FREEZE-THAW CYCLING AND THE HYDRAULIC CONDUCTIVITY OF GCLs AND COMPACTED CLAY LINERS

In cold regions, unprotected liners and covers can freeze during the winter months, potentially affecting hydraulic performance. This technical reference includes two studies which investigate the performance of liners exposed to freeze-thaw cycling. These studies are each discussed separately below.

Kraus et al., 1997

In research organized by the U.S. Environmental Protection Agency and the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL), hydraulic conductivity tests were conducted in the laboratory and field on geosynthetic clay liners (GCLs) and compacted clay liners to determine if their hydraulic conductivity is affected by freezing and thawing.

Compacted Clay Liners

Hydraulic conductivity tests were performed on specimens obtained from compacted clay liner test plots before and after a winter season. Results indicated that the compacted clay liners had an increase in hydraulic conductivity of several orders of magnitude, from approximately 1×10^{-8} cm/sec to greater than 1×10^{-5} cm/sec. Extensive crack networks were present in the after-winter specimens. These cracks serve as preferential flow paths and are the primary cause for the high hydraulic conductivities that were measured.

GCLs

In the laboratory, three specimens of Bentomat ST and four specimens of Claymax 200R were frozen and thawed 20 times, and no increase in hydraulic conductivity was measured. All values were very low, ranging from 2.9×10^{-9} cm/s to 4.9×10^{-9} cm/s for the initial condition and from 1.7×10^{-9} cm/s to 3.3×10^{-9} cm/s for the specimens exposed to 20 freeze-thaw cycles.

In field test pads, three specimens of Bentomat ST and Claymax 500SP were exposed to one winter of freeze-thaw cycling. The outdoor freezing and thawing did not cause an increase in hydraulic conductivity with the exception of one field test containing a seamed section of Claymax 500SP, a discontinued stitch-bonded GCL. However, a replicate of this test showed no increase in hydraulic conductivity. Thus, the anomaly may have been due to installation quality.

Podgorney and Bennett, 2006

A similar evaluation of freeze-thaw resistance of GCLs was performed in 2006 by the Idaho National Engineering Environmental Laboratory (INEEL). Samples of three GCLs, Bentomat ST, Bentomat DN, and Claymax 200R, were exposed to repeated freeze-thaw cycles in the laboratory at pressures encompassing final cover (20 kPa) and bottom liner (60 kPa) applications. Samples were tested in the laboratory after 3, 9, 15, 21, 30, 45, 75, 100, 125, and 150 freeze-thaw cycles. Hydraulic conductivity testing found no appreciable changes, even after 150 freeze-thaw cycles.

The results of the laboratory and field test pads indicate that Bentomat and Claymax 200R GCLs were not adversely affected by freezing and thawing. Examination of the GCLs while frozen and after thawing reveal why these materials do not incur the increases in hydraulic conductivity typical of compacted clay liners. Ice segregation does occur in GCLs, but the cracks formed during ice segregation close when the bentonite thaws because the thawed bentonite is very soft and compressible.

Freeze-Thaw Cycling and Hydraulic Conductivity of Bentonitic Barriers

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Abstract: Hydraulic conductivity tests were conducted in the laboratory and field on geosynthetic clay liners (GCLs) and a sand-bentonite mixture to determine if their hydraulic conductivity is affected by freezing and thawing. In the laboratory, specimens of three GCLs were frozen and thawed 20 times, and no increase in hydraulic conductivity was measured. The hydraulic conductivity of the compacted sand-bentonite also did not increase after freezing and thawing. In the field, two types of GCLs and a sand-bentonite test pad (constructed with the same mixture used in the laboratory) were exposed to one or two winters of freeze-thaw cycling. No large increase in hydraulic conductivity was measured for the field test conducted with the sand-bentonite mixture. An increase in hydraulic conductivity was observed in only one of the field tests with GCLs. Examination of thawed GCLs and specimens of the sand-bentonite mixture showed no evidence of cracking that is commonly found in thawed compacted clays.

INTRODUCTION

Designers of hydraulic barriers are considering materials that are more cost-effective and resilient than compacted clay. One characteristic of alternative materials that is of particular importance in cold regions is resistance to increases in hydraulic conductivity caused by freeze-thaw cycling. Numerous studies have shown that compacted clays undergo large increases in hydraulic conductivity when exposed to freeze-thaw cycling [e.g., Zimmie and La Plante (1990); Chamberlain et al. (1990); Benson and Othman (1993); Othman et al. (1994); Chamberlain et al. 1995)]. However, the results of recent laboratory studies indicate that the hydraulic conductivity of geosynthetic clay liners (GCLs) and sand-bentonite mixtures are not affected by freeze-thaw cycling [e.g., Wong and Haug (1991); Shan and Daniel (1991)].

The objective of the present study is to conduct laboratory tests that confirm the findings of others and to assess whether the laboratory results are representative of field conditions. To meet this objective, three types of GCLs and one sand-bentonite mixture were exposed to freeze-thaw cycling using laboratory procedures, and were then tested for hydraulic conductivity. Field tests were conducted by exposing two types of GCLs and a test pad constructed of the sand-bentonite mixture to freeze-thaw cycling. Field and laboratory hydraulic conductivity tests were then conducted on GCLs and the sand-bentonite mixture.

BACKGROUND

In several laboratory and field studies, freezing and thawing has been shown to have a detrimental impact on the hydraulic conductivity of compacted clays. For compacted clays having an initial hydraulic conductivity less than 1×10^{-9} m/s, freezing and thawing generally increases the hydraulic conductivity one to three orders of magnitude [e.g., Zimmie and La Plante (1990); Kim and Daniel (1992); Othman et al. (1994); Chamberlain et al. (1995); Benson et al. (1995)]. Cracks induced by desiccation incurred as water migrates to the freezing front, and the formation of ice lenses are the primary causes of these increases in hydraulic conductivity (Chamberlain et al. 1995; Othman and Benson 1993a). After thawing, these cracks become preferential conduits for flow that result in increases in hydraulic conductivity (Othman and Benson 1993b; Benson and Othman 1993).

Not all barrier soils become cracked and more conductive when frozen and thawed. Wong and Haug (1991) show that compacted mixtures of Ottawa sand and sodium-bentonite do not incur increases in hydraulic conductivity when frozen and thawed. In fact, a decrease in hydraulic conductivity occurred for all specimens. Wong and Haug (1991) hypothesize that the hydraulic conductivity decreases because freeze-thaw cycling promotes additional hydration, and during thaw consolidation, the bentonite particles compress into gaps existing between the sand grains.

Several testing programs have shown that GCLs are resistant to damage caused by freeze-thaw cycling. GCLs are geocomposites consisting of a thin layer of dry bentonite sandwiched between two geotextiles or glued to a geomembrane. When exposed to water, the bentonite in the GCL hydrates and swells to form a thin layer having low hydraulic conductivity. GCLs are manufactured in large sheets that are delivered to the site on rolls. The GCLs are unrolled on-site, and seams are made by overlapping adjacent GCLs. In some cases, dry powdered bentonite is added in the seam between adjacent GCLs. A detailed description of GCLs can be found in Estornell and Daniel (1992).

Geoservices (1989) evaluated how freeze-thaw cycling affects the hydraulic conductivity of the GCL Claymax. They conducted laboratory tests on 76 mm diameter specimens using flexible-wall permeameters. An initial hydraulic conductivity of 4×10^{-12} m/s was measured at an effective confining pressure of 196 kPa and a hydraulic gradient of 1,000. The saturated specimen was then repeatedly frozen and thawed three-dimensionally. After 10 freeze-thaw cycles, the hydraulic conductivity was 1.5×10^{-12} cm/s. Similar findings for Claymax have been reported by Shan and Daniel (1991) and Chen-Northern (1988). A detailed summary of these studies can be found in Kraus (1994).

GeoSyntec (1991) studied how freeze-thaw cycling affects the hydraulic conductivity of the GCL Bentomat. Specimens of GCL 71 mm in diameter were permeated in flexible-wall permeameters under an effective confining pressure of 35 kPa and a hydraulic gradient of 30. The specimens were subjected to four freeze-thaw cycles, with the hydraulic conductivity of

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each specimen measured after each cycle. The hydraulic conductivity of the Bentomat specimens ranged between 1×10^{-11} and 6×10^{-11} m/s after each cycle, with no increasing or decreasing trends.

Tests to evaluate the effect of freeze-thaw cycling on Bentomat have also been performed by Robert L. Nelson and Associates (1993). Two sets of tests were conducted. In the first set, six specimens were permeated after undergoing up to six freeze-thaw cycles with no initial hydration (i.e., no initial saturation or permeation). In the second set, only one specimen was tested. It was exposed to 10 freeze-thaw cycles, with its hydraulic conductivity being measured after each thaw. No significant increase or decrease in hydraulic conductivity was observed in either set of tests. The hydraulic conductivity ranged between 1.1×10^{-11} and 4.0×10^{-11} m/s for the specimens in the first set of tests, and 1.9×10^{-11} and 3.3×10^{-11} m/s for the second set.

The findings of these studies suggest that bentonitic barriers are resistant to damage caused by freeze-thaw cycling. The study described herein, which includes laboratory and field testing, shows similar results.

MATERIALS USED IN THIS STUDY

Sand-Bentonite Mixture

One sand-bentonite mixture was used. The sand-bentonite mixture was prepared in the field using a pugmill prior to construction of the test pad used for field testing. The sand component is a poorly graded, clean, medium to fine sand that is classified as SP in the Unified Soil Classification System. More than 90% of the sand passed the No. 30 sieve, and less than 5% passed the No. 200 sieve. The bentonite component is CG-50, a granular sodium bentonite with no polymer additives that was supplied by American Colloid Corporation. Methylene blue titration tests performed on grab samples of the mixture showed the average bentonite content was 12% by weight (Kraus 1994). Compaction curves corresponding to standard and modified Proctor compaction (ASTM 1993) are shown in Fig. 1(a). Other characteristics of the mixture are described in Kraus (1994).

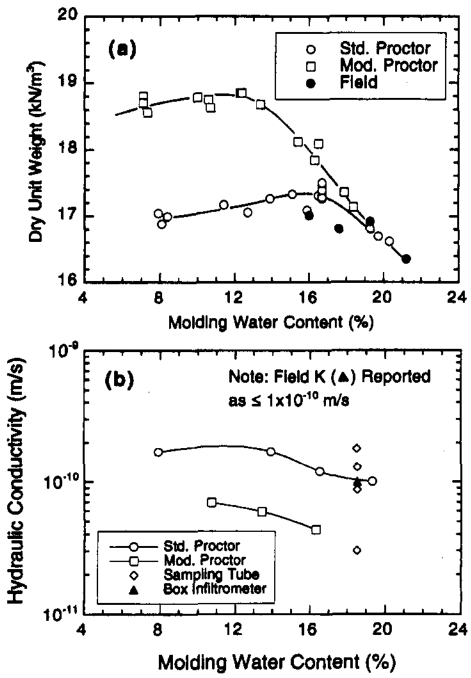


FIG. 1. Curves for Sand-Bentonite: (a) Compaction Curves; (b) Hydraulic Conductivity Curves

Geosynthetic Clay Liners

Three GCLs were used in the laboratory portion of this study: Claymax 200R, Bentomat CS, and Bentofix. Schematics of these GCLs are shown in Fig. 2. The field tests were conducted using Claymax 500SP (a stitched version of 200R), Bentomat CS, and Gundseal. Results of the tests on Gundseal are not described in the present paper, but are discussed in detail by Erickson et al. (1994). For the laboratory tests, two rolls of each GCL (2 m wide and 4 m long) were shipped to the University of Wisconsin-Madison, Madison, Wisc., by the manufacturers. The rolls were wrapped in plastic to minimize uptake of water.

METHODS: SAND-BENTONITE MIXTURE

Hydraulic Conductivity Water-Content Relationship

Some of the specimens of sand-bentonite compacted to determine compaction curves [Fig. 1(a)] were also used to determine the hydraulic conductivity water-content relationships. The specimens were tested in flexible-wall permeameters using an effective stress of 21 kPa, backpressure of 345 kPa, and hydraulic gradient of 30. Tap water from Madison was used as the permeant. Results of the hydraulic conductivity tests are shown in Fib. 1(b). The hydraulic conductivity is nearly insensitive to molding water content, and is moderately sensitive to compactive effort. Similar results have been reported by Haug and Wong (1992).

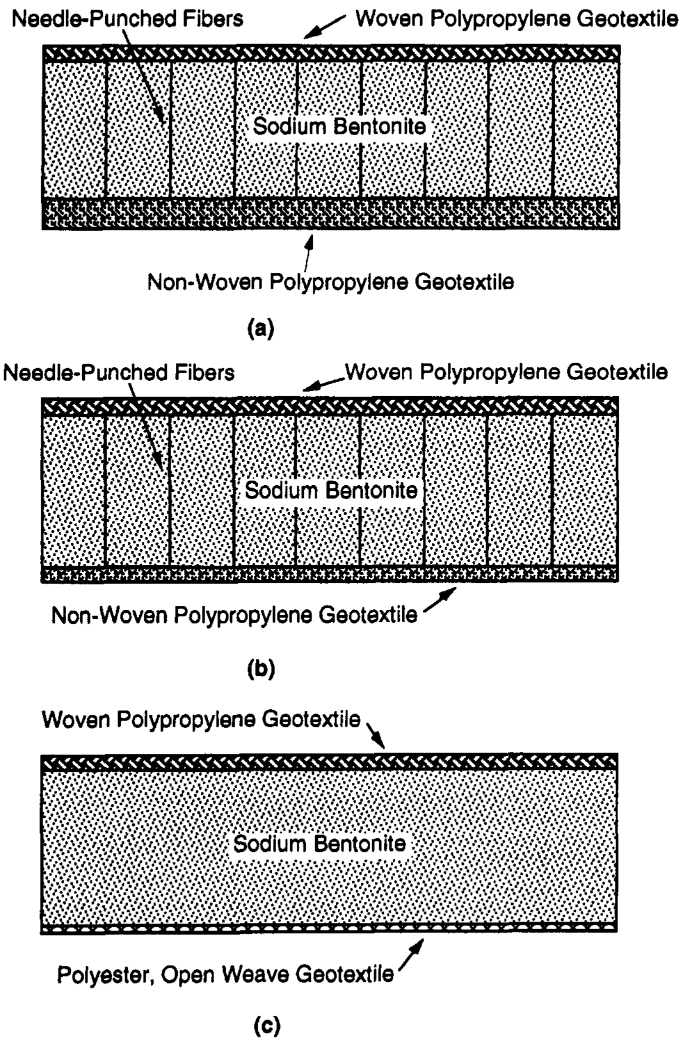


FIG. 2. Geosynthetic Clay Liners: (a) Bentofix; (b) Bentomat; (c) Claymax

Standard Freeze-Thaw Tests

Eight specimens of the sand-bentonite mixture were compacted at a water content of 18%, which is similar to the water content used for construction of the sand-bentonite test pad. The specimens were compacted using procedures described in ASTM D 698. After compaction, three specimens were placed in flexible-wall permeameters for saturation to determine their initial hydraulic conductivity. Procedures described in ASTM D 5084 (ASTM 1993) were followed. An average effective stress of 21 kPa and hydraulic gradient of 30 were used, and a backpressure of 345 kPa was applied. Permeation continued for 60 d. The remaining five specimens were wrapped with plastic to prevent desiccation.

After the initial hydraulic conductivity tests were complete, the permeated specimens were carefully removed from the permeameters and sealed in plastic wrap to prevent desiccation. The specimens were then placed in a laboratory freezer (temperature = −20°C) and frozen three-dimensionally in a closed system using the free-standing (unconfined) procedure (Othman et al. 1994). No slumping of the specimens occurred during thawing. A closed system was used to simulate the field condition, where free access to water below the frost line did not exist (see subsequent discussion). The specimens were left in the freezer for at least 24 h, at which point they were removed and allowed to thaw at room temperature (25°C). After 24 h of thawing, the specimens were placed back in the freezer. Othman et al. (1994) and Kraus (1994) have shown that 24 h of cooling or warming is sufficient for the specimen to equilibrate with the surrounding air temperature. This procedure was repeated until the desired number of freeze-thaw cycles was attained. A similar procedure was used to freeze and thaw the remaining five specimens that were not permeated.

The writers note that the state of stress undoubtedly changed as the specimens were removed from the permeameters for freezing or placed in the permeameters after thawing. However, because the effective stress during permeation was low, any change in stress that occurred was probably small. Furthermore, Othman and Benson (1993a) have shown that small changes in stress have little effect on the hydraulic conductivity of stiff-compacted clayey soils, such as the sand-bentonite being tested.

The hydraulic conductivities of the three specimens permeated prior to freezing were measured again after one, three, and five freeze-thaw cycles using conditions similar to those previously described. The hydraulic conductivities of the other five specimens were measured after the desired number of freeze-thaw cycles was attained. To minimize disturbance when installing specimens in the permeameter, specimens to be permeated were removed from the freezer and directly placed in flexible-wall permeameters for thawing.

Field Tests

A test pad was constructed to assess whether freeze-thaw cycling in the field would affect the hydraulic conductivity of the sand-bentonite mixture. Prior to construction, a high-density polyethylene (HDPE) geomembrane overlain by a geocomposite drain (nonwoven geotextile on each side of a HDPE geonet) was placed on a prepared subgrade. The test pad was constructed directly on top of the geocomposite drain. The test pad was 21 m long by 9 m wide and had a thickness of 0.6 m. It was constructed in four lifts using a vibrating smooth-wheel compactor at water contents of 0–5% wet of standard Proctor optimum water content. Relative compaction exceeding 95% of standard Proctor maximum dry unit weight was obtained [Fig. 1(b)]. Construction was completed in October 1992.

After construction, the test pad was covered with a 0.15 mm thick polyethylene sheet and 0.1 m of sand to minimize desiccation. Thermistors were buried at various depths in the test pad, and a weather station was installed to record air temperature and the climatic condition. A datalogger was used to collect the data at 5 min intervals. Chamberlain et al. (1995) provide a detailed description of the instrumentation.

A box infiltrometer was installed to measure the field hydraulic conductivity of the test pad (Fig. 3). The infiltrometer was designed to measure hydraulic conductivity before and after exposure to freeze-thaw cycling without disturbing the structure of the soil. Immediately following construction of the test pad, trenches were excavated to leave a 1.3 by 1.3 by 0.6 m deep block of undisturbed soil. An HDPE box with an open top and bottom was placed around the block of soil and welded to the underlying HDPE geomembrane. Pipes were connected to the geocomposite drain to carry any percolation to a sump. The annular space between the block and HDPE was filled with a bentonite grout to prevent sidewall leakage. A nonwoven geotextile was placed on top of the block of soil, which was then covered with a layer of washed gravel. An HDPE lid was seamed to the walls of the box, which contained a riser pipe for adding water to the system and for measuring inflow. Hydraulic conductivity was computed using the rate of inflow and the hydraulic gradient corresponding to full wetting of the test pad. This computation yields a conservative estimate of the hydraulic conductivity.

A freely draining boundary existed beneath the base of the infiltrometer and the remainder of the test pad, which prevented a significant quantity of water from accumulating. As a result, the sand-bentonite mixture was frozen in a condition similar to a closed system; that is, free access to water was not available below the frost line. A similar condition is likely to exist in a landfill final cover.

Laboratory Tests on Specimens Collected from Test Pad

Specimens were removed from the sand-bentonite test pad with thin-wall sampling tubes (71 mm diameter) in June 1993

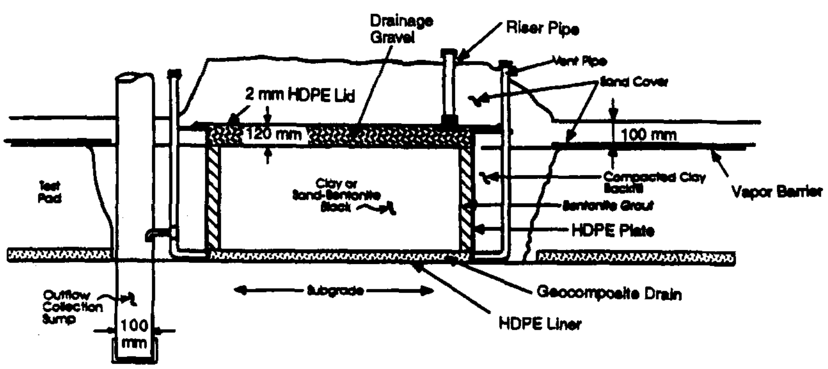


FIG. 3. Box Infiltrometer Used to Measure Field Hydraulic Conductivity of Sand-Bentonite Test Pad

after one winter of exposure. The specimens were extruded from the tubes in the laboratory, where their hydraulic conductivity was measured in flexible-wall permeameters. The testing conditions used were similar to those used when testing the laboratory compacted specimens.

Specimens were collected in sampling tubes even though previous studies have shown that disturbance during sampling and extrusion can mask the effects that freeze-thaw cycling has on the hydraulic conductivity of compacted clay (Othman et al. 1994; Chamberlain et al. 1995; Benson et al. 1995). However, these studies have shown that the primary mechanism of disturbance is closure of the cracks formed by freeze-thaw cycling. No cracks were observed in the sand-bentonite after freeze-thaw cycling, both in the field and laboratory (see subsequent discussion). Thus, the writers believe that significant disturbance did not occur in the specimens removed from the test pad. Nevertheless, because of the potential for disturbance, the reported hydraulic conductivity of these specimens must be viewed with caution.

METHODS: GEOSYNTHETIC CLAY LINERS

Laboratory Tests on Small Specimens

Specimens for hydraulic conductivity testing were selected by unrolling the GCLs on the laboratory floor and locating a random point away from the edge of the roll. A piece of plywood was placed underneath the GCL, and a razor knife was used to cut out circular specimens (diameter = 150 mm). Efforts were made to keep loose bentonite in the GCLs from spilling out of the edges by moistening the edges prior to cutting. This procedure was used to make three specimens each of Bentofix and Bentomat, and four specimens of Claymax. The specimens were weighed and their diameter and thickness were measured.

The specimens were placed in flexible-wall permeameters for saturation and to measure their initial hydraulic conductivity. The protocol described in Geosynthetic Research Institute (GRI) test method GCL-2 (Geosynthetic Research Institute 1994) was used, which is an adaptation of ASTM D 5084 specifically for use with GCLs. Before the membrane was installed, a thin layer of bentonite paste was placed around the edge of the GCL to help prevent short circuiting of flow between the geotextiles. An average effective stress of 14 kPa and hydraulic gradient of 75 were applied, but no backpressure was used. The effective stress of 14 kPa was assumed to simulate field conditions where a GCL would be used in a final cover. Also, it was the lowest effective stress that could be reliably maintained with the laboratory apparatus. Tap water from Madison was used as the permeant. The specimens were hydrated with the confining stress and hydraulic gradient applied.

After the initial hydraulic conductivity tests were complete, the specimens were carefully removed from the permeameters by sliding them onto sheets of expanded polystyrene. Extreme care was used to avoid disturbing the structure of the bentonite. The specimens were then sealed in plastic freezer bags to prevent desiccation and frozen in a closed system using the free-standing procedure (Othman et al. 1994). A closed system was used to simulate the field condition, where free access to water did not exist below the frost line.

After freezing, the specimens were allowed to thaw at room temperature (25°C). Data were collected from control specimens instrumented with thermocouples (Fig. 4), and it was found that 24 h is adequate to ensure that complete freezing or thawing of a GCL occurs. If the specimens were to be permeated after thawing, they were thawed in the permeameters. Otherwise, they were thawed on the sheet of expanded polystyrene. This procedure was repeated until the desired

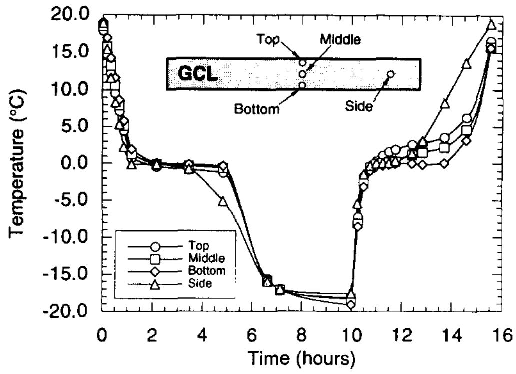


FIG. 4. Temperatures within Geosynthetic Clay Liner Specimen during Freezing and Thawing

number of freeze-thaw cycles was attained. The hydraulic conductivity of each specimen was measured after one, three, five, and 20 freeze-thaw cycles.

Field Tests

Field tests were conducted using lagoons and large rectangular test pans lined with GCLs Claymax 500SP, Bentomat CS, or Gundseal. The lagoons were 8 m wide, 10 m long, and 0.6 m deep. One type of GCL was placed in each lagoon. The GCL was placed on a nonwoven geotextile overlying a 25 mm thick layer of sand and a thicker layer of gravel. The gravel layer was equipped with a sump for collecting leakage from the GCL. The GCLs were overlain by a gravel layer 0.25 m thick and covered with water having a depth of 0.3 m. Thermistors were placed below the GCLs to determine when the GCLs became frozen.

The test pans (Fig. 5) were of two different sizes. The larger test pans (1.34 × 1.34 m) were constructed by welding sections of HDPE plate stock. The smaller test pans (0.84 × 0.84 m) were manufactured HDPE storage bins. Each test pan contained a double-ring seepage-collection system that separated potential side leaks from leakage through the central portion of the GCL. A thin layer of pea gravel was placed in the pans to support the GCL and drain the effluent. A 0.25 mm thick layer of pea gravel was placed on the GCLs. Pea gravel was also placed around the perimeter of the pans to the same level as the gravel within the pans. Thermistors were placed below the GCLs in the test pans to determine when the GCLs froze.

Three lagoons and nine test pans were used. Each lagoon was used to assess a single GCL: Claymax 500SP, Bentomat CS, or Gundseal. A group of three test pans was used to test each GCL. Each group contained one large test pan and two smaller test pans. The large test pan and one of the two small test pans in each group contained a GCL with a seam installed in accordance with the manufacturers' specifications. The Claymax GCLs were seamed using an overlap, whereas an overlap containing a stream of dry bentonite was used to seam the Bentomat GCLs. The third pan in each group contained a seamless GCL specimen.

Water was initially added to a depth of 30 mm in the test pans to allow the bentonite to hydrate. After one week, the water level was increased to 250 mm. The bentonite was allowed to hydrate in this condition for one month. After one month, seepage data were recorded. The water level was kept constant during the duration of the tests, and the water was not drained prior to winter. The hydraulic gradient ranged from 5 to 15 and averaged 10. Hydraulic conductivity of the GCLs was determined from the measured rates of outflow. Measurements of before-winter hydraulic conductivity were made through December 1993. Measurements of hydraulic conductivity after thawing began in April 1994. Kraus (1994) pro-

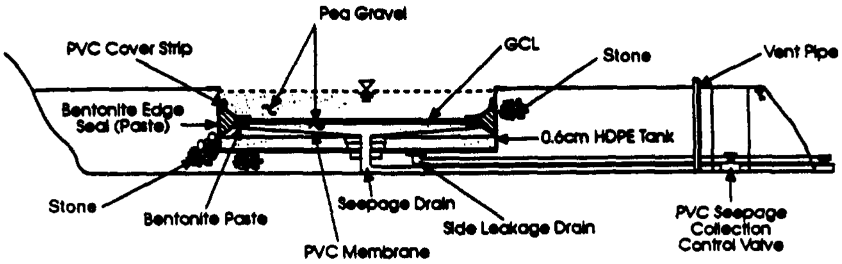


FIG. 5. Test Pans Used to Assess Field Hydraulic Conductivity of Geosynthetic Clay Liners

vides a detailed description of the method used to monitor flows in the test pans. The GCLs were assumed to be fully hydrated when steady seepage from the base occurred.

Freely draining conditions existed beneath the base of the lagoons and the test pans. Consequently, a significant quantity of water did not collect beneath the GCLs. As a result, the GCLs were frozen in a condition resembling a closed system, where free access to water is not available below the frost line. Similar conditions are likely to exist in a landfill final cover.

Laboratory Tests on Large Specimens from Lagoons

Leaks in the seepage-collection systems for the lagoons prevented successful measurements of the field hydraulic conductivity of these GCLs. Nevertheless, the lagoons remained ponded, and temperatures beneath the GCLs were continuously monitored. During decommissioning of the lagoons in June 1994, two specimens each of Bentomat and Claymax were removed from the lagoons for laboratory testing. Large rectangular specimens (1×1 m) were cut using a razor knife, slid onto stiff sheets of 10 mm thick HDPE plate stock, and sealed with plastic wrap for shipping. Extreme care was taken to prevent disturbance of the hydrated bentonite when cutting, sealing, and transporting the specimens. Nevertheless, flexure of the HDPE plate did occur, which may have resulted in some disturbance.

Large flexible-wall permeameters were used to measure the hydraulic conductivity of these specimens using GRI test method GCL-2. Circular specimens having a diameter of 0.45 were trimmed from the field samples. A bentonite paste was applied to the edge of the specimens to prevent sidewall leakage and short circuiting between the geotextiles. An effective stress of 14 kPa and hydraulic gradient of 75 were used. No backpressure was applied.

A rhodamine WT dye tracer showed that leakage between the specimen and the membrane occurred when testing the Bentomat specimens. These specimens were removed from the permeameter and trimmed to a diameter of 0.3 m, and placed in another flexible-wall permeameter for testing. Sidewall leakage continued to be a problem for one of the smaller Bentomat specimens, and additional measures were not successful in correcting the problem. The writers note that the sidewall leakage was a testing problem and should not be attributed to damage incurred by freeze-thaw cycling.

RESULTS AND ANALYSIS

Sand-Bentonite Mixture

Specimens Frozen and Thawed in Laboratory

Hydraulic conductivities of the sand-bentonite specimens frozen and thawed in the laboratory are shown in Fig. 6. No change in hydraulic conductivity occurred for the specimens permeated prior to freezing (i.e., specimens that were essentially saturated) or those frozen directly after compaction.

These findings are consistent with the conclusion of Wong

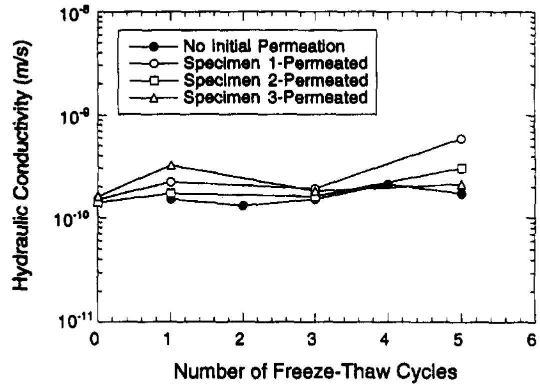


FIG. 6. Hydraulic Conductivity of Laboratory-Compacted Sand-Bentonite Exposed to Freeze-Thaw

and Haug (1991); i.e., freezing and thawing of sand-bentonite does not result in an increase in hydraulic conductivity. Unlike the results of Wong and Haug (1991), however, a decrease in hydraulic conductivity did not occur after exposure to freeze-thaw cycling for the tests conducted in this study. Thus, it appears that freeze-thaw cycling has no detrimental impact on the hydraulic conductivity of sand-bentonite mixtures nor does it necessarily have a beneficial impact.

Field Tests

Freezing of the sand-bentonite test pad began in November 1992 and was steady by mid- to late December 1992. In mid- to late March 1993, thawing became steady. Complete thawing of the test pad had occurred by the first week in April 1993. The test pad remained frozen for about 3.5 months (Erickson et al. 1994). Similar behavior occurred during the following winter. Temperature records show that once steady freezing was established, freeze-thaw cycling only occurred in the overburden material and not in the sand-bentonite mixture (Kraus 1994). The records also show that the entire thickness of the test pad was frozen during both winters. Thus, the sand-bentonite mixture underwent two cycles of freeze thaw.

The field hydraulic conductivity of the sand-bentonite test pad was measured with the box infiltrometer after the test pad had been exposed to two winters. No measurements of hydraulic conductivity were made prior to winter because of problems associated with the flow-monitoring system and the early onset of winter after construction. Flow monitoring before winter was also hampered by hydration of the bentonite at the top of the test pad. Thus, no comparison of hydraulic conductivity can be made for conditions before and after freeze-thaw cycling.

A hydraulic conductivity less than 1×10^{-10} m/s was measured during testing in June and July 1994, which indicates that the sand-bentonite was an effective hydraulic barrier after exposure to two freeze-thaw cycles. The hydraulic conductivity is reported as an upper bound rather than a specific value, because the writers believe that 1×10^{-10} m/s is the lowest hydraulic conductivity that can be accurately measured with the box infiltrometer.

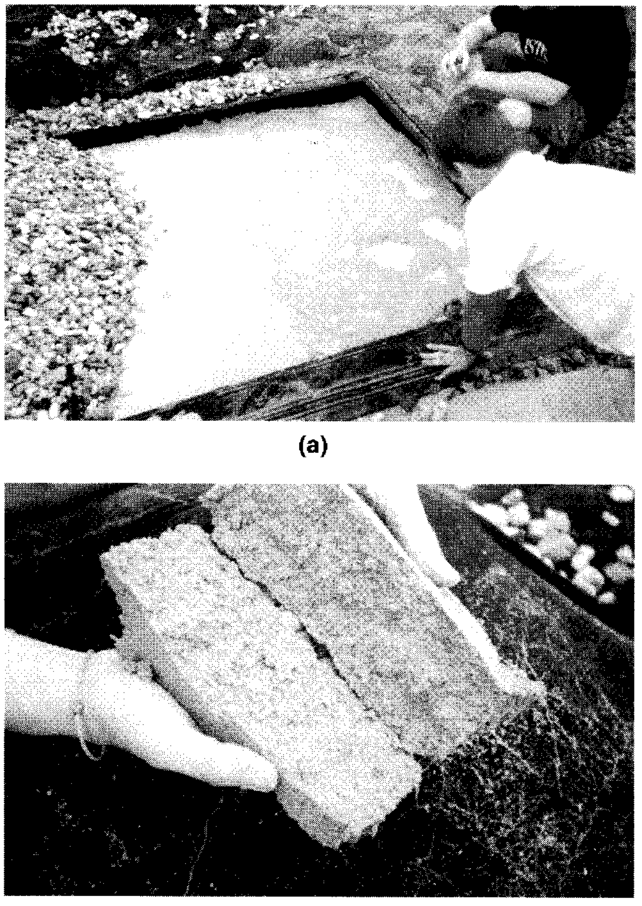


FIG. 7. Structure of Sand-Bentonite in Test Pad after Thawing: (a) Uncracked Surface inside Box Infiltrometer; (b) Uncracked Sand-Bentonite from inside Infiltrometer

Visual examination of the soil during disassembly of the box infiltrometer in June 1994 revealed that the mixture was soft and contained none of the crack structures typically seen in compacted clays exposed to freeze-thaw cycling (Fig. 7). A similar structure was observed in a test pit prior to the first winter (Civil Engineering Consultants 1993). The lack of cracks or other macrostructural defects is consistent with the low hydraulic conductivity measured with the box infiltrometer.

Water content of the sand-bentonite mixture was measured at three depths within the box infiltrometer during dismantling. Samples at depths of 70, 140, and 200 mm had water contents of 42.1, 20.4, and 18.2%. The water contents from depths of 70 and 140 mm are higher than the water content at which the test pad was compacted, and are probably the result of hydration of the bentonite during infiltration. Also, the presence of high water contents in the upper surface of the test pad and lower water contents at depth indicate that the sand-bentonite mixture was able to retain water after exposure to freeze-thaw cycling. The water content at 200 mm is also similar to the compaction water content (≈18%), which indicates that water did not penetrate to an appreciable depth in the sand-bentonite mixture. Had freezing damaged the sand-bentonite, higher water contents would probably have been measured at depth.

Laboratory Tests on Specimens Collected in Sampling Tubes

Hydraulic conductivities of the specimens removed from the sand-bentonite test pad in June 1994 using thin-wall sampling tubes (diameter = 71 mm) are summarized in Table 1. Their hydraulic conductivity ranges between 3.0×10^{-11} and 1.8×10^{-10} m/s. The average hydraulic conductivity of the four specimens is 1.1×10^{-10} m/s, which is similar to the hydraulic conductivity measured with the box infiltrometer. Thus, significant disturbance of the sand-bentonite mixture probably did not occur during a sampling and extrusion. The hydraulic conductivity probably varied because of variations in bentonite content. Significant variability in bentonite content was observed when excavating test pits after construction (Civil Engineering Consultants 1993). However, the bentonite content of each specimen was not measured.

TABLE 1. Hydraulic Conductivity of Specimens Removed from Sand-Bentonite Test Pad Using Thin-Wall Sampling Tubes

Sample depth (m) (1)	Hydraulic conductivity (m/s) (2)
0.15	1.3×10^{-10}
0.25	1.8×10^{-10}
0.35	8.7×10^{-11}
0.45	3.0×10^{-11}

Comparison of Laboratory and Field Tests

Comparison of the field and laboratory results indicates that the sand-bentonite mixture was unaffected by freeze-thaw cycling. The field hydraulic conductivity of the test pad ($<1 \times 10^{-10}$ m/s) compares well with hydraulic conductivity of the laboratory compacted specimens ($\sim 1 \times 10^{-10}$ m/s at field water content and dry unit weight), the hydraulic conductivities of the specimens frozen and thawed in the laboratory ($\sim 2 \times 10^{-10}$ m/s), and the average hydraulic conductivity of the specimens collected in sampling tubes (1.1×10^{-10} m/s).

Geosynthetic Clay Liners

Specimens Frozen and Thawed in Laboratory

Initial hydration and saturation of the GCL specimens required three to four weeks. During this period, the hydraulic conductivity decreased and the outflow to inflow ratio increased, both slowly, as the bentonite hydrated. In contrast, the hydraulic conductivity was essentially steady from the onset for the GCLs exposed to freeze-thaw cycling. For these specimens outflow was equal to inflow nearly immediately following the onset of permeation (Kraus 1994). The difference in equilibration times can be attributed to the additional time required to hydrate the bentonite when the GCLs were initially permeated.

Results of the hydraulic conductivity tests are summarized in Fig. 8 and Table 2. All of the hydraulic conductivities are very low, ranging between 2.9×10^{-11} and 4.9×10^{-11} m/s for the initial condition and 1.7×10^{-11} m/s and 3.3×10^{-11} cm/s for the specimens exposed to 20 freeze-thaw cycles. Furthermore, for all three GCLs a small decrease in hydraulic conductivity apparently occurred as a consequence of freeze-thaw cycling (Fig. 8, Table 2). This decrease in hydraulic conductivity is probably the result of thaw consolidation (Chamberlain and Gow 1979) or particle reorientation that occurred when the stress changed slightly between permeation and freezing.

The slight decrease in hydraulic conductivity that occurred is evident in the ratio K_{20}/K_0, which is defined as the hydraulic conductivity of a specimen after 20 freeze-thaw cycles divided by its initial hydraulic conductivity (Table 2). The ratio varied between 0.55 and 0.66 for the Bentomat GCLs, 0.45 and 1.10 for the Bentofix GCLs, and 0.57 and 0.89 for the Claymax GCLs. That is, for all but one of the GCL specimens, a slight decrease in hydraulic conductivity occurred after 20 freeze-thaw cycles. A t-test confirmed that the decrease in hydraulic

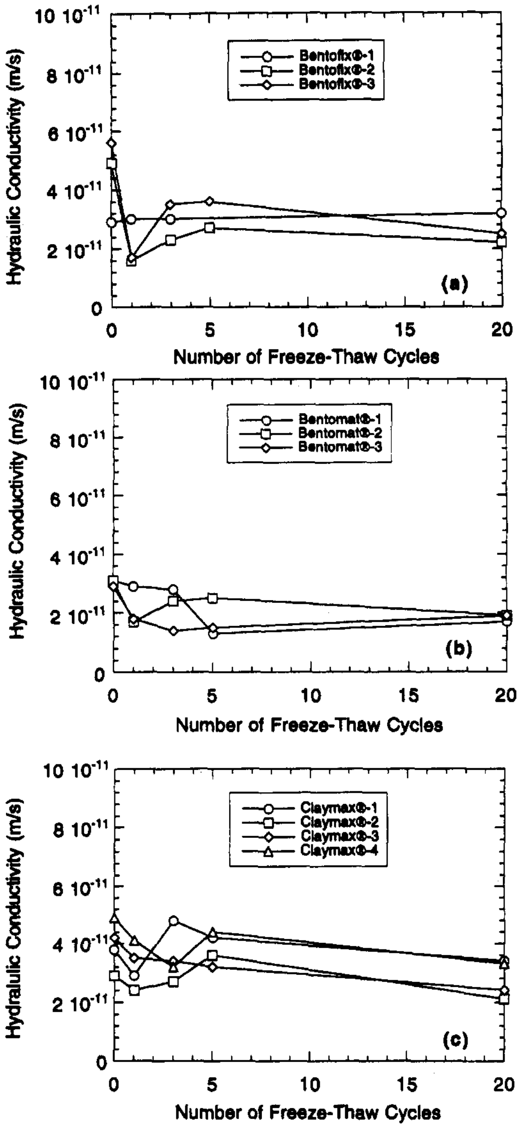


FIG. 8. Hydraulic Conductivity of Laboratory-Tested Geosynthetic Clay Liners versus Number of Freeze-Thaw Cycles: (a) Bentofix; (b) Bentomat; (c) Claymax

conductivity is statistically significant (Kraus 1994). However, from a practical perspective, this small decrease in hydraulic conductivity is insignificant.

GCLs Frozen and Thawed in Field-Test Pans

The GCLs in the test pans underwent one freeze-thaw cycle (one winter of exposure). In Table 3, hydraulic conductivities are summarized for the Claymax and Bentomax GCLs. Results of the tests with Gundseal are described in Erickson et al. (1994). Steady seepage was measured from five of the six test pans prior to winter. The only pan from which no effluent was collected contained an unseamed specimen of Bentomat. Both the Claymax and Bentomat GCLs had low hydraulic conductivity prior to winter, ranging from 1.0×10^{-10} to 2.8×10^{-10} m/s (Table 3). After winter, steady seepage was collected from the six test pans. The postwinter hydraulic conductivities of the Bentomat and Claymax GCL test pans ranged from 1.0×10^{-10} to 3.0×10^{-10} m/s. The only exception was one of the seamed Claymax GCLs, which had a hydraulic conductivity of 7.0×10^{-9} m/s (Table 3).

The effect of freeze-thaw cycling on the hydraulic integrity of seamed GCLs can be examined by comparing the average postwinter hydraulic conductivity of specimens containing seams with the postwinter hydraulic conductivity of the specimen without a seam for each GCL type (Table 3). The average hydraulic conductivity of the seamed Bentomat specimens after exposure to freeze-thaw cycling was 1.7×10^{-10} m/s, which is the same as the postwinter hydraulic conductivity of the unseamed Bentomat specimen (1.0×10^{-10} m/s). The two seamed Claymax specimens had an average postwinter hydraulic conductivity of 5.0×10^{-10} m/s, whereas the unseamed Claymax specimen had a postwinter hydraulic conductivity of 2.8×10^{-10} m/s. Thus, slightly higher postwinter hydraulic conductivities were measured for the seamed specimens for Claymax GCLs. Nevertheless, the change in hydraulic conductivity is small.

GCL Specimens Removed from Lagoons

The GCLs in the lagoons underwent two freeze-thaw cycles (two winters of exposure). Hydraulic conductivities of the GCL specimens removed from the test ponds are summarized in Table 4. Low hydraulic conductivities ($<10^{-9}$ m/s) were measured for the three specimens that were successfully tested.

The bentonite components of the Bentomat specimens were examined after testing. The bentonite in the specimen for which the hydraulic conductivity was not measured showed no structural change (e.g., cracks) often attributed to freeze-thaw cycling and appeared identical to the bentonite in the specimen having low hydraulic conductivity (Kraus 1994). This finding is consistent with the results of the dye tracer test. If the bentonite component of the untested GCL had been damaged by freeze-thaw cycling, dye would have flowed through the bentonite as well as along the sidewall. However, no dyed bentonite was observed in the dye tracer test (Kraus 1994).

Comparison of Laboratory and Field Results

Results of the field and laboratory tests are similar. For the conditions tested, freeze-thaw cycling had essentially no effect

TABLE 2. Hydraulic Conductivity of Geosynthetic Clay Liners Frozen and Thawed in Laboratory

Sample number (1)	Initial hydraulic conductivity, K_0 (m/s) (2)	Hydraulic Conductivity after n Freeze-Thaw Cycles, K_n (m/s)				$K_{20}K_0$ (7)
		K_1 (3)	K_3 (4)	K_5 (5)	K_{20} (6)	
Bentofix-1	2.9×10^{-11}	3.0×10^{-11}	2.8×10^{-11}	Not performed	3.2×10^{-11}	1.10
Bentofix-2	4.9×10^{-11}	1.6×10^{-11}	2.3×10^{-11}	2.7×10^{-11}	2.2×10^{-11}	0.45
Bentofix-3	5.6×10^{-11}	1.7×10^{-11}	3.5×10^{-11}	3.6×10^{-11}	2.5×10^{-11}	0.45
Bentomat-1	3.1×10^{-11}	2.9×10^{-11}	2.8×10^{-11}	1.3×10^{-11}	1.7×10^{-11}	0.55
Bentomat-2	3.1×10^{-11}	1.7×10^{-11}	2.4×10^{-11}	2.5×10^{-11}	1.9×10^{-11}	0.61
Bentomat-3	2.9×10^{-11}	1.8×10^{-11}	1.4×10^{-11}	1.5×10^{-11}	1.9×10^{-11}	0.66
Claymax-1	3.8×10^{-11}	2.9×10^{-11}	4.8×10^{-11}	4.2×10^{-11}	3.4×10^{-11}	0.89
Claymax-2	2.9×10^{-11}	2.4×10^{-11}	2.7×10^{-11}	3.6×10^{-11}	2.1×10^{-11}	0.72
Claymax-3	4.2×10^{-11}	3.5×10^{-11}	3.4×10^{-11}	3.2×10^{-11}	2.4×10^{-11}	0.57
Claymax-4	4.9×10^{-11}	4.1×10^{-11}	3.2×10^{-11}	4.4×10^{-11}	3.3×10^{-11}	0.67

TABLE 3. Field Hydraulic Conductivity of Geosynthetic Clay Liners in Field-Test Pans

Specimen (1)	Seam? (2)	Before-winter hydraulic conductivity (m/s) (3)	After-winter hydraulic conductivity (m/s) (4)	K_A/K_B[a] (5)
Bentomat, 1.8 m^2	Yes	1.5×10^{-10}	1.9×10^{-10}	1.3
Bentomat, 0.7 m^2	Yes	1.0×10^{-10}	1.4×10^{-10}	1.4
Bentomat, 0.7 m^2	No	No outflow	1.0×10^{-10}	NA[b]
Claymax, 1.8 m^2	Yes	2.8×10^{-10}	7.0×10^{-9}	25.0
Claymax, 0.7 m^2	Yes	2.0×10^{-10}	3.0×10^{-10}	1.5
Claymax, 0.7 m^2	No	2.4×10^{-10}	2.8×10^{-10}	1.2

[a]K_A/K_B is defined as the ratio of the after-winter hydraulic conductivity to the before-winter hydraulic conductivity.
[b]NA = not applicable.

TABLE 4. Hydraulic Conductivity of Geosynthetic Clay Liner Specimens Removed from Lagoons

Specimen (1)	Diameter (m) (2)	Hydraulic conductivity (m/s) (3)
Bentomat	0.30	Not measured[a]
Bentomat	0.30	1.7×10^{-10}
Claymax	0.45	3.5×10^{-10}
Claymax	0.45	6.3×10^{-10}

[a]Sidewall leakage and disturbance occurred.

on the hydraulic conductivity of the GCLs. The only exception is the one test conducted with a seamed Claymax GCL; this GCL was significantly more permeable after winter. It is not clear whether this increase in hydraulic conductivity can be attributed to the seam because no increase in hydraulic conductivity was measured for the other seamed Claymax GCL. Furthermore, when the Claymax GCLs were installed in the test pans, the seam was not necessarily constructed using the edge of the roll. The version of Claymax GCL that was used has stitching to enhance strength, but this stitching is not included near the edges of the roll, which are normally used when constructing field seams. Thus, the seam may have contained stitches, which may have affected the performance of the GCL.

There is also a distinct difference between the hydraulic conductivities of the specimens tested in the laboratory versus those measured in the field. The hydraulic conductivities of the specimens frozen and thawed in the laboratory are approximately one order of magnitude lower than those exposed to winter weather. Although the exact cause for this difference is not known, the writers believe that it may have been caused by the higher effective stress and higher gradient used when permeating in the laboratory. Estornell and Daniel (1992) have shown that the hydraulic conductivity of a GCL is very sensitive to effective stress, particularly when the effective stress is low. The 14 kPa effective stress used in the laboratory is significantly higher than the effective stress existing in the field (~3 kPa), but was the lowest effective stress that could be reliably used in the laboratory apparatus.

Structure of Sand-Bentonite and Geosynthetic Clay Liners

Sand-Bentonite

Specimens of sand-bentonite compacted in the laboratory were examined prior to freezing, while frozen, and after thawing to determine why no increase in hydraulic conductivity occurred when they were exposed to freeze-thaw cycling. A band saw was used to cut open specimens while they were frozen. Two cuts were made; the first cut was made along the diameter of the specimen to obtain a vertical cross section, and the second cut was made to obtain a horizontal cross section. A razor blade was used to remove smeared soil that formed during sawing. The unfrozen specimens were split using a screwdriver and then cleansed of disturbed soil using a razor blade.

The structures prior to freezing, while frozen, and after thawing were essentially identical. The mixture appeared to be a homogeneous matrix of sand having voids filled with hydrated bentonite. The frozen specimen contained no segregated ice or cracks (Fig. 9). Also, the thawed specimen contained none of the cracks typically observed in thawed compacted clays (Kraus 1994). The lack of segregated ice and the absence of cracks are consistent with the lack of change in hydraulic conductivity that was observed.

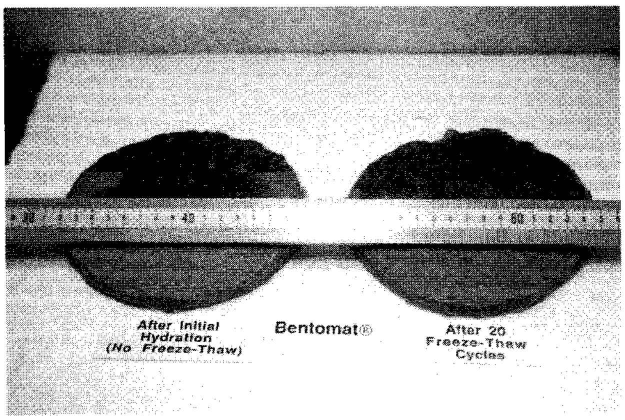
Similar observations were made in the field. Examination of test pits in the sand-bentonite test pad before and after thawing showed that the mixture was devoid of cracks that cause increases in hydraulic conductivity (Civil Engineering Consultants, 1993; Kraus 1994). In addition, specimens removed using a core barrel when the test pad was frozen showed that ice lenses did not form in the sand-bentonite. The specimens removed in sampling tubes were also devoid of cracks.

(a)

(b)

FIG. 9. Structure of Sand-Bentonite while Frozen: (a) Horizontal Section; (b) Vertical Section

(a)



(b)

FIG. 10. Hydrated and Thawed Geosynthetic Clay Liners: (a) Cross Section of Frozen Geosynthetic Clay Liner; (b) Bentonite Component

Geosynthetic Clay Liners

The GCLs frozen and thawed in the laboratory were also examined to determine why their hydraulic conductivity did not increase. Vertical and horizontal sections of frozen specimens of GCLs were prepared using the same procedure used to prepare the frozen specimens of sand-bentonite.

Small randomly oriented lenses of segregated ice existed on the horizontal and vertical [Fig. 10(a)] sections. These lenses undoubtedly caused cracking of the clay matrix when they formed. However, examination of thawed specimens revealed that they are devoid of cracks like those commonly encountered in thawed compacted clays and appear identical to specimens hydrated but never frozen [Fig. 10(b)]. The specimens removed from the lagoons also were devoid of cracks. Apparently, because the hydrated bentonite is very soft after thawing, the cracks created when the segregated ice melts close on thawing. This is in direct contrast to compacted clays, which are relatively stiff when thawed and thus retain the cracks formed during freezing.

SUMMARY AND CONCLUSIONS

The results of the laboratory and field tests show that the sand-bentonite mixture and GCLs that were tested are not adversely affected by freezing and thawing in a closed system. Nearly identical hydraulic conductivities were measured in the field and laboratory for the sand-bentonite mixture after freezing and thawing. For the GCLs lower hydraulic conductivities were measured in the laboratory. However, in the laboratory and field, freezing and thawing did not cause an increase in hydraulic conductivity. The only exception is one GCL field test, which contained a seamed section of Claymax GCL. The hydraulic conductivity of this GCL increased by a factor of 25. However, a replicate of this test showed no increase in hydraulic conductivity.

Examination of the sand-bentonite mixture and GCLs, while frozen, and after thawing revealed why these materials do not incur the increases in hydraulic conductivity typical of compacted clays. For the sand-bentonite mixture, ice segregation does not occur during freezing, and thus no cracks form. Consequently, the macrostructure after thawing appears identical to the macrostructure observed before thawing, and no large increase in hydraulic conductivity occurs. In contrast, ice segregation does occur in GCLs, but the cracks formed during ice segregation close when the bentonite thaws because the thawed bentonite is very soft and compressible. Consequently, GCLs also do not undergo increases in hydraulic conductivity.

Although the findings of this study are encouraging, the writers recommend that designers carefully consider the use of sand-bentonite mixtures and GCLs in situations where freezing will occur. This is particularly important in applications where the GCL or sand-bentonite mixture is the sole hydraulic barrier. Only long-term field tests, where GCLs and sand-bentonite mixtures are monitored for a extended number of years, will provide the definitive information regarding the long-term performance of GCLs and sand-bentonite mixtures subjected to freezing conditions.

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Evaluating the Long-Term Performance of Geosynthetic Clay Liners Exposed to Freeze-Thaw

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Abstract: An important consideration for landfill liners and covers constructed in the frost zone of cold climates is the possible deterioration in performance due to freeze-thaw cycling over the design life of the liner or cover system. Several examples in the literature show that geosynthetic clay liners can withstand a limited number of freeze-thaw events, but data on long-term freeze-thaw performance are lacking. The objective of this study was to examine the long-term performance of geosynthetic clay liners exposed to repeated freeze-thaw cycles, encompassing their application as a final cover as well as a bottom liner. Measurements of hydraulic conductivity were performed after as many as 150 freeze-thaw cycles, with no appreciable increases observed.

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Introduction

Geosynthetic clay liners (GCLs) have become an increasingly common component in landfill liner and cover systems since their introduction in the early 1980s (Mazzieri and Pasqualini 2000). An important consideration for liners and covers constructed in the frost zone of cold climates is the possible deterioration in performance due to freeze-thaw cycling over the design life of the liner or cover system, which can be hundreds to even thousands of years (INEEL 2002). Previous studies have established that GCLs retain their hydraulic properties after 20–30 freeze-thaw events (Hewitt and Daniel 1997; Kraus et al. 1997), largely due to the self-healing characteristics of the sodium bentonite material used in their construction. However, data on the long-term performance of GCLs exposed to freeze-thaw are lacking. This data is necessary for justifying design assumptions associated with long-term performance.

The objective of this study is to examine the long-term performance of GCLs exposed to freeze-thaw cycles expected in final cover and liner systems. The results will provide designers and regulators with a technical basis for long-term performance assessment of existing liners and covers as well as the assumptions used in future designs. In order to meet this objective, laboratory measurements of hydraulic conductivity of three common GCLs were made for up to 150 freeze-thaw cycles.

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Methods

Hydraulic conductivity was measured using a flexible-wall permeameter system under falling-head/rising-tail conditions. The flexible wall permeameter was chosen because the method is considered reliable for measuring the hydraulic conductivity at low flow rates that would be typical of GCL materials (Wong and Haug 1991) and to prevent the possibility preferential sidewall flow that would yield artificially high hydraulic conductivity values (Petrov et al. 1997a). Laboratory procedures for determining hydraulic conductivity were developed in accordance with relevant American Society for Testing and Materials (ASTM) standards (ASTM 1999, 2001) and the recent literature (Koerner 1997; Othman et al., 1994; Petrov et al. 1997a,b).

Tests were planned to examine the hydraulic conductivity after 3, 9, 15, 21, 30, 45, 75, 100, 125, and 150 freeze-thaw cycles. Test samples were obtained by cutting 70-mm disks from bulk rolls of three GCL types, Bentomat ST (GCL-1), Bentomat DN (GCL-2), and Claymax 200R (GCL-3). A separate group of three replicate samples were prepared from each respective GCL type for each planned number of freeze-thaw cycles, so that the hydraulic conductivity of each sample was measured only twice, once as a prefreeze-thaw baseline and once after the total number of freeze-thaw events were completed.

The samples were backpressure saturated at 276 kPa with a confining pressure of 345 kPa for a minimum of 48 h using a permeant of deionized water (DI). DI was chosen as the permeant for the analysis to ensure that all changes observed in the hydraulic conductivity can be attributed to the freeze-thaw process only, and not to cation exchange processes between the permeant and the sodium bentonite used in the construction of the GCLs. Jo et al. (2005) showed that significant changes in hydraulic conductivity can occur due to cation exchange between the liner materials and ionic permeant solutions. The authors also showed that samples permeated with DI showed little change in hydraulic conductivity after more than 60 pore volumes were permeated through GCL specimens, which further lends confidence to our

Table 1. Baseline Hydraulic Conductivity Results at Effective Stresses of 20 and 60 kPa for the Three GCLs Used in the Study

GCL	Hydraulic conductivity (cm/s)	Standard deviation (cm/s)
20 kPa Analysis		
GCL-1	2.5×10^{-9}	1.6×10^{-10}
GCL-2	2.9×10^{-9}	1.6×10^{-10}
GCL-3	2.0×10^{-9}	3.5×10^{-10}
60 kPa Analysis		
GCL-1	1.7×10^{-9}	8.7×10^{-10}
GCL-2	2.0×10^{-9}	8.1×10^{-10}
GCL-3	9.0×10^{-10}	4.0×10^{-10}

results representing only changes due the freeze-thaw.

In order to establish a baseline hydraulic conductivity, samples were analyzed prior to freeze-thaw at effective stresses of 20 and 60 kPa. A hydraulic gradient of 150 was used for the analysis. The lower effective stress corresponds to an application of a GCL as a cover system, whereas a higher stress of 60 kPa simulates the conditions of an evaporative pond liner, or as a conservative analysis for a landfill bottom liner. These assumptions are based on measurements collected at recently constructed evaporation ponds at the Idaho National Laboratory (Podgorney and Bennett 2004) with 4 m of standing water (~52 kPa effective stress at the GCL).

To prepare the samples for the freeze-thaw cycles, the flexible membrane was left wrapped around the sample and it was placed in a sealed plastic bag. Samples intended for the same number of freeze-thaw cycles were laid flat and kept in separate airtight containers. The containers were cycled in and out of a laboratory freezer (average temperature of $-17°C$) every 24 h (ASTM 1997).

The samples were retested once the planned number of freeze-thaw cycles were reached. Two replicate samples of each GCL type for each number of freeze-thaw cycles were retested at 60 kPa effective stress, while the remaining sample was retested at an effective stress of 20 kPa. The hydraulic gradient for all retests remained the same as the original testing conditions.

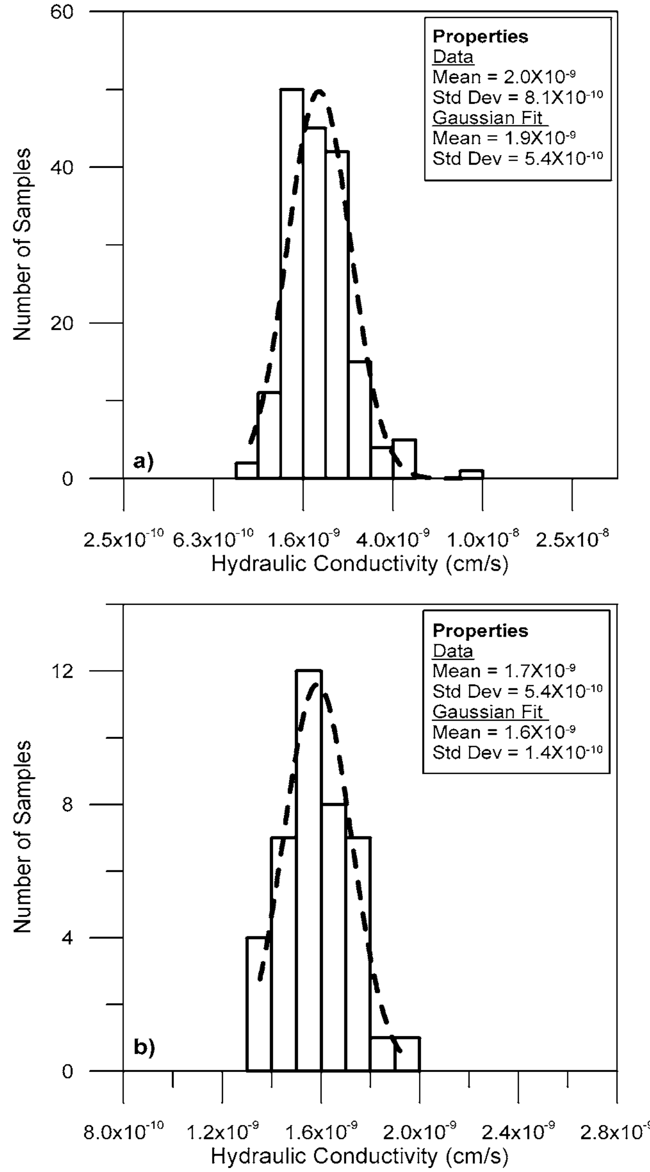

Fig. 1. Histograms and Gaussian fits to: a) the log transformed baseline hydraulic conductivity analysis for geosynthetic clay liner GCL-2 at 60 kPa; and b) numerous measurements conducted on a single GCL-2 sample at 60 kPa

Results and Discussion

A baseline hydraulic conductivity for each of the GCL types at both effective stresses was established by making repeated measurements on all of the samples. The results of the baseline sampling are summarized in Table 1. In general, the baseline data show a lognormal distribution with nearly all data falling within one standard deviation of the mean. Due to the number of samples and measurements that were used to establish the baseline (approximately 200 total measurements on 30 samples of each GCL type), we surmised that these results represent the variability of the materials themselves and not the laboratory methodology. Therefore, in order to assess the variability inherent in our methodology, numerous measurements were made on a single sample (GCL-2 at 60 kPa) over a three-month period to evaluate the variability in the sampling methods. No discernable trends were evident in the data, which resulted in a dataset that fit a Gaussian distribution with a mean hydraulic conductivity value of 1.66×10^{-9} cm/s. Fig. 1 shows a representative histogram of the baseline analysis and results of the single sample analysis, both with a Gaussian fit applied to the data. The goodness of fit of the initial measurements to a Gaussian model gave us confidence in our laboratory methods and procedures.

All of the GCLs tested performed well after repeated exposure to freeze-thaw, with no significant changes in hydraulic conductivity. The results of the analysis are shown in Fig. 2. There is a general decrease in measured hydraulic conductivity for most of the GCLs after the first few freeze-thaw cycles. This is likely the result of thaw consolidation or reorientation of the particles within the liner materials due to changes in the stress state upon freezing and thawing (Chamberlain and Gow 1979; Kraus et al. 1997). Following the initial decrease, the measured value of hydraulic conductivity is generally higher at lower effective stress for all GCL types, but neither case shows a significant decrease in performance.

Fig. 2(a) details the hydraulic conductivity of GCL-1 for both the 20 and 60 kPa effective stresses. The measured values are generally parallel to each other, with a few small spikes in the

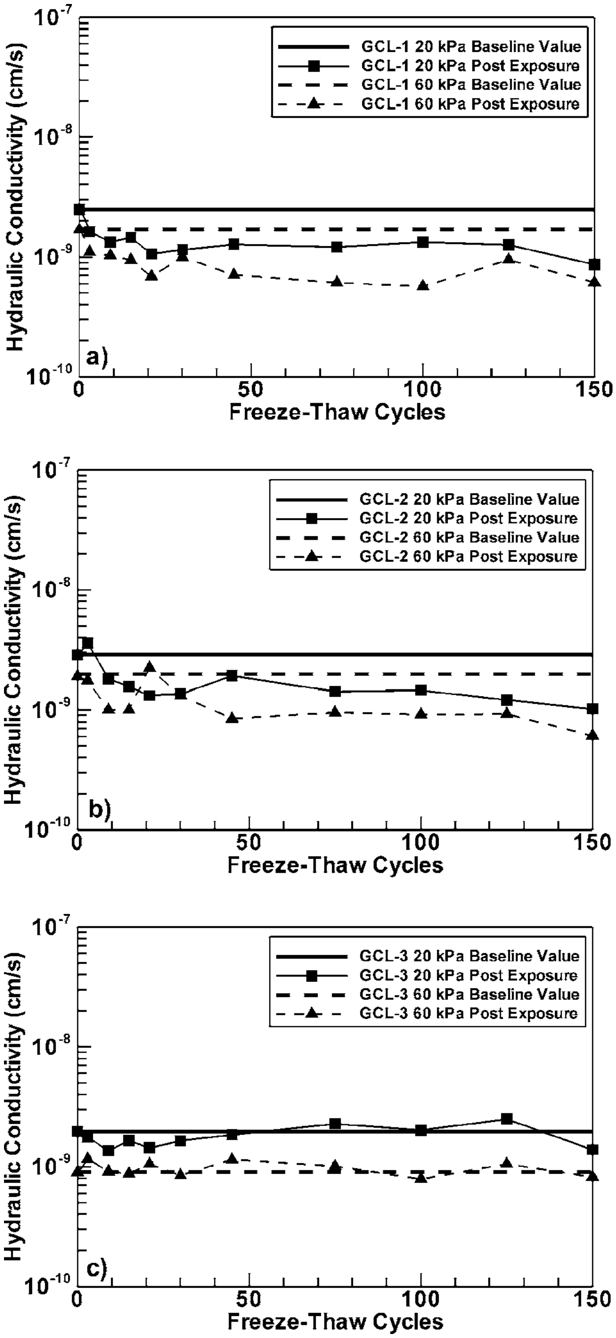

Fig. 2. Hydraulic conductivity variation with freeze-thaw cycling for: (a) GCL-1; (b) GCL-2; and (c) GCL-3. Values plotted for the 60 kPa tests are the average of two replicate samples.

measurements. In Fig. 2(b) (GCL-2), the hydraulic conductivity at 60 kPa showed a minor increase at 21 freeze-thaw cycles, but still remained within one standard deviation of the mean baseline value, with the 20 and 60 kPa sample values generally paralleling each other for the remaining freeze-thaw cycles. The hydraulic conductivity of GCL-3 [Fig. 2(c)] showed a slight increasing trend from 21 to 125 freeze-thaw cycles at 20 kPa, only to return to less than the baseline values after 150 freeze-thaw cycles. The mean of the baseline measurements is also shown for all GCL types in Fig. 2. In general, the postfreeze-thaw hydraulic conductivity is less than or falls within one standard deviation of the mean of the baseline hydraulic conductivity.

Summary and Conclusions

An evaluation of several commonly available GCLs exposed to repeated freeze-thaw cycling was performed, encompassing their application as a final cover (20 kPa) as well as a bottom liner (60 kPa). Laboratory analysis of the hydraulic conductivity was performed after as many as 150 freeze-thaw cycles, with no appreciable changes observed.

The long-term susceptibility of GCLs to increased hydraulic conductivity as a response to repeated freeze-thaw cycling is minimal, largely due to the self-healing characteristics of the sodium bentonite used in their construction. GCLs perform well and maintain efficiency as a barrier to flow after 150 freeze-thaw cycles. Other factors, such as proper installation (Estornell and Daniel 1992), permeant chemistry and cation exchange (Jo et al. 2005), physical disturbance or damage (Mazzieri and Pasqualini 2000), desiccation (Boardman and Daniel 1996), etc., have been shown to significantly affect the hydraulic conductivity and are likely to exhibit much more control on the long-term performance of GCLs.

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