oriented parallel to the freezing front. The size and spacing of ice lenses depend on the relative magnitude of the availability of water and the freezing rate (Andersland and Anderson 1978).

The term open system refers to the presence of an external water supply available to the soil during freezing. Likewise, when soil is isolated from external sources of water, freezing is said to occur in a closed system. Experiments with closed-system freezing verify that water contents increase in the frozen zone and decrease in the unfrozen zone (Benson and Othman 1993), indicating that moisture migration occurs within the soil. Whether the system is open or closed appears to have

[1]Geotech. Engr., Haley & Aldrich, Inc., Cambridge, MA 02141.
[2]Prof. of Civ. Engrg., Univ. of Illinois, Urbana, IL 61801.

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TABLE 1. Summary of Hydraulic Conductivity Tests on GCLs Subjected to Freeze-Thaw Cycles

GCL (1)	Reference (2)	Effective stress (kPa) (3)	Hydraulic gradient (4)	Number of freeze-thaw cycles (5)	Hydraulic conductivity before freeze-thaw (m/s) (6)	Ratio of hydraulic conductivity before freeze-thaw to value after freeze-thaw (7)
Claymax	GeoServices Inc. (1989)	197	1,000	10	4×10^{-12}	0.4
	Chen-Northern Inc., Denver, Colo., unpublished report (1988)	14	10	10	1×10^{-11}	2.2
	Shan (1990)	14	10	5	2×10^{-11}	1.1
Bentomat	GeoSyntec Consultants (1991a)	34	30	4	2×10^{-11}	2–3
Gundseal	GeoSyntec Consultants (1991b)	—	235	4	1×10^{-11}	1.0

little impact on the results of tests conducted with compacted clay (Chamberlain et al. 1990; Zimmie 1992; Othman et al. 1994). With GCLs, it is assumed that freezing in the field will approximate a closed system since the thin GCL is likely to freeze quickly over its full thickness.

Chamberlain and Gow (1979) and Othman and Benson (1992) photographed thin sections cut from frozen soil and demonstrated that cracking occurs as a result of freezing. Even when cracks are not visible to the eye, microscopic cracks may be present (Chamberlain et al. 1990). When the ice-filled cracks thaw, they form an aggregated structure bounded by horizontal cracks left by ice lenses and vertical desiccation cracks, produced as water is drawn to the freezing zone (Othman et al. 1994). Research indicates that after freeze-thaw, flow occurs primarily through the crack network rather than through the pore space of the soil (Benson and Othman 1993).

Effect on Hydraulic Conductivity

When soils are permeated with water after freezing and thawing, flow preferentially occurs through the crack network, i.e., secondary porosity. Thus, cracks that develop during freeze-thaw cycling increase the hydraulic conductivity of the soil. The literature shows that natural and compacted clay soils that have hydraulic conductivities on the order of 10^{-9}–10^{-12} m/s before freeze-thaw typically have hydraulic conductivities in the 10^{-8} m/s range after freeze-thaw (Othman et al. 1994).

The rate of freezing influences the size and frequency of ice lenses (Mitchell 1993). Othman and Benson (1992) found that faster freezing rates increased the hydraulic conductivity, but the effect of the rate of freezing on hydraulic conductivity after freeze-thaw was less than an order of magnitude.

Othman and Benson (1993) explored the relationship between ultimate freezing temperature and hydraulic conductivity for three Wisconsin clays. The variations in hydraulic conductivity for soils frozen at temperatures below $-1°C$ were negligible.

Tests on natural and compacted clays show that increases in the hydraulic conductivity of greater than one order of magnitude typically occur during the first cycle of freeze-thaw. Subsequent cycles result in smaller increases in the hydraulic conductivity, with minimal changes occurring after 3–10 cycles (Chamberlain et al. 1990; Zimmie and LaPlante 1990; Wong and Haug 1991; Othman and Benson 1992; Othman et al. 1994). From the available literature, 3–5 freeze-thaw cycles are sufficient to determine the effects of freeze-thaw. Changes in hydraulic conductivity are similar when samples are frozen one-dimensionally and three-dimensionally (Zimmie et al. 1991; Othman and Benson 1992).

Effective stress influences the vulnerability of clays to freeze-thaw damage; hydraulic conductivity increases less at higher effective stress (Fig. 1).

MATERIALS

Three GCLs were selected for testing to cover the range of types of commercial GCLs available. The first GCL was a geotextile-encased, needle-punched GCL (Bentomat, SS grade bentonite), which contains a woven geotextile on one side and a nonwoven geotextile on the other side. The nonwoven geotextile was faced downward.

A second GCL tested was a geotextile-encased, stitch-bonded GCL (Claymax 500SP). The two woven geotextiles on this material are stitched together with parallel rows of stitches spaced 100 mm apart and oriented parallel to the long direction of the tank. The manufacturer of this material leaves the outer 225 mm (9 in.) of the material unstitched so that overlapped zones will not contain stitches along the length of the panels. However, with the small pieces used in this study, material was used that contained stitches in the overlapped zone.

The third GCL tested was a geomembrane-supported GCL (Gundseal) with a 0.5 mm (20 mil)-thick smooth, high density polyethylene (HDPE) component. The GCL was installed with the HDPE component on the top and the bentonite on the bottom.

Both intact and overlapped panels were tested, except the geomembrane-supported GCL, for which only the overlapped material was tested. Estornell and Daniel (1992) showed that the measurable seepage does not occur through the intact (non-overlapped) GCL because the geomembrane component blocks seepage.

Overlaps were 225 mm wide for all overlapped GCLs. The centerline of the overlap matched the centerline of the tanks. For the needle-punched GCL, dry bentonite was applied in the overlap at an application rate of 0.4 kg/m as recommended by the manufacturer. Additional dry bentonite is not required by the manufacturer in the overlapped zone for the other two GCLs, and none was used.

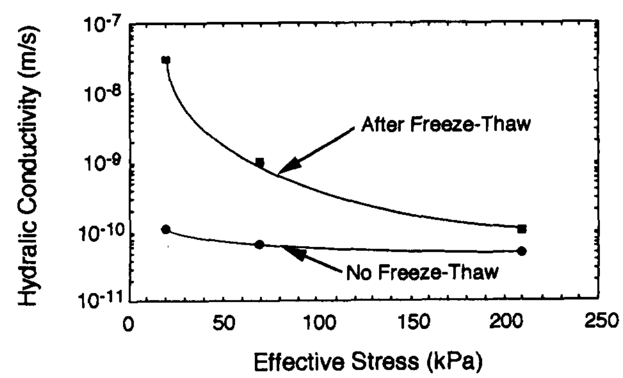

FIG. 1. Effect of Compressive Stress on Hydraulic Conductivity of a Compacted Clay Subjected to Freeze-Thaw (Othman and Benson 1991)

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METHODS

Laboratory Tests

Hydraulic conductivity tests were performed on 100-mm-diameter test specimens in flexible-wall permeameters. Test specimens were consolidated to an effective stress of 12.4 kPa, back-pressure saturated, and permeated with tap water. After equilibrium was reached, the cell water was drained from the permeater, but the GCL test specimen was left intact (confined by the latex membrane and porous end pieces). The empty cell was then placed in a freezer for 24 h to freeze the GCL at −20°C. No confining pressure was applied to the GCL during the freezing. The GCL was then thawed for 24 h at room temperature. When the freeze-thaw cycling was complete, the cell was filled with water and the hydraulic conductivity determined under the same testing conditions used before freeze-thaw (Hewitt 1994).

Tank Tests

Testing was performed using the same epoxy-coated steel tanks that are described by Estornell and Daniel (1992) and LaGatta (1992). The tanks measured 2.4 m (8 ft) in length, 1.2 m (4 ft) in width, and 0.9 m (3 ft) in height. A hole drilled in the base of the tanks served as an outlet to collect flow. The tanks were raised off the floor with wooden blocks. Tests using these tanks are referred to as bench-scale tests since they are larger than normal-sized laboratory permeation tests (Estornell and Daniel 1992).

Each test arrangement was constructed by placing gravel over the base of the tanks, and then covering the gravel with a geotextile. Thermocouples were placed on top of the geotextile. Then the GCL (intact panel, or two overlapped panels with the overlap running the length of the tank) was placed on top of the geotextile. A bentonite side seal was placed around the perimeter, and the edges of the tank were bolted to a metal frame.

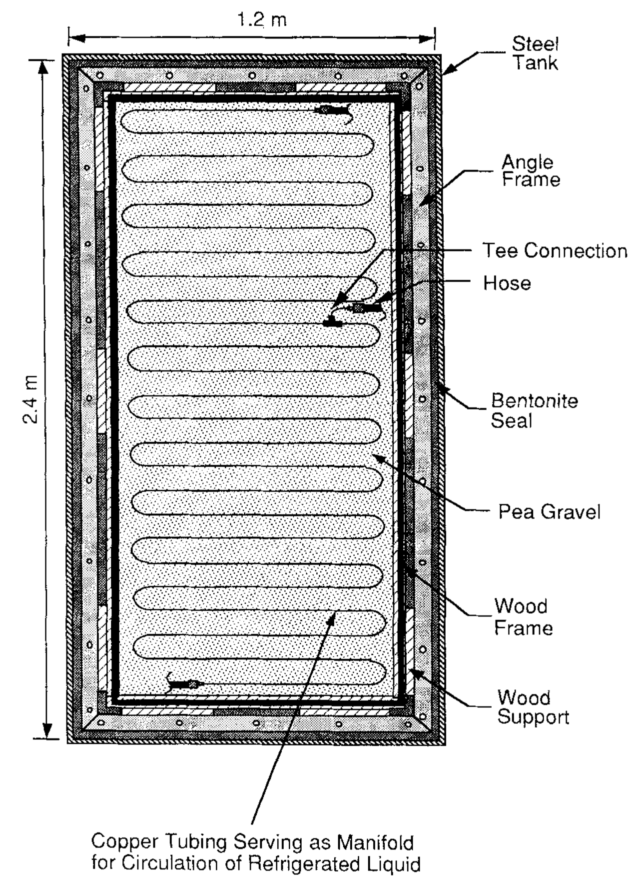

FIG. 2. Plan View of Tank Showing Copper Tubing Used for Cooling

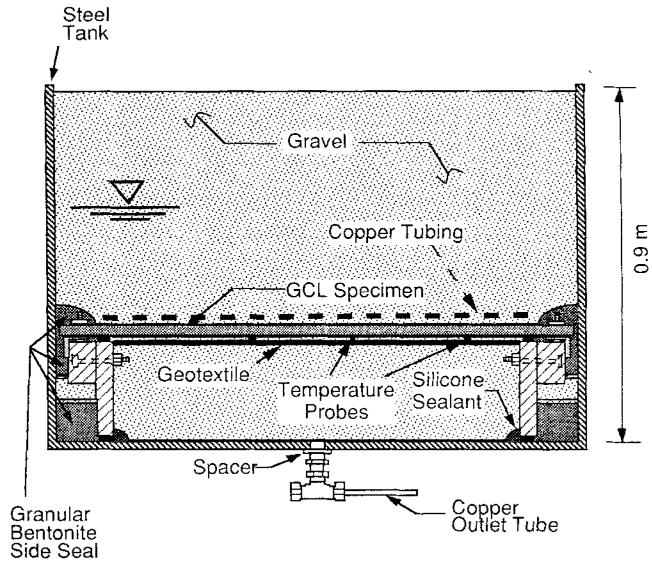

FIG. 3. Cross Section of Tank

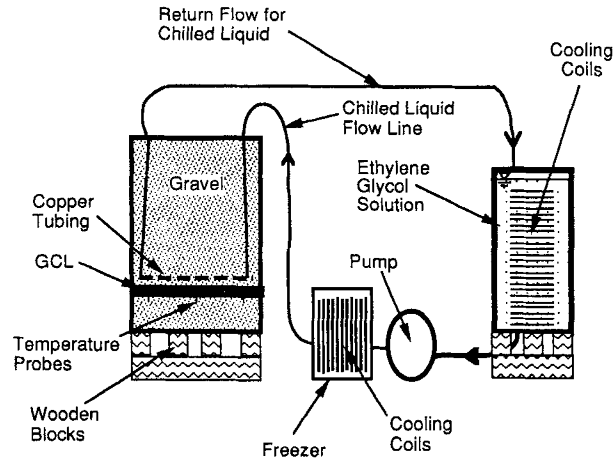

FIG. 4. System for Freezing GCLs in Tanks

The GCL was covered with 25 mm of pea gravel. Next, a cooling manifold consisting of 12-mm-outside diameter (OD) soft copper tubing (through which refrigerated liquid was later circulated) was placed on the gravel. The copper tubing was bent into a manifold using 100-mm-diameter bends in the pattern shown in Fig. 2. A cross sectional view, showing the copper tubing located just above the GCL, is shown in Fig. 3. Additional gravel was placed over the cooling tubes to provide a total of 625 mm of rounded pea gravel overburden on the GCL.

Water was then introduced into the gravel to hydrate the GCLs. Over a period of 2–3 d the depth of water ponded on the GCL was slowly raised to 300 mm.

A freezing system (Fig. 4) was used to circulate 170 L of an ethylene glycol solution (1:1 mixture with water), chilled to less than −17°C (0°F), through the copper manifold. After flowing through the tubing, the refrigerant liquid passed from the tank into a cooling reservoir, where two thermoelectric cooling units chilled the liquid. Then the mixture passed through a secondary chilling unit consisting of a coil of copper tubing housed in a freezer. After leaving the secondary chilling unit, the cooled liquid (at −17°C) was pumped through the tubing above the GCL. Return fluid from the GCL was typically at temperatures of −4 to −1°C.

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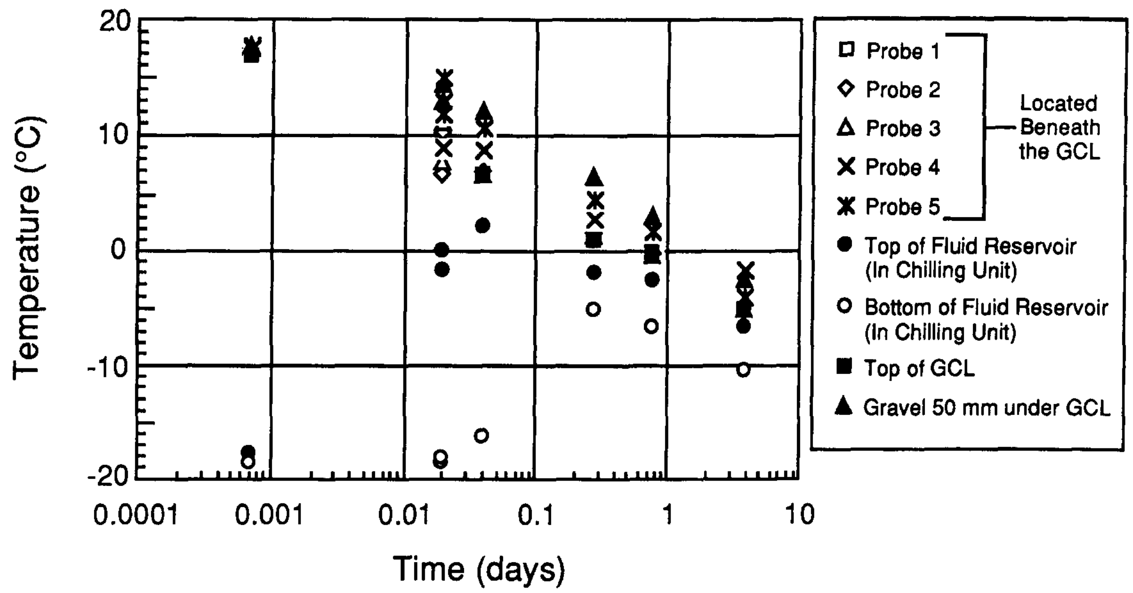

FIG. 5. Typical Measurements of Temperature during Freezing Cycle

TABLE 2. Summary of Experimental Results for Zero, One, and Three Freeze-Thaw Cycles

GCL (1)	Type of test (2)	$\bar{\sigma}$ (kPa) (3)	Hydraulic Conductivity (m/s): Zero freeze-thaw cycles (4)	One freeze-thaw cycle (5)	Three freeze-thaw cycles (6)
Geotextile-encased, needle-punched GCL	Bench-scale (intact)	7.6	2×10^{-11}	3×10^{-11}	2×10^{-11}
	Bench-scale (overlap)	7.6	4×10^{-11}	7×10^{-11}	3×10^{-11}
	Flexible-wall	12.4	2×10^{-11}	3×10^{-11}	3×10^{-11}
Geotextile-encased, stitch-bonded GCL	Bench-scale (intact)	7.6	3×10^{-11}	5×10^{-11}	7×10^{-11}
	Bench-scale (overlap)	7.6	1×10^{-10}	1×10^{-7}	7×10^{-8}
	Flexible-wall (no stitching)	10.3	2×10^{-11}	4×10^{-12}	3×10^{-11}
	Flexible-wall (with stitching)	10.3	2×10^{-11}	2×10^{-11}	2×10^{-11}
Geomembrane-supported GCL	Bench-scale (overlap)	7.6	No flow[a]	—	No flow[b]
	Flexible-wall (bentonite only)	12.4	3×10^{-11}	2×10^{-11}	2×10^{-11}

Note: $\bar{\sigma}$ = effective stress (kPa); — = not available.
[a]No flow occurred during 25 days of permeation.
[b]No flow occurred during 52 days of permeation.

The steel tank was heavily insulated with both fiberglass wall insulation and foil-sided foam sheathing. Although insulation was placed in the space beneath the tank, cooling efficiency still suffered due to heat transfer through the bottom of the tank, wood foundation, and concrete floor. To offset the heat gain, an air conditioned, insulated chamber was constructed around the entire experimental setup.

Thermistors were used to monitor temperature. The probes were rated to −46°C, with an accuracy of ±0.05°C. Two probes located in the gravel above the GCL measured the temperature at the top of the GCL. In contact with the bottom of the GCL, 5–6 probes read the temperature underneath the GCL. Freezing occurred from the top down. Thus, when both the top and the bottom of the GCL were frozen, it was assumed that the entire GCL test specimen was frozen.

The GCL specimens were hydrated and permeated with tap water prior to freeze-thaw. When the hydraulic conductivity became steady, the water in the tank was drained by gravity until only 25–50 mm remained above the GCL. Chilled refrigerant liquid was then circulated through the copper tubing above the GCL. The temperature probes were monitored, and circulation of the fluid continued until all temperature probes read less than −1°C. In 4–5 d, the temperature of the GCL dropped from 20°C to −1°C. Typical temperature readings from the thermistors are presented in Fig. 5. After stopping the fluid circulation, the GCL was allowed to thaw under ambient conditions. The temperature rose from −1°C to above 10°C in 3–4 d. Each GCL sample was subjected to three cycles of freeze-thaw.

RESULTS

The objective of the testing program was to evaluate the impact of freeze-thaw on the hydraulic conductivity of three GCLs. For comparison, bench-scale tests were performed on 1.2 m × 2.4 m test specimens in the steel tanks, and small-scale tests were performed on 100-mm diameter specimens that were permeated in flexible-wall permeameters.

A summary of the results of the testing program is presented in Table 2. The water content and thickness of the GCL samples were measured immediately after the tests were dismantled (Table 3). The results are discussed for each material in alphabetical order.

Geotextile-Encased, Needle-Punched GCL

Bench-Scale Test on Intact Specimen

The intact (i.e., nonoverlapped) needle-punched GCL was hydrated prior to freeze-thaw. No outflow occurred for the first 50 d of flooding under a hydraulic head of 300 mm of water. Outflow did finally begin, and, as shown by the open squares in Fig. 6, the hydraulic conductivity increased from an initial value of 8×10^{-13} m/s and equilibrated at a hydraulic conductivity of about 2×10^{-11} m/s.

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TABLE 3. Water Content and Thickness Data after Three Freeze-Thaw Cycles

GCL (1)	Type of test (2)	Average final water content (%) (3)	Average hydrated thickness (mm) (4)
Geotextile-encased, needle-punched GCL	Bench-scale (intact)	179	13
	Bench-scale (overlap)	254	13
	Flexible-wall	257	13.3
Geotextile-encased, stitch-bonded GCL	Bench-scale (intact)	275	13
	Bench-scale (overlap)	286	13
	Flexible-wall (no stitching)	201	12.2
	Flexible-wall (with stitching)	245	13.7
Geomembrane-supported GCL	Bench-scale (overlap)	154[a]	13[a]
	Flexible-wall (bentonite only)	218	5.4

[a]Hydrated portion of clay.

At the end of 1 freeze-thaw cycle, the GCL was permeated. Results are shown by the solid triangles in Fig. 6. It was convenient to graph the hydraulic conductivity using day zero as the day when permeation was initiated for each stage of permeation, rather than a running plot of days, since the number of days employed for the freeze-thaw process varied. Thus, the graphs (including those in Fig. 6) start over at day zero. A steady hydraulic conductivity of 3×10^{-11} m/s was reached almost immediately. This value is essentially identical to the hydraulic conductivity before freeze-thaw.

After three freeze-thaw cycles, no flow through the sample was observed for 23 d. However, a few grams of viscous bentonite sludge oozed from the outlet hole after 10 d. In order to initiate flow, the hydraulic gradient was raised from 25 to 41 by increasing the head of liquid in the tank. Flow through the sample began again after 32 d, and a hydraulic conductivity of about 2×10^{-11} m/s was achieved within the next 14 d. This is the same value as before freeze-thaw.

No migration of bentonite was evident either in the GCL or in the underlying gravel during the breakdown of the test. The origin of the small amount of bentonite that plugged the outlet hole is unknown, but it is likely that the bentonite originated from bentonite dust present on the base of the tank at the time the materials were placed in the tank.

Bench-Scale Test on Overlapped Panels

Flow through the overlapped sample started after 4 d of hydration (Fig. 7). The hydraulic conductivity rose from an initial value of 4×10^{-12} m/s to a steady value of 3×10^{-11} m/s after 10+ days of permeation. After undergoing one freeze-thaw cycle, the overlapped GCL panels achieved a hydraulic conductivity of 7×10^{-11} m/s. The hydraulic conductivity of the overlapped panels decreased to 3×10^{-11} m/s after three freeze-thaw cycles. Thus, the hydraulic conductivity essentially doubled after the first freeze-thaw cycle, but after three freeze-thaw cycles, the hydraulic conductivity was back to slightly below the initial value before freeze-thaw. This variation is considered to be within the range of possible experimental error. Thus, the application of three freeze-thaw cycles had no significant effect on the intact or overlapped specimens of the needle-punched GCL.

Small-Scale Test Specimen

An intact, 100-mm-diameter sample of the needle-punched GCL was permeated in a flexible-wall permeameter and had a hydraulic conductivity of 2×10^{-11} m/s prior to freeze-thaw. After both one and three cycles of freeze-thaw, the hydraulic conductivity was 3×10^{-11} m/s. The results from the flexible-wall hydraulic conductivity tests were similar to the results of tests in the tanks for this GCL, i.e., there was no adverse effect from freeze-thaw.

Geotextile-Encased, Stitch-Bonded GCL

Bench-Scale Test on Intact Specimen

Flow through the intact GCL started almost immediately (Fig. 8). During 33 d of permeation before freeze-thaw, the hydraulic conductivity leveled off at about 3×10^{-11} m/s.

Following one freeze-thaw cycle, the hydraulic conductivity had increased slightly to 5×10^{-11} m/s after 9 d of permeation. Upon completion of three freeze-thaw cycles, the hydraulic conductivity leveled out after 32 d of permeation at 7×10^{-11} m/s, or about twice the value before freeze-thaw. This increase

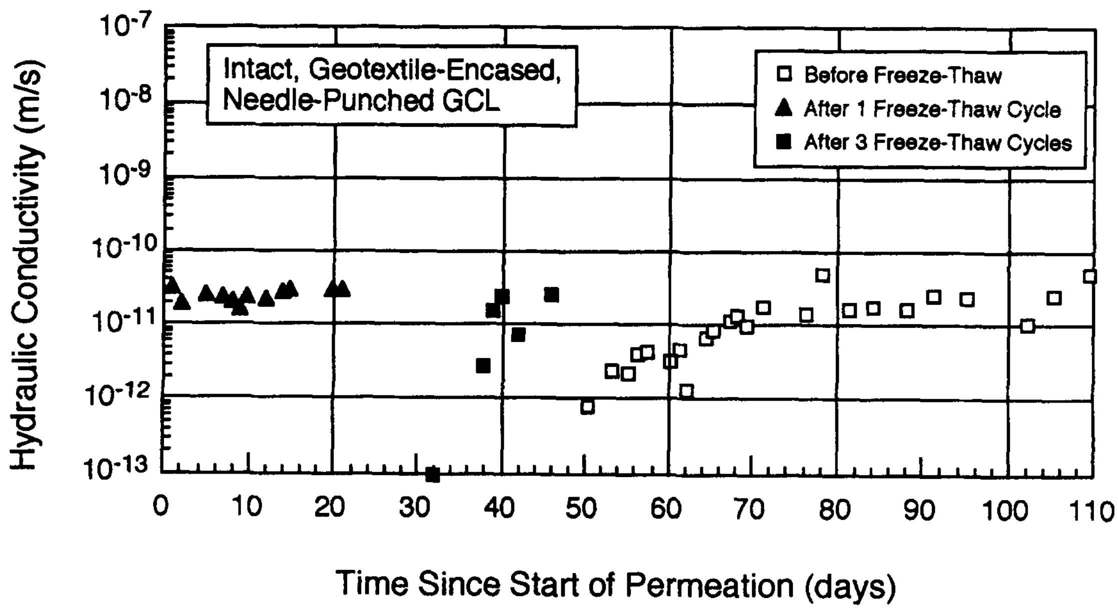

FIG. 6. Hydraulic Conductivity of Intact, Geotextile-Encased, Needle-Punched GCL

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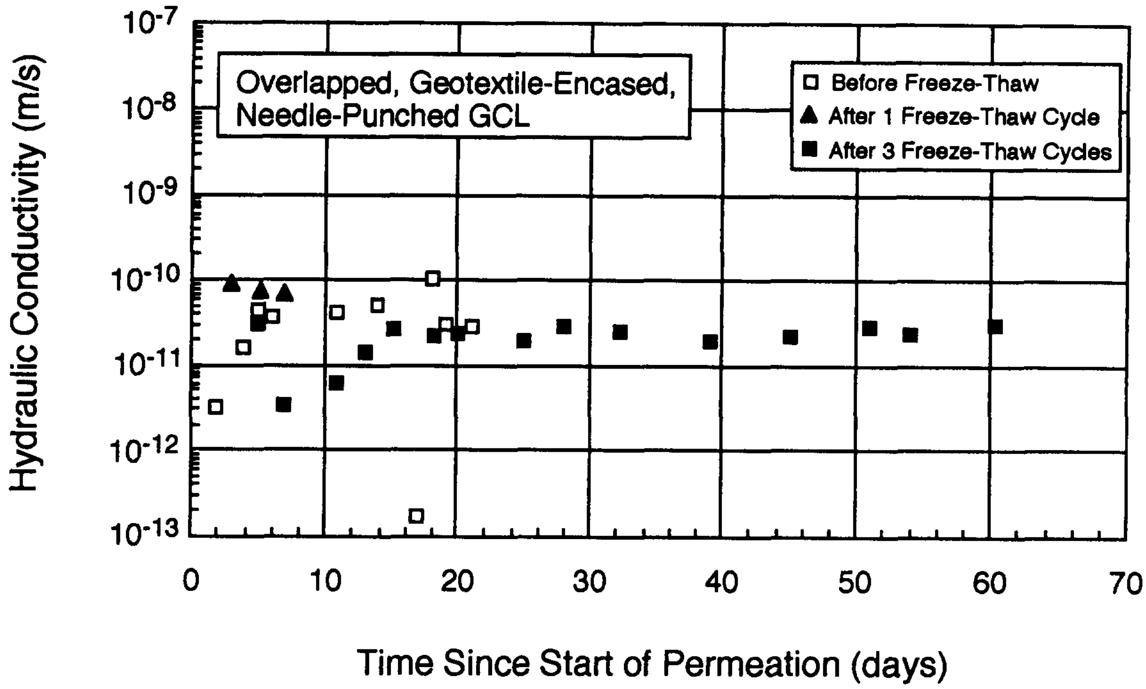

FIG. 7. Hydraulic Conductivity of Overlapped, Geotextile-Encased, Needle-Punched GCL

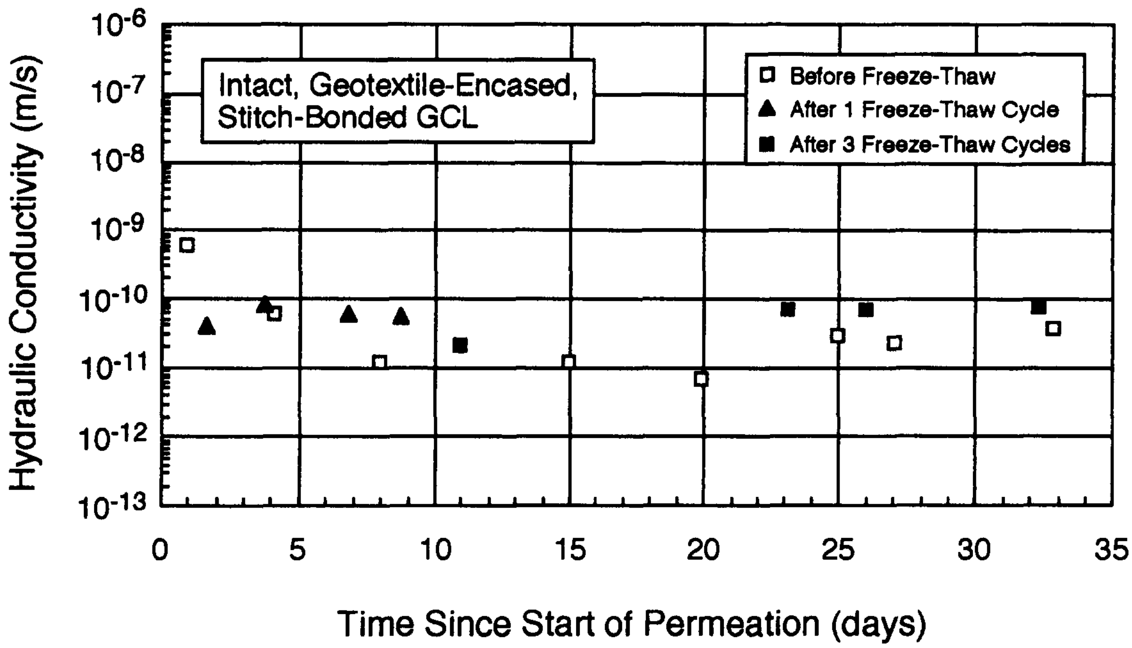

FIG. 8. Hydraulic Conductivity of Intact, Geotextile-Encased, Stitch-Bonded GCL

is within the range of possible experimental error and is not considered significant.

Bench-Scale Test on Overlapped Panels

Outflow started immediately after the overlapped panels were hydrated (Fig. 9). The hydraulic conductivity decreased from an initial value of 2×10^{-8} m/s and leveled off at about 1×10^{-10} m/s during the last two weeks of permeation.

After one freeze-thaw cycle, the overlapped panels initially attained a hydraulic conductivity of 1×10^{-11} m/s during the first 8 d of permeation. However, the hydraulic conductivity increased to 1×10^{-7} m/s in the next 4 d of permeation. The writers have no explanation for this sudden increase. Nothing unusual occurred, other than the unexpected 1,000-fold increase in hydraulic conductivity.

The hydraulic conductivity after three freeze-thaw cycles was 7×10^{-8} m/s, which is only slightly less than the value observed at the end of the first freeze-thaw cycle and that is 700 times larger than the value before freeze-thaw. Freeze-thaw caused an increase of about 3 orders of magnitude in the hydraulic conductivity of this overlapped GCL.

Examination of the overlapped panels after the test revealed nothing that explained the increase in hydraulic conductivity. However, the water contents of the intact GCL away from the seam averaged 320%, while the water content in the area of the overlapped seam was substantially lower. In the overlap area, the top GCL panel had a water content of 228%, while the water content of the bottom GCL panel was 277%. Experience has shown that the water content of hydrated GCLs is very sensitive to compressive stress, and the logical explanation for a lower water content in the overlap is higher com-

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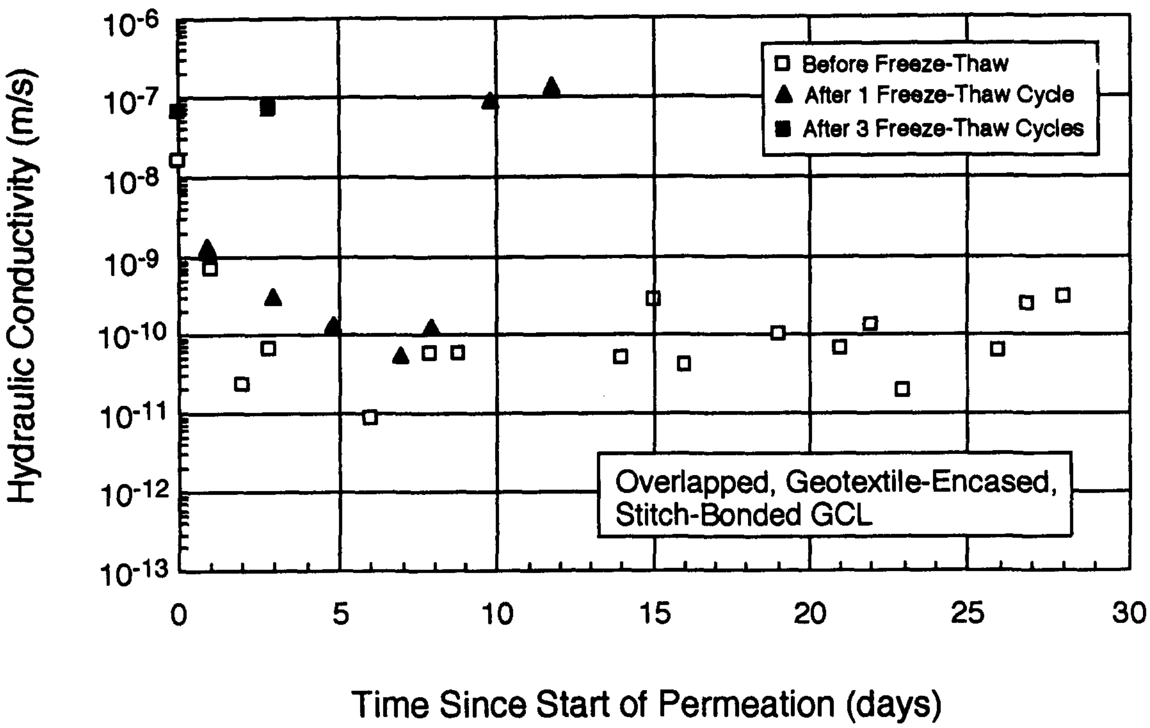

FIG. 9. Hydraulic Conductivity of Overlapped, Geotextile-Encased, Stitch-Bonded GCL

pressive stress. The overlap did stick up slightly higher than the adjacent panels and would tend to form a "high spot" where overburden loads might tend to focus. But if the compressive stress were higher in the overlapped zone, the increased compressive stress would not tend to compromise the integrity of the overlap. If anything, the quality of the overlap should be better at higher compressive stress.

When this type of GCL is hydrated, the material appears to be "quilted," with the GCL being thinner at the stitches and thicker away from the stitches. Prior to freeze-thaw, the overlapped panels did self-seal even with the stitches in the overlapped zone. Perhaps the stitches made the overlap more vulnerable to freeze-thaw damage. No data are available, however, to prove or disprove this hypothesis.

For full-sized rolls, the manufacturer of this GCL leaves the edges of the GCL panels in the direction parallel to the length of the roll unstitched so that the overlap is free of stitching. However, the ends of the panels, which are also overlapped, do contain stitches.

As noted earlier, Erickson et al. (1994) performed field tests on GCLs that were subjected to freeze-thaw, and the only GCL that showed an increase in hydraulic conductivity was this same geotextile-encased, stitch-bonded GCL. The results reported by Erickson et al. are consistent with those reported in this study. Since the field tests reported by Erickson et al. were fairly small scale, it is assumed that some (perhaps all) of the overlaps contained stitched material.

Small-Scale Test Specimens

Two 100-mm-diameter specimens were permeated in flexible-wall permeameters. One specimen was trimmed to include a 100-mm-long section of stitching down the middle of the test specimen, while the other specimen was trimmed from the zone between stitching, and therefore contained no stitches.

The hydraulic conductivity of both test specimens was 2×10^{-11} m/s prior to freeze-thaw. After three freeze-thaw cycles, the hydraulic conductivity of the specimens was essentially the same as before freeze-thaw cycling (Table 2). Thus, from the bench-scale test on the intact, stitch-bonded material and from these flexible-wall hydraulic conductivity tests, there does not seem to be anything inherent about the stitch bonding that makes the material more or less vulnerable to damage from freeze-thaw. The data suggest that the concern about the freeze-thaw integrity of this material lies with the overlaps, not with the parent material.

Geomembrane-Supported GCL

Bench-Scale Test on Overlapped Panels

A bench-scale test involving overlapped panels of the geomembrane-supported GCL produced no outflow during testing. The overlapped panels were permeated for 25 d before they were subjected to freeze-thaw. After three cycles of freeze-thaw, the overlapped panels were permeated for 52 d, during which time no outflow occurred.

When the test was completed, the overlap was examined. Along the length of the overlap, bentonite was hydrated only 50–65 mm in from the edge of the overlap; everywhere else, the bentonite was dry (the only point that the bentonite had direct access to water was along the overlap, and this was the only point where the bentonite was hydrated). The average water content of the hydrated bentonite was 154%. The water content of the unhydrated bentonite 100 mm into the overlap was 20%, which is the same as the as-delivered water content.

Test on Small-Scale Test Specimen

The bentonite component of this GCL was separated from the attached geomembrane using a knife and careful trimming. The 4-mm–thick sample of bentonite without the HDPE component was permeated in a flexible-wall permeameter. The hydraulic conductivity of the bentonite before freeze-thaw was 3×10^{-11} m/s. After three freeze-thaw cycles, the hydraulic conductivity of the bentonite decreased slightly to 2×10^{-11} m/s.

PRACTICAL IMPLICATIONS

Although freeze-thaw resistance may vary somewhat between specific GCLs, there is little doubt that GCLs, as a class

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of barrier material, better withstand the effects of freeze-thaw than ordinary compacted clay liners. With few exceptions, all of the data at laboratory, bench, and field scales indicate that most GCLs can withstand freeze-thaw cycling without undergoing a significant increase in hydraulic conductivity.

GCLs may be exposed to freeze-thaw during construction or, if they are located near the ground surface (e.g., in a landfill cover system), during service. Construction-related freeze-thaw should not be of much concern; the data consistently show that most GCLs can withstand several freeze-thaw cycles without damage.

An important issue is whether it is appropriate to design a final cover system that locates a GCL in the freeze-thaw zone. Although there is a high probability that a GCL subjected to repeated freeze-thaw cycles over a long period of time would continue to function effectively, too few data are available to demonstrate long-term hydraulic integrity conclusively. It appears that the most appropriate design approach is to assume that the GCL will probably remain undamaged by freeze-thaw but to recognize that there is a risk of long-term damage. In many situations, the GCL is placed beneath a geomembrane, and the effect of increased hydraulic conductivity of the bentonite in a GCL on the overall performance of the system (if any) would not be very large. Also, in many situations, the final cover has a specific design life during which time leachate is collected from the underlying waste; again, the effects of an unexpected, increased hydraulic conductivity would not be large. In some situations, the consequences of increased hydraulic conductivity in the bentonite component of a GCL as a result of possible freeze-thaw damage might be severe, in which case the designer would be encouraged to locate the GCL below the freeze-thaw zone.

One special case warrants discussion. Some GCLs are designed with the bentonite sandwiched between two geomembranes with the intent of keeping the bentonite essentially dry, except at locations of leaks in the geomembrane or its seams. Dry GCLs are not damaged by freeze-thaw because of the tremendous swelling and self-healing ability of bentonite when it hydrates. For instance, Shan and Daniel (1991) showed that large punctures made in dry GCLs self seal when the bentonite hydrates. If a GCL is used in a situation where the bentonite can reasonably be expected to remain dry, there should be no concern about the effects of freeze-thaw upon the hydraulic integrity of the dry bentonite.

CONCLUSIONS

The objective of this study was to assess the impact of freeze-thaw cycling on the hydraulic conductivity of GCLs. Hydraulic conductivity tests were performed on intact and overlapped GCLs that were subjected to up to three freeze-thaw cycles. Three commercial GCLs were tested.

The geotextile-encased, needle-punched GCL that was tested maintained a low hydraulic conductivity ($<1 \times 10^{-9}$ m/s, which is a common regulatory maximum) even after three freeze-thaw cycles. Neither the parent GCL material nor overlaps between GCL panels were damaged by three freeze-thaw cycles.

Results of tests on a geotextile-encased, stitch-bonded GCL were different for the parent material and overlapped panels of the material. The parent material was essentially unaffected by three freeze-thaw cycles and maintained a low hydraulic conductivity (well below 1×10^{-9} m/s) even after freeze-thaw. Overlapped panels of this type of GCL were affected by freeze-thaw and underwent approximately a 1,000-fold increase in hydraulic conductivity (final value after freeze thaw $\approx 1 \times 10^{-7}$ m/s). However, the test panels contained stitching in the overlapped area. The manufacturer leaves the edges of full-sized panels unstitched so that overlapped zones will not contain stitching. It is possible that the stitching may somehow have influenced the results of these tests, although Erickson et al. (1994) found similar results in field-scale tests on larger panels. Larger-scale tests are recommended to evaluate the issue of stitches in the overlap.

No outflow occurred from overlapped panels of the geomembrane-supported GCL. Due to the presence of the geomembrane, flow could only occur through the overlapped area or the edge seal. The bentonite in the overlap was hydrated about 50 mm into the 225-mm–wide overlapped seam. Freeze-thaw cycling did not alter the hydraulic integrity of the overlap. A sample of the bentonite component of this GCL tested in a flexible-wall permeameter did not undergo any increase in hydraulic conductivity after freeze-thaw cycling.

It is concluded that under the conditions of these tests, most GCLs (intact and overlapped panels) can withstand at least three freeze-thaw cycles without undergoing a significant increase in hydraulic conductivity.

The reader is cautioned not to inappropriately extrapolate the results of these tests. The tests were performed under carefully controlled conditions in laboratory devices at a compressive stress of about 8 kPa. The GCLs were subjected to only three freeze-thaw cycles, and the conditions of freeze-thaw were not superimposed with other environmental stresses (e.g., differential settlement and desiccation). The data in this paper will hopefully provide useful information, but ultimately, field data are needed to understand how GCLs perform in the field.

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