EFFECT OF FREEZE-THAW ON THE HYDRAULIC CONDUCTIVITY OF BARRIER MATERIALS: LABORATORY AND FIELD EVALUATION

by

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FOREWORD

The U.S. Environmental Protection Agency is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The National Risk Management Research Laboratory is the Agency's center for investigation of technological and management approaches for reducing risks from threats to human health and the environment. The focus of the Laboratory's research program is on methods for the prevention and control of pollution to air, land, water and subsurface resources; protection of water quality in public water systems ; remediation of contaminated sites and ground water; and prevention and control of indoor air pollution. The goal of this research effort is to catalyze development and implementation of innovative, cost-effective environmental technologies; develop scientific and engineering information needed by EPA to support regulatory and policy decisions; and provide technical support and information transfer to ensure effective implementation of environmental regulations and strategies.

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E. Timothy Oppelt, Director
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ABSTRACT

Tests were performed in the laboratory to assess the impact of freeze-thaw on the hydraulic conductivity of two compacted clays and three alternative barrier materials: a sand-bentonite mixture, three geosynthetic clay liners (GCLs), and three paper mill sludges. Results of laboratory tests on the clays, sand-bentonite mixture, and GCLs were compared to data obtained from the COLDICE (Construction of Liners Deployed in Cold Environments) project conducted by the U. S. Army Cold Regions Research and Engineering Laboratory (CRREL) and CH2M Hill, Inc. The COLDICE project is a large-scale field study designed to evaluate the effect of freeze-thaw on the hydraulic conductivity of barrier materials. Results of laboratory tests performed on the paper mill sludges were compared to results of hydraulic conductivity tests performed in a small-scale field study conducted at the University of Wisconsin-Madison. The small-scale field study consisted of compacting paper mill sludge in large PVC pipes and measuring their hydraulic conductivity before and after exposure to freeze-thaw. Tests were also performed on the paper mill sludges to determine how effective stress and permeation time affect hydraulic conductivity.

Results of this project show that:

(1) The hydraulic conductivity of compacted clay increases as a result of exposure to freeze-thaw. Cracks that form due to desiccation (induced by freezing) and formation of ice lenses are responsible for the increase in hydraulic conductivity. Furthermore, greater increases in hydraulic conductivity occur in the field relative to those that are observed in freeze-thaw tests conducted in the laboratory. Larger cracks and a more blocky structure occur in the field. The exact cause of this difference in structure is not known. It possibly can be attributed to differences in soil structure prior to freezing.

(2) The hydraulic conductivity of the bentonitic barrier materials (sand-bentonite mixture, geosynthetic clay liners (GCLs)) tested in this study was insensitive to freeze-thaw. This was observed in the field (COLDICE data) and in the laboratory. Although segregated ice was observed in sections of frozen specimens, no cracks were observed in the sand-bentonite mixture or GCLs after thawing. Apparently, cracks in the soft bentonite close during thawing and thus no increase in hydraulic conductivity occurs. This behavior is in

direct contrast to the behavior of compacted clays, which are relatively stiff and retain the cracks incurred during freezing after thawing has occurred.

(3) Hydraulic conductivities less than 1 x 10^{-9} m/s were obtained when compacting the three paper mill sludges wet of optimum water content. Two of the sludges behaved like clay when subjected to freeze-thaw. Their hydraulic conductivity increased one to two orders of magnitude. In contrast, the other sludge was resistant to freeze-thaw if it was permeated after each thaw. However, if this sludge was frozen and thawed without intermittent permeation, the hydraulic conductivity increased approximately one order of magnitude.

(4) The small-scale field tests with the sludge were inconclusive. When the field specimens were permeated in the pipes, a reduction in hydraulic conductivity was observed after one winter of freeze-thaw. However, when the specimens were removed from the pipes as slices and permeated in flexible-wall permeameters, increases in hydraulic conductivity of approximately one order of magnitude were observed. This discrepancy in hydraulic conductivity may have been the result of disturbance incurred when the specimens were sliced from the pipes. Nevertheless, the effect that freeze-thaw has on paper mill sludges in the field is not clear. Large-scale field tests are recommended to address this issue.

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Financial support for this study was provided by the United States Environmental Protection Agency (EPA) under cooperative agreement CR 821024-01-0 and by the National Council of the Paper Industry for Air and Stream Improvement (NCASI). Mr. Robert Landreth was the Project Officer for EPA and Mr. Van Maltby was the contact person at NCASI. Support for sampling and hydraulic conductivity testing of the block specimens was provided by James Clem Corporation and Colloid Environmental Technologies Company (CETCO). This report has not been reviewed by NCASI, James Clem, or CETCO and no endorsement should be implied.

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SECTION 1

INTRODUCTION

The low hydraulic conductivity of compacted clays has led to their frequent use in landfill liners and covers, caps over contaminated soil, and other applications where minimizing fluid flow is desired. However, the hydraulic integrity of compacted clay can be compromised if it freezes. When the temperature of compacted clay falls below 0°C, water present in the clay freezes and ice lenses form. Concurrently, soil below the freezing front desiccates as water is pulled to the growing ice lenses (Benson and Othman 1993, Chamberlain et al. 1995). As the temperature of the clay later rises above freezing, the ice lenses thaw, leaving behind a network of cracks that allow rapid transmission of water (Chamberlain et al. 1990, Benson and Othman 1993).

Because of the detrimental impact that freeze-thaw has on compacted clay, alternative materials are being considered for use in hydraulic barrier applications in northern climates. Three alternative materials and two clays were examined in this study. The alternative materials were a sand-bentonite mixture, geosynthetic clay liners (GCLs), and paper mill sludges. Previous research indicates that the hydraulic conductivity of sand-bentonite mixtures decreases after exposure to freezing and thawing (Wong and Haug 1992). Recent studies have also suggested that GCLs are resistant to the detrimental effects of freeze-thaw (e.g., Geoservices 1989, GeoSyntec 1991, Shan and Daniel 1991). Because of their high water content and fibrous nature, paper mill sludges may also be resistant to increases in hydraulic conductivity.

The objective of this study was to evaluate and compare the effect that freezing and thawing has on the hydraulic conductivity of clays, sand-bentonite mixtures, GCLs, and paper industry sludges under laboratory and field conditions. To meet this objective, a battery of hydraulic conductivity tests were conducted in the laboratory on specimens prepared under conditions that yield low hydraulic conductivity. The hydraulic conductivity of each specimen was measured before and after the specimen had been exposed to a specified number of freeze thaw cycles. Results of the laboratory tests were compared to data from the COLDICE project, a recent large-scale field study evaluating the impact of freeze-thaw on compacted clays and GCLs (Chamberlain et al. 1994), and small-scale field tests using paper mill sludges that were conducted as part of this study.

SECTION 2

BACKGROUND

2.1 IMPACTS OF FREEZE-THAW ON COMPACTED CLAY

The deleterious effect that freeze-thaw has on the hydraulic conductivity of compacted clays is well documented. Chamberlain et al. (1990) have shown that changes in soil structure that occur during freeze-thaw can result in significant increases in the hydraulic conductivity of compacted clays. They compacted five clays at optimum water content and measured their hydraulic conductivities in consolidometers. For four of the clays, the hydraulic conductivity increased one to two orders of magnitude after being exposed to freeze-thaw. Chamberlain et al. (1990) attributed the increases in hydraulic conductivity to macroscopic horizontal and vertical cracks that formed during freeze-thaw.

Othman and Benson (1993a) examined how freeze-thaw affected the hydraulic conductivity of three compacted clays. Specimens were compacted using standard and modified Proctor efforts at water contents equal to or exceeding optimum water content. Then, they were subjected to one or three-dimensional freeze-thaw. Factors investigated were molding water content, compactive effort, dimensionality of freezing, ultimate temperature below freezing, and temperature gradient. Othman and Benson (1993a) found that the hydraulic conductivity of all three clays increased about two orders of magnitude and attributed the increases in hydraulic conductivity to a network of cracks that formed during freezing. Results of their study are shown in Figure 2.1.

Similar results have been documented by other investigators (e.g., Zimmie and LaPlante 1990, Kim and Daniel 1992, Bowders and McClelland 1994). Othman et al. (1994) provide a review and synthesis of these studies. They report that compacted clays having an initial hydraulic conductivity less than 1×10^{-9} m/s generally undergo an increase in hydraulic conductivity of 1 to 2 orders of magnitude when subjected to freeze-thaw. Greater increases in hydraulic conductivity occur for clays having lower initial hydraulic conductivity, specimens frozen more quickly, and tests conducted at lower effective stress.

Three studies have been performed in the field to assess the impact of freeze-thaw on the hydraulic conductivity of compacted clay. Benson and Othman (1993) performed small-scale field tests. Two specimens of compacted clay were prepared in PVC pipes (diameter = 0.30 m, length = 0.91 m). One specimen was kept in the laboratory as a "control" specimen, and was permeated to determine the as-compacted hydraulic conductivity. The other specimen ("field" specimen) was buried in the ground in January 1991 and subjected to two months of winter weather. The field specimen was instrumented with thermocouples and fiberglass moisture probes at various depths to monitor temperature and water content while the specimen was in the ground.

The field specimen was removed from the ground in March 1991 and permeated in the laboratory. No significant change in overall hydraulic conductivity was observed between the control and field specimens. However, when the field specimen was sliced horizontally into separate specimens (which were then permeated in a large-scale flexible-wall permeameter), increases in hydraulic conductivity of 1.5 to 2 orders of magnitude were observed for specimens sliced from above the freezing plane. In contrast, a specimen removed from just below the freezing plane showed a slight increase in hydraulic conductivity, and the specimen removed from 0.3 m below the freezing plane showed no increase in hydraulic conductivity. Figure 2.2 shows the results obtained by Benson and Othman (1993). Benson and Othman (1993) attributed the increase in hydraulic conductivity above the freezing plane to horizontal and vertical cracks that formed as a result of freeze-thaw. They attributed the increase in hydraulic conductivity just below the freezing plane to vertical cracks that formed as a result of desiccation, which occurred as a result of water redistribution during freezing.

Benson et al. (1995) conducted a full-scale field test to determine if increases in hydraulic conductivity occur in the field that are similar to those observed in laboratory tests. A test pad was constructed and instrumented at a site in southeastern Michigan. Temperatures within the test pad were monitored and recorded throughout the winter of 1992-93.

Hydraulic conductivity of the test pad was measured in the laboratory and in the field before and after winter. Laboratory hydraulic conductivity tests were performed in flexible-wall permeameters on large block specimens (diameter = 0.30 m) and on small specimens (diameter = 71 mm) taken from the test pad using thin-wall sampling tubes (Shelby tubes). Field measurements of hydraulic conductivity were made using sealed double-ring infiltrometers (SDRIs).

Results of the laboratory tests indicated that an increase in hydraulic conductivity occurred as a result of freeze-thaw. Increases in hydraulic conductivity were seen in specimens extracted from the zone in which freezing occurred (depth ≤

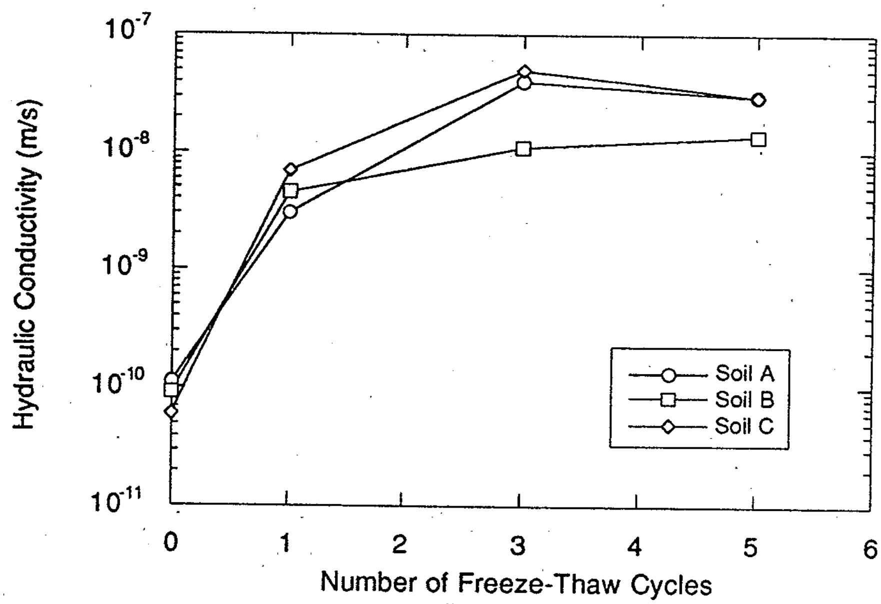


Figure 2.1. Hydraulic conductivity vs. number of freeze-thaw cycles for three Wisconsin clays (after Othman and Benson 1993a).

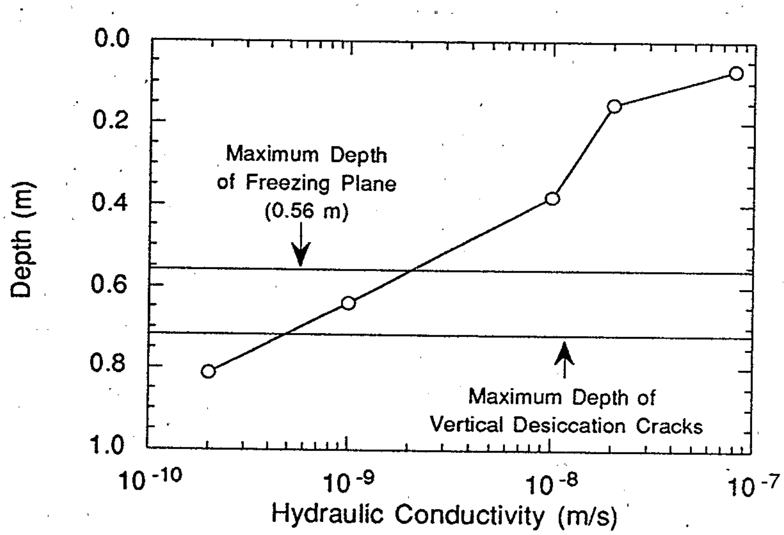


Figure 2.2. Hydraulic conductivity vs. depth for tests performed on specimens sliced from "field" specimen (after Benson and Othman 1993).

0.5 m), whereas no increase in hydraulic conductivity was found for specimens taken from below the depth of frost penetration. In contrast, results of the SDRI tests showed no increase in hydraulic conductivity after winter exposure. Benson et al. (1995) state that no increase in hydraulic conductivity was observed in the SDRI tests because soil below the depth of freezing controlled the infiltration rate.

Erickson et al. (1994) examined the effect of freezing and thawing on two compacted clay test pads constructed for the COLDICE (Construction Of Liners Deployed In Cold Environments)/CPAR (Construction Productivity Advancement Research) project at a landfill near Milwaukee, Wisconsin. The test pads were instrumented with thermistors and a weather station was used to record the soil temperature distribution, number of freeze-thaw cycles, depth of frost penetration, and climatic conditions throughout the winter. Hydraulic conductivities of the test pads were measured before and after exposure to winter weather.

Hydraulic conductivities of the test pads were assessed in the laboratory using specimens collected by three sampling methods: large blocks, thin-wall sampling tubes (Shelby tubes), and as cores, which were removed from the test pads while the soil was frozen. The large block specimens (diameter = 0.30 m) were taken before and after the winter of 1992-93. Thin-wall sampling tubes (diameter = 71 mm) were used to remove specimens in June 1993. Frozen cores (diameter = 71 mm) were collected in March 1993 and March 1994.

Increases in hydraulic conductivity of up to 4 orders of magnitude were observed for the specimens removed from the soil subjected to freeze-thaw. Erickson et al. (1994) state that the increase in hydraulic conductivity of the compacted clay is a result of the formation of cracks due to the formation of ice lenses and shrinkage of the soil caused by redistribution of water.

2.2 BENTONITIC BARRIER MATERIALS

2.2.1 Sand-Bentonite Mixtures

Wong and Haug (1991) examined how freeze-thaw affected the hydraulic conductivity of sand-bentonite mixtures consisting of a sodium bentonite from western Canada and Ottawa sand. Varying amounts of sodium bentonite were mixed with the Ottawa sand and the mixtures were compacted according to ASTM D 698 (standard Proctor). The specimens were extruded and permeated in fixed- and flexible-wall permeameters. After initial permeation was complete, the specimens were exposed to an ultimate temperature of -20°C for a minimum of 6 hours in a closed system (no external water supply). The specimens were then allowed to thaw at room temperature. After thawing, their hydraulic conductivity was measured. This procedure was repeated until 5 freeze-thaw cycles were completed.

Figure 2.3 shows the results of their study. A decrease in hydraulic conductivity was observed in all specimens as a result of freeze-thaw. Wong and Haug (1991) provided two possible explanations for the decrease in hydraulic conductivity: (1) freeze-thaw promotes hydration of the bentonite, lowering the hydraulic conductivity towards long-term test values or (2) thaw consolidation compresses the bentonite into gaps between the sand grains.

Erickson et al. (1994) examined how freeze-thaw affected a sand-bentonite mixture in the field. A test pad with a sand-bentonite mixture was constructed for the COLDICE project, adjacent to the two clay test pads described in Section 2.1. A large box infiltrometer (1.3 m x 1.3 m) was constructed in the field to assess the in situ hydraulic conductivity of the test pad after winter. Hydraulic conductivity was also measured on specimens removed from the test pad as blocks, using thin-wall tubes, and as frozen cores. The hydraulic conductivity of the sand-bentonite test pad was 4 x 10^{-10} m/s before winter and 5 x 10^{-10} m/s after winter.

Erickson et al. (1994) concluded that sand-bentonite mixtures that are mixed properly with a large enough percentage of bentonite can be resistant to increases in hydraulic conductivity caused by freeze-thaw.

2.2.2 Geosynthetic Clay Liners (GCLs)

Several studies have been performed to evaluate how freeze-thaw affects the hydraulic conductivity of geosynthetic clay liners (GCLs). Geoservices (1989), Shan (1990), and Chen-Northern (1988) studied how freeze-thaw affects the hydraulic conductivity of the GCL Claymax®. Geoservices (1989) measured an initial hydraulic conductivity of 4 x 10^{-12} m/s for Claymax®. The hydraulic conductivity tests were conducted at an effective stress of 196 kPa and hydraulic gradient of approximately 1000. The hydraulic conductivity of the specimens after 10 cycles of freeze-thaw was 1.5 x 10^{-12} m/s.

Shan (1990) measured the hydraulic conductivity of Claymax® before and after 5 cycles of freeze-thaw. The samples were permeated using an effective stress of 14 kPa and a hydraulic gradient of 10. The initial hydraulic conductivity was 2.0 x 10^{-11} m/s. After 5 cycles of freeze-thaw, the hydraulic conductivity was 2.2 x 10^{-11} m/s.

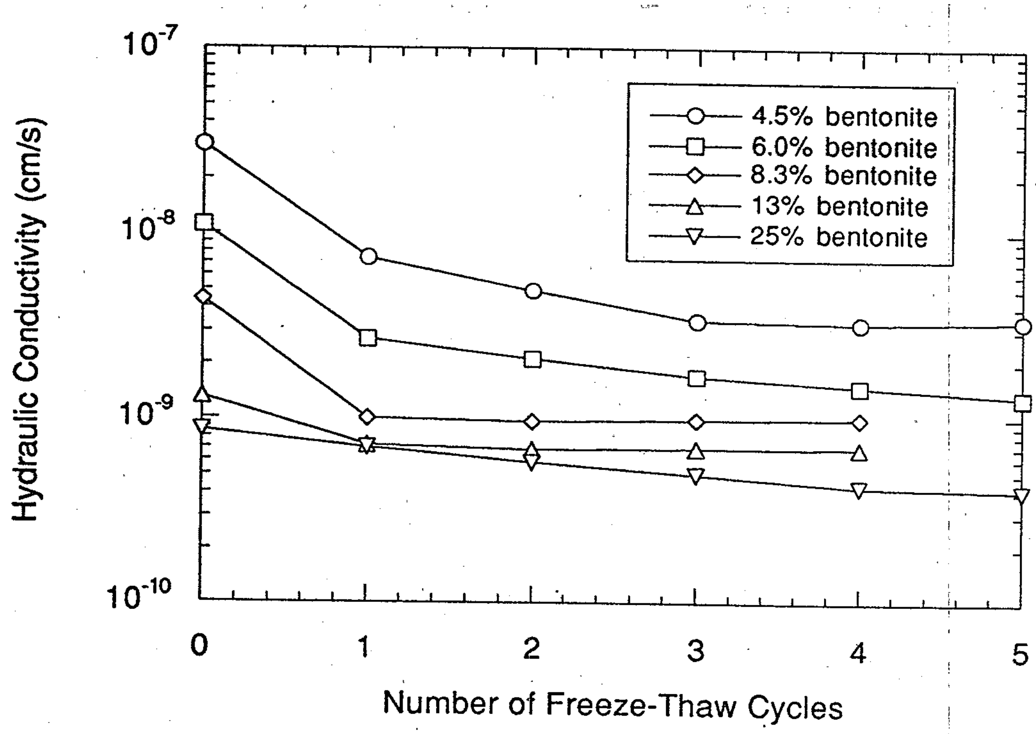


Figure 2.3. Hydraulic conductivity vs. number of freeze-thaw cycles for sand-bentonite mixtures (after Wong and Haug 1991).

Chen-Northern (1988) subjected specimens of Claymax® to 10 cycles of freeze-thaw. The specimens were permeated after 0, 3, and 10 cycles of freeze-thaw using procedures similar to those used by Shan (1990). The initial hydraulic conductivity was 1.0×10^{-11} m/s. After 3 freeze-thaw cycles the hydraulic conductivity was 2.3×10^{-11} m/s, and after 10 freeze-thaw cycles, it was 2.2×10^{-11} m/s.

GeoSyntec (1991) studied how freeze-thaw affected the hydraulic conductivity of the GCL Bentomat®. Initially and after each freeze-thaw cycle, the specimen was permeated with de-aired water at an effective stress of 34.5 kPa and hydraulic gradient of 30. Flexible-wall permeameters were used. The hydraulic conductivity of the Bentomat® fluctuated between 1×10^{-11} and 6×10^{-11} m/s for various cycles of freeze-thaw, with no increasing or decreasing trends being observed.

Freeze-thaw tests were also performed on Bentomat® by Robert L. Nelson and Associates, Inc. (1993). Two sets of tests were performed. In the first set, several specimens were permeated after undergoing a designated number of freeze-thaw cycles (up to six cycles). In the second set, a single specimen was used that was permeated after each freeze-thaw cycle (up to 10 freeze-thaw cycles). The hydraulic conductivities ranged between 1.1×10^{-11} m/s and 4.0×10^{-11} m/s for the first set of tests, and 1.9×10^{-11} m/s and 3.3×10^{-11} m/s for the second set. Results of the tests performed by Robert L. Nelson & Associates, Inc. (1993) are shown in Figure 2.4.

2.3 PAPER MILL SLUDGE

Because some pulp and paper mill sludges (wastes created in the paper making process) have been shown to possess properties similar to clays, interest has arisen in using them in construction of landfill liners and covers (NCASI 1989). Nonetheless, information regarding the geotechnical properties of paper mill sludge is scant (Genthe 1993).

The National Council of the Paper Industry for Air and Stream Improvement (NCASI) performed hydraulic conductivity tests on 11 paper mill sludges of various origins (NCASI 1989). Tests were performed on specimens compacted using standard Proctor procedures (ASTM D 698), except only 10 blows were applied per lift. The specimens were compacted at their as-received water content, which ranged from 120 to 409%. Their hydraulic conductivity ranged from 4.2×10^{-6} to 5.8×10^{-10} m/s. The variability in the hydraulic conductivity test results was probably caused by the variability in molding water content and sludge type.

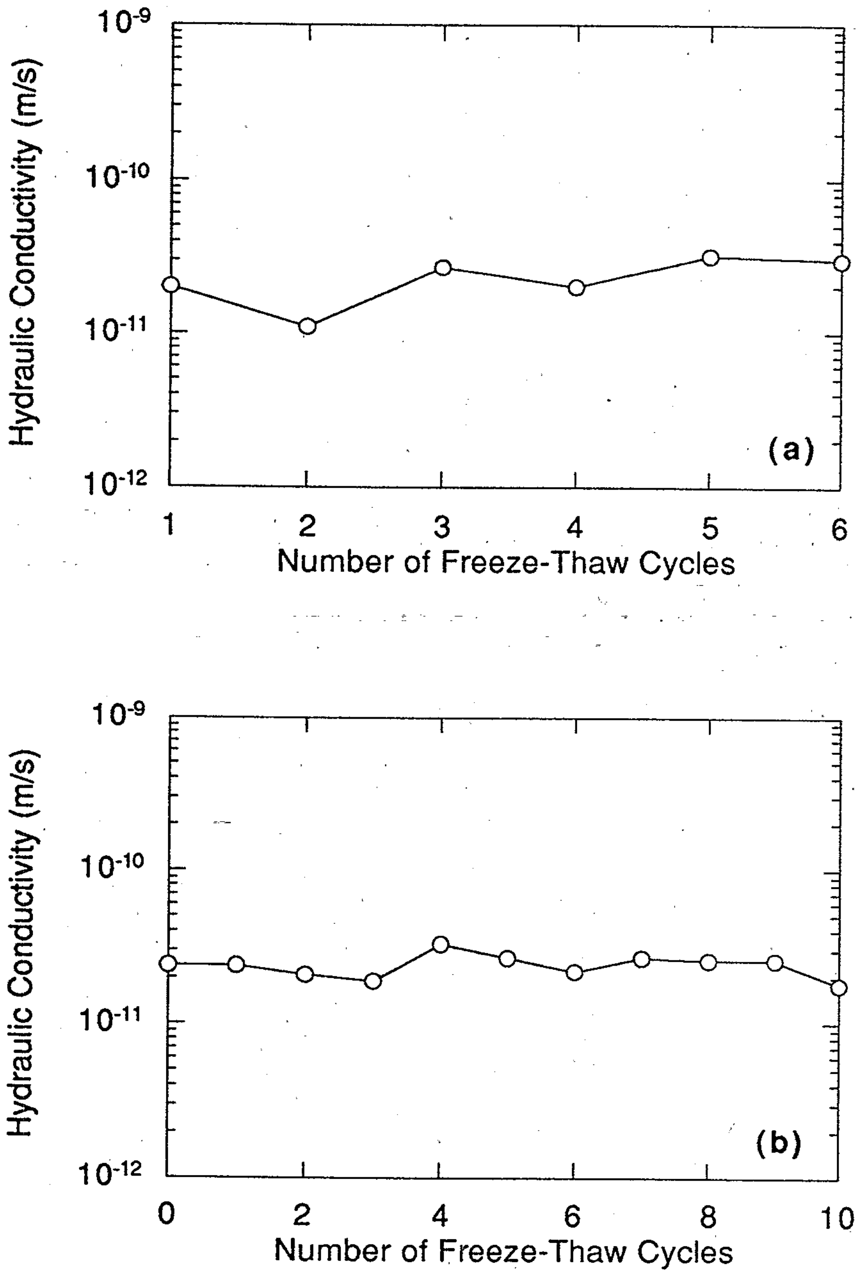


Figure 2.4. Hydraulic conductivity vs. number of freeze-thaw cycles for Bentomat® for test set 1 (a) and test set 2 (b) (after Robert L. Nelson & Associates 1991).

Zimmie et al. (1994) examined the geotechnical properties of a paper mill sludge from Erving Paper Co. in Massachusetts. Compaction, hydraulic conductivity, consolidation, and shear strength tests were performed. The effects that freeze-thaw and effective stress have on the hydraulic conductivity of sludge were also examined.

Zimmie et al. (1994) report that the compaction curve for the sludge was developed by gradually drying the sludge from its high as-received water content and compacting specimens at various water contents using standard Proctor compaction effort (ASTM D 698). The maximum dry unit weight and optimum water content were determined, and the curve was similar to curves for compacted clays. However, the maximum dry unit weight (8.1 kN/m^3) was much lower than that for most clays, whereas optimum water content (49%) was much higher.

The compacted specimens were permeated in flexible-wall permeameters to determine the hydraulic conductivity-water content relationship. The hydraulic conductivity was found to be much lower for specimens compacted at water contents wet of optimum, relative to the hydraulic conductivity of specimens compacted at water contents near or dry of optimum. This behavior is similar to that of compacted clays (Mitchell et al. 1965, Benson and Daniel 1990, Daniel and Benson 1990). However, the lowest hydraulic conductivities were obtained for specimens compacted 50% wet of optimum water content, where for clays the lowest hydraulic conductivities are generally obtained 1-3% wet of optimum. For sludge specimens compacted greater than 50% wet of optimum, hydraulic conductivities less than 1×10^{-9} m/s were obtained.

Zimmie et al. (1994) also performed hydraulic conductivity tests on specimens removed from a landfill cover constructed with the same paper mill sludge. The specimens were removed using thin-wall sampling tubes (diameter = 71 mm) and permeated in flexible-wall permeameters using a confining stress of 34.5 kPa and hydraulic gradient of 21. Eleven of the 14 specimens taken from the landfill had hydraulic conductivities $\leq 1 \times 10^{-9}$ m/s. The three remaining specimens were all collected immediately after construction and had hydraulic conductivities in the 10^{-9} m/s range. All of the specimens removed from the landfill at least 3 months after construction had hydraulic conductivity $< 1 \times 10^{-9}$ m/s. The hydraulic conductivity of the sludge apparently decreased with time as a result of consolidation.

The effect that freeze-thaw has on the hydraulic conductivity of the paper mill sludge was also examined by Zimmie et al. (1994). Specimens were compacted at a water content of 170% in a 76 mm-diameter mold using standard Proctor effort. After compaction, the specimens were wrapped in plastic to prevent desiccation and frozen one-dimensionally. After the desired number of freeze-thaw cycles, the specimens were placed in flexible-wall permeameters and permeated at effective stresses of 34.5, 69, and 138 kPa using a hydraulic gradient of 21.

Results of the freeze-thaw tests showed that the paper mill sludge was affected by freeze-thaw (Figure 2.5). The hydraulic conductivity of the sludge increased approximately one order of magnitude after 10 freeze-thaw cycles. Similar increases in hydraulic conductivity occurred at each effective stress. However, increasing the effective stress from 34.5 kPa to 138 kPa decreased the hydraulic conductivity of the sludge approximately one order of magnitude at each freeze-thaw cycle (Fig. 2.5).

Maltby and Eppstein (1994) describe a field study in which paper mill sludges were used in landfill cover test cells. The field study was undertaken to compare the performance of paper mill sludge and compacted clay when used as hydraulic barriers. The comparison was based on water balance computations (e.g., runoff and percolation). One of the two test cells containing paper mill sludge was constructed with a combined (primary and secondary treatment) sludge and the other was constructed with a primary sludge. Construction of the test cells was completed in November 1987.

Maltby and Eppstein (1994) observed after 5 years that: (1) the test cells constructed with sludge consolidated more than those constructed with clays, (2) the cells containing sludge had greater amounts of runoff than the cells constructed with clay, (3) percolation was lower for the cells containing paper mill sludge, and (4) the average field hydraulic conductivities for the cells containing sludge were lower than those containing compacted clay (9.6×10^{-10} m/s and 4.4×10^{-9} m/s for the cells containing sludge; 1.4×10^{-8} m/s and 1.5×10^{-8} m/s for the cells containing compacted clay).

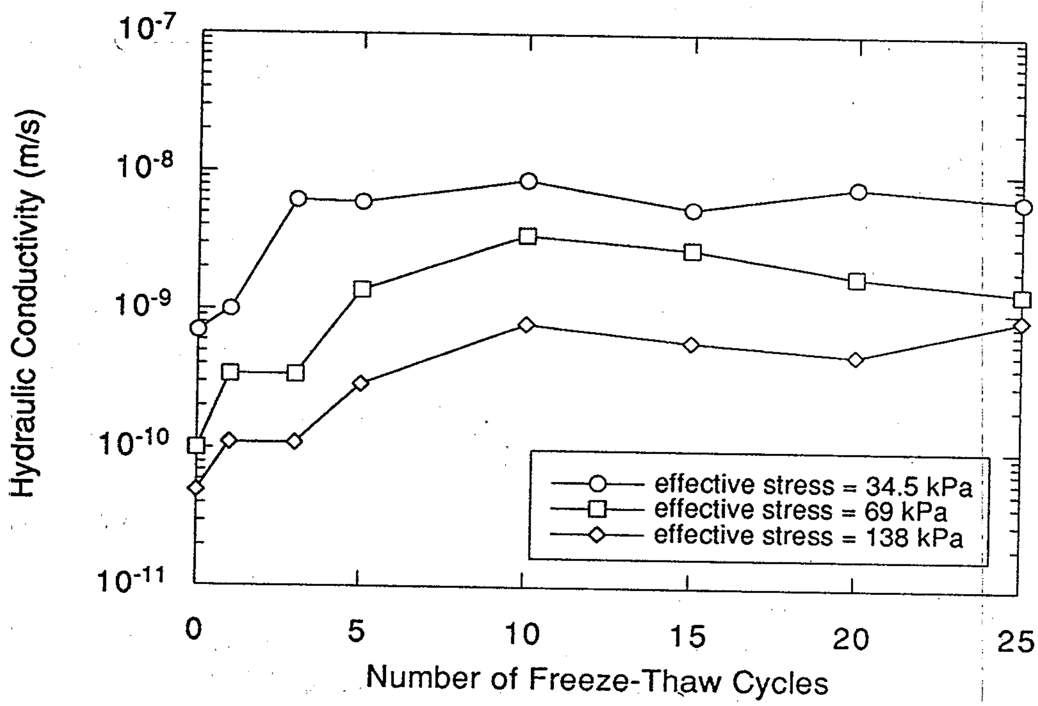


Figure 2.5. Hydraulic conductivity vs. number of freeze-thaw cycles at various effective stresses (after Zimmie et al. 1994)

SECTION 3

MATERIALS

3.1 CLAYS

3.1.1 Index Properties

Two clays were used in the testing program: Parkview clay and Valley Trail clay. Parkview clay is a low plasticity glacial till, whereas Valley Trail clay is a moderately plastic glacio-lacustrine clay. Both clays have been used in the construction of landfill liner and cover systems and were used to construct test pads for the COLDICE project (Sec. 2.1). Bulk samples of both clays used in this project were obtained from the COLDICE test pads.

Parkview clay is from a glacial deposit in Germantown, Wisconsin. It has a liquid limit of 30, plastic limit of 15, and plasticity index of 15 (ASTM D 4318). The location of Parkview clay on the plasticity chart is shown in Fig. 3.1. Particle size analyses of the clay (Fig. 3.2) showed that it is composed of 0.5% gravel, 11.5% sand, and 88.0% fines (particle sizes < 0.075 mm) based on definitions in the Unified Soil Classification System (USCS) (ASTM D 421). Clay content (particles finer than 2 μm) was found to be 36.5% by hydrometer analysis (ASTM D 422). Specific gravity tests on Parkview clay showed the clay has a specific gravity of 2.81 (ASTM D 854). Parkview clay is classified as CL in the USCS (ASTM D 2487).

Valley Trail clay is from a lacustrine deposit in Berlin, Wisconsin. It has a liquid limit of 45, plastic limit of 19, and plasticity index of 26. The location of Valley Trail clay on the plasticity chart is shown in Fig. 3.1. Particle size analyses of the clay (Fig. 3.2) showed that it is composed of 0.6% gravel, 3.8% sand, and 95.6% fines based on definitions in the USCS. Clay content was found to be 51.2% by hydrometer analysis. Specific gravity tests on Valley Trail clay showed the clay has a specific gravity of 2.77. Valley Trail clay is classified as CL-CH in the USCS.

3.1.2 Compaction

Compaction tests were conducted on the two clays to determine the relationships between dry unit weight, water content, and compactive effort. Two compactive efforts were used: standard Proctor (ASTM D 698) and modified Proctor (ASTM D 1557).

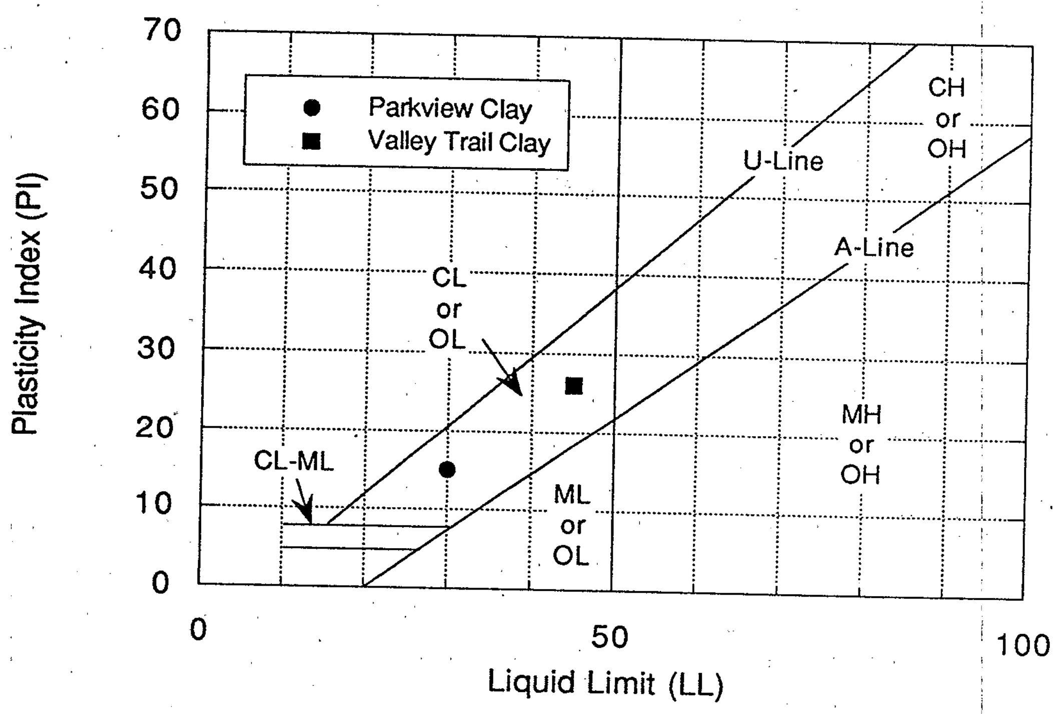


Figure 3.1. Plasticity chart showing locations of Parkview and Valley Trail clays.

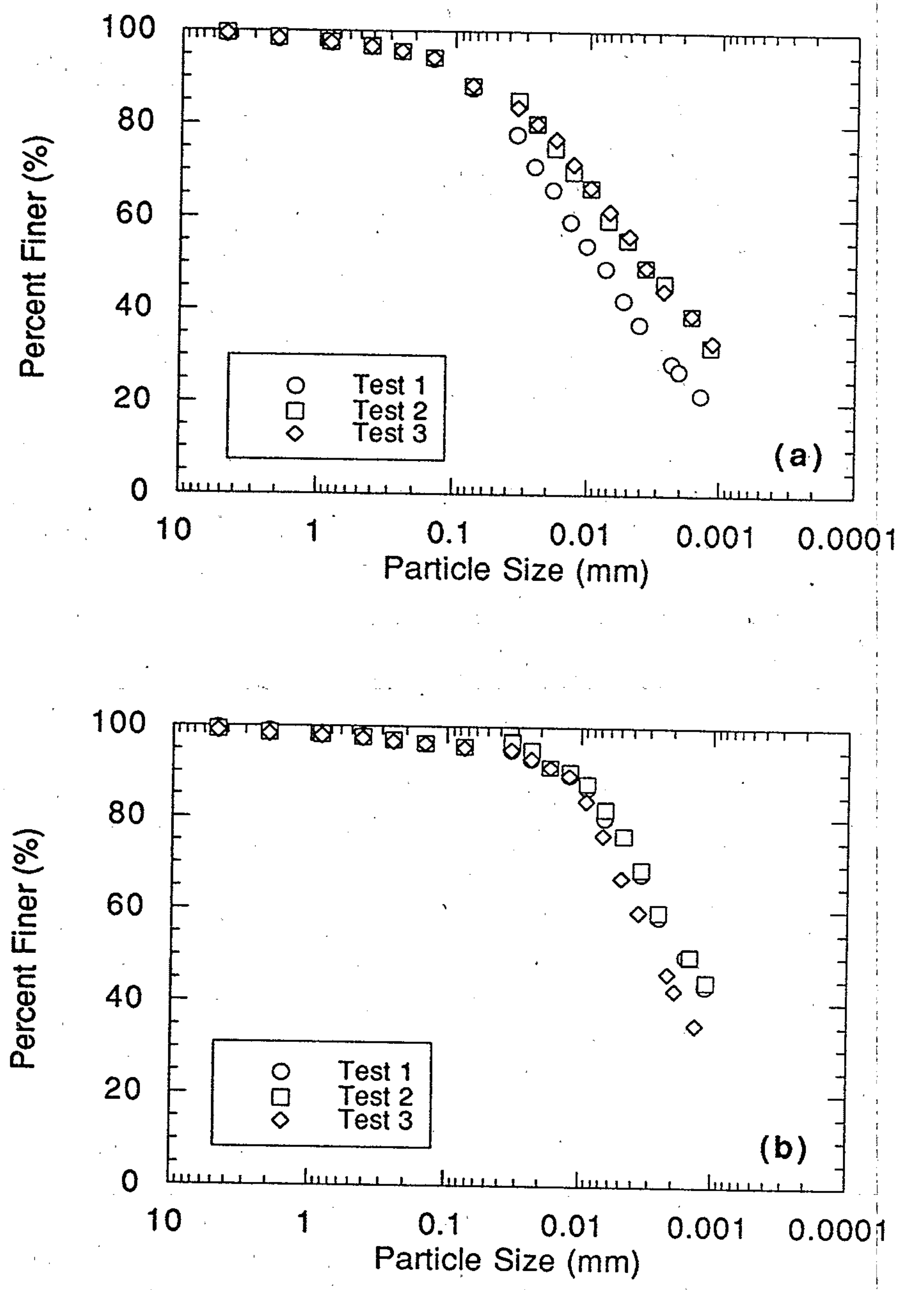


Figure 3.2. Results of particle size analyses for Parkview (a) and Valley Trail (b) clays.

Prior to compaction, the soil was air dried and crushed to pass the No. 4 sieve (particle size < 4.75 mm). The soil was then uniformly mixed with tap water from Madison, Wisconsin to a pre-determined water content. The moistened clay was sealed in a plastic bag or bucket and allowed to hydrate for at least 24 hours prior to compaction.

Compaction curves are shown in Figs. 3.3 and 3.4. For Parkview clay, optimum water contents of 14.1 and 9.6% were obtained for standard and modified Proctor compactive efforts, respectively. The maximum dry unit weights corresponding to these water contents are 18.8 and 21.1 kN/m^3. For Valley Trail clay, optimum water contents of 17.9 and 14.2% were obtained for standard and modified Proctor compactive efforts, respectively. The maximum dry unit weights corresponding to these water contents are 17.3 and 19.1 kN/m^3.

3.2 BENTONITIC BARRIER MATERIALS

3.2.1 Sand-Bentonite Mixture

3.2.1.1 Index Properties

One sand-bentonite mixture was used in the testing program. The sand-bentonite mixture was obtained from one of the COLDICE test pads (Sec. 2.2.1). The sand-bentonite mixture was prepared in the field using a pugmill prior to construction of the test pad (Erickson et al. 1994). The sand component is a clean mortar sand, which was purchased from a concrete supplier near the landfill site. The sand is a poorly graded, clean, medium to fine sand and is classified as SP in the USCS. More than 90% of the sand passed the No. 30 sieve and less than 5% passed the No. 200 sieve (Fig. 3.5). The bentonite component is a granular sodium bentonite (American Colloid CG-50) with no polymer additives.

The sand-bentonite mixture has a liquid limit of 42, plastic limit of 29, and plasticity index of 13. Methylene blue titration tests were performed to measure the bentonite content of the sand-bentonite. Measurements were made on grab samples of the mixture from a drum stored in the laboratory. The average bentonite content was 12% by weight. Specific gravity tests showed that the sand-bentonite mixture has a specific gravity of 2.70.

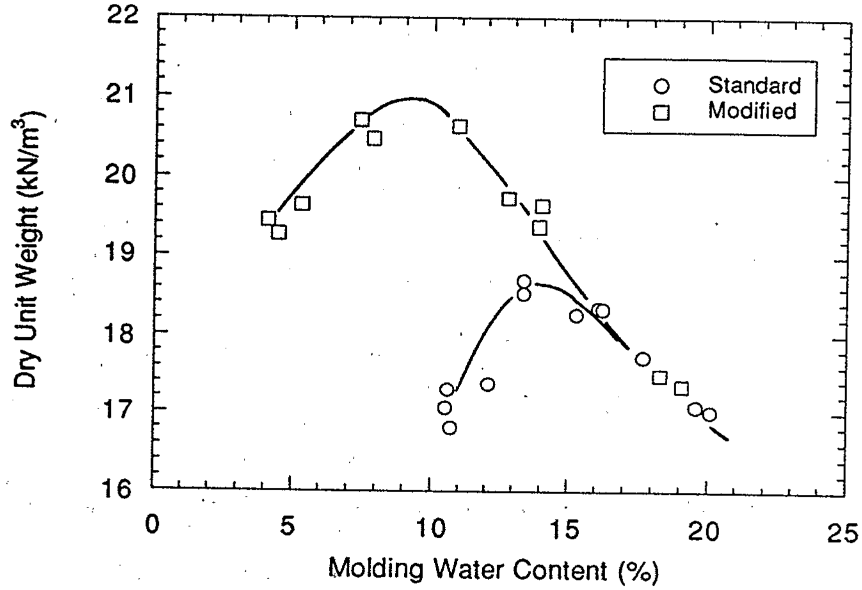


Figure 3.3. Compaction curves for Parkview clay.

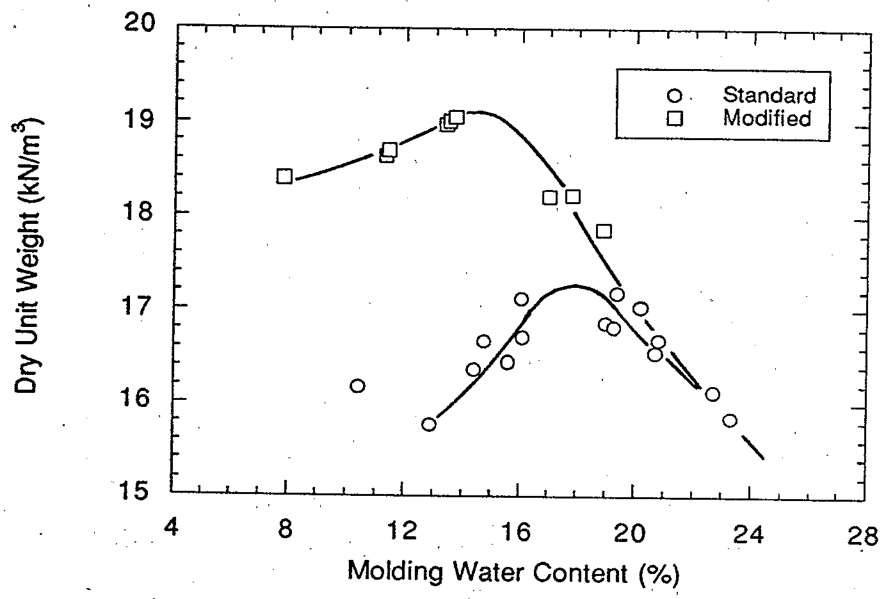


Figure 3.4. Compaction curves for Valley Trail clay.

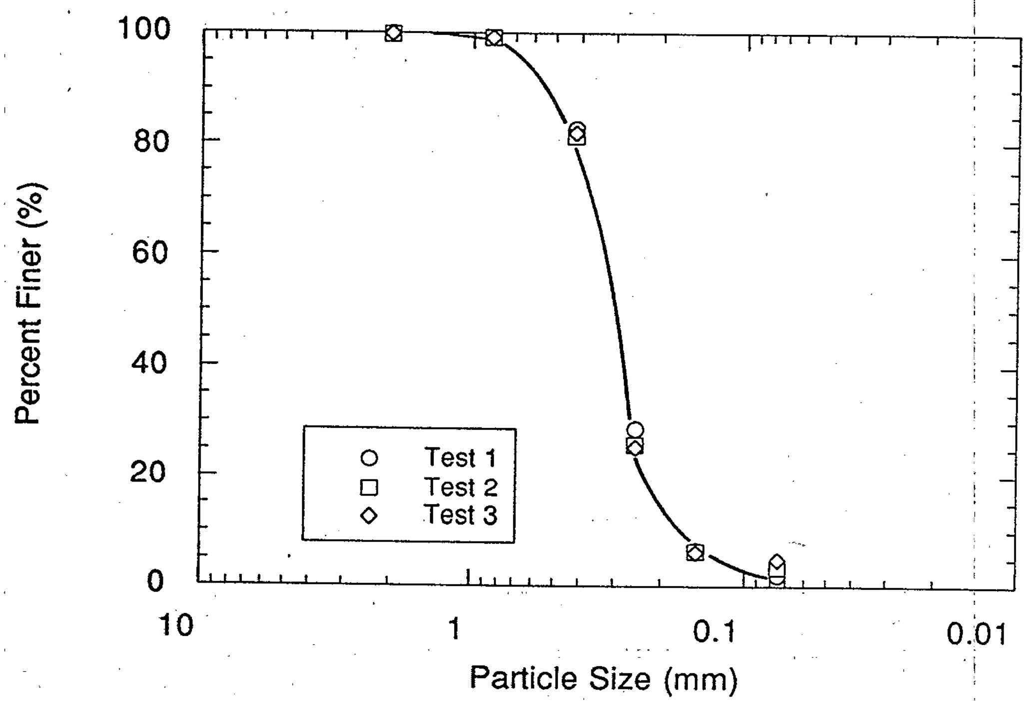


Figure 3.5. Results of particle size analysis for sand component of sand-bentonite mixture.

3.2.1.2 Compaction

Compaction tests were conducted to determine the relationships between dry unit weight, water content, and compactive effort. Two compactive efforts were used: standard Proctor and modified Proctor.

Prior to compaction, the sand-bentonite was air dried and crushed to pass the No. 4 sieve. The sand-bentonite was then uniformly mixed with tap water from Madison, Wisconsin to a pre-determined water content. The moistened mixture was sealed in a plastic bag or bucket and allowed to temper for at least 24 hours prior to compaction.

Compaction curves for the sand-bentonite mixture are shown in Fig. 3.6. Optimum water contents of 16.5 and 12.3% were obtained for standard and modified Proctor compactive efforts, respectively. The maximum dry unit weights corresponding to these water contents are 17.4 and 18.8 kN/m^3.

3.2.2 Geosynthetic Clay Liners (GCLs)

Geosynthetic clay liners (GCLs) are commercially manufactured products that consist of highly swelling bentonitic clay either sandwiched between two geotextiles or glued to a geomembrane. Three geosynthetic clay liners were used in this study: Bentofix®, Bentomat®, and Claymax®. Two of the GCLs (Bentomat® and Claymax®) were used as liners for test ponds and test pans in the COLDICE project (Erickson et al. 1994).

Two rolls of each GCL were shipped to the University of Wisconsin-Madison by their manufacturers. The rolls were wrapped in plastic to prevent absorption of water and stored in the Environmental Geotechnics Laboratory at the University of Wisconsin-Madison.

Bentofix® is manufactured by the National Seal Company (NSC) by needle-punching loose granular bentonite between two geotextiles (Fig. 3.7). For this project, a Bentofix® GCL with a 140 g/m^2 upper, woven polypropylene geotextile and a 270 g/m^2 lower, non-woven polypropylene geotextile was used. The mass per unit area of the Bentofix® GCL was 6.8 kN/m^2 (ASTM D 5261). Free swell tests performed on the bentonite from Bentofix® using GRI GCL-1showed that the average free swell was 18.1 mm. Results of the mass per unit area and free swell tests are shown in Table 3.1.

Bentomat® is manufactured by the Colloid Environmental Technologies Company (CETCO) by needle-punching granular Volclay® bentonite between two

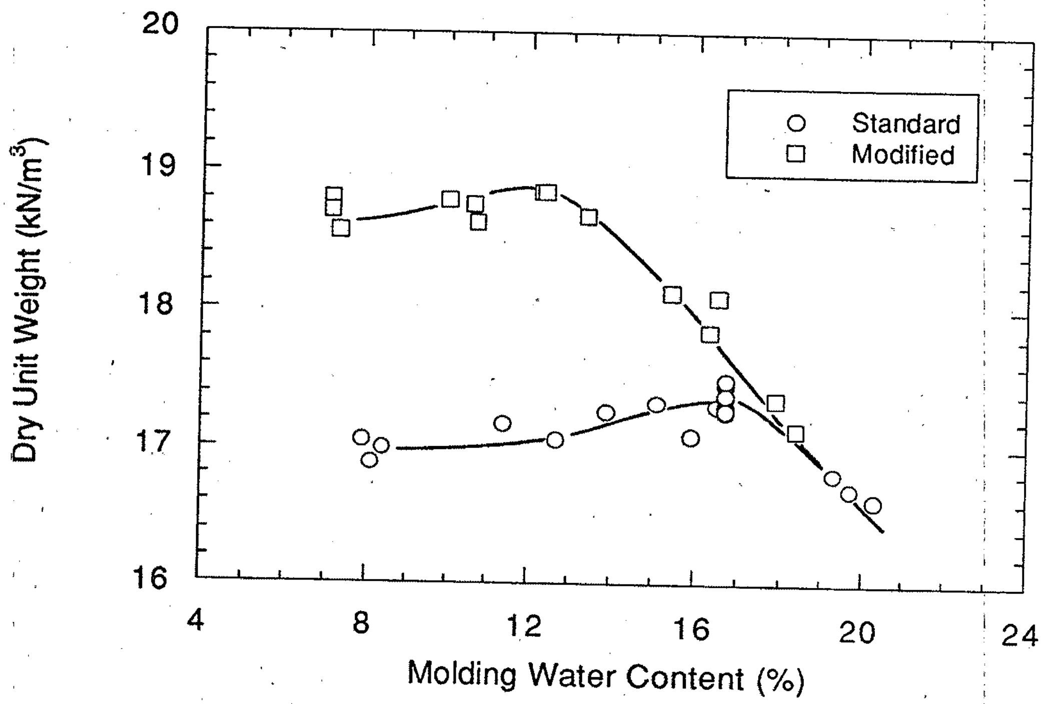


Figure 3.6. Compaction curves for sand-bentonite.

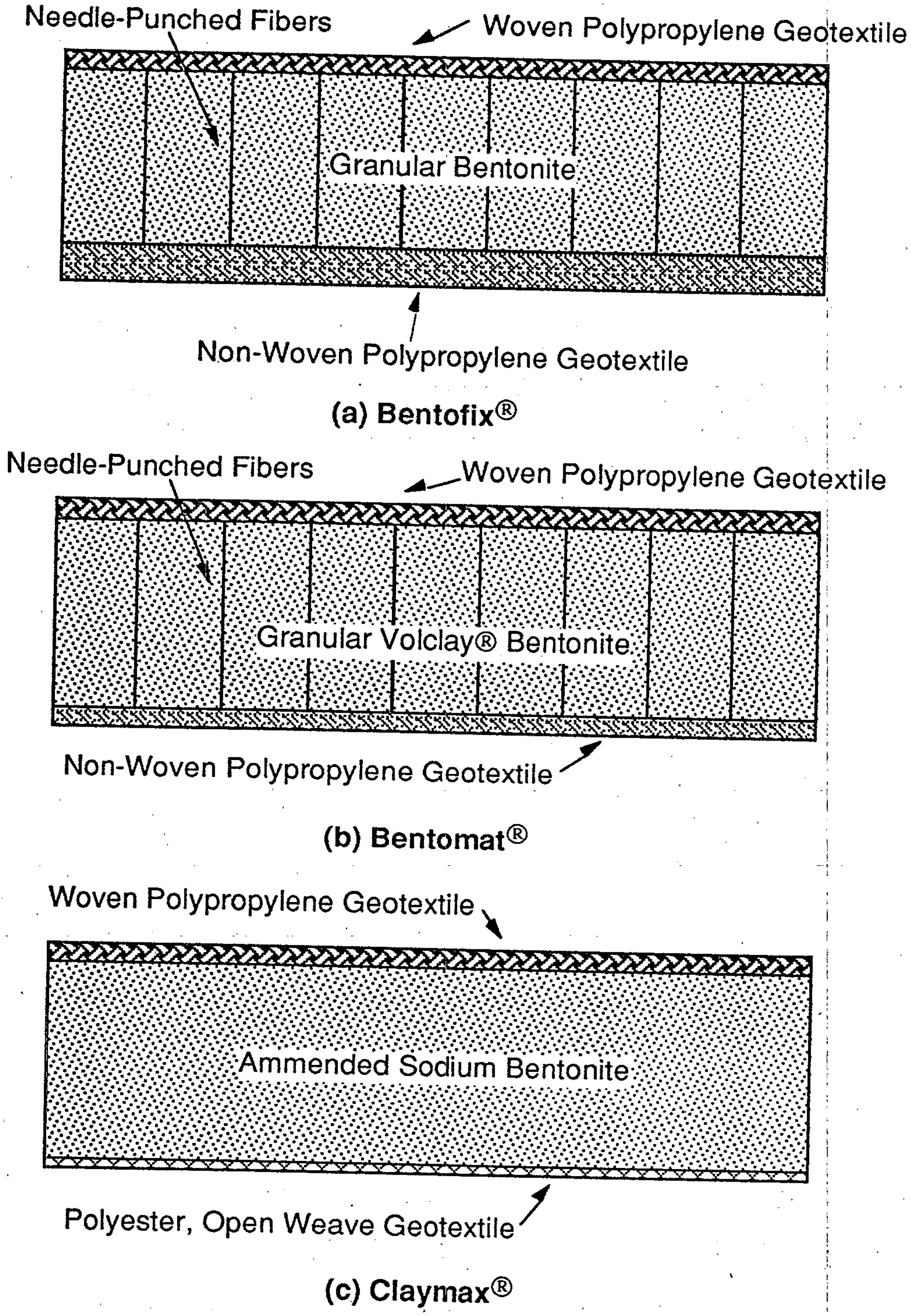


Figure 3.7. Schematic diagrams of Bentofix® (a), Bentomat® (b), and Claymax® (c) GCLs.

Table 3.1. Results of GCL mass per unit area and free swell tests.

Specimen Number	Mass per Unit Area (kg/m^2)	Free Swell (mm)
Bentofix-1	7.4	12.3
Bentofix-2	6.5	9.5
Bentofix-3	6.4	7.1
Bentomat-1	6.1	16.5
Bentomat-2	6.1	18.0
Bentomat-3	no test	19.8
Claymax-1	6.5	5.6
Claymax-2	6.4	6.6
Claymax-3	6.4	7.9

geotextiles (Fig. 3.7) (Daniel and Estornell 1990). For this project, Bentomat® "CS" with a 140 g/m^2 upper, woven polypropylene geotextile and a 140 g/m^2 lower, non-woven polypropylene geotextile was used. The mass per unit area of the Bentomat® was 6.1 kN/m^2. Free swell tests performed on bentonite from Bentomat® showed that the average free swell was 9.6 mm (Table 3.1).

Claymax® is manufactured by the James Clem Corporation in Arlington Heights, Illinois. It is comprised of amended sodium bentonite sandwiched between two woven, polypropylene geotextiles (Fig. 3.7). The bentonite is adhered to the two geotextiles using a non-toxic, water soluble adhesive (Daniel and Estornell 1990).

For this project, Claymax® 200R with a 140 g/m^2 upper polypropylene geotextile and 25 g/m^2 lower polyester, open-weave geotextile was used. The mass per unit area of the Claymax® used was 6.4 kN/m^2. Free swell tests performed on bentonite from Claymax® showed that the average free swell was 6.7 mm (Table 3.1).

3.3 PAPER MILL SLUDGES

3.3.1 Index Tests

Three paper industry sludges were used in the testing program, and are referred to as sludges A, B, and C. Sludge A is a combined sludge; the sludge is composed of primary sludge from the clarification of raw wastewater and biological sludge from an activated sludge treatment plant. Sludge A is from a non-integrated mill which produces specialty grades and coated and uncoated book grades. Sludge B is a primary paper mill sludge from a non-integrated mill which produces specialty coated, lightweight coated, coated bag, and pressure sensitive paper. Sludge C is a combined (primary and biological) sludge from a de-inking mill which produces disposable garments and napkin and tissue paper. Sludges A and B are from paper mills in Michigan, whereas Sludge C is from a paper mill in Massachusetts. Bulk samples of the sludges were supplied by the National Council of the Paper Industry for Air and Stream Improvement (NCASI) office in Kalamazoo, Michigan.

Attempts were made to determine the liquid and plastic limits of the three sludges. However, difficulties were encountered when performing the Atterberg limits tests. The fibrous nature of the sludge prevents changes in the behavior of the sludge with changes in water content. Therefore, measurements of the liquid and plastic limits were not possible. Similar difficulties with Atterberg limit tests have been reported by NCASI (1989) and Genthe (1993).

Sludge A contains 58.9% fines as determined by wash sieving the sludge past the No. 200 sieve. The ash content of Sludge A is 56.0% (ASTM D 2974). Fractionation of Sludge A by wet screening was found to be 78.5% (TAPPI T 261). The weighted average fiber length of Sludge A is 0.24 mm (TAPPI T 233).

Sludge B contains 75.8% fines as determined by wash sieving the sludge past the No. 200 sieve. The ash content was found to be 53.1%. Fractionation of Sludge B by wet screening was found to be 85.5%. The weighted average fiber length of Sludge B is 0.12 mm.

Sludge C contains 79.8% fines as determined by wash sieving past the No. 200 sieve. The ash content of Sludge C is 44.4%. Fractionation of Sludge C by wet screening is 76.5%, whereas the weighted average fiber length of Sludge C is 0.29 mm.

3.3.2 Compaction

Compaction tests were conducted on the three sludges to determine the relationship between dry unit weight and water content. Standard Proctor compactive effort was used.

Prior to compaction, the sludge was allowed to air dry from its "as-received" water content. At various times, a grab sample was taken, sealed in a plastic bag or bucket, and allowed to equilibrate at least 24 hours prior to compaction. This method was used because previous research has shown that re-wetting completely air-dried sludge results in a loss of plasticity (NCASI 1989, Zimmie et al. 1994).

Compaction curves for the three sludges are shown in Figs. 3.8-3.10. For Sludge A, the optimum water content is 40% and the maximum dry unit weight is 8.7 kN/m^3. For Sludge B, optimum water content is 97% and the maximum dry unit weight is 6.0 kN/m^3. For Sludge C, the optimum water content is 72%, whereas the maximum dry unit weight is 6.4 kN/m^3.

Results of the compaction tests indicate that sludges have compaction properties similar to those of clays. However, the optimum water contents determined for the sludges are higher in comparison to typical optimum water contents for clays (~10-30%) and the maximum dry unit weights are lower than those for clays (~15-19 kN/m^3).

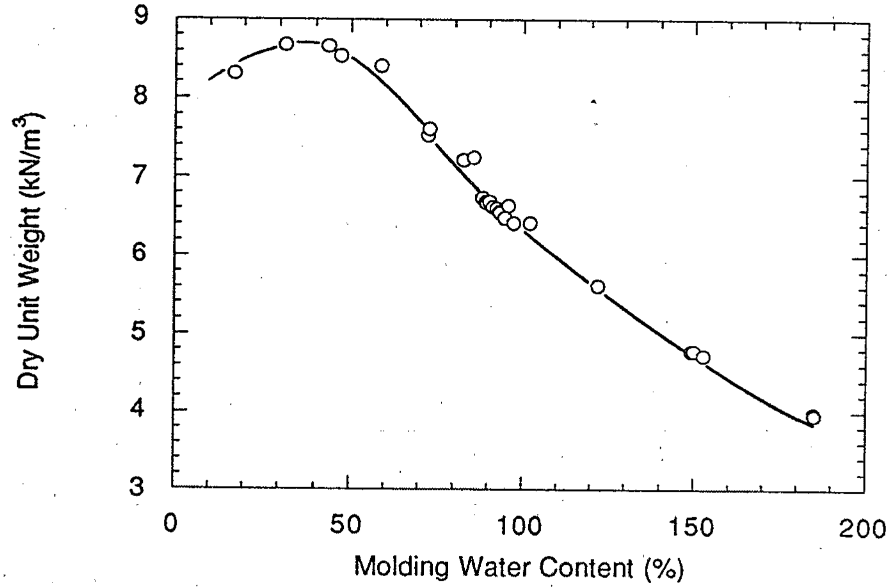


Figure 3.8. Compaction curve for Sludge A.

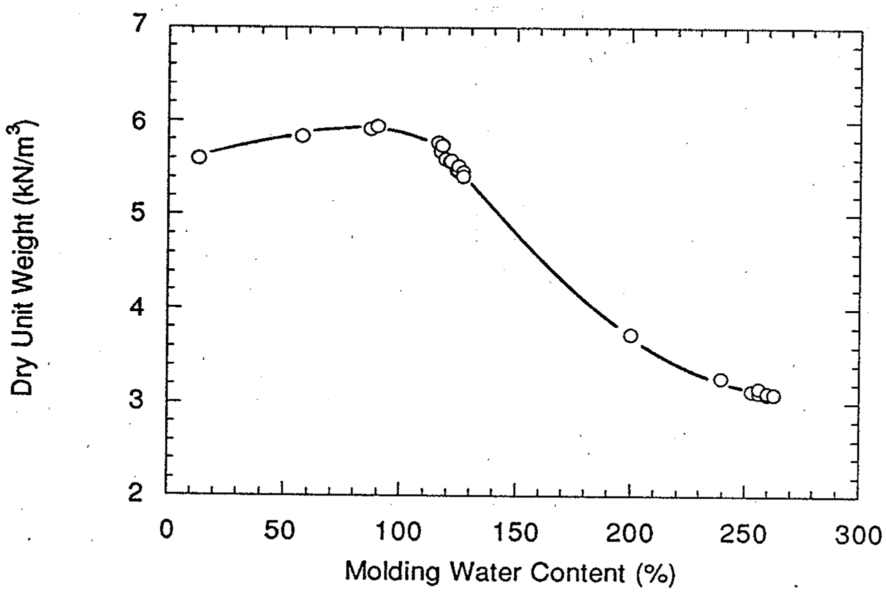


Figure 3.9. Compaction curve for Sludge B.

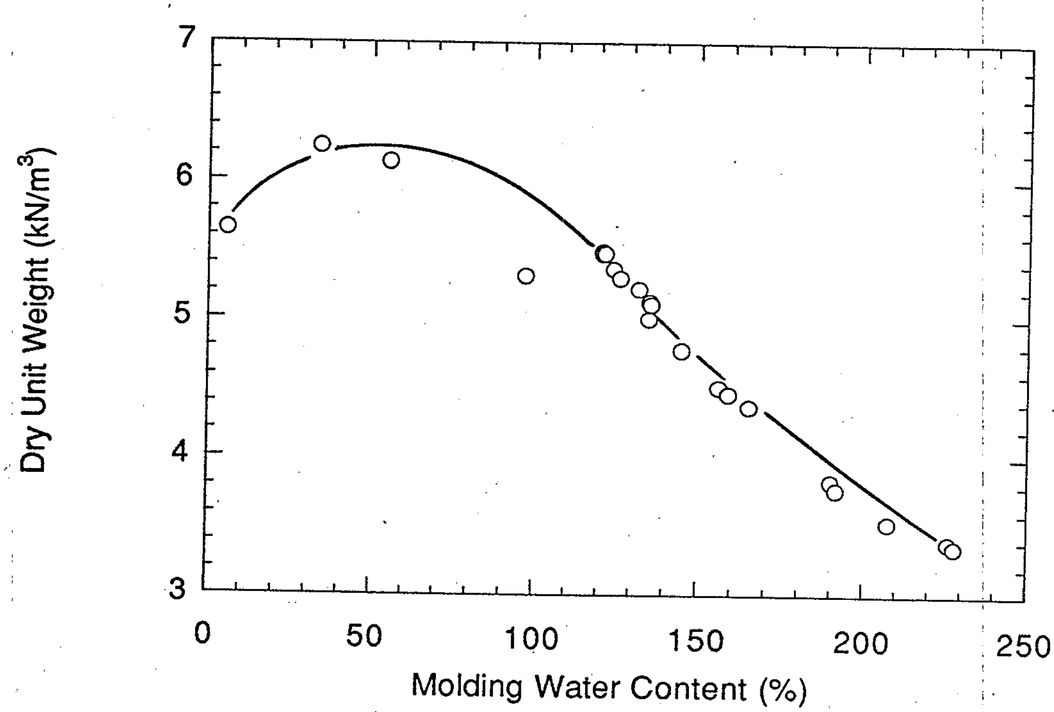


Figure 3.10. Compaction curve for Sludge C.

SECTION 4

METHODS

4.1 CLAYS

4.1.1 Field Methods

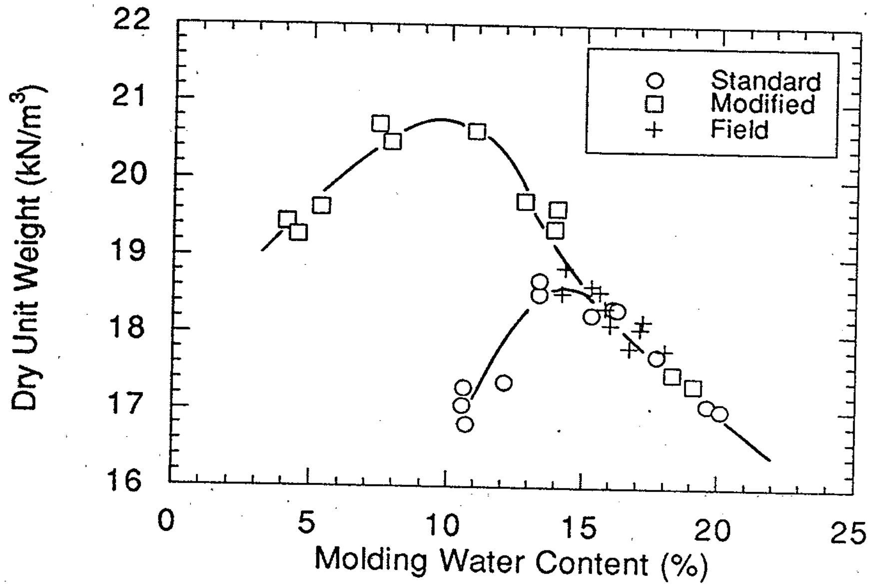
4.1.1.1 COLDICE Test Pads

The tests performed on clay in this study were conducted for comparison to field data collected from tests on large-scale test pads constructed for the COLDICE project. The COLDICE project was conducted by CH2M Hill, Inc., the U. S. Army Cold Regions Research and Engineering Laboratory (CRREL), and a suite of industrial partners at a landfill near Milwaukee, Wisconsin (Erickson et al. 1994) as a Construction Productivity Advancement Research (CPAR) project. Assistance was also provided by the University of Wisconsin-Madison. The objective of the COLDICE project was to evaluate how freeze-thaw affects the hydraulic conductivity of compacted clays and geosynthetic clay liners (GCLs) at field-scale.

Four test pads in the COLDICE project were constructed with compacted clay. Two of the pads were constructed with Parkview clay and two were constructed with Valley Trail clay. The test pads were labeled: PV-2, PV-3, VT-4, and VT-5 (Chamberlain et al. 1995). Each test pad was 9 m by 21 m. Two test pads had thicknesses of 0.6 m (PV-2 and VT-5), and two had thicknesses of 0.9 m (PV-3 and VT-4). Two thicknesses were used such that the effects of fully- or partially-penetrating frost could be examined (Erickson et al. 1994).

A layer of high-density polyethylene (HDPE) geomembrane was placed above a prepared subgrade and a geocomposite drain (non-woven geotextile on each side of a geonet) was placed above the HDPE geomembrane (Erickson et al. 1994). Clay was placed in 0.15 m loose lifts and the lifts were compacted with a Caterpillar 825C tamping foot compactor at water contents 2-5% wet of standard Proctor optimum. Relative compaction exceeding 95% of standard Proctor maximum dry unit weight was obtained for each test pad (Benson et al. 1994). All of the measurements of molding water content and dry unit weight made during construction fell wet of the line of optimums (Benson et al. 1994) (Fig. 4.1). Construction of the test pads was completed in October 1992 (Erickson et al. 1994).

The 0.6 m-thick pads (PV-2 and VT-5) were covered with a 0.15 mm thick polyethylene sheet and 0.1 m of sand to minimize desiccation. Test pad PV-3 was



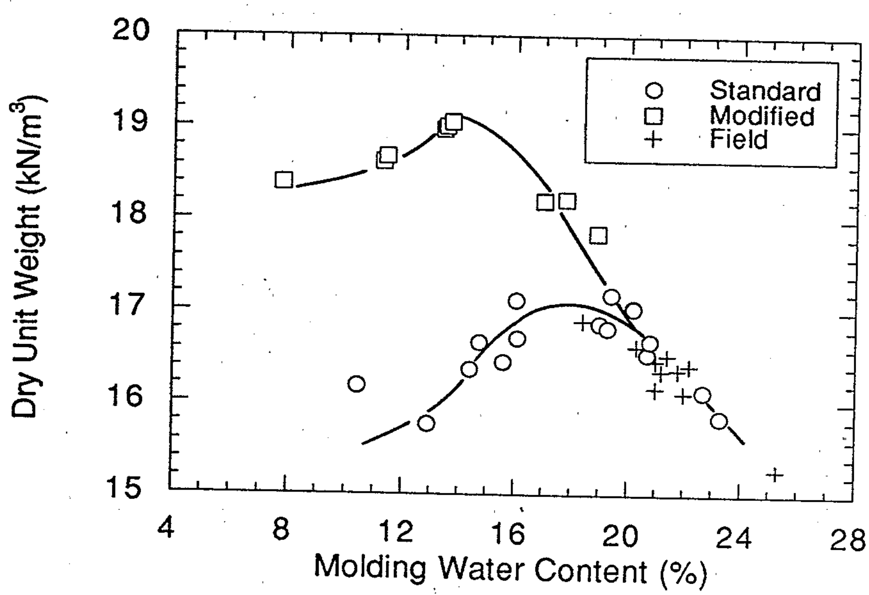


Figure 4.1. Compaction curves and field compaction data for Parkview (a) and Valley Trail (b) test pads.

covered with a needle-punched non-woven geotextile and 0.3 m of gravel. Test pad VT-4 was covered with 0.3 m of well-graded sand.

An array of thermistors was placed within the test pads and an automated weather station was installed at the COLDICE field site (Erickson et al. 1994). Measurements of frost depth and climatic conditions were recorded every five minutes using a Campbell Scientific datalogger. Hourly averages were computed and transferred to a computer at the CRREL laboratory in Hanover, New Hampshire via a cellular phone and computer modem (Erickson et al. 1994). Figure 4.2 is diagram of the COLDICE project field test layout.

4.1.1.2 In Situ Box Infiltrometers

Erickson et al. (1994) installed box infiltrometers to measure the field-scale hydraulic conductivity of the test pads. The infiltrometers were designed to measure hydraulic conductivity before and after exposure to freeze-thaw without disturbing the structure of the soil. Infiltrometers were placed in test pads PV-2 and PV-3. No infiltrometers were installed in either of the Valley Trial test pads.

Figure 4.3 is a schematic of the box infiltrometers. Immediately following construction of the test pads, trenches were excavated to leave a 1.3 m by 1.3 m block of undisturbed soil. An HDPE box with an open top and bottom was placed around the block of soil and seamed to the underlying HDPE geomembrane. Pipes and filters were connected to the geocomposite drain to carry any infiltration to a sump for measurement. The annular space between the block of clay and the HDPE was filled with a bentonite grout to prevent sidewall leakage.

A non-woven geotextile was placed on top of the block of soil and 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. The infiltrometers were covered with 0.6 m of sand to prevent uplift of the lids. The sand layer was reduced to a thickness of 0.1 m (level with the surrounding overburden) during winter months to allow penetration of the freezing plane into the compacted clay.

4.1.1.3 Laboratory Assessment of Field-Scale Hydraulic Conductivity

Hydraulic conductivity tests were performed in the laboratory on specimens removed from the test pads to assess field-scale hydraulic conductivity. Specimens were removed from the field by three methods: as large blocks (diameter = 0.4 m),

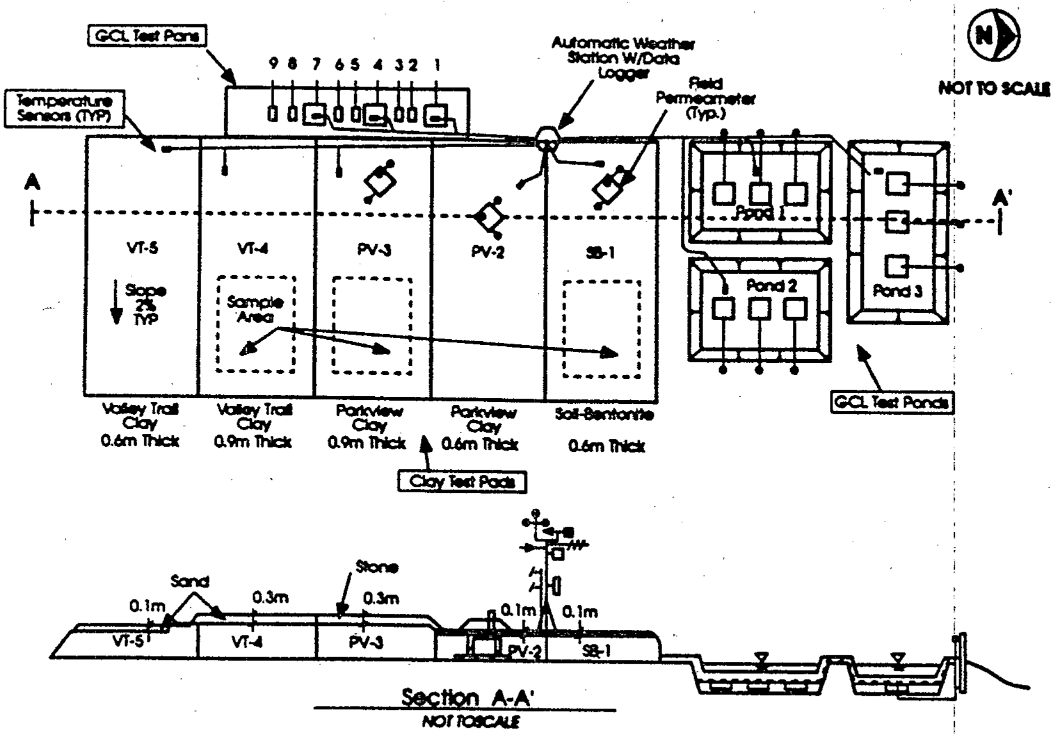


Figure 4.2. COLDICE project field test layout (from Erickson et al. 1994).

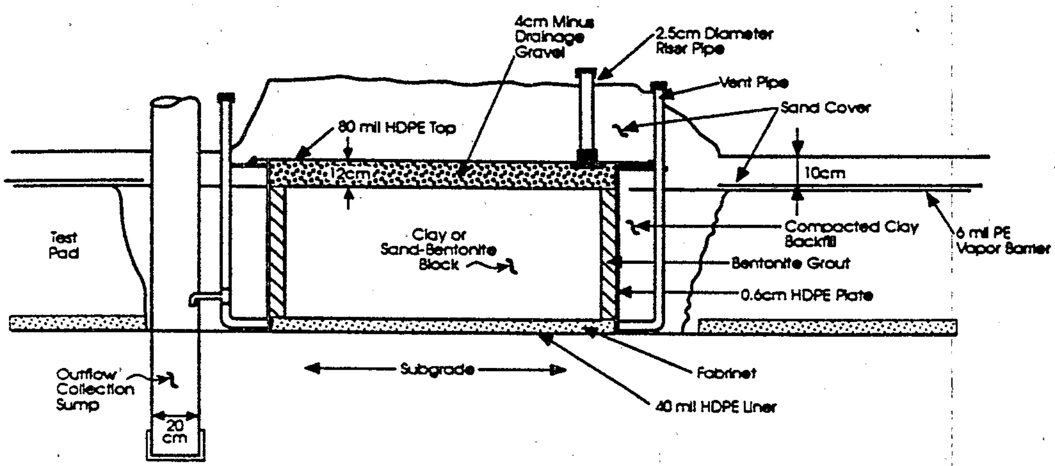


Figure 4.3. Schematic of in situ box infiltrometer (from Erickson et al. 1994).

using thin-wall sampling tubes (Shelby tubes, diameter = 71 mm), and as frozen cores (diameter = 71 mm). The specimens removed as blocks and with thin-wall tubes were collected by personnel from the University of Wisconsin-Madison. Personnel from CRREL and CH2M Hill, Inc. obtained the frozen cores.

Large block specimens were removed before freezing in December 1992 and after thawing in June 1993. Thin-wall sampling tubes were used in June 1993. A frozen core barrel sampler developed at CRREL was used to remove frozen specimens in March 1993. The frozen core barrel sampler is designed to remove a soil specimen while the soil is frozen. Removing specimens while frozen prevents disturbance and preserves the soil and ice structure (Benson et al. 1994). Flexible-wall permeameters were used to measure the hydraulic conductivity of all specimens removed from the COLDICE test pads (Figs. 4.4 and 4.5).

The large block specimens were removed using a procedure developed at the University of Wisconsin-Madison. Othman et al. (1994) describe the procedure in detail. The following is a brief summary of the sampling procedure:

1. A location for sampling is chosen and marked and the surface is cleaned and leveled. For this project, cleaning consisted of removing 0.1 to 0.3 m of gravel or sand (and underlying geosynthetics) overlying the clay.

2. Trenches are excavated around the marked area using a shovel. The specimen is trimmed from the remaining block of soil.

3. A PVC ring (inside diameter = 0.40 m, height = 0.30 m) is placed on the surface of the block of soil. The ring has a vertical cut that is used to expand the ring during removal of the specimen in the laboratory. Excess soil around the ring is gently trimmed away and the ring is slowly pushed by hand over the block of soil in a manner similar to trimming a specimen for consolidation testing (Fig. 4.6). Trimming of excess soil is continued until the ring is pushed to full depth (~0.30 m).

4. The specimen is separated from the underlying soil by pressing a flat spade into the underlying soil around the perimeter of the ring or by

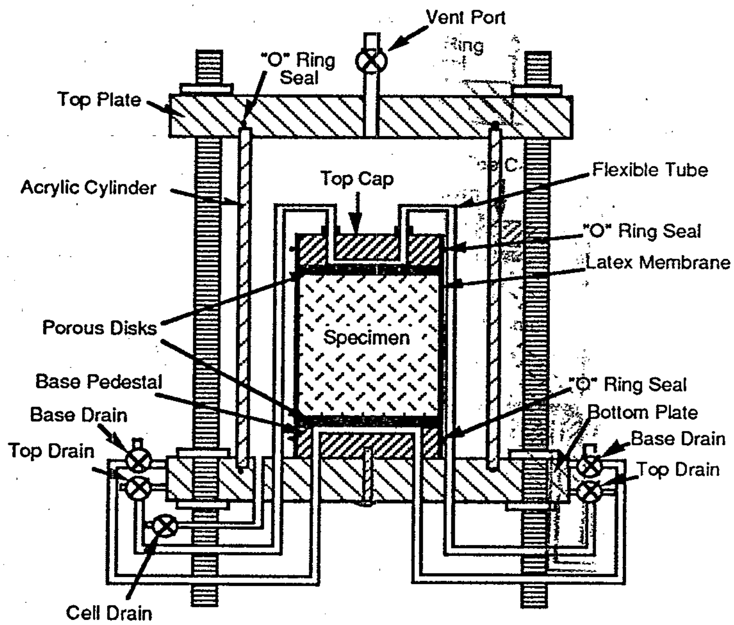


Figure 4.4. Flexible-wall permeameter.

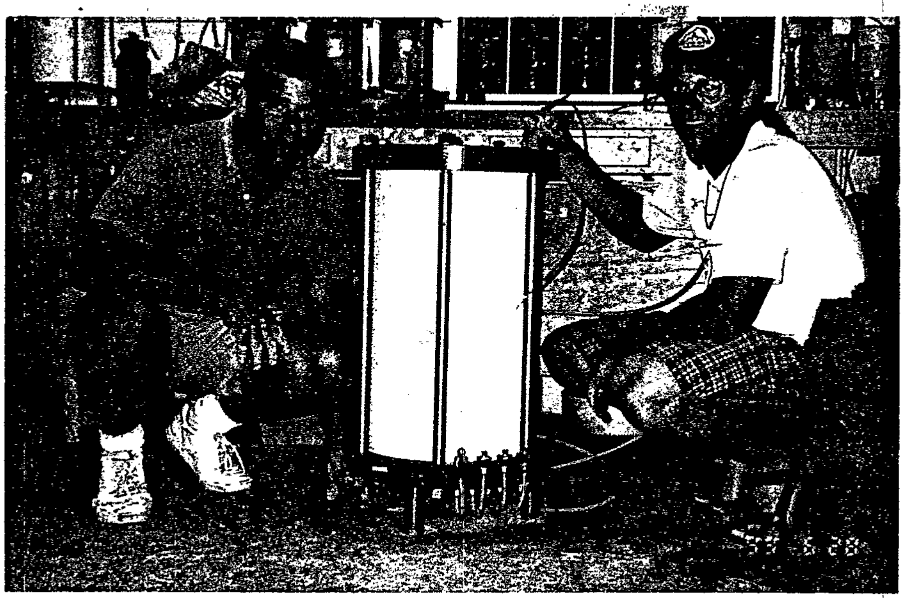


Figure 4.5. Large flexible-wall permeameter used for measuring hydraulic conductivity of block specimens.

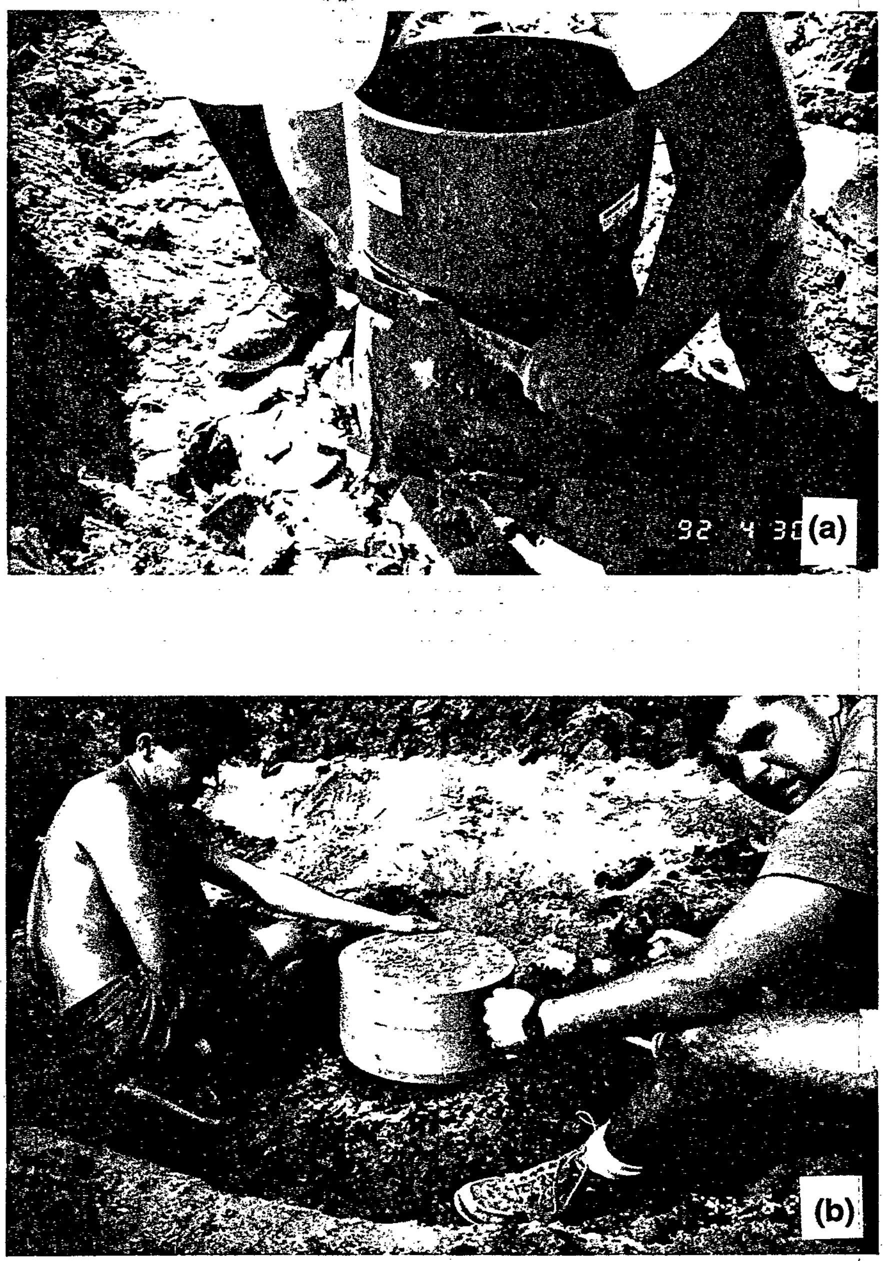


Figure 4.6. Trimming of block specimen (a) and separating block specimen from underlying soil using a wire saw (b).

using a wire saw (Fig 4.6). Once the specimen is separated from the underlying soil, excess soil is trimmed away and it is placed on a pallet.

5. The specimen is sealed with two layers of plastic wrap to prevent desiccation during transport to Madison, where it is placed in a humid room until testing.

Block specimens were taken along one continuous profile at three depths (0-0.3 m, 0.3-0.6 m, and 0.6-0.9 m) from the 0.9 m-thick test pads (PV-3 and VT-4). Three specimens were removed from the test pad before winter (December 1992) and four specimens were removed after one winter (June 1993). A second specimen was obtained in June 1993 from a depth of 0-0.3 m to obtain an additional measurement of the surficial hydraulic conductivity.

Before being placed in permeameters, the PVC ring was removed from the specimens and excess or disturbed soil was trimmed away until the specimens had a diameter of 0.3 m and a height of 0.15 to 0.20 m. The block specimens were placed in large flexible-wall permeameters and permeated at an average effective stress of 10.5 kPa, hydraulic gradients of 4 to 5, and a backpressure of 413 kPa. Tap water from Madison, Wisconsin was used as the permeant. The specimens were permeated until the hydraulic conductivity measurement was steady (no upward or downward trend over time) and the ratio of outflow to inflow was between 0.75 and 1.25.

Specimens were also removed from the COLDICE test pads using thin-wall sampling tubes (diameter = 71 mm). Specimens were removed from the test pads in June 1993, after one winter of exposure. The sampling tubes were sealed in the field and shipped to the University of Wisconsin-Madison. In the laboratory, the specimens were extruded from the sampling tubes, sealed in plastic wrap, and stored in a high humidity room prior to hydraulic conductivity testing.

The specimens collected in thin-wall tubes were permeated in flexible-wall permeameters at an average effective stress of 7 kPa and hydraulic gradients ranging from 2 to 5. A backpressure of 280 kPa was used. Tap water from Madison, Wisconsin was used as the permeant. Specimens were permeated until hydraulic conductivity was steady and the ratio of outflow to inflow was between 0.75 and 1.25

The core barrel sampler developed at CRREL was used to remove specimens from the COLDICE test pads in March 1993 while the soil was frozen (Erickson et al.

1994, Benson et al. 1994). The core barrel sampler removes a specimen having a diameter of 71 mm and length up to 0.9 m (Fig 4.7). A power auger was used to slowly advance the core barrel so as not to melt the frozen soil. The barrel was then retracted and the frozen specimen was removed from the barrel. The specimens were then wrapped in plastic and packaged in an insulated box with ice packs for overnight shipping to CRREL. All of the specimens obtained with the core barrel were removed by personnel from CH2M Hill, Inc. or CRREL as part of the COLDICE project.

Storage and placement of the core barrel specimens in flexible-wall permeameters was conducted in a cold room at CRREL by CRREL staff (Chamberlain et al. 1995). The frozen core specimens were allowed to thaw and consolidate at an average effective stress of 7 kPa. Hydraulic conductivity tests were then performed at the same average effective stress using hydraulic gradients ranging from 2 to 5. A backpressure of 380 kPa was used and tap water from Hanover, New Hampshire was used as the permeant (Chamberlain et al. 1995).

4.1.2 Laboratory Methods

4.1.2.1 Hydraulic Conductivity-Water Content Relationships

Specimens of the Parkview and Valley Trail clays that were compacted to determine compaction curves corresponding to standard and modified Proctor efforts (Sec. 3.1.2) were also used to determine the corresponding hydraulic conductivity-water content relationships. After compaction, the specimens were extruded from the compaction molds, sealed in plastic wrap to prevent desiccation, and stored until permeation.

The specimens were placed in flexible-wall permeameters for saturation and measurement of hydraulic conductivity. The falling head-rising tailwater method was used (ASTM D 5084-Method D). An average effective stress of 7 kPa, hydraulic gradient of 12, and backpressure of 128 kPa were used. Tap water from Madison, Wisconsin was used as the permeant.

Each test was terminated when the hydraulic conductivity was steady (change < ± 25% and no increasing or decreasing trend) and the ratio of outflow to inflow was between 0.75 and 1.25 for four consecutive readings. The hydraulic conductivity was reported as the arithmetic mean of the last four measurements.

4.1.2.2 Standard Freeze-Thaw Tests

Three specimens each of Parkview clay and Valley Trail clay were compacted at standard Proctor effort at water contents similar to the water content used in construction of the COLDICE test pads. These water contents also yielded the lowest hydraulic conductivities determined in Sec 4.1.2.1. Each specimen was extruded from its compaction mold, sealed in plastic wrap to prevent desiccation, and stored until permeation.

The clay specimens were placed in flexible-wall permeameters to determine their initial hydraulic conductivity (before exposure to freeze-thaw). Test conditions identical to those described in Sec. 4.1.2.1 were employed. After the initial hydraulic conductivity tests were complete, the specimens were carefully removed from the permeameters. They were then sealed in plastic wrap and duct tape to prevent desiccation and placed in a laboratory freezer for cooling. Extreme care was used when handling the specimens to avoid disturbing the soil structure.

The free-standing procedure described by Othman et al. (1994) was used to freeze the specimens in a closed system (no external supply of water). They were cooled to an ultimate temperature of -20°C at a freezing rate of approximately 52 mm/hr. The free-standing procedure results in three-dimensional freezing as opposed to one-dimensional freezing which occurs in the field. Othman and Benson (1993b) and Zimmie and LaPlante (1990) have shown, however, that the dimensionality of freezing does not affect the change in hydraulic conductivity, even though it does result in somewhat different ice and crack structures.

The specimens were left in the freezer for at least 24 hours, at which point they were removed and allowed to thaw at room temperature (25°C). After 24 hours of thawing, the specimens were placed back in the freezer. Data collected from control specimens instrumented with thermocouples showed that the 24 hour period was more than adequate to ensure that complete freezing or thawing occurred (Fig. 4.8). This procedure was repeated until the desired number of freeze-thaw cycles was attained.

The hydraulic conductivity of each specimen was measured in flexible-wall permeameters after 1, 3, and 5 freeze-thaw cycles. To minimize disturbance, frozen specimens were removed from the freezer and placed in flexible-wall permeameters to thaw. The cell pressure and hydraulic gradient were applied immediately. The falling head-constant tailwater method for measuring hydraulic conductivity was used (ASTM

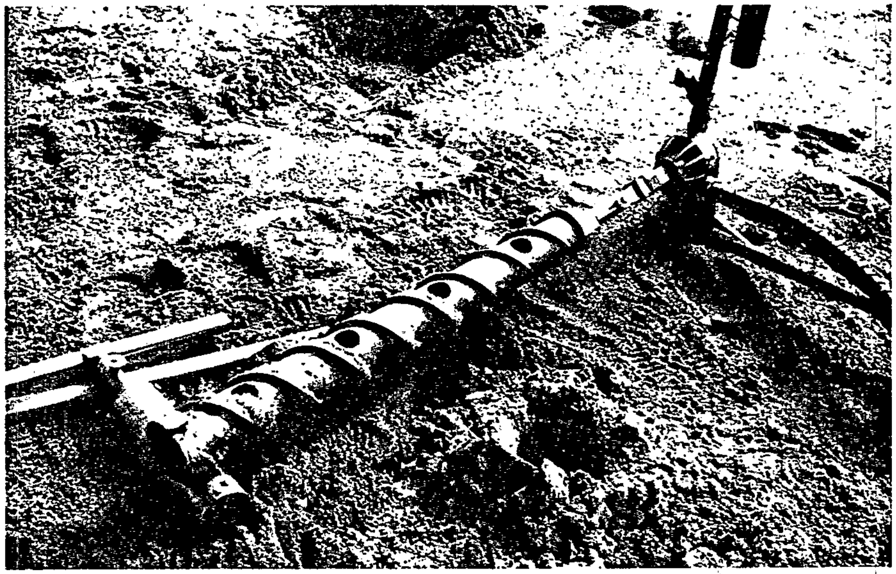


Figure 4.7. CRREL frozen soil core barrel sampler.

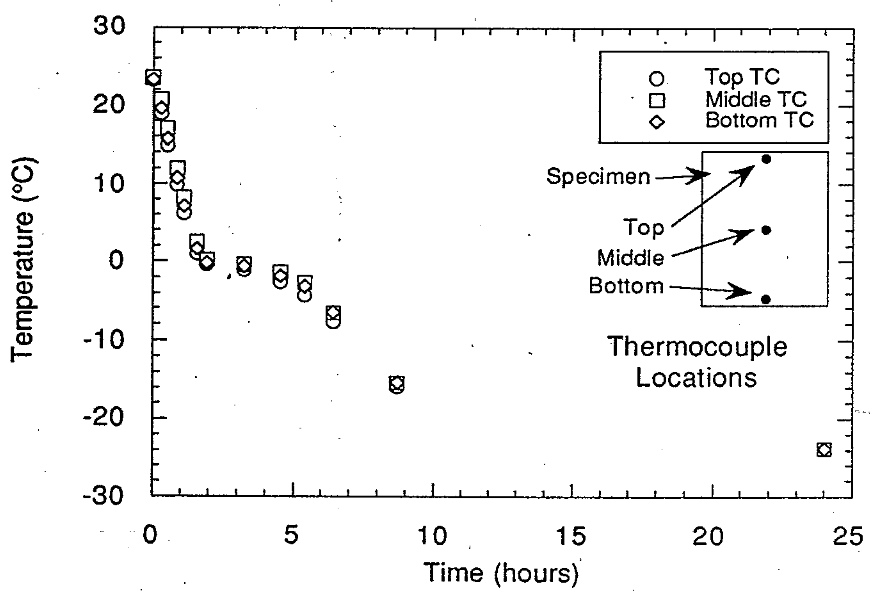


Figure 4.8. Temperature vs. time for Valley Trail clay during three-dimensional freezing.

D5084-Method C). An average effective stress of 10 kPa and hydraulic gradient of 12 was used. Termination criteria identical to those described in Sec. 4.1.2.1 were used.

4.1.2.3 One-Dimensional Freeze-Thaw Tests

Compacted specimens of Parkview and Valley Trail clay were subjected to one-dimensional freeze-thaw to replicate freezing processes that occur in the field. The hydraulic conductivity of these specimens was then measured to compare with hydraulic conductivities of specimens removed from the COLDICE test pads. The compacted specimens were subjected to the same number of freeze-thaw cycles observed in the COLDICE test pads.

Three specimens each of Parkview and Valley Trail clay were compacted at standard Proctor effort at water contents similar to the water contents used for construction of the COLDICE test pads. The specimens were removed from their compaction molds and sealed in plastic wrap.

The specimens were instrumented with thermocouples at the top, middle, bottom, and along their side. They were then wrapped in 0.1 m thick R-11 fiberglass building insulation and placed on a sheet of expanded polystyrene. A circular heating element (diameter = 0.15 m) was placed beneath the polystyrene sheet. The top of the specimen was left exposed to the ambient temperature of the freezer (-20°C). Figure 4.9 is a diagram of the one-dimensional freezing set-up; a similar method to one-dimensionally freeze compacted specimens was used by Othman and Benson (1993b). Figure 4.10 contains photographs of the equipment used to induce and monitor one-dimensional freezing.

Temperatures within the specimens were recorded while freezing (Fig. 4.11). The specimens were removed from the freezer when no further decrease in temperature was occurring. The specimens were allowed to thaw at room temperature (25°C) for at least 24 hours.

Three specimens of each clay were subjected to three different freezing rates (one freezing rate per specimen). The freezing rates were varied by changing the thickness of the polystyrene between the specimen and heating element. After freezing and thawing, the hydraulic conductivity of each specimen was measured in a flexible-wall permeameter. An average effective stress of 10 kPa and hydraulic gradient of 12 was used. No backpressure was applied. Tests were terminated when the hydraulic conductivity was steady and the ratio of outflow to inflow was between

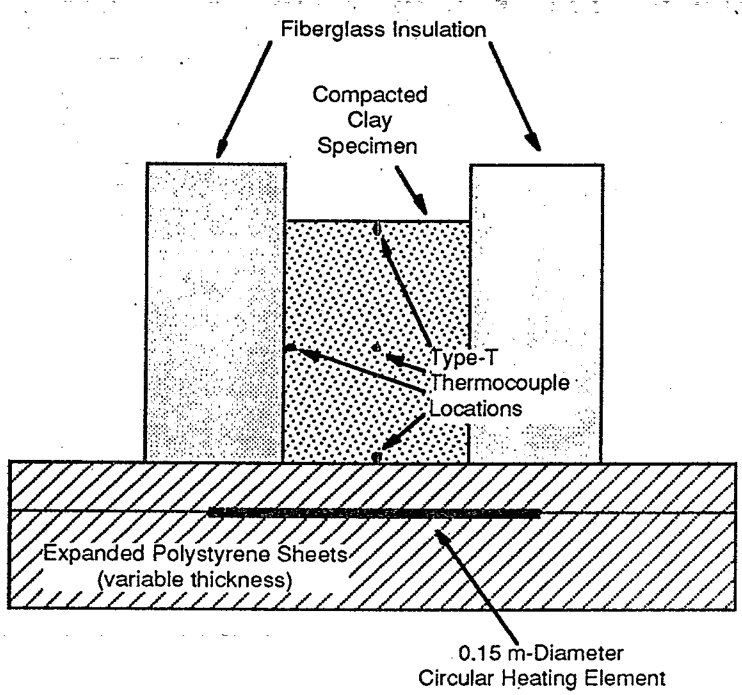


Figure 4.9. One-dimensional freezing set-up.

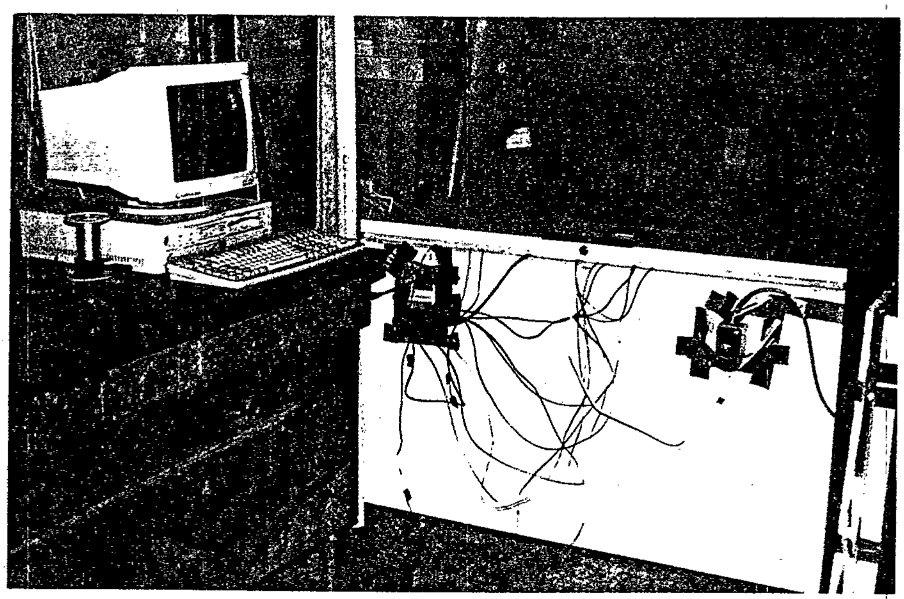


Figure 4.10. Freezer and data acquisition system used for one-dimensional freezing of compacted clay specimens.

0.75 and 1.25 for four consecutive readings. The hydraulic conductivity was reported as the arithmetic mean of the last four hydraulic conductivity measurements.

4.2 SAND-BENTONITE MIXTURE

4.2.1 Field Methods

4.2.1.1 COLDICE Test Pads

A test pad consisting of a sand-bentonite mixture was also constructed in the COLDICE project, adjacent to the four clay test pads described in Sec. 4.1.1.1. The sand-bentonite test pad, labeled SB-1, was 9 m by 21 m and had a thickness of 0.6 m (Erickson et al. 1994) (Fig. 4.2). It was constructed with similar procedures as the test pads constructed with clay, except that it was compacted using a smooth vibrating wheel compactor. The test pad was covered with a 0.15 mm-thick polyethylene sheet and 0.1 m of sand to minimize desiccation. Construction of the sand-bentonite test pad was completed in October 1992. All of the measurements of molding water content and dry unit weight made during construction of the test pad fell wet of the line of optimums (Fig. 4.12). Like the clay test pads, the sand-bentonite test pad was instrumented with thermistors to record temperature at different depths.

4.2.1.2 In Situ Box Infiltrometers

A box infiltrometer was also installed in the sand-bentonite test pad to measure hydraulic conductivity in the field (Fig 4.3). The infiltrometer was the same as those described in Sec. 4.1.1.2, and was installed using similar methods (Erickson et al. 1994).

4.2.1.3 Laboratory Assessment of Field-Scale Hydraulic Conductivity

Hydraulic conductivity tests were performed in the laboratory on specimens removed from the sand-bentonite test pad to assess the field-scale hydraulic conductivity. Specimens were removed from the field by three methods: as large blocks, using thin-wall sampling tubes (Shelby tubes), and as frozen cores. Sampling of the sand-bentonite test pad was performed concurrently with sampling from the clay test pads and similar sampling methods were employed. The sampling methods and schedule are described in Sec. 4.1.1.3. Flexible-wall permeameters were used to measure the hydraulic conductivity of specimens removed from the sand-bentonite test pad.

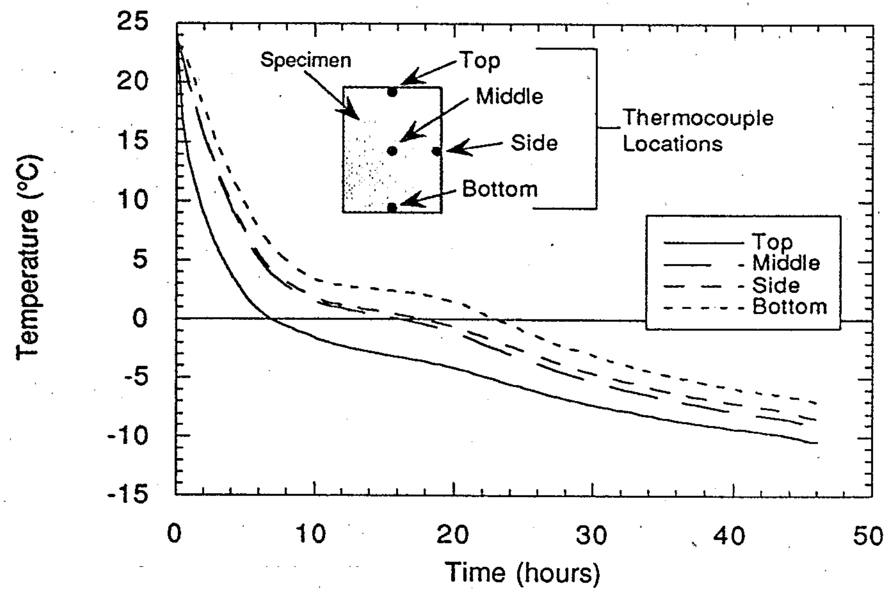


Figure 4.11. Temperature vs. time for one-dimensional freezing of Parkview clay in the laboratory.

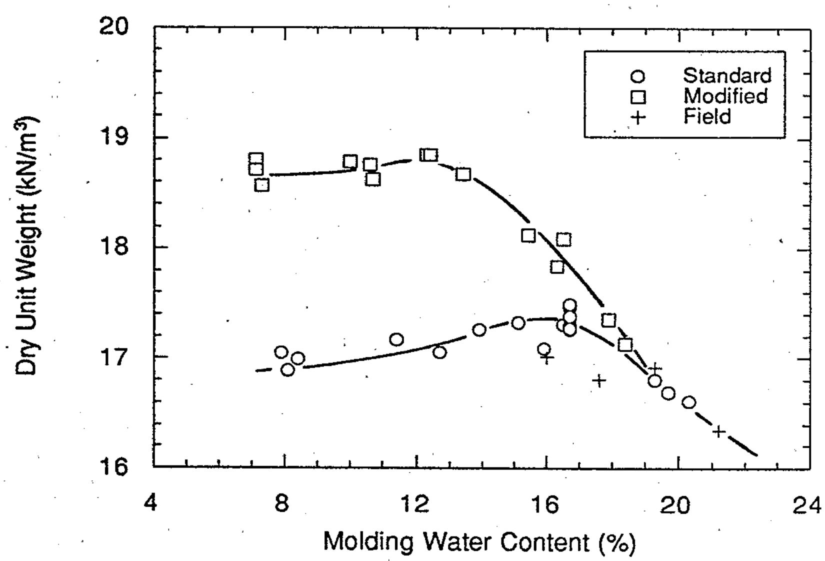


Figure 4.12. Compaction curve and field compaction data for sand-bentonite mixture.

Three block specimens were removed from the sand-bentonite test pad in December 1992 (before freezing) and in June 1993 (after freezing). Because the sand-bentonite pad was only 0.6 m thick, only two specimens were removed along one continuous vertical profile (0-0.3 m and 0.3-0.6 m). The third specimen was removed from a location adjacent to the first two specimens at an intermediate depth of 0.15-0.45 m.

Before being placed in permeameters, the PVC ring was removed from the specimens and excess or disturbed soil was trimmed away until the specimen had a diameter of 0.3 m and a height of 0.15 to 0.20 m. The block specimens were permeated at an average effective stress of 10.5 kPa, hydraulic gradients of 4 to 5, and using a backpressure of 413 kPa. One specimen (before winter, 0.15-0.45 m) was tested at a higher hydraulic gradient (8.0) to reduce the time required to reach equilibrium. The hydraulic gradient was increased by reducing the effluent pore water pressure to 406 kPa. Increasing the hydraulic gradient also increased the average effective stress to 14 kPa. Tap water from Madison, Wisconsin was used as the permeant. The specimens were permeated until the hydraulic conductivity was steady (no upward or downward trend over time) and the ratio of outflow to inflow was between 0.75 and 1.25. The latter criterion was not met by the specimen collected before winter from a depth of 0.15-0.45 m, which was permeated for 55 days without reaching equal inflow and outflow.

Specimens were also removed from the sand-bentonite test pad with thin-wall sampling tubes (Shelby tubes) in June 1993, after one winter of exposure. The sampling tubes were sealed in the field and shipped to the University of Wisconsin-Madison. The specimens were extruded from the sampling tubes, sealed in plastic wrap, and stored in a high humidity room to await hydraulic conductivity testing.

The specimens removed in thin-wall tubes were permeated in flexible-wall permeameters at an average effective stress of 28 kPa using a hydraulic gradient of 25. No backpressure was used. Tap water from Madison, Wisconsin was used as the permeant. The specimens were permeated until hydraulic conductivity was steady and the ratio of outflow to inflow was between 0.75 and 1.25

Specimens were also removed from the sand-bentonite test pad in March 1993 while the soil was frozen. Personnel from CH2M Hill, Inc. and CRREL collected the specimens using the core barrel described in Sec. 4.1.1.3 (Erickson et al. 1994). Storage and hydraulic conductivity testing were performed at CRREL. Hydraulic conductivity of the frozen cores was measured in flexible-wall permeameters. The frozen core specimens were allowed to thaw and consolidate under an average effective stress of 7 kPa. Hydraulic conductivity tests were then performed at that average effective stress using hydraulic gradients ranging from 2 to 5. A backpressure of 380 kPa was used. Tap water from Hanover, New Hampshire was used as the permeant.

4.2.2 Laboratory Methods

4.2.2.1 Hydraulic Conductivity-Water Content Relationship

Specimens of sand-bentonite that were compacted to determine compaction curves corresponding to standard and modified Proctor efforts (Sec 3.2.1.2) were also used to determine the hydraulic conductivity-water content relationships. The specimens were extruded from the compaction molds, sealed in plastic wrap, and stored until permeation.

The specimens were placed in flexible-wall permeameters for saturation and to measure their hydraulic conductivity, which was measured while the specimens were saturating. The falling head-rising tailwater method was used. An average effective stress of 21 kPa and hydraulic gradient of 30 were used. A backpressure of 345 kPa was applied. Tap water from Madison, Wisconsin was used as the permeant fluid.

Each test was terminated when the hydraulic conductivity was steady (change < ±25% and no increasing or decreasing trend) and the ratio of outflow to inflow was between 0.75 and 1.25 for four consecutive readings or when the test time had reached 30 days. For specimens which had reached steady conditions, the hydraulic conductivity was reported as the arithmetic mean of the last four measurements. For specimens which did not reach steady conditions in 30 days, the hydraulic conductivity was reported as the last measurement. For all of the specimens which had not reached steady conditions in 30 days, the hydraulic conductivity was steady and the ratio of outflow to inflow was approaching 1.0.

4.2.2.2 Standard Freeze-Thaw Tests

Three specimens of the sand-bentonite mixture were compacted at a water content similar to the water content used for construction of the sand-bentonite test pad (Sec. 4.2.1.1). Each specimen was extruded from the compaction mold and sealed in plastic wrap to prevent desiccation and stored until permeation. The sand-bentonite specimens were placed in flexible-wall permeameters to determine their initial hydraulic conductivity. Conditions and termination criteria identical to those described in Sec. 4.2.2.1 were employed.

After the initial hydraulic conductivity tests were complete, the specimens were carefully removed from the permeameters. Extreme care was used to avoid disturbing the structure of the specimens. They were then sealed in plastic wrap to prevent desiccation and placed in a laboratory freezer for cooling. The free-standing procedure was used to freeze the sand-bentonite specimens (Sec. 4.1.2.2). The specimens were left in the freezer for at least 24 hours, at which point they were removed and allowed to thaw at room temperature (25°C). After 24 hours of thawing, the specimens were placed back in the freezer. This procedure was repeated until the desired number of freeze-thaw cycles was attained.

The hydraulic conductivity of each specimen was measured after 1, 3, and 5 freeze-thaw cycles. To minimize disturbance, the frozen specimens were removed from the freezer and directly placed in flexible-wall permeameters for thawing. The cell pressure and hydraulic gradient were applied immediately. An average effective stress of 21 kPa and hydraulic gradient of 30 were applied. A backpressure of 345 kPa was used.

4.3 GEOSYNTHETIC CLAY LINERS (GCLs)

4.3.1 Field Methods

4.3.1.1 COLDICE Test Ponds and Pans-Field Measurement of Hydraulic Conductivity

Large-scale GCL test ponds were constructed in October 1992 and large-scale test pans were constructed in September 1993 by personnel from CH2M Hill, Inc. as part of the COLDICE project (Fig. 4.2). The ponds and pans were used to assess the impact that freeze-thaw had on the hydraulic conductivity of GCLs (Erickson et al. 1994). The test pans were constructed because of difficulties encountered the previous year (1992) with the seepage collection system in the GCL test ponds (Erickson et al. 1994). Consequently, the only successful hydraulic conductivity tests were performed using the GCL test pans. Tests were performed on three GCLs: Bentomat®, Claymax®, and Gundseal®.

Nine rectangular test pans were constructed in three groups (one group for each GCL). Each group of test pans contained one large test pan (surface area = 1.8 m^2) and two smaller test pans (surface area = 0.7 m^2). The large test pans and one of the two small test pans contained GCLs with seams that were installed in accordance with the manufacturers' specifications. The third pan in each group contained a seamless GCL specimen (Erickson et al. 1994).

The large test pans were constructed by welding pieces of HDPE geomembrane plate stock together. The smaller test pans were manufactured storage bins constructed of HDPE. Each test pan contained a seepage collection system with drains. A GCL specimen was placed over a thin layer of pea gravel to act as a support and drain for the GCL. The GCL was covered with a 0.25 m-thick layer of pea gravel. The test pans were then surrounded by pea gravel to the same level of the gravel within the pans (Fig. 4.13) (Erickson et al. 1994).

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 0.25 m. 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 by measuring outflow. Measurements of before-winter hydraulic conductivity were made through December 1993. Measurements after winter began in April 1994 (Erickson et al 1994).

4.3.1.2 Laboratory Assessment of Field-Scale Hydraulic Conductivity

During decommissioning of the COLDICE GCL test ponds and pans in June 1994, four specimens of Bentomat® and Claymax® (two specimens of each GCL) were removed from the test ponds by personnel from the University of Wisconsin-Madison. The GCLs in the test ponds had been exposed to two winters and two freeze-thaw cycles. Specimens, approximately 0.8 m by 0.8 m, were cut using a razor knife, placed on 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. The specimens were stored prior to permeation in a high humidity room at the University of Wisconsin-Madison.

Large flexible-wall permeameters were used to measure the hydraulic conductivity of the GCL specimens. The protocol described in Geosynthetic Research Institute (GRI) test method GCL-2 was employed, which is an adaptation of ASTM D 5084 specifically for use with GCLs. Circular specimens were cut from the 0.8 m by 0.8 m sections with a razor knife to a diameter of 0.45 m. A bentonite paste was applied to the edge of the specimens to prevent sidewall leakage between the specimen and the membrane. The falling head-constant tailwater method was employed for permeation. An effective stress of 28 kPa and hydraulic gradient of 75 were used. No backpressure was applied. The hydraulic conductivity tests were run until the hydraulic conductivity was steady and outflow equaled inflow for four consecutive measurements.

The two Bentomat® specimens had very high flow rates. Dye was injected into the influent and the permeameter was then disassembled to attempt to locate the high seepage zones. It was found that sidewall leakage between the specimen and the membrane was the cause of the high flow rates for both Bentomat® specimens. The Bentomat® specimens were removed from the permeameter and trimmed to a diameter of 0.3 m and placed in another flexible wall permeameter. Bentonite paste was applied around the edges of the specimen to alleviate the sidewall leakage problem. Similar testing conditions and termination criteria were used when re-testing the Bentomat® specimens. Sidewall leakage continued to be a problem for one of the smaller Bentomat® specimens, and additional measures were not successful in correcting the problem.

4.3.2 Laboratory Methods

Laboratory tests were conducted on Bentofix®, Bentomat®, and Claymax® (Fig. 3.7). Tests were not conducted on Gundseal®, because freeze-thaw is unlikely to affect the hydraulic performance of the geomembrane component of the Gundseal® GCL. Also, the GCL Bentofix® was only used in the laboratory freeze-thaw tests and was not evaluated in the field.

4.3.2.1 Laboratory Measurement of Hydraulic Conductivity

Specimens for hydraulic conductivity testing were selected by unrolling the GCLs on the laboratory floor and locating a point away from the edge of the roll where the specimens were likely to have uniform bentonite content. A piece of plywood was placed underneath the GCL and a razor knife was used to carefully cut out circular specimens (diameter = 0.15 m). Efforts were made to keep loose bentonite in the GCLs from spilling out of the edges. This procedure was used to make three specimens each of Bentofix® and Bentomat® and four specimens of Claymax® (Fig. 4.14). The specimens were weighed and their diameter and thickness were measured

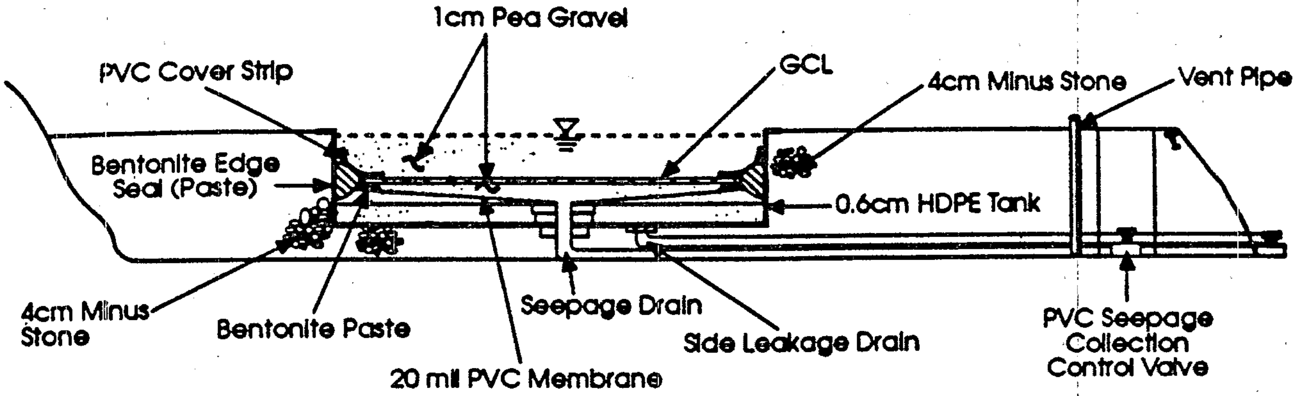


Figure 4.13. Schematic of GCL test pan used at the COLDICE field site (from Erickson et al. 1994).

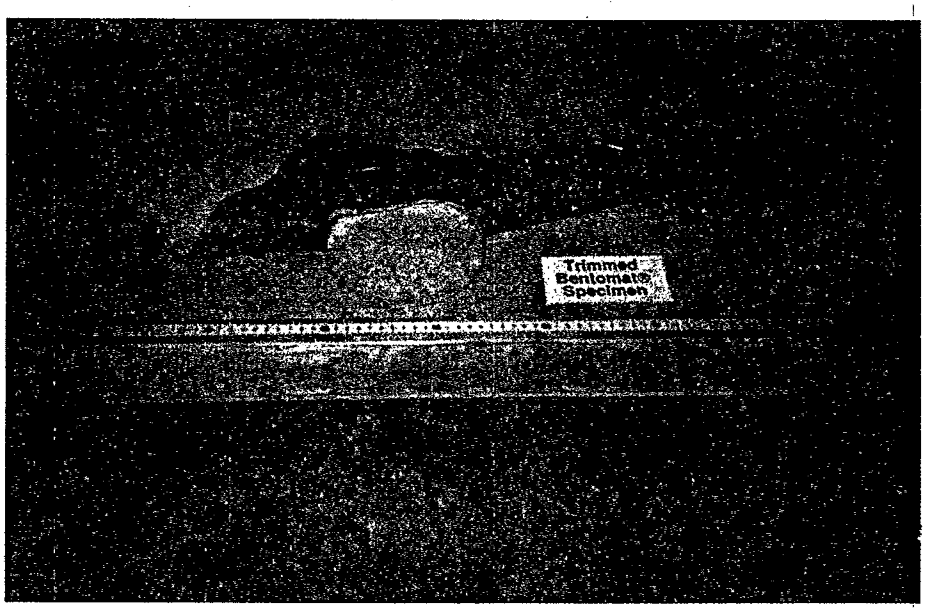


Figure 4.14. Photograph of trimmed Bentomat® specimen for laboratory testing.

using calipers. A bentonite paste was then applied to the edges of each specimen to prevent short circuiting during permeation.

The specimens were placed in flexible-wall permeameters for saturation and to define their initial hydraulic conductivity. The hydraulic conductivity was measured while the specimens were saturating. The protocol described in GRI test method GCL-2 was employed. An average effective stress of 7 kPa and hydraulic gradient of 75 were applied, and no backpressure was used. Tap water from Madison, Wisconsin was used as the permeant.

The tests were terminated when the hydraulic conductivity was steady (change smaller than ± 25% and no increasing or decreasing trend) and the ratio of outflow to inflow was between 0.75 and 1.25 for four consecutive readings. The hydraulic conductivity was reported as the arithmetic mean of the last four measurements.

4.3.2.2 Standard Freeze-Thaw Tests

After the initial hydraulic conductivity tests were complete, the GCL 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 hydrated bentonite. Calipers were used to measure their dimensions. They were then sealed in plastic freezer bags to prevent desiccation and placed in a laboratory freezer for cooling. An identical procedure was used after each freeze-thaw-permeate cycle.

The free-standing procedure (Othman et al. 1994) was used to freeze the specimens in a closed system. They were cooled to an ultimate temperature of -20°C at a freezing rate of approximately 12 mm/hr. This procedure results in three-dimensional freezing as opposed to one-dimensional freezing which occurs in the field. Nevertheless, because the GCL specimens are thin and wide relative to specimens of compacted clay, freezing was approximately one-dimensional (Fig. 4.15).

The specimens were left in the freezer for at least 24 hours, at which point they were removed and allowed to thaw at room temperature (25°C). After 24 hours of thawing, the specimens were placed back in the freezer. Data collected from control specimens instrumented with thermocouples (Fig. 4.15) showed that 24 hours was more than adequate to ensure that complete freezing or thawing occurred. This procedure was repeated until the desired number of freeze-thaw cycles was attained.

The hydraulic conductivity of each specimen was measured after 1, 3, 5, and 20 freeze-thaw cycles. To minimize disturbance, frozen specimens were removed from the freezer and directly placed into flexible-wall permeameters in the frozen state. The cell pressure and hydraulic gradient were applied immediately. Hydraulic conductivity was measured during and subsequent to thawing. Test parameters and termination criteria identical to those described in Sec. 4.3.2.1 were used.

4.4 PAPER MILL SLUDGES

4.4.1 Field Methods

4.4.1.1 Compaction of Pipe Specimens

Large specimens of compacted paper mill sludge were constructed by compacting paper mill sludge in a poly vinyl chloride (PVC) pipe (diameter = 0.35 m, length = 0.6 m) (Fig. 4.16). Two specimens were constructed for each sludge. One specimen of each sludge was used to determine the initial hydraulic conductivity (herein referred to as the "control" specimen). The other specimen was instrumented with thermocouples and buried in the ground outside the Environmental Geotechnics Laboratory at the University of Wisconsin-Madison (herein referred to as the "field" specimen). The field specimens were buried in the ground in early December 1993 and allowed to freeze one-dimensionally. The specimens were removed from the ground in March 1994 and were permeated to determine the hydraulic conductivity after exposure to freeze-thaw. Benson and Othman (1993) conducted similar small-scale field tests on a pipe specimen of compacted clay.

A PVC plate was used at the bottom of the pipe to confine the specimen. A geonet and non-woven geotextile were placed at the bottom of the specimen prior to compaction to provide for filtration and drainage during permeation. The specimens were compacted directly in the pipe using a compaction energy equal to standard Proctor energy and molding water contents which yield the lowest hydraulic conductivities for the three sludges (see Sec. 4.4.2.1). The specimens were compacted in six 0.1-m-thick lifts. Compaction was performed by dropping a 11.8 kg cylindrical weight with a diameter of 100 mm 120 times on each lift from a height of 0.3 m (Fig. 4.17). A flexible PVC geomembrane was placed on top of the compacted paper mill sludge in the field specimens and sealed to the inside of the PVC pipe to prevent desiccation.

4.4.1.2 Instrumentation and Burial of Pipe Specimens

Thermocouples were placed in the field specimens at the center of the pipe between each lift so the temperature within the specimen could be measured with

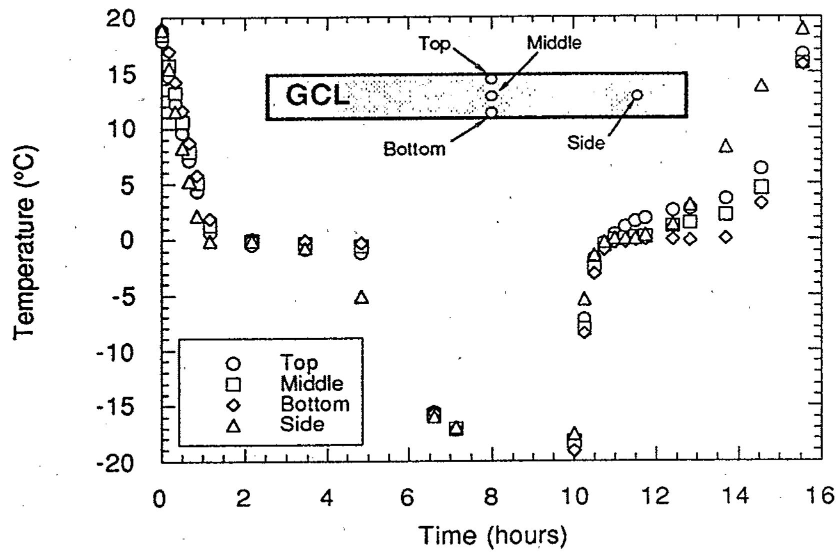


Figure 4.15. Temperature vs. time for Bentomat® GCL frozen three-dimensionally.

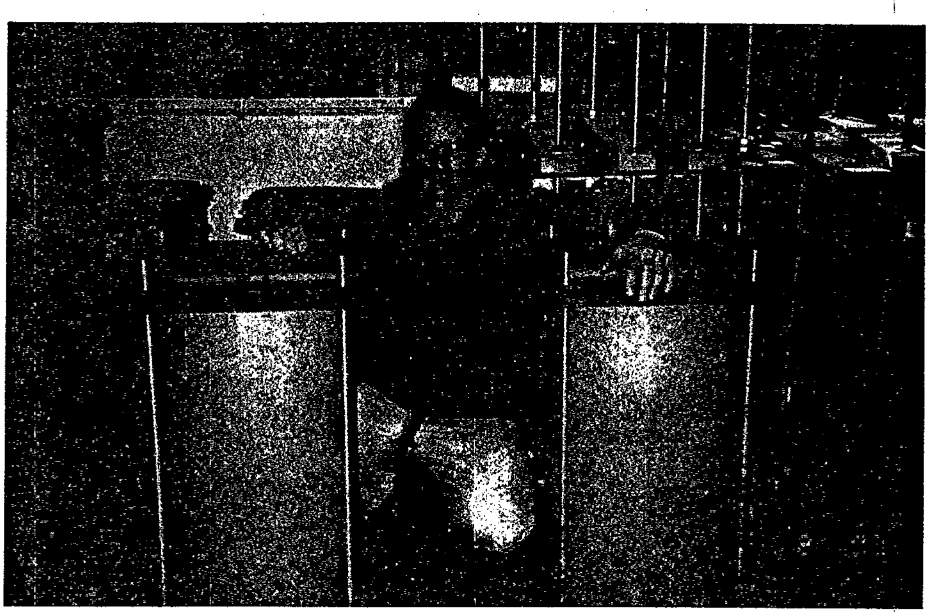


Figure 4.16. Small-scale field pipe specimens.

Figure 4.17. Compaction of paper mill sludge pipe specimen.

depth. Teflon® coated Type-T thermocouples were used. Five thermocouples were placed in each pipe specimen. Temperatures within the pipe specimens were recorded by a Campbell Scientific CR10 Datalogger every hour between mid-December 1993 and late March 1994. Air temperature and relative humidity were also recorded every hour by the datalogger. A graph of air temperature vs. time is located in Appendix B. Figure 4.18 is a photograph of the data acquisition set-up.

The field specimens were buried in the ground in early December 1993, before any ground freezing had occurred. A large trench was excavated and the three field specimens were placed next to each other in the trench (Fig 4.19). The trench was then backfilled level with the top of the compacted sludge in the pipe specimens. The top of the sludge, overlain by the PVC geomembrane was exposed to the ambient air temperature.

4.4.1.3 Permeation of Pipe Specimens

The pipe specimens were designed to be used as large rigid-wall permeameters. The control specimens were permeated while the field specimens were buried in the ground, whereas the field specimens were permeated after exposure to one winter. Brass fittings were placed in the top and bottom plates of the pipe specimens to allow for inflow and outflow of water. The constant headwater-constant tailwater method was used to measure the hydraulic conductivity of the pipe specimens in accordance with methods described in the ASTM draft standard for rigid-wall hydraulic conductivity tests. Mariotte bottles were used to apply a constant head. Tests were performed at a hydraulic gradient of 3.

The tests were terminated when the hydraulic conductivity was steady and the ratio of outflow to inflow was between 0.75 and 1.25 for four consecutive readings. The hydraulic conductivity of the specimens is reported as the arithmetic mean of the last four hydraulic conductivity measurements.

High initial values of the outflow to inflow ratio were observed for all pipe specimens during testing. It was determined that excessive gas build-up was taking place within the specimens. This gas build up was preventing inflow and increasing outflow as a result of increased pore pressures in the specimens. To correct this problem, venting pipes were installed in the top plates. After the venting pipes were installed, accurate readings of outflow and inflow were possible.

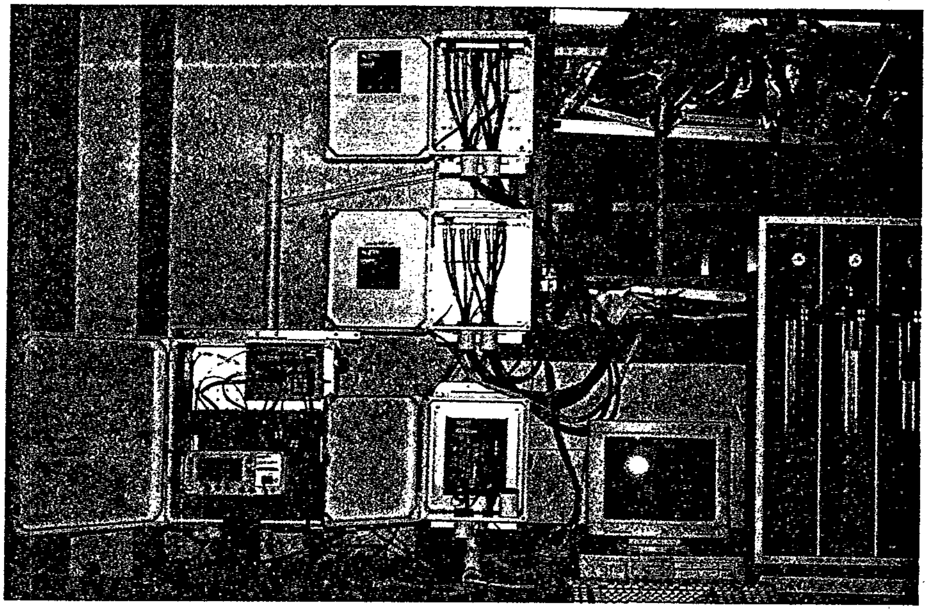


Figure 4.18. Data acquisition set-up for buried pipe specimens.

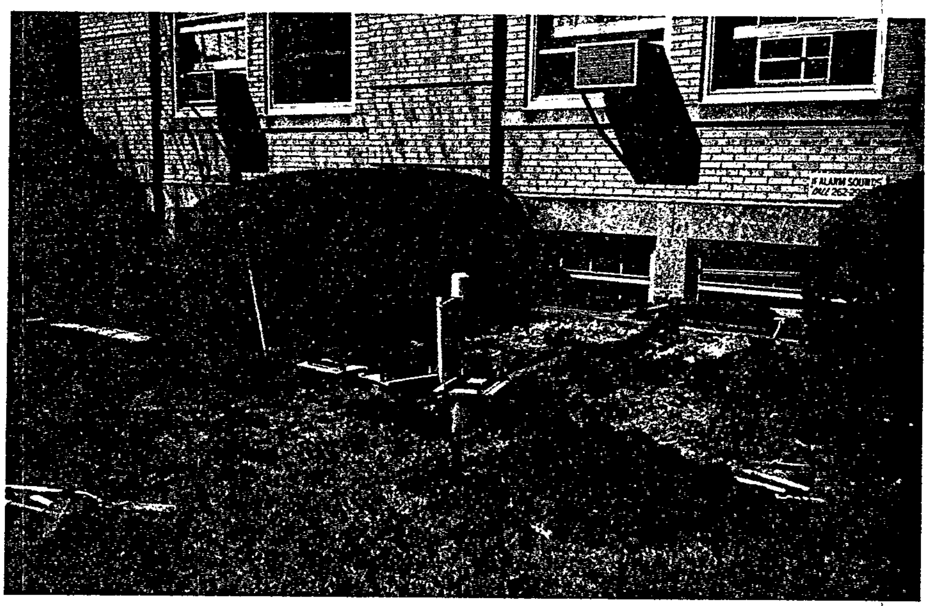


Figure 4.19. Burial of pipe specimens in the ground outside the Environmental Geotechnics Laboratory at the University of Wisconsin-Madison.

4.4.1.4 Measurement of Hydraulic Conductivity in Flexible-Wall Permeameters

Following permeation, the pipe specimens were sliced into horizontal sections that were subsequently permeated to investigate how depth influenced hydraulic conductivity. Benson and Othman (1993) showed that the hydraulic conductivity of the compacted clay varied with depth for their pipe specimen.

A circular saw was used to slice the pipe into horizontal sections. The sections were then separated from each other by slicing through the compacted paper mill sludge with a carpenter's saw. Vertical cuts were made in the pipe around the sludge sections and the remaining pieces of PVC were carefully removed to prevent disturbance (Fig 4.20). The sections of compacted paper mill sludge were trimmed to a diameter of 0.3 m and heights ranging from 0.1 to 0.2 m. The specimens were then placed in large flexible-wall permeameters (Fig. 4.5). An average effective stress of 18 kPa was applied to the specimens. Hydraulic gradients ranged from 8 to 16. No backpressure was used. Termination criteria described in Section 4.4.1.3 were followed.

4.4.2 Laboratory Methods

4.4.2.1 Hydraulic Conductivity-Water Content Relationships

Specimens that were compacted to determine the compaction curves for the three paper mill sludges (Sec. 3.3.2) were used to determine the hydraulic conductivity-water content relationships. The specimens were placed in rigid-wall compaction mold permeameters for saturation and to measure their hydraulic conductivity. The rigid-wall permeameters contained a double ring in the base plate to provide a check for sidewall leakage. The constant head-constant tailwater method was used in accordance with methods described in the ASTM draft standard for rigid wall hydraulic conductivity tests. A lead weight was placed on the specimen to simulate an overburden stress of 7 kPa during hydraulic conductivity testing. Hydraulic gradients ranging from 6 to 12 were applied, and tap water from Madison, Wisconsin was used as the permeant.

Each test was terminated when the hydraulic conductivity was steady (change < ±25% and no increasing or decreasing trend) and the ratio of outflow to inflow was between 0.75 and 1.25 for four consecutive readings. The hydraulic conductivity was reported as the arithmetic mean of the last four measurements.

Difficulties were encountered when permeating the paper mill sludge in the rigid-wall permeameters. Gases produced as a result of biological activity within the paper mill sludge blocked inflow and increased outflow as a result of increased pore pressures within the specimens. A venting tube, similar to those used when permeating the pipe specimens (Sec. 4.4.1.3), was placed in the top plate of the permeameter (Fig 4.21). Use of the venting tube alleviated the problem and reduced testing time.

4.4.2.2 Standard Freeze-Thaw Tests

Four specimens of sludge A and three specimens of sludges B and C were compacted at standard Proctor effort at water contents yielding the lowest hydraulic conductivities determined in Sec 4.4.2.1 (herein referred to as "low-K" water contents) and at water contents at which they were received at the University of Wisconsin-Madison (herein referred to as "as-received" water contents). Each specimen was compacted, sealed in its compaction mold using plastic wrap to prevent desiccation, and stored until permeation.

The sludge specimens were placed in rigid-wall compaction mold permeameters to determine their initial hydraulic conductivity (before exposure to freeze-thaw). Test conditions and termination criteria similar to those described in Sec. 4.4.2.1 were employed for the initial hydraulic conductivity tests. After the initial hydraulic conductivity tests were complete, the excess water was drained from the permeameters and the entire permeameter was placed in the laboratory freezer.

The free-standing procedure (Othman et al. 1994) was used to freeze the specimens in a closed system. They were cooled to an ultimate temperature of -20°C. The specimens were left in the freezer for at least 24 hours, at which point they were removed and allowed to thaw at room temperature (25°C). After 24 hours of thawing, the specimens were placed back in the freezer. This procedure was repeated until the desired number of freeze-thaw cycles was attained. The hydraulic conductivity of each specimen was measured after a various number of freeze-thaw cycles (up to 5 cycles).

Sidewall leakage was a problem for the specimens exposed to freeze-thaw. Volume change of the specimen due to freezing and subsequent thawing resulted in a gap between the specimen and the wall of the compaction mold. To eliminate this problem, the specimens were extruded from their compaction molds and placed in flexible-wall permeameters for hydraulic conductivity testing. The falling head-constant tailwater method for measuring hydraulic conductivity was used for specimens which had been subjected to freeze-thaw. An average effective stress of 10 kPa and hydraulic gradient of 12 were used. No backpressure was applied.

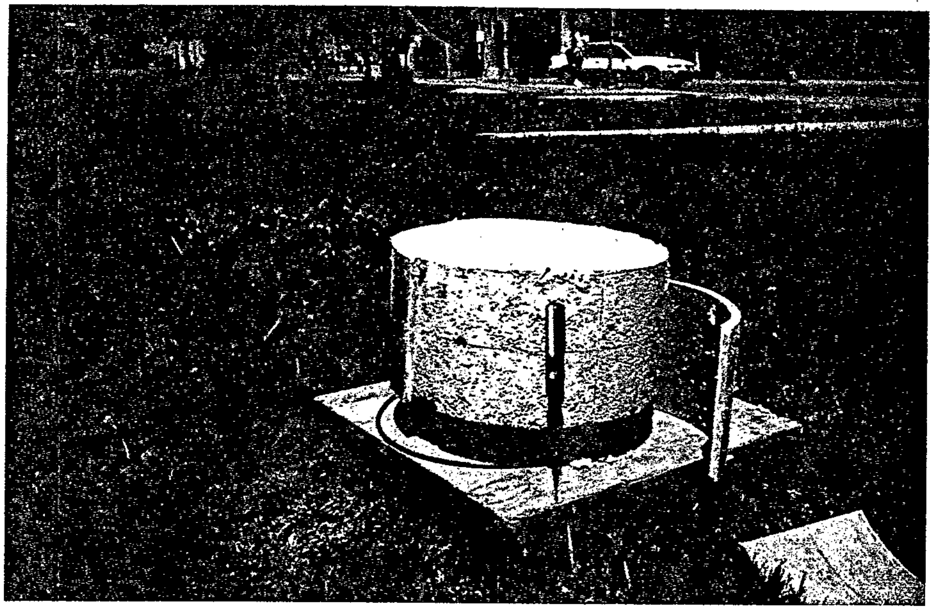


Figure 4.20. Photograph of sliced sludge specimen for hydraulic conductivity testing in flexible-wall permeameter.

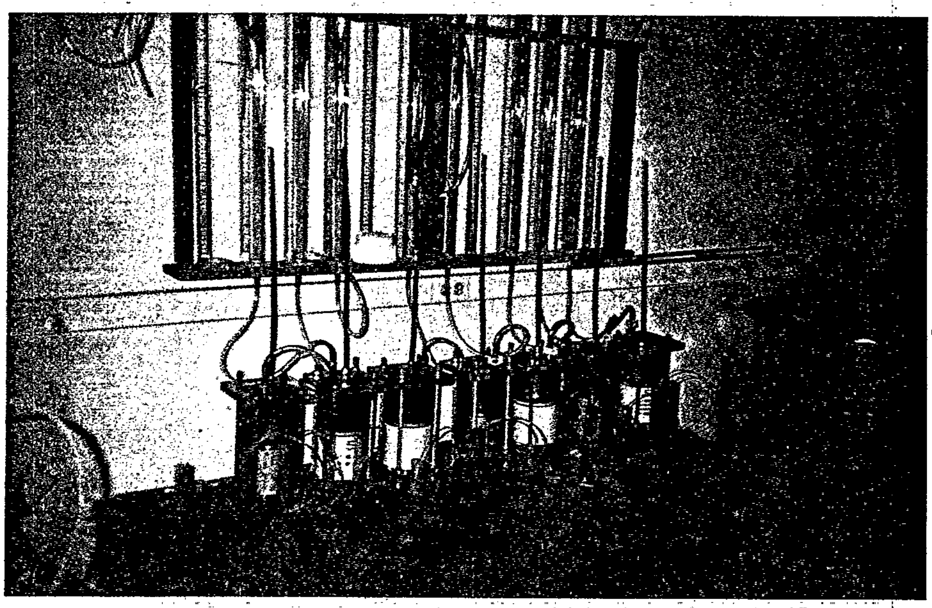


Figure 4.21. Test set-up for hydraulic conductivity testing of compacted paper mill sludge specimens.

Hydraulic conductivity was measured subsequent to thawing. Termination criteria similar to those described in Sec. 4.4.2.1 were used.

4.4.2.3 Effective Stress Tests

Tests were performed to determine the relationship between hydraulic conductivity and effective stress for the three paper mill sludges. One specimen of each sludge was compacted at standard Proctor effort at the molding water content that yields the lowest hydraulic conductivity for that sludge (low-K water content, Sec. 4.4.2.2). Hydraulic conductivity tests were performed in flexible-wall permeameters at effective stresses of 7, 35, 46, and 81 kPa and hydraulic gradients ranging from 6 to 9 were used. Termination criteria similar to those described in Sec. 4.4.2.1 were used. Following the completion of a test, the effective stress was increased by increasing the cell pressure in the permeameter and the specimen was allowed to consolidate for about 7 days after which, the hydraulic gradient was applied. Hydraulic conductivity was measured by monitoring outflow from the specimens.

4.4.2.4 Long-Term Hydraulic Conductivity Tests

Biological activity in compacted paper mill sludges has been reported in other experiments (NCASI 1989, Maltby and Eppstein 1994) and was observed for the three sludges tested in this project. Therefore, hydraulic conductivity tests were performed on two specimens of each sludge to determine if the hydraulic conductivity of the three sludges is affected by time.

Specimens were compacted at standard Proctor effort. One specimen of each sludge was compacted at the water content yielding the lowest hydraulic conductivity (low-K water content, Sec. 4.4.2.2) and the other specimen was compacted at the as-received water content (Sec. 4.4.2.2). Double-ring compaction-mold permeameters were used to measure hydraulic conductivity of the specimens. A lead weight was placed on the specimens during permeation to simulate an overburden pressure equal to 7 kPa. A venting tube was attached to the top plate of the permeameter, which was used to allow gases produced by biological activity in the sludge to escape. A hydraulic gradient of 7 was applied across the specimens and termination criteria similar to those described in Sec. 4.4.2.1 were used.

SECTION 5

RESULTS
CLAYS

5.1 FIELD TESTS

5.1.1 Freeze-Thaw Monitoring

Temperatures were monitored by CRREL personnel throughout the winter of 1992-93 in the Parkview and Valley Trail test pads constructed for the COLDICE project. Freezing of the test pads began in November 1992 and was steady in mid- to late December 1992. In mid- to late March 1993, thawing became steady. Complete thaw of the test pads occurred by the first week in April 1993. The test pads remained frozen for about 3.5 months (Erickson et al. 1994).

Figures 5.1 and 5.2 show frost zones in the test pads over time. Freezing records show that once steady freezing was established, freeze-thaw cycling only occurred in the overburden material and not in the compacted clay. It was determined that the Parkview and Valley Trail test pads were subjected to one freeze-thaw cycle during the winter of 1992-93 (Figs. 5.1 and 5.2). The maximum depths of frost penetration in the Parkview and Valley Trail test pads were 0.70 and 0.55 m, respectively. An average freezing rate of 0.03 mm/hr was measured for each test pad.

5.1.2 In Situ Box Infiltrometers

In situ box infiltrometers were installed in the two test pads constructed with Parkview clay to measure the hydraulic conductivity of the test pads after exposure to freeze-thaw. Installation of the infiltrometers and measurement of hydraulic conductivity were performed by personnel from CH2M Hill, Inc. No box infiltrometers were installed in either of the Valley Trail test pads (Erickson et al. 1994).

Erickson et al. (1994) made attempts to measure the hydraulic conductivity of the Parkview test pad in spring 1993 by filling the PVC riser pipe in the top of the infiltrometers with water and measuring the water level within the pipe. Any water which was added to the riser pipe immediately drained such that no measurement of the water level could be made. The high flow rates were either the result of increased hydraulic conductivity due to freeze-thaw or a leak in the infiltrometers. The exact cause of the high flow rates could not be determined (Erickson et al. 1994).

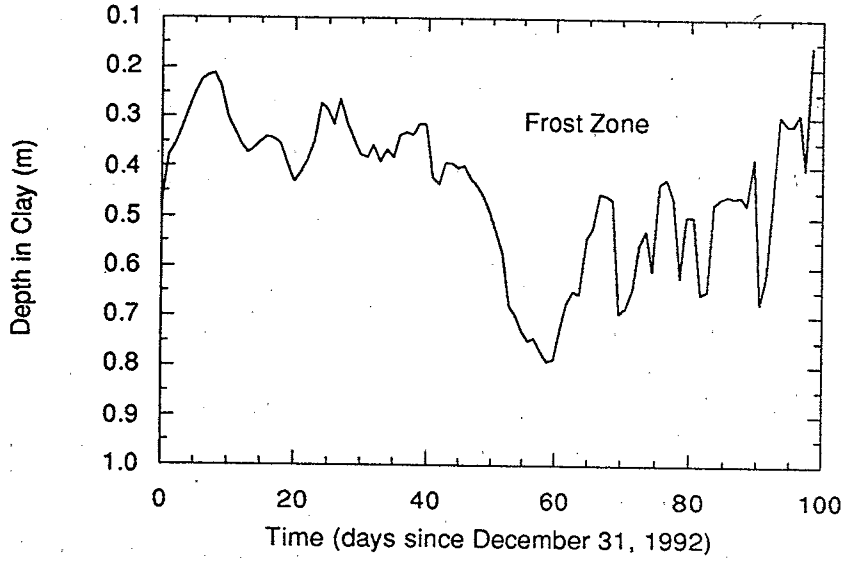


Figure 5.1. Frost depth vs. time in the Parkview test pad (from Chamberlain 1994, personal communication).

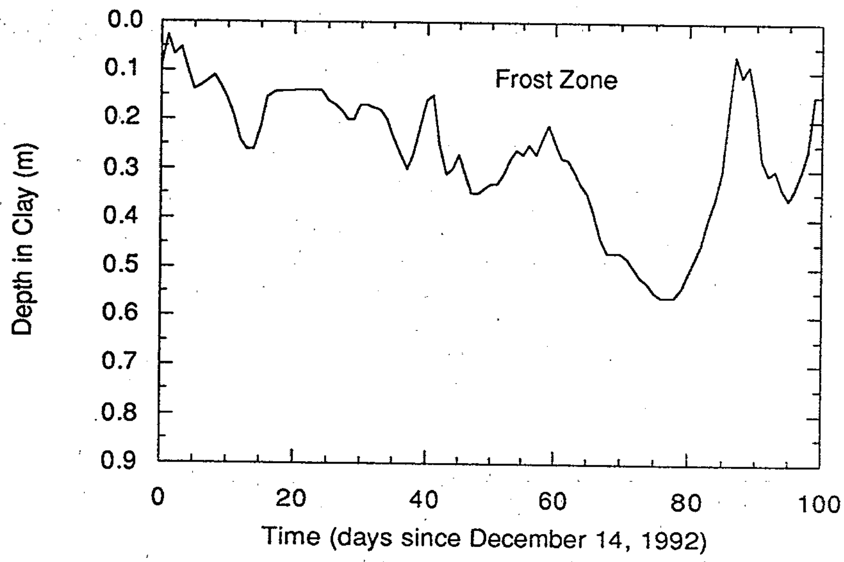


Figure 5.2. Frost depth vs. time in the Valley Trail test pad (from Chamberlain 1994, personal communication).

Sand covering one of the infiltrometers was removed and the top of the infiltrometer was cut open by personnel from CH2M Hill, Inc. and the University of Wisconsin-Madison. Shovels were used to excavate and examine the compacted clay. Figure 5.3 is a photograph of the soil at the surface of the Parkview test pad from within one of the box infiltrometers. The soil appeared blocky, containing numerous horizontal and vertical cracks. This type of structure has been observed in other experiments examining the effect of freeze-thaw on the hydraulic integrity of compacted clays at field-scale (Benson and Othman 1993, Erickson et al. 1994, Benson et al. 1995, Chamberlain et al. 1995).

5.1.3 Laboratory Assessment of Field-Scale Hydraulic Conductivity

Hydraulic conductivity tests were performed on specimens removed from the Parkview and Valley Trail test pads as blocks, with thin-wall sampling tubes (Shelby tubes), and as frozen cores. A summary of the results of the hydraulic conductivity tests are shown in Fig. 5.4.

5.1.3.1 Block Specimens

Hydraulic conductivity of the block specimens removed in June 1993 from COLDICE test pads PV-3 and VT-4 was measured in flexible-wall permeameters at the University of Wisconsin-Madison. Table 5.1 is a summary of the hydraulic conductivities for specimens removed from the Parkview test pad. All of the specimens removed before winter had hydraulic conductivities less than 1×10^{-9} m/s, whereas the specimens removed from the test pad after winter above the maximum frost depth had hydraulic conductivities greater than 1×10^{-7} m/s. The specimen removed after winter from below the maximum frost depth had a hydraulic conductivity of 2.5×10^{-10} m/s (Fig. 5.4).

Similar results were obtained for block specimens removed from the Valley Trail test pad (Table 5.2). The specimens removed from the test pad before winter and the specimen removed from the test pad after winter below the maximum frost depth all had hydraulic conductivities less than 1×10^{-9} m/s. The hydraulic conductivities for all of the specimens removed from the Valley Trail pad after winter above the maximum frost depth were greater than 1×10^{-7} m/s (Fig 5.4).

After permeation, the block specimens were cut open to examine their structure. The specimens were opened by pushing a screwdriver into the soil and prying until

Figure 5.3. Photograph of soil inside box infiltrometer-Parkview test pad.

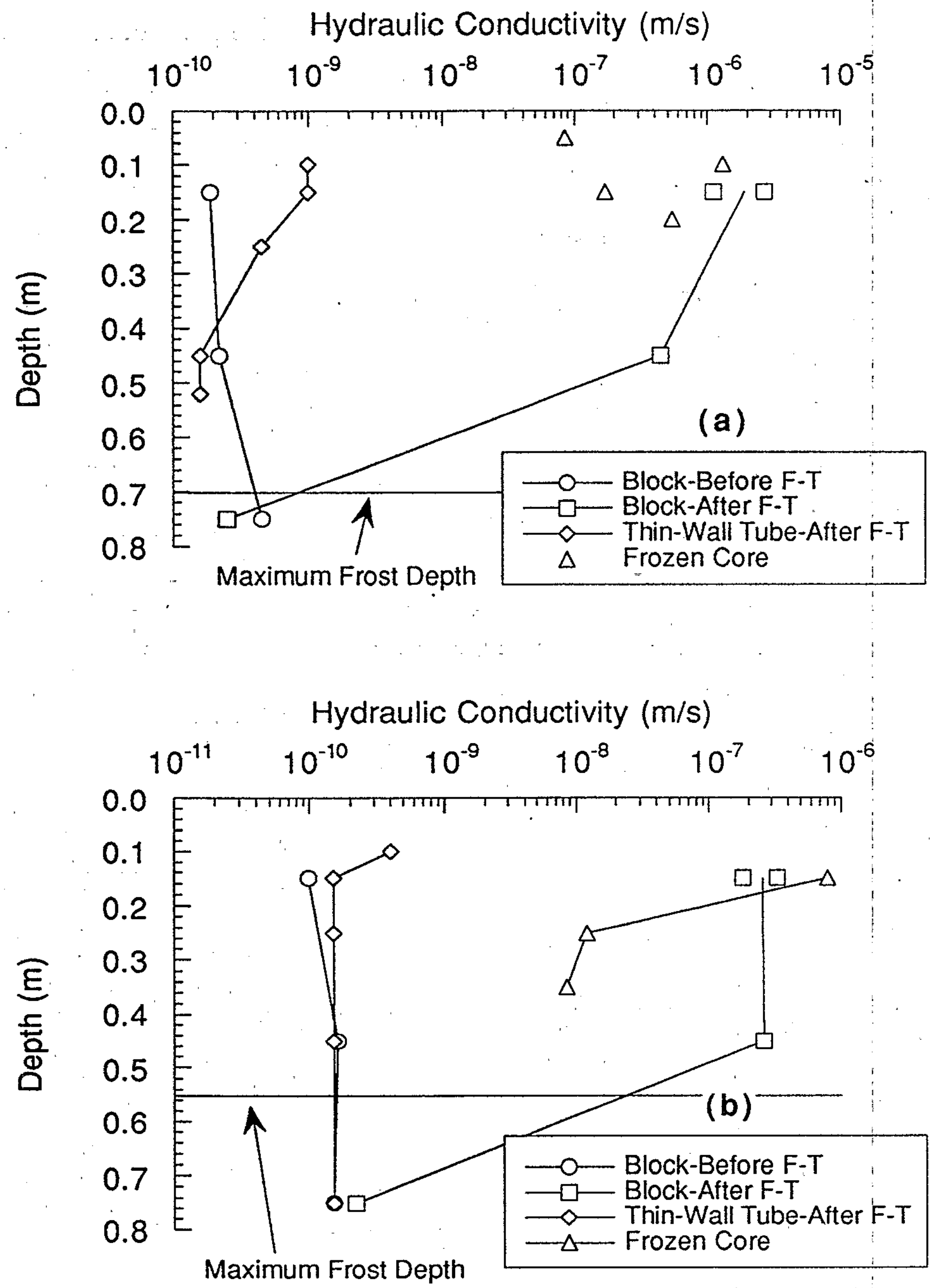


Figure 5.4. Hydraulic conductivity vs. depth for specimens removed from the Parkview (a) and Valley Trail (b) test pads.

Table 5.1. Results of hydraulic conductivity tests on block specimens removed from the Parkview test pad.

Specimen[1]	Sample Depth (m)	Hydraulic Conductivity (m/s)
PV-Block-Before-1	0-0.3	1.9×10^{-10}
PV-Block-Before-2	0.3-0.6	2.2×10^{-10}
PV-Block-Before-3	0.6-0.9	4.5×10^{-10}
PV-Block-After-1	0-0.3	2.7×10^{-6}
PV-Block-After-1-R[2]	0-0.3	1.1×10^{-6}
PV-Block-After-2	0.3-0.6	4.4×10^{-7}
PV-Block-After-3	0.6-0.9	2.5×10^{-10}

Notes:
1. PV = Parkview clay; Block = Block specimen; Before = Sampled before winter; After = Sampled after winter; -1, -2, -3 = Specimen number.
2. R = Replicate specimen from depth of 0-0.3 m.

Table 5.2. Results of hydraulic conductivity tests on block specimens removed from the Valley Trail test pad.

Specimen[1]	Sample Depth (m)	Hydraulic Conductivity (m/s)
VT-Block-Before-1	0-0.3	9.8×10^{-11}
VT-Block-Before-2	0.3-0.6	1.6×10^{-10}
VT-Block-Before-3	0.6-0.9	1.5×10^{-10}
VT-Block-After-1	0-0.3	3.3×10^{-7}
VT-Block-After-1-R[2]	0-0.3	1.8×10^{-7}
VT-Block-After-2	0.3-0.6	2.6×10^{-7}
VT-Block-After-3	0.6-0.9	2.2×10^{-10}

Notes:
1. VT = Valley Trail clay; Block = Block specimen; Before = Sampled before winter; After = Sampled after winter; -1, -2, -3 = Specimen number.
2. R = Replicate specimen from depth of 0-0.3 m.

the soil cracked. This method prevents smearing of the soil, which can mask the internal structure.

Figure 5.5 contains photographs of specimens from the Parkview and Valley Trail test pads removed before exposure to freeze-thaw. The photographs in Fig. 5.5 are characteristic of the soil structure existing in both test pads before winter. The soil is dense and homogeneous and no cracks are evident. This structure is consistent with the low hydraulic conductivity that was measured.

In contrast, Fig. 5.6 contains photographs of the internal structure of specimens removed from a depth of 0-0.3 m in the Parkview and Valley Trail test pads after exposure to freeze-thaw. The specimens appear blocky and contain numerous horizontal and vertical cracks. Horizontal cracks were most likely the result of the formation of ice lenses within the soil. Vertical cracks were most likely caused by desiccation incurred by migration of water during freezing of the soil. The high hydraulic conductivity of the specimens is attributed to the existence of these horizontal and vertical cracks.

Figure 5.7 contains photographs of the Parkview and Valley Trail specimens removed from the test pads from a depth of 0.6-0.9 m. These specimens were collected from below the maximum depth of frost penetration, and thus were never frozen. None of the cracks that were present in the shallow specimens exist in these specimens. The soil is a dense, homogeneous mass that appears similar to the soil as it existed prior to freezing (Fig 5.5). The absence of cracks and the homogeneity of the soil structure is consistent with the low hydraulic conductivity of these specimens.

5.1.3.2 Specimens Collected in Thin-Wall Tubes

Hydraulic conductivity was also measured on specimens removed in June 1993 from test pads PV-3 and VT-4 using thin-wall sampling tubes (Shelby tubes). The hydraulic conductivity tests were performed at the University of Wisconsin-Madison. Results of the tests are summarized in Fig. 5.4 and Table 5.3. All of the specimens removed in thin-wall tubes had hydraulic conductivities less than 1×10^{-9} m/s.

Hydraulic conductivities measured on specimens removed using thin-wall sampling tubes after winter were similar to the hydraulic conductivities measured on block specimens removed before winter, but much lower than the hydraulic conductivities of block specimens removed after winter above the maximum frost depth. The low hydraulic conductivities of these specimens were most likely the result of disturbance of the specimens during sampling and extrusion which masked the

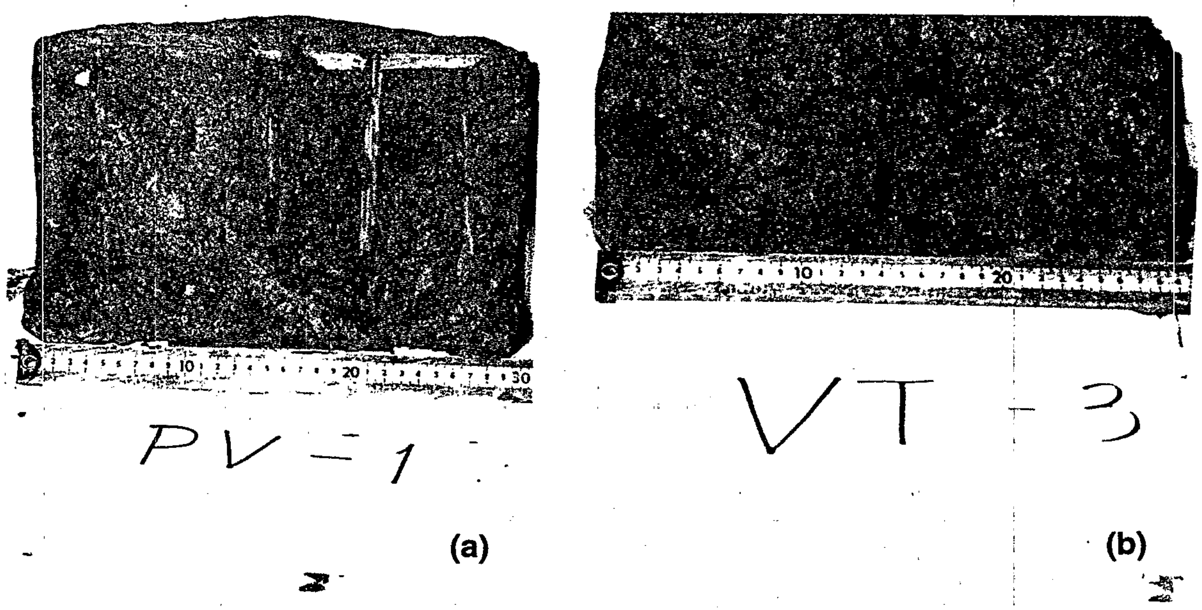


Figure 5.5. Interior of block specimens removed before winter from the Parkview (depth = 0-0.3 m) (a) and Valley Trail (depth = 0.6-0.9 m) (b) test pads.

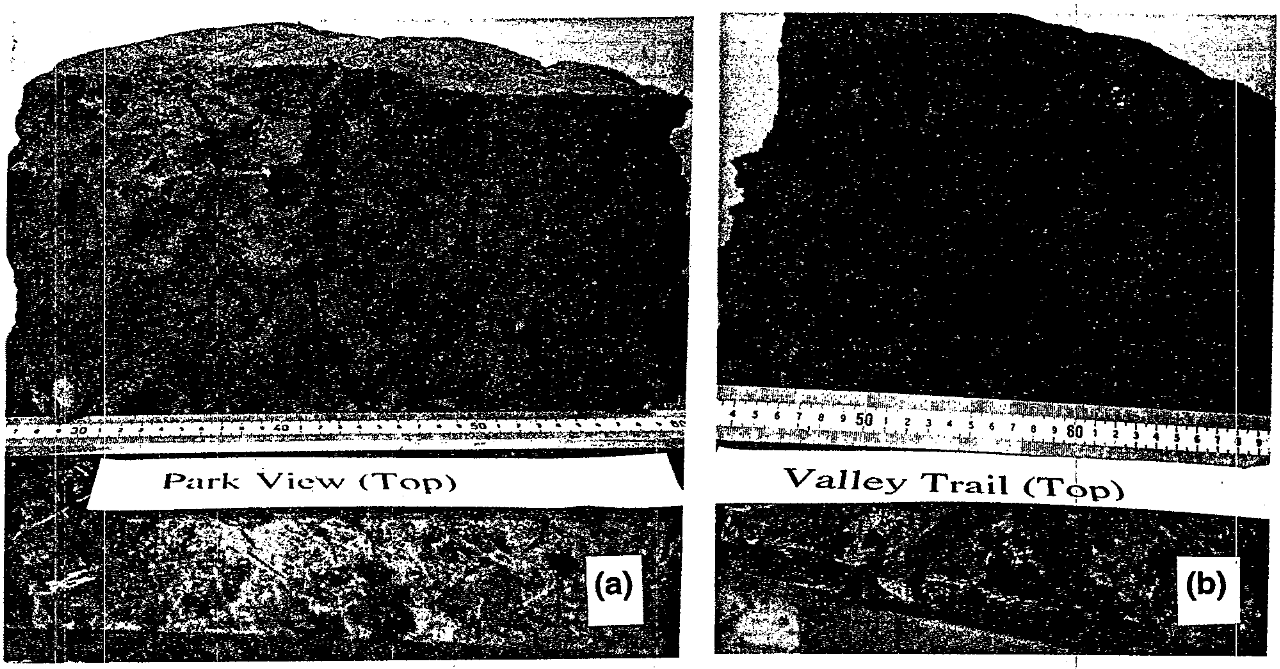


Figure 5.6. Interior of block specimens removed after winter from a depth of 0-0.3 m from the Parkview (a) and Valley Trail (b) test pads.

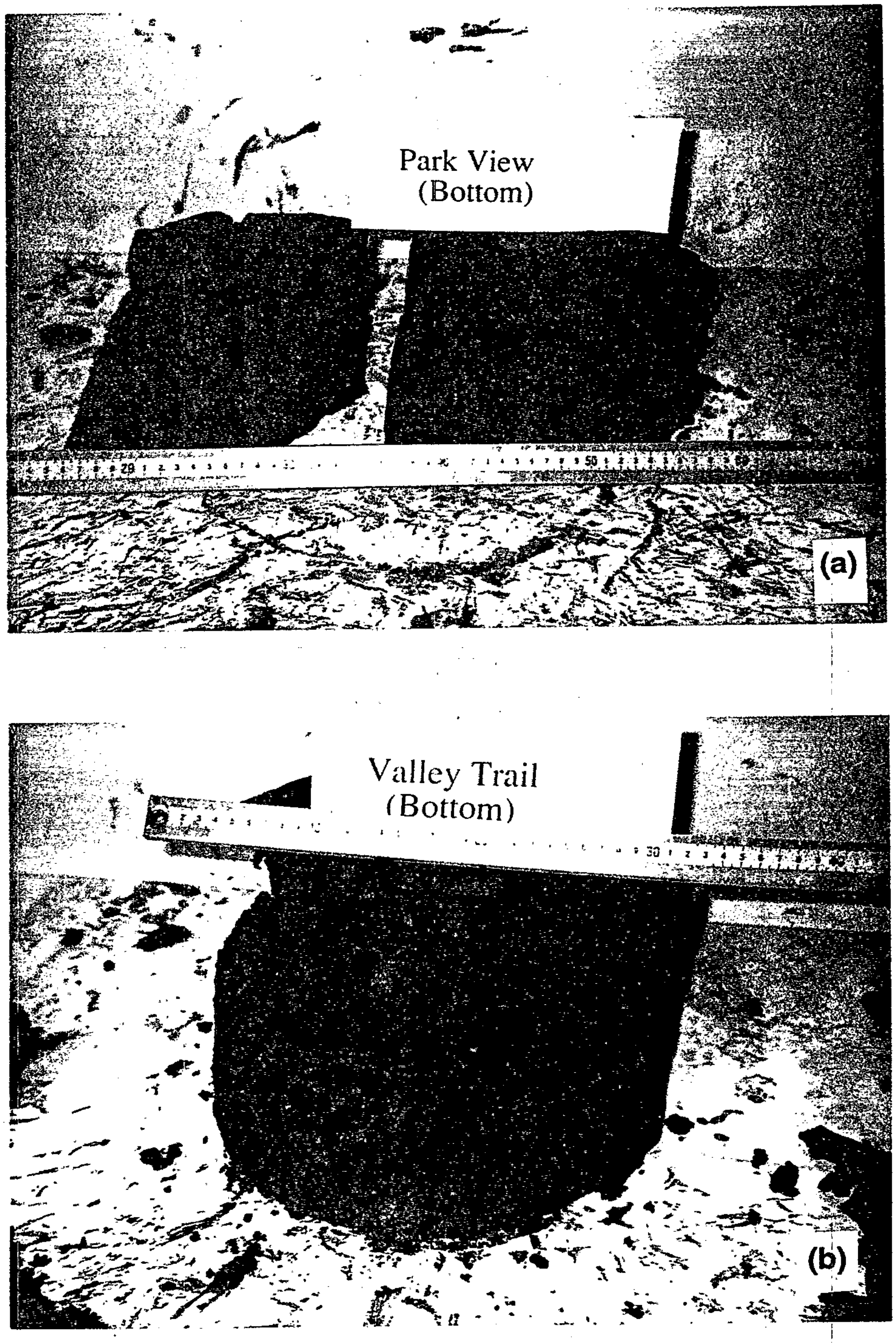


Figure 5.7. Interior of block specimens removed after winter from a depth of 0.6-0.9 m from the Parkview (a) and Valley Trail (b) test pads.

Table 5.3. Results of hydraulic conductivity tests on thin-wall tube specimens removed from the COLDICE test pads.

Specimen[1]	Sample Depth (m)	Hydraulic Conductivity (m/s)
PV-TW-1	0.10	1.0×10^{-9}
PV-TW-2	0.15	1.0×10^{-9}
PV-TW-3	0.25	4.5×10^{-10}
PV-TW-4	0.45	1.6×10^{-10}
PV-TW-5	0.52	1.6×10^{-10}
VT-TW-1	0.07	4.0×10^{-10}
VT-TW-2	0.15	1.5×10^{-10}
VT-TW-3	0.25	1.5×10^{-10}
VT-TW-4	0.45	1.5×10^{-10}
VT-TW-5	0.52	1.5×10^{-10}

Note:
1. PV = Parkview; VT = Valley Trail; TW = Thin-wall tube specimen; -1, -2, -3, -4, -5 = Specimen number.

effects of freeze-thaw. Figure 5.8 shows photographs of specimens removed from the Parkview and Valley Trail test pads after exposure to freeze-thaw. Neither specimen contains a crack network similar to those observed in the block specimens. The absence of cracks is consistent with the low hydraulic conductivity of these specimens.

5.1.3.3 Frozen Core Specimens

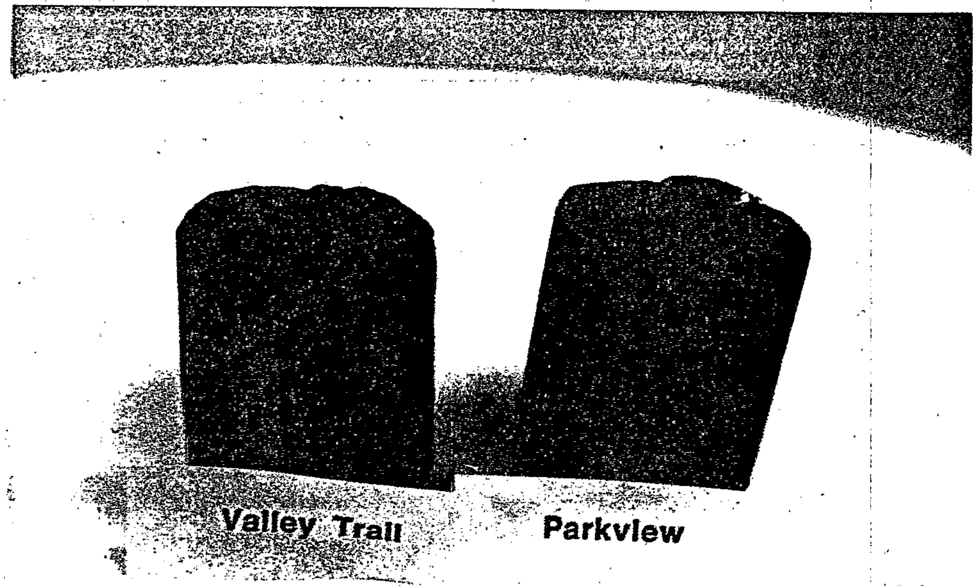
Hydraulic conductivity tests were performed on specimens removed from the Parkview and Valley Trail test pads in March 1993 while they were frozen. The tests were performed at the CRREL laboratory by CRREL personnel. Four specimens were removed from the Parkview test pad at depths of 0.05, 0.1, 0.15, and 0.2 m and three were removed from the Valley Trail test pad at depths of 0.15, 0.25, and 0.35 m (Chamberlain et al. 1995). Results of the hydraulic conductivity tests are summarized in Fig. 5.4 and Table 5.4.

The hydraulic conductivities of the frozen core specimens are similar to the hydraulic conductivities measured on the block specimens, and much higher than the hydraulic conductivities measured on specimens removed using thin-wall sampling tubes having the same diameter (71 mm).

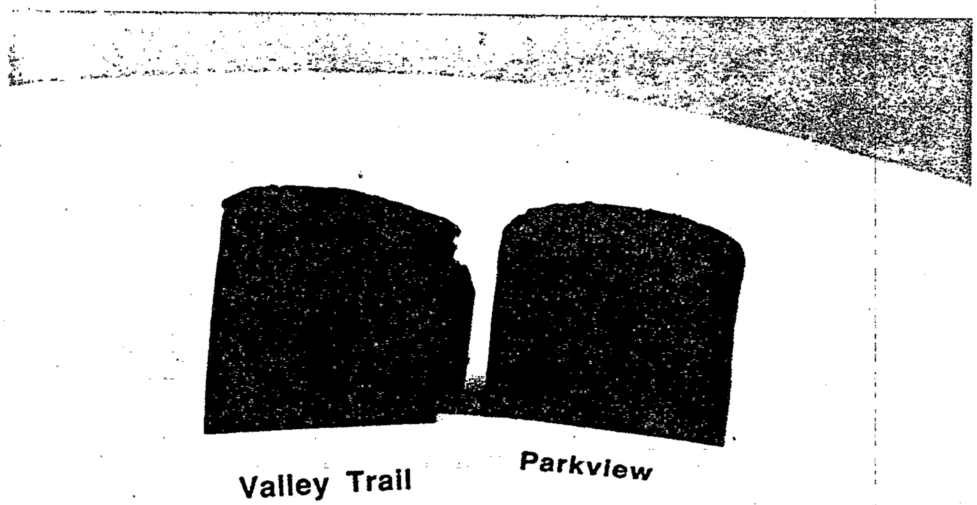
Figure 5.9 is a photograph of a frozen specimen removed from the Parkview test pad using the CRREL core barrel. The specimen contains cracks and ice lenses typically observed in compacted clays subjected to freezing. The presence of cracks is consistent with the high hydraulic conductivities of these specimens.

5.1.3.4 Structure of Compacted Clay Subjected to Freeze-Thaw

The increase in hydraulic conductivity for the Parkview and Valley Trail clays exposed to freeze-thaw is related to the soil structure in the test specimens. Test pits excavated in June 1993 revealed a structure similar to the structure observed in the box infiltrometers. The soil appeared blocky and contained numerous orthogonal cracks (Fig. 5.10). Soil within the test pits could be broken apart into chunks and was no longer a plastic, homogeneous mass as it was before winter. The horizontal cracks were spaced approximately 5-10 mm apart near the surface of the test pad and increased with depth. Vertical cracks were spaced approximately 20-30 mm apart. The increase in hydraulic conductivity observed in block specimens and frozen cores (Tables 5.1, 5.2, and 5.4) is a direct result of the existence of these horizontal and vertical cracks.



(a)



(b)

Figure 5.8. Specimens removed after winter from the Parkview and Valley Trail test pads using a thin-wall tube (a) and their internal structure (b).

Table 5.4. Results of hydraulic conductivity tests on specimens removed from the COLDICE test pads with CRREL frozen core barrel (from Chamberlain 1994, personal communication).

Specimen[1]	Sample Depth (m)	Hydraulic Conductivity (m/s)
PV-CB-1	0.05	8.5×10^{-8}
PV-CB-2	0.1	1.3×10^{-6}
PV-CB-3	0.15	1.7×10^{-7}
PV-CB-4	0.2	5.4×10^{-7}
VT-CB-1	0.15	8.0×10^{-7}
VT-CB-2	0.25	1.2×10^{-8}
VT-CB-3	0.35	8.5×10^{-9}

Note:
1. PV = Parkview; VT = Valley Trail; CB = CRREL core barrel specimen; -1, -2, -3, -4 = Specimen number.

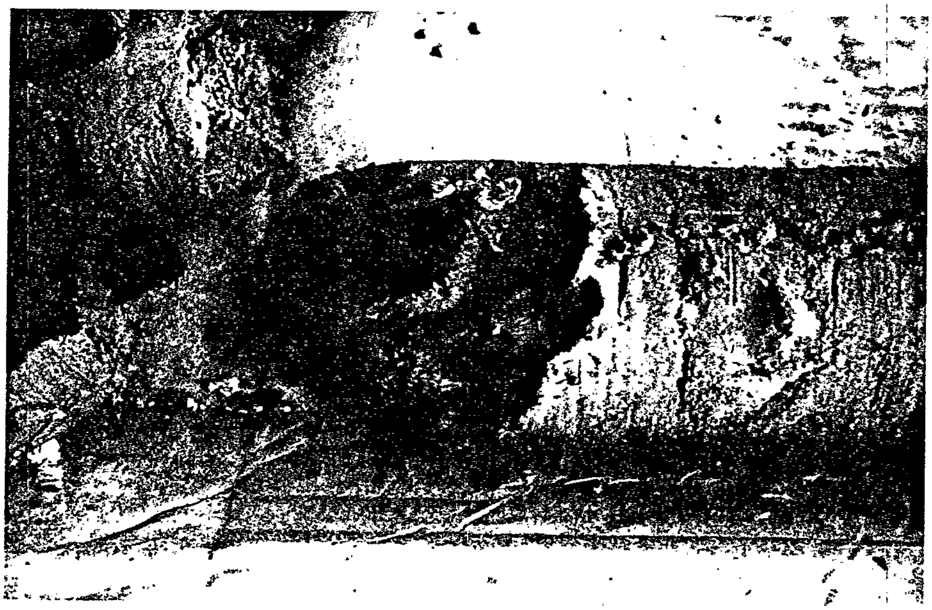


Figure 5.9. Specimen removed from Parkview test pad while frozen using CRREL core barrel (from Erickson 1994, personal communication).

Figure 5.10. Test pit excavated in Valley Trail test pad showing blocky soil structure caused by freeze-thaw.

5.2 LABORATORY TESTS

5.2.1 Hydraulic Conductivity-Water Content Relationships

Hydraulic conductivity was measured on specimens of Parkview and Valley Trail clay compacted to determine compaction curves corresponding to standard and modified Proctor effort (Sec. 3.1.2). Results of the hydraulic conductivity tests are shown in Figs. 5.11 and 5.12 and are summarized in Appendix A.

The hydraulic conductivity of the specimens decreases as the molding water content or compactive effort increases (Figs. 5.11 and 5.12). The lowest hydraulic conductivities occur at molding water contents slightly wet of optimum molding water content for both compactive efforts (see Figs. 3.3 and 3.4). These results are typical for compacted clays (Mitchell et al. 1965, Benson and Daniel 1990, Daniel and Benson 1990).

5.2.2 Standard Freeze-Thaw Tests

Three specimens of each clay were compacted using standard Proctor effort at the molding water content at which the Parkview and Valley Trail test pads were constructed (≈16 and 21%, respectively). The specimens were subjected to freeze-thaw using the free-standing procedure (Sec. 4.1.2.2). The hydraulic conductivity of each specimen was measured after 0, 1, 3, and 5 freeze-thaw cycles. Results of the standard freeze-thaw tests are summarized in Figure 5.13 and Table 5.5.

The hydraulic conductivity of both clays increased when subjected to freeze-thaw (Fig. 5.13). The average initial hydraulic conductivity and average hydraulic conductivity after five freeze-thaw cycles for the Parkview specimens were 1.9×10^{-10} and 2.5×10^{-8} m/s, respectively. That is, the average hydraulic conductivity of the Parkview specimens increased by more than two orders of magnitude after exposure to five freeze-thaw cycles.

The average initial hydraulic conductivity and average hydraulic conductivity after five freeze-thaw cycles for the Valley Trail specimens were 1.3×10^{-10} and 6.4×10^{-9} m/s, respectively, which corresponds to increase in hydraulic conductivity by a factor of 50 as a result of freeze-thaw. These results are consistent with results reported in other studies (Chamberlain et al. 1990, Zimmie and LaPlante 1990, Kim and Daniel 1992, Othman and Benson 1993, Bowders and McClelland 1994).

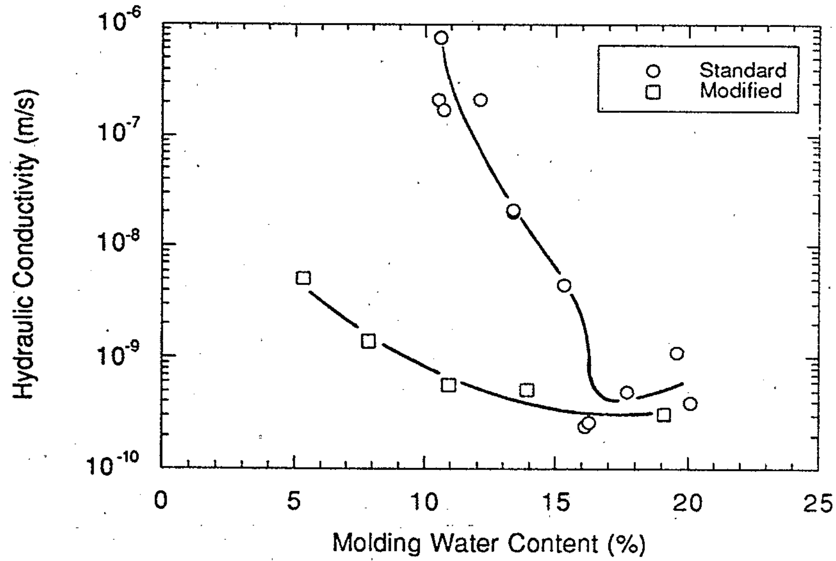


Figure 5.11. Hydraulic conductivity vs. molding water content for Parkview clay.

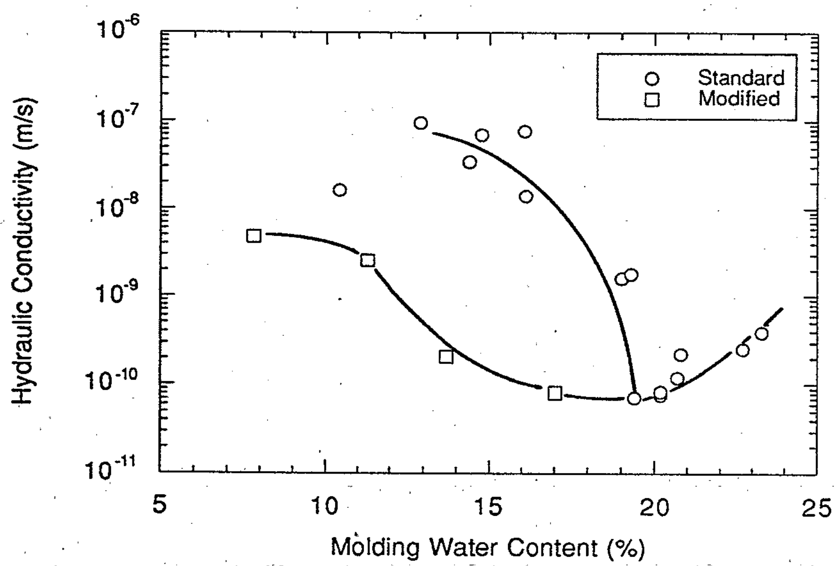
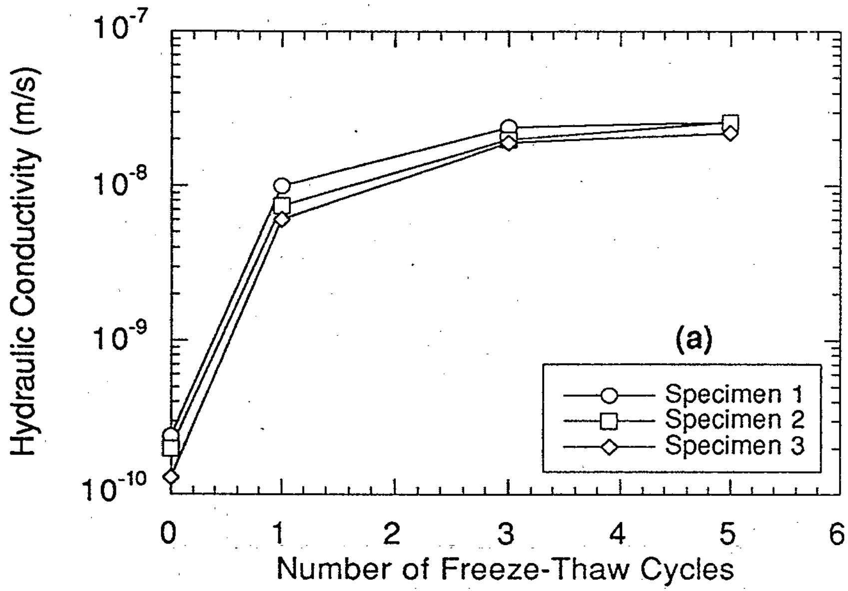


Figure 5.12. Hydraulic conductivity vs. molding water content for Valley Trail clay.



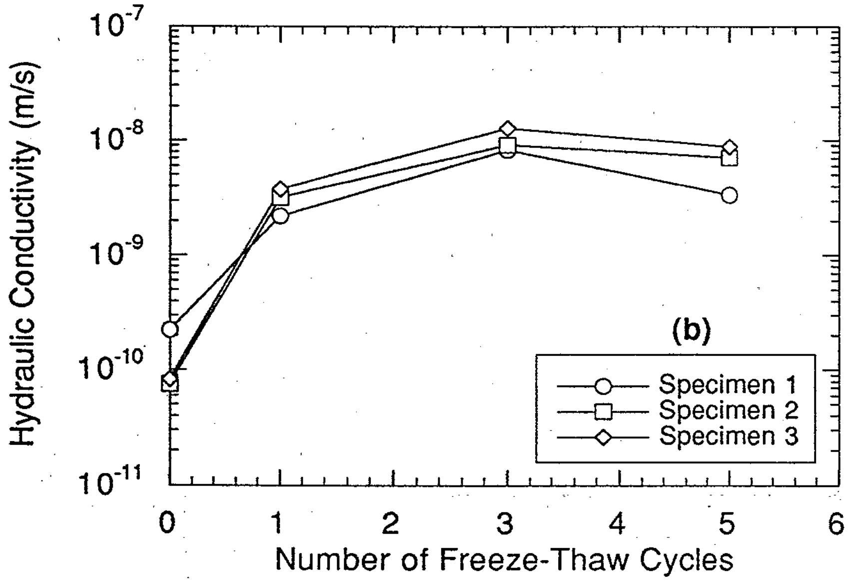


Figure 5.13. Hydraulic conductivity vs. number of freeze-thaw cycles for Parkview (a) and Valley Trail (b) clay.

Table 5.5. Results of freeze-thaw tests on specimens of Parkview and Valley Trail clay compacted in the laboratory.

Sample Number[1]	Initial Hydraulic Conductivity K_0 (m/s)	Hydraulic Conductivity After n Freeze-Thaw Cycles, K_n (m/s)			$\frac{K_5}{K_0}$ (2)
		K_1	K_3	K_5	
PV-3D-1	2.4×10^{-10}	1.0×10^{-8}	2.4×10^{-8}	2.6×10^{-8}	108
PV-3D-2	2.0×10^{-10}	7.4×10^{-9}	2.0×10^{-8}	2.6×10^{-8}	130
PV-3D-3	1.3×10^{-10}	6.1×10^{-9}	1.9×10^{-8}	2.2×10^{-8}	169
VT-3D-1	2.2×10^{-10}	2.2×10^{-9}	8.3×10^{-9}	3.4×10^{-9}	15
VT-3D-2	7.6×10^{-11}	3.2×10^{-9}	9.1×10^{-9}	7.1×10^{-9}	93
VT-3D-3	8.3×10^{-11}	3.8×10^{-9}	1.3×10^{-8}	8.8×10^{-9}	106

Note:
1. PV = Parkview; VT = Valley Trail; 3D = Specimen was frozen and thawed three-dimensionally; -1, -2, -3 = Specimen Number.
2. K_5/K_0 = Hydraulic conductivity of specimen after exposure to 5 freeze-thaw cycles divided by hydraulic conductivity before exposure to freeze-thaw.

5.2.3 One-Dimensional Freeze-Thaw Tests

To determine if differences in freezing rate affect the increase in hydraulic conductivity caused by freeze-thaw, the relationship between hydraulic conductivity and freezing rate was determined for three specimens of each clay. Methods described in Sec. 4.1.2.3 were used. The specimens were subjected to one freeze-thaw cycle so that they could be compared with the field data.

Figures 5.14 and 5.15 show the relationship between hydraulic conductivity and freezing rate for each clay. Laboratory data from the standard freeze-thaw tests and field data from the COLDICE project are also presented. The hydraulic conductivities for the standard freeze-thaw tests are the averages of three specimens. No trend between hydraulic conductivity and freezing rate is evident.

5.3 COMPARISON OF FIELD AND LABORATORY TEST RESULTS

Summaries of results from the hydraulic conductivity tests performed in the field and in the laboratory on clays is shown in Tables 5.6. and 5.7. An increase in hydraulic conductivity occurred as a result of freeze-thaw for both clays regardless of whether freeze-thaw occurred in the field or was simulated one- or three-dimensionally in laboratory tests.

Increases in hydraulic conductivity up to 4 orders of magnitude were observed for specimens removed from the COLDICE test pads as large blocks. Similar hydraulic conductivities were measured for specimens removed from the test pads as frozen cores. However, an increase in hydraulic conductivity was not observed for the specimens collected in sampling tubes. Othman et al. (1994) and Benson et al. (1995) report that sampling as block specimens or frozen cores preserves the structure of compacted clay subjected to freeze-thaw, whereas sampling with thin-wall tubes disturbs the soil structure which results in a specimen that is not representative of the field condition. The findings of this study are consistent with those of Othman et al. (1994) and Benson et al. (1995).

Hydraulic conductivities of the Parkview and Valley Trail specimens frozen using the standard three-dimensional freeze-thaw method increased by factors of 130 and 50, respectively, after five cycles of freeze-thaw. The specimens frozen and thawed using the one-dimensional method increased in hydraulic conductivity by factors of 62 to 140, respectively, after one freeze-thaw cycle. In contrast, the hydraulic conductivity of the block specimens (which are assumed to reflect field conditions) increased in hydraulic conductivity more than three orders of magnitude in a single

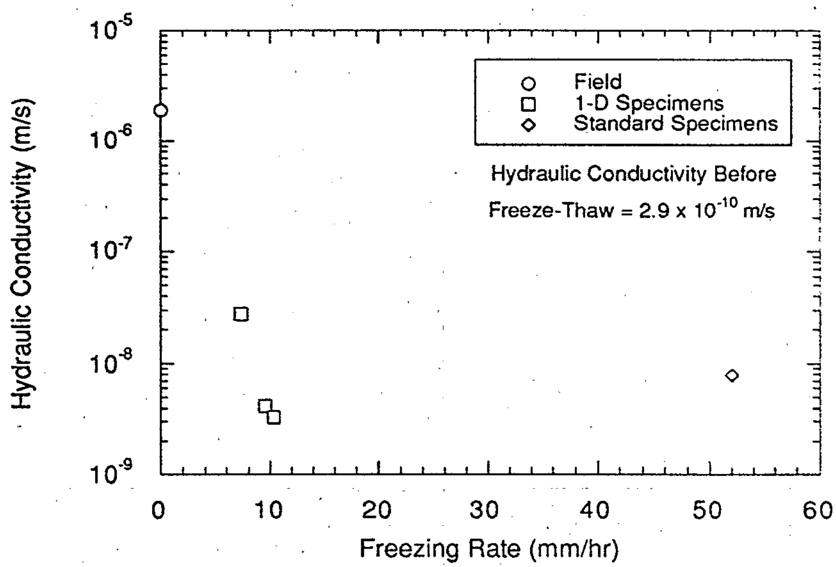


Figure 5.14. Hydraulic conductivity vs. freezing rate for Parkview clay.

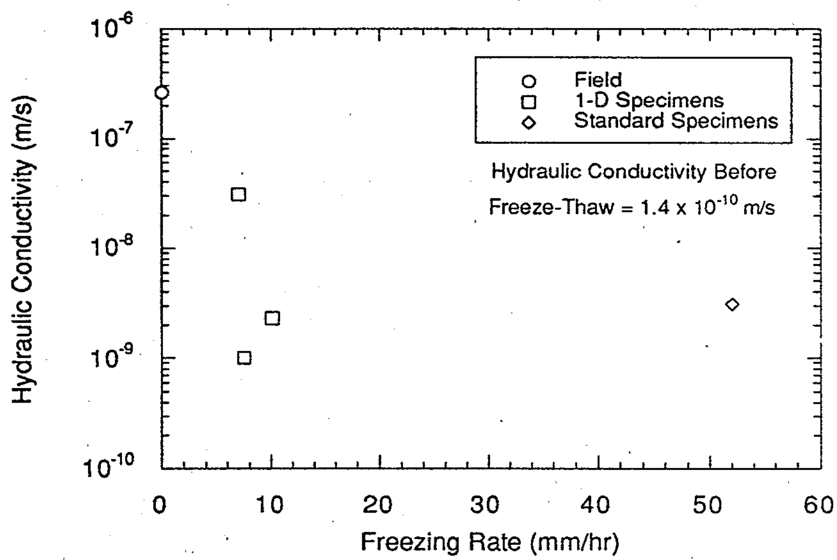


Figure 5.15. Hydraulic conductivity vs. freezing rate for Valley Trail clay.

Table 5.6. Summary of hydraulic conductivity tests performed on Parkview field and laboratory specimens.

Specimen(1)	Sample Depth (m)	Initial Hydraulic Conductivity(2) (m/s)	Final Hydraulic Conductivity(2) (m/s)	$\frac{K_f}{K_i}$ (3)
PV-Block	0-0.3	1.9×10^{-10}	1.9×10^{-6}	10,000
PV-Block	0.3-0.6	2.2×10^{-10}	4.4×10^{-7}	2,000
PV-Block	0.6-0.9	4.5×10^{-10}	2.5×10^{-10}	0.56
PV-TW-1	0.10	2.9×10^{-10} (4)	1.0×10^{-9}	0.35
PV-TW-2	0.15	2.9×10^{-10} (4)	1.0×10^{-9}	0.35
PV-TW-3	0.25	2.9×10^{-10} (4)	4.5×10^{-10}	1.6
PV-TW-4	0.45	2.9×10^{-10} (4)	1.6×10^{-10}	0.55
PV-TW-5	0.52	2.9×10^{-10} (4)	1.6×10^{-10}	0.55
PV-CB-1	0.05	2.9×10^{-10} (4)	8.5×10^{-8}	290
PV-CB-2	0.1	2.9×10^{-10} (4)	1.3×10^{-6}	4,500
PV-CB-3	0.15	2.9×10^{-10} (4)	1.7×10^{-7}	590
PV-CB-4	0.2	2.9×10^{-10} (4)	5.4×10^{-7}	1,800
PV-Lab 3-D	N/A	1.9×10^{-10}	2.5×10^{-8} (5)	130
PV-Lab 1-D	N/A	1.9×10^{-10} (6)	1.2×10^{-8} (7)	62

Notes:
1. PV = Parkview; Block = Block specimen(s); TW = Thin-wall tube specimen; CB = CRREL core barrel specimen; Lab 3-D = Laboratory compacted specimens frozen three-dimensionally; Lab 1-D = Laboratory compacted specimens frozen one-dimensionally; -1, -2, -3, -4, -5 = Specimen number.
2. Hydraulic conductivities are reported as averages for specimens removed from the test pad from a depth of 0-0.3 m after winter (2 specimens) and for 3D and 1D laboratory compacted specimens (3 specimens).
3. Change in hydraulic conductivity (K_f/K_i) is defined as the final hydraulic conductivity divided by the initial hydraulic conductivity.
4. No specimens collected before winter in thin wall tubes or as frozen cores, thus average hydraulic conductivity is reported as the average hydraulic conductivity for the block specimens collected before winter.
5. Average hydraulic conductivity after 5 freeze-thaw cycles.
6. Initial hydraulic conductivity tests were not performed on specimens frozen one-dimensionally. The initial value is assumed to be similar to the average initial hydraulic conductivity of the specimens frozen three-dimensionally because they were compacted under identical conditions (compactive effort and molding water content).

Table 5.7. Summary of hydraulic conductivity tests performed on Valley Trail field and laboratory specimens.

Specimen[1]	Sample Depth (m)	Initial Hydraulic Conductivity[2] (m/s)	Final Hydraulic Conductivity[2] (m/s)	$\frac{K_f}{K_i}$ [3]
VT-Block	0-0.3	9.8×10^{-11}	2.6×10^{-7}	2,600
VT-Block	0.3-0.6	1.6×10^{-10}	2.6×10^{-7}	1,600
VT-Block	0.6-0.9	1.5×10^{-10}	2.2×10^{-10}	1.5
VT-TW-1	0.07	1.4×10^{-10} [4]	4.0×10^{-10}	2.8
VT-TW-2	0.15	1.4×10^{-10} [4]	1.5×10^{-10}	1.1
VT-TW-3	0.25	1.4×10^{-10} [4]	1.5×10^{-10}	1.1
VT-TW-4	0.45	1.4×10^{-10} [4]	1.5×10^{-10}	1.1
VT-TW-5	0.52	1.4×10^{-10} [4]	1.5×10^{-10}	1.1
VT-CB-1	0.15	1.4×10^{-10} [4]	1.2×10^{-8}	86
VT-CB-2	0.25	1.4×10^{-10} [4]	8.0×10^{-7}	5,700
VT-CB-3	0.35	1.4×10^{-10} [4]	8.5×10^{-9}	61
VT-Lab 3-D	N/A	1.3×10^{-10}	6.4×10^{-9} [5]	50
VT-Lab 1-D	N/A	1.3×10^{-10} [6]	1.8×10^{-8} [7]	140

Notes:
1. VT = Valley Trail; Block = Block specimen(s); TW = Thin-wall tube specimen; CB = CRREL core barrel specimen; Lab 3-D = Laboratory compacted specimens frozen and thawed three-dimensionally; Lab 1-D = Laboratory compacted specimens frozen one-dimensionally; -1, -2, -3, -4, -5 = Specimen number.
2. Hydraulic conductivities are reported as averages for specimens removed from the test pad from a depth of 0-0.3 m after winter (2 specimens) and for 3D and 1D laboratory compacted specimens (3 specimens).
3. Change in hydraulic conductivity (K_f/K_i) is defined as the final hydraulic conductivity divided by the initial hydraulic conductivity.
4. No specimens collected before winter in thin wall tubes or as frozen cores, thus average hydraulic conductivity is reported as the average hydraulic conductivity for the block specimens collected before winter.
5. Average hydraulic conductivity after 5 freeze-thaw cycles.
6. Initial hydraulic conductivity tests were not performed on specimens frozen one-dimensionally. The initial value is assumed to be similar to the average initial hydraulic conductivity of the specimens frozen three-dimensionally because they were compacted under identical conditions (compactive effort and molding water content).

cycle of freeze-thaw. Thus, for these soils the increase in hydraulic conductivity that occurs in the field is an order of magnitude larger than the increase in hydraulic conductivity measured in the laboratory using one-dimensional or three-dimensional freezing methods. Benson and Othman (1993) reported a similar difference in their field and laboratory tests.

The cause of this difference is not clear. However, the cracks occurring in the field were more widely spaced and had larger aperture than those that occurred in specimens frozen and thawed in the laboratory (Figs. 5.7 and 5.10 vs. Fig. 5.16). Furthermore, the ice lenses observed in the core specimens (Fig. 5.9) were more randomly oriented than those observed in the specimens frozen and thawed in the laboratory (Fig. 5.16). However, without a more detailed study of changes in soil fabric and structure, the mechanism responsible for the difference in the increase in hydraulic conductivity occurring in the laboratory and field cannot be determined with certainty.

Figure 5.16. Interior of Parkview specimen frozen and thawed in the laboratory.

SECTION 6

RESULTS
SAND-BENTONITE MIXTURE

6.1 FIELD TESTS

6.1.1 Freeze-Thaw Monitoring

Temperatures were monitored by CRREL personnel in the sand-bentonite test pad constructed for the COLDICE project throughout the winter of 1992-93. Freezing of the test pad began in November 1992 and was steady in mid- to late December 1992. In mid- to late March 1993, thawing became steady. Complete thaw 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).

Figure 6.1 shows a profile of frost penetration over time. Freezing records show that once steady freezing was established, freeze-thaw cycling only occurred in the overburden material and not in the sand-bentonite mixture. Figure 6.1 shows that frost had fully penetrated the test pad. It was determined that the sand-bentonite mixture was subjected to one freeze-thaw cycle during the winter of 1992-93 (Fig. 6.1).

6.1.2 In Situ Box Infiltrometers

In situ hydraulic conductivity of the sand-bentonite test pad was measured by personnel from CH2M Hill, Inc. after the test pad had been exposed to two winters. A box infiltrometer (Sec. 4.1.1.2) was used. A hydraulic conductivity of 5×10^{-10} m/s was measured in June and July 1994 (Erickson et al. 1994). No measurement of field hydraulic conductivity was made before the test pad had frozen. Therefore, no comparison of hydraulic conductivity before and after winter could be made. However, visual examination of the soil during disassembly of the infiltrometer revealed that the mixture was soft and contained none of the crack structures typically seen in compacted clays exposed to freeze-thaw. Similar structure was observed prior to winter when the first set of block specimens was collected. Thus, it appeared that the sand-bentonite mixture had not been affected by freeze-thaw.

Water content of the sand-bentonite mixture was measured at three depths within the box infiltrometer by personnel from the University of Wisconsin-Madison. Samples were taken at depths of 0.07 m, 0.14 m, and 0.2 m. The water contents were 42.1, 20.4, and 18.2%, respectively. These water contents were all higher than the water content at which the test pad was compacted (≈17%). The high water contents near the surface of the test pad were probably the result of hydration and swelling of the bentonite. Also, the presence of high water contents in the upper surface of the test pad indicates that the sand-bentonite mixture was able to retain water after exposure to freeze-thaw.

6.1.3 Laboratory Assessment of Field-Scale Hydraulic Conductivity

Hydraulic conductivity tests were performed at the University of Wisconsin-Madison on block specimens removed from the sand-bentonite test pad. Tests were performed on three specimens removed before winter and three specimens removed after one winter of exposure. Results of the hydraulic conductivity tests are summarized in Table 6.1.

Two of the specimens removed before winter (depths = 0-0.3 m and 0.3-0.6 m) had high hydraulic conductivity (> 1.0×10^{-8} m/s), whereas the third specimen (depth = 0.15-0.45 m) had very low hydraulic conductivity (3.1×10^{-11} m/s). The specimen having low hydraulic conductivity (intermediate depth (0.15-0.45 m) was permeated for 55 days before the test was terminated. The specimen never met the outflow/inflow criterion, but the hydraulic conductivity was steady for most of the testing period. The final outflow/inflow ratio was approximately 0.2.

The high hydraulic conductivity of the other two specimens was caused by loss of bentonite (i.e., "piping" of bentonite). The effluent burettes for these specimens were clouded with bentonite soon after testing was initiated.

Piping of bentonite also occurred in all three specimens removed from the sand-bentonite test pad after winter. Bentonite was also present in the effluent burettes of all three specimens soon after the hydraulic conductivity testing began.

Hydraulic conductivity tests were also performed at the University of Wisconsin-Madison on specimens removed from the sand-bentonite test pad in June 1994 using a thin-wall sampling tube (diameter = 71 mm). Results of the tests are summarized in Table 6.2. The specimens were removed from a depth of 0-0.6 m. The average hydraulic conductivity for the four sand-bentonite specimens was 1.1×10^{-10} m/s.

Hydraulic conductivity tests were also performed at CRREL on specimens removed from the test pad as 71 mm-diameter frozen cores. All of the specimens exhibited piping of bentonite. Therefore, no laboratory assessment of post-winter hydraulic conductivity could be made from the specimens removed as frozen cores or those removed as blocks.

Table 6.1. Results of hydraulic conductivity tests on block specimens removed from the sand-bentonite test pad.

Specimen[1]	Sample Depth (m)	Hydraulic Conductivity (m/s)
SB-Block-Before-1	0-0.3	1.2×10^{-7}
SB-Block-Before-2	0.3-0.6	3.1×10^{-11}
SB-Block-Before-3	0.6-0.9	2.4×10^{-8}
SB-Block-After-1	0-0.3	6.6×10^{-7}
SB-Block-After-2	0.3-0.6	2.4×10^{-7}
SB-Block-After-3	0.6-0.9	5.7×10^{-8}

Notes:
1. SB = Sand-bentonite; Block = Block specimen; Before = Sampled before winter; After = Sampled after winter; -1, -2, -3 = Specimen number.

Table 6.2. Results of hydraulic conductivity tests on thin-wall tube specimens removed from the sand-bentonite test pad.

Specimen[1]	Sample Depth (m)	Hydraulic Conductivity (m/s)
SB-TW-1	0.15	1.3×10^{-10}
SB-TW-2	0.25	1.8×10^{-10}
SB-TW-3	0.35	8.7×10^{-11}
SB-TW-4	0.45	3.0×10^{-11}

Note:
1. SB = Sand-bentonite; TW = Specimen sampled using a thin-wall tube; -1, -2, -3, -4 = Specimen number.

6.2 LABORATORY TESTS

6.2.1 Hydraulic Conductivity-Water Content Relationships

Hydraulic conductivity was measured for four specimens compacted with standard Proctor effort and four compacted with modified Proctor effort (Fig. 6.2). Results of the hydraulic conductivity tests are tabulated in Appendix A.

Examination of Fig. 6.2 reveals that the hydraulic conductivity of the sand-bentonite mixture is less sensitive to molding water content than the hydraulic conductivity of compacted clays (e.g., Sec. 5.2.1). The results also show that the hydraulic conductivity of the sand-bentonite mixture is not sensitive to compactive effort for molding water contents dry of optimum, which is in direct contrast to the behavior of most compacted clays.

One specimen (modified Proctor compactive effort, molding water content = 7.3%) showed anomalously high hydraulic conductivity. Bentonite was noticed in the effluent burette during permeation. Examination of the specimen after it was removed from the permeameter showed a thin zone devoid of bentonite along the entire side of the specimen (i.e., "piping" of the bentonite had occurred). This piping explains the bentonite seen in the effluent and the high hydraulic conductivity that was measured. Other than the thin zone low in bentonite, the specimen appeared to be a dense, homogeneous, low-conductivity mass.

6.2.2 Standard Freeze-Thaw Tests

Three specimens were compacted at standard Proctor effort at the water content at which the sand-bentonite test pad was compacted for the COLDICE project (≈17%, see Fig. 4.12). The hydraulic conductivity of each specimen was measured after 0, 1, 3, and 5 freeze-thaw cycles. All of the specimens were permeated for a minimum of 30 days. The hydraulic conductivity for each specimen was steady when the test was terminated. However, the outflow/inflow criterion was not met for any of the specimens after any number of freeze-thaw cycles. Results of the freeze-thaw tests conducted on the sand-bentonite mixture are summarized in Fig. 6.3 and Table 6.3.

All three specimens exhibited piping of bentonite after three freeze-thaw cycles and one specimen exhibited piping of bentonite after five freeze-thaw cycles. Specimens that exhibited piping of bentonite were removed from their permeameters and examined. A thin zone (≈5 mm wide) appearing low in bentonite was observed along the side of each specimen, which was continuous from one end of the specimen

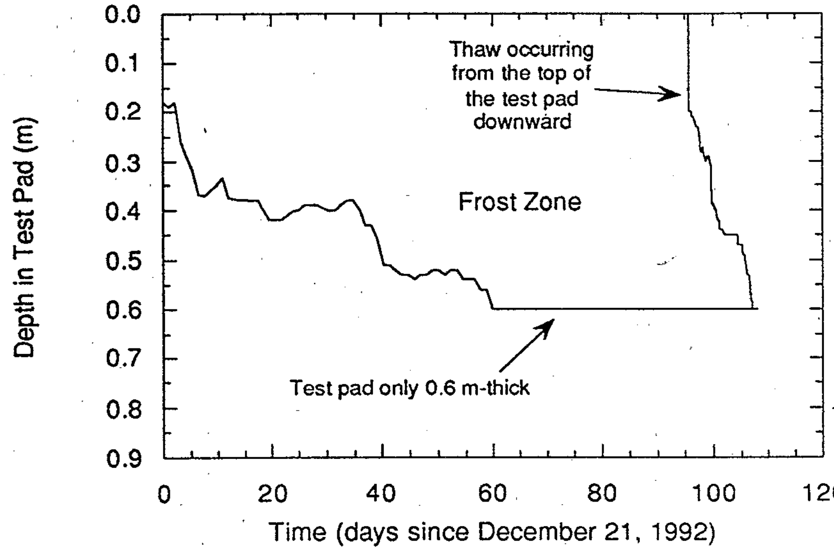


Figure 6.1. Depth of frost penetration vs. time for the COLDICE sand-bentonite test pad (after Chamberlain 1994, personal communication).

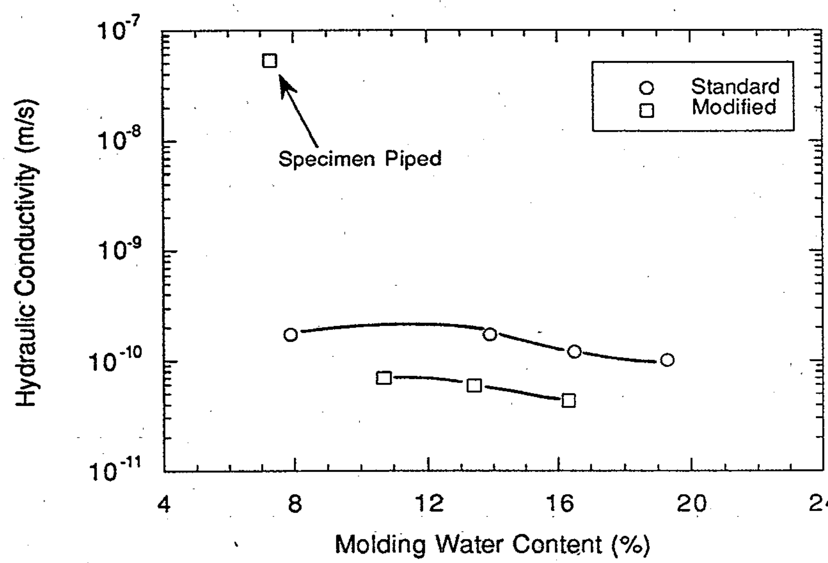


Figure 6.2. Hydraulic conductivity vs. molding water content for sand-bentonite mixture.

to the other. To correct the piping problem, a bentonite paste consisting of powdered bentonite mixed with tap water was applied to these zones. The specimens were placed in their permeameters and permeated again. Addition of the bentonite paste alleviated the piping problem. One specimen piped again after 5 freeze-thaw cycles. The same procedure was used to correct the problem with that specimen.

Because zones low in bentonite were only observed on the sides of the specimens, piping of bentonite is likely a result of particle movement under a high hydraulic gradient (≈30) while thawing and not a direct result of freeze-thaw.

6.3 COMPARISON OF FIELD AND LABORATORY TEST RESULTS

A summary of the results of the field and laboratory hydraulic conductivity tests is shown in Table 6.4. A quantitative comparison of field- and laboratory-scale hydraulic conductivities for the sand-bentonite is difficult because the quantity of field data is sparse. All but one of the block specimens removed from the test pad before winter piped and all of the block specimens removed from the test pad after winter piped. Nevertheless, a qualitative comparison between the effect of freeze-thaw on sand-bentonite at field- and laboratory-scales is possible.

Visual examination of the soil within the box infiltrometer revealed that the hydraulic integrity of the sand-bentonite mixture was not deleteriously affected by exposure to freeze-thaw. The top of the sand-bentonite within the box infiltrometer was soft and saturated, whereas soil within the box infiltrometer installed in the Parkview clay test pad was cracked and did not prevent the flow of water (Sec. 5.1.2). The high water contents, which decreased with depth (Sec. 6.1.2), occurred because the sand-bentonite mixture restricted infiltration and allowed the bentonite to swell. These conditions are consistent with the low hydraulic conductivity that was measured by Erickson et al. (1994) after two winters of exposure and two freeze-thaw cycles (Table 6.4).

The block specimens removed before and after winter exposure were examined following permeation to observe their structure. The specimens were opened by prying them apart with a long screwdriver. This method prevents smearing of the specimen, which occurs with a saw or blade. Zones rich in bentonite were found when the specimens were cut open (Fig 6.4), which are believed to be the result of poor mixing of the sand and bentonite during preparation. The high hydraulic conductivity of the block specimens was most likely the result of insufficient mixing of the sand and bentonite and not freeze-thaw, because high hydraulic conductivities were measured

Table 6.3. Results of freeze-thaw tests on sand-bentonite specimens compacted in the laboratory.

Specimen(1)	Initial Hydraulic Conductivity K_0 (m/s)	Hydraulic Conductivity After n Freeze-Thaw Cycles, K_n (m/s)			$\frac{K_5}{K_0}$ (2)
		K_1	K_3	K_5	
SB-3D-1	1.5×10^{-11}	2.2×10^{-11}	1.9×10^{-11}	5.1×10^{-11}	3.4
SB-3D-2	1.4×10^{-11}	1.7×10^{-11}	1.6×10^{-11}	3.0×10^{-11}	2.1
SB-3D-3	1.6×10^{-11}	3.2×10^{-11}	1.8×10^{-11}	2.1×10^{-11}	1.3

Notes:
1. SB = Sand-bentonite; 3D = Specimen was frozen and thawed three-dimensionally; -1, -2, -3 = Specimen number.
2. K_5/K_0 = Hydraulic conductivity of specimen after 5 freeze-thaw cycles divided by the hydraulic conductivity before exposure to freeze-thaw.

Table 6.4. Summary of freeze-thaw test results for sand-bentonite mixture.

	Hydraulic Conductivity, K, by Sampling Method (m/s)			
	Box Infiltrometers(1)	Block Specimens(2)	Thin-Walled Tubes(3)	Laboratory Compacted Specimens(4)
Before Freeze-Thaw	N/A(5)	3.1×10^{-11}	N/A	1.5×10^{-11}
After Freeze-Thaw	$< 5 \times 10^{-10}$	N/A	1.1×10^{-10}	3.4×10^{-11}
K_A/K_B (6)	N/A	N/A	N/A	2.3

Notes:
1. Hydraulic conductivity was only measured after winter using a box infiltrometer (Erickson et al. 1994).
2. Before freeze-thaw value is for one specimen (depth = 0.15-0.45 m). All of the specimens removed after winter piped.
3. Specimens were only collected in thin-wall sampling tubes after winter.
4. Values are averages for three specimens. After freeze-thaw value is the average hydraulic conductivity of three specimens after 5 cycles of freeze-thaw.
5. N/A = not available.
6. K_A/K_B is defined as the ratio of average before freeze-thaw hydraulic conductivity to average after freeze-thaw hydraulic conductivity.

for specimens removed from the test pads before and after winter. Examination of the block specimens also showed that exposure to freeze-thaw did not result in cracking of the sand-bentonite (Fig. 6.4) as was observed for the Parkview and Valley Trail clays (Sec. 5.1.3.4).

The freeze-thaw tests performed on the specimens prepared in the laboratory also showed that freeze-thaw did not affect the hydraulic conductivity of the sand-bentonite mixture (Fig. 6.3). A two-tailed t-test was performed to compare the mean hydraulic conductivity after five freeze-thaw cycles and the mean initial hydraulic conductivity. A confidence interval of 0.05 was used, which corresponds to a critical t-score (t_{cr}) of 2.13. A t-statistic of 1.89 was calculated, which is less than t_{cr}. Therefore, freeze-thaw had no statistically significant effect on the hydraulic conductivity of the sand-bentonite mixture. Furthermore, the internal structure of the sand-bentonite specimens showed no signs of cracking in the frozen or thawed states (Fig. 6.5).

The specimens collected in thin-wall tubes also had low hydraulic conductivity. One of the specimens was opened to reveal the soil structure after exposure to freeze-thaw. Figure 6.6 is a photograph of the opened specimen. A homogeneous soil mass is evident; none of the crack structures typically seen in compacted clays subjected to freeze-thaw exist. Thus, based on similar structures existing in the box infiltrometer, block specimens, thin-wall tube specimens, and laboratory compacted specimens and the low hydraulic conductivity measured in both the field (box infiltrometer) and laboratory (laboratory compacted specimens), it is inferred that freeze-thaw does not affect this sand-bentonite mixture.

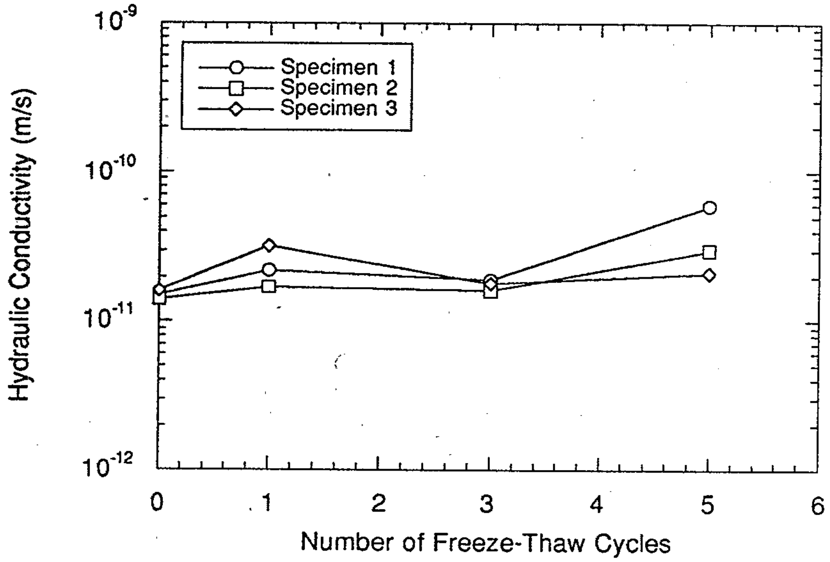


Figure 6.3. Hydraulic conductivity vs. number of freeze-thaw cycles for sand-bentonite.

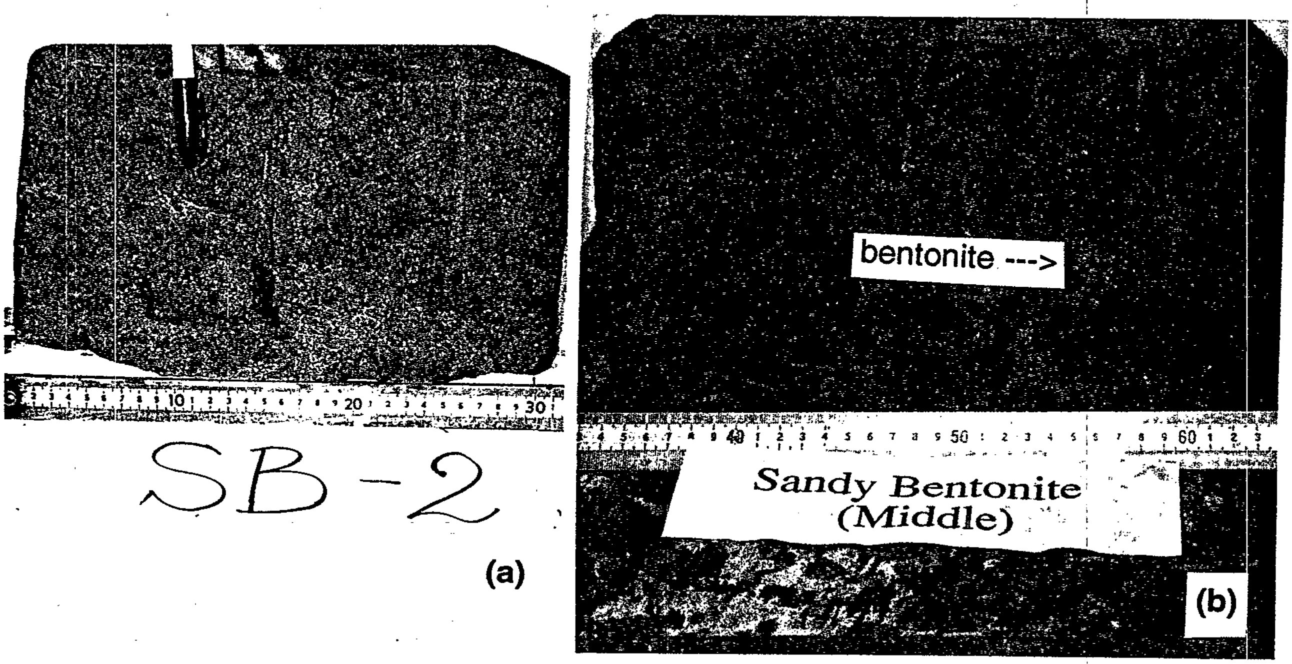


Figure 6.4. Photograph of sand-bentonite block specimens before exposure to freeze-thaw (a) and after exposure to freeze-thaw (b) showing internal structure and bentonite-rich zones.

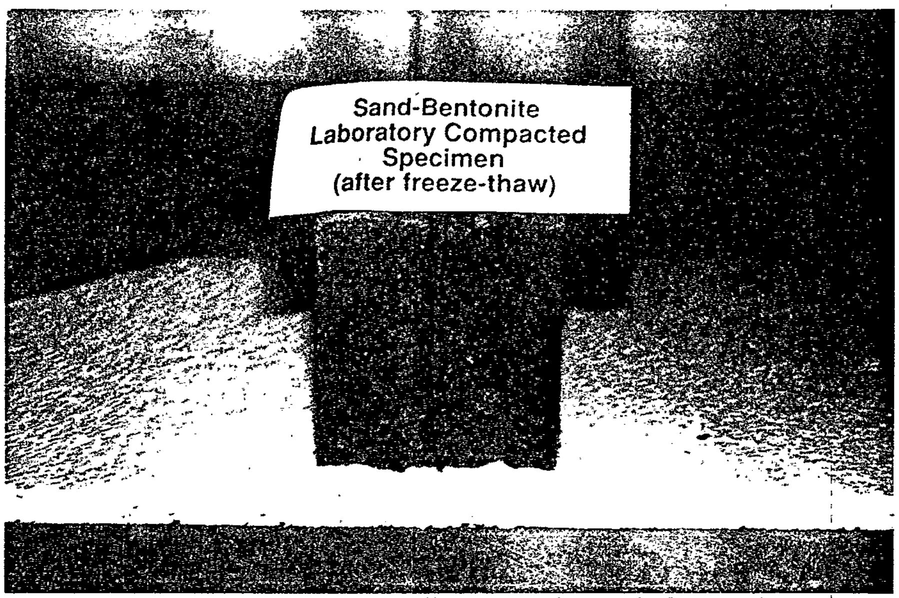


Figure 6.5. Photograph of internal structure of sand-bentonite specimen compacted in the laboratory and subjected to freeze-thaw.

Figure 6.6. Photograph of the internal structure of sand-bentonite specimen removed from the COLDICE test pad after winter using a thin-wall tube.

SECTION 7

RESULTS
GEOSYNTHETIC CLAY LINERS (GCLs)

7.1 FIELD TESTS

7.1.1 GCL Test Ponds and Pans

Temperatures beneath the GCLs were monitored by CRREL personnel during the winters of 1992-93 and 1993-94 in the test ponds and over the winter of 1993-94 in the test pans (Fig. 7.1). From the temperature data, it was determined that the GCLs in the test ponds underwent 2 freeze-thaw cycles (one each winter) and the GCLs in the test pans underwent 1 freeze-thaw cycle. Hydraulic conductivity of the GCLs was measured in the GCL test pans before and after the winter of 1993-94 by monitoring outflow. Hydraulic conductivity of the test ponds was not measured because of problems caused by leaks (Erickson et al. 1994). Results of the hydraulic conductivity tests are summarized in Table 7.1.

Seepage was collected before winter from all but one of the test pans (Erickson et al. 1994). The GCL test pan from which no seepage was collected apparently was still hydrating when seepage monitoring was terminated. Analysis of the seepage data showed that all of the GCLs had low hydraulic conductivity ($\approx 1.0 \times 10^{-10}$ to 2.8×10^{-10} m/s).

All of the GCL test pans had measurable amounts of seepage after winter. The average post-winter hydraulic conductivities of the Bentomat® and Claymax® GCL test pans were 1.4×10^{-10} and 2.9×10^{-10} m/s, respectively (Erickson et al. 1994).

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

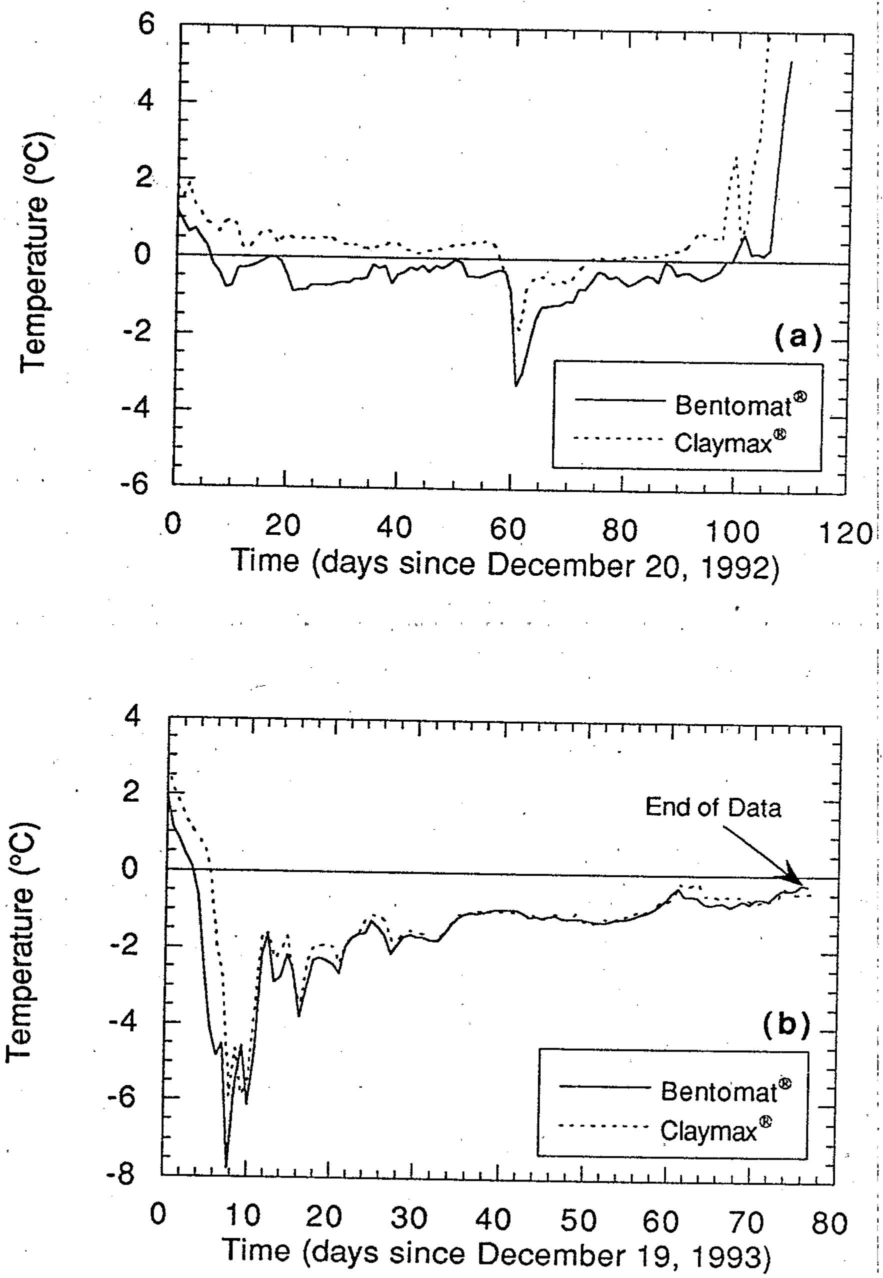


Figure 7.1. Temperature vs. time beneath the GCLs in the COLDICE test ponds for the winters of 1992-93 (a) and 1993-94 (b) (from Chamberlain 1994, personal communication).

Table 7.1. Summary of hydraulic conductivity test results for the GCL test pans used in the COLDICE project (from Erickson 1994, personal communication).

Specimen	Seam?	Before-Winter Hydraulic Conductivity (m/s)	After-Winter Hydraulic Conductivity (m/s)	$\frac{K_A}{K_B}$ (1)
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}	N/A(2)
Claymax®, 1.8 m^2	Yes	2.8×10^{-10}	7.0×10^{-10}	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

Note:

1. K_A/K_B is defined as the ratio of after-winter hydraulic conductivity to before-winter hydraulic conductivity.
2. N/A = Not Applicable

conclude that the hydraulic integrity of these GCLs was not affected by exposure to freeze-thaw.

7.1.2 Laboratory Assessment of Field-Scale Hydraulic Conductivity

Hydraulic conductivity was measured on GCL specimens removed from the COLDICE GCL test ponds after exposure to two winters (i.e., two freeze-thaw cycles). Methods described in Sec. 4.3.1.2 were followed. The hydraulic conductivity tests required less than one week to meet the termination criteria. Results of the tests are summarized in Table 7.2.

Hydraulic conductivity was measured on two 0.45 m-diameter specimens of Claymax® and two 0.30 m-diameter specimens of Bentomat®. Originally, the Bentomat® specimens had a diameter of 0.45 m. However, very high flow rates were measured when they were permeated. To determine the cause of the high hydraulic conductivity, rhodamine dye was added to the influent water to stain the flow paths. Examination of the specimens after the permeameter was disassembled showed that sidewall leakage occurred because of short-circuiting through geotextiles near the edge of each specimen. To eliminate this problem, the Bentomat® specimens were trimmed to a diameter of 0.30 m and re-tested.

The hydraulic conductivities of the Bentomat® specimens were 2.5×10^{-8} and 1.7×10^{-10} m/s, whereas the Claymax® specimens had hydraulic conductivities of 3.5×10^{-10} and 6.3×10^{-10} m/s (Table 7.2). The high hydraulic conductivity for the one 0.30 m-diameter Bentomat® specimen (BMT-PND-1) was measured after attempts were made to prevent sidewall leakage. The high hydraulic conductivity of specimen BMT-PND-1 is attributed to either sidewall leakage that could not be corrected or disturbance during handling, but not freeze-thaw.

Figure 7.2 is a photograph of the two Bentomat® specimens after hydraulic conductivity testing. The bentonite component of the Bentomat® specimen BMT-PND-1 shows no structural changes often attributed to freeze-thaw (e.g., cracks), and appears similar to the bentonite component of the Bentomat® specimen having low hydraulic conductivity (BMT-PND-2).

7.2 LABORATORY TESTS

7.2.1 Laboratory-Scale Hydraulic Conductivity Tests

Hydraulic conductivity tests were performed on three 0.15-m-diameter specimens of Bentofix® and Bentomat® and four 0.15-m-diameter specimens of Claymax®. Initial

Table 7.2. Results of hydraulic conductivity tests on GCL specimens removed from the COLDICE test ponds.

Specimen[1]	Diameter (m)	Hydraulic Conductivity (m/s)
BMT-PND-1	0.30	2.5×10^{-8}
BMT-PND-2	0.30	1.7×10^{-10}
CMX-PND-1	0.45	3.5×10^{-10}
CMX-PND-2	0.45	6.3×10^{-10}

Note:

1. BMT = Bentomat®; CMX = Claymax®; PND = Specimen removed from test pond; -1, -2 = Specimen number.

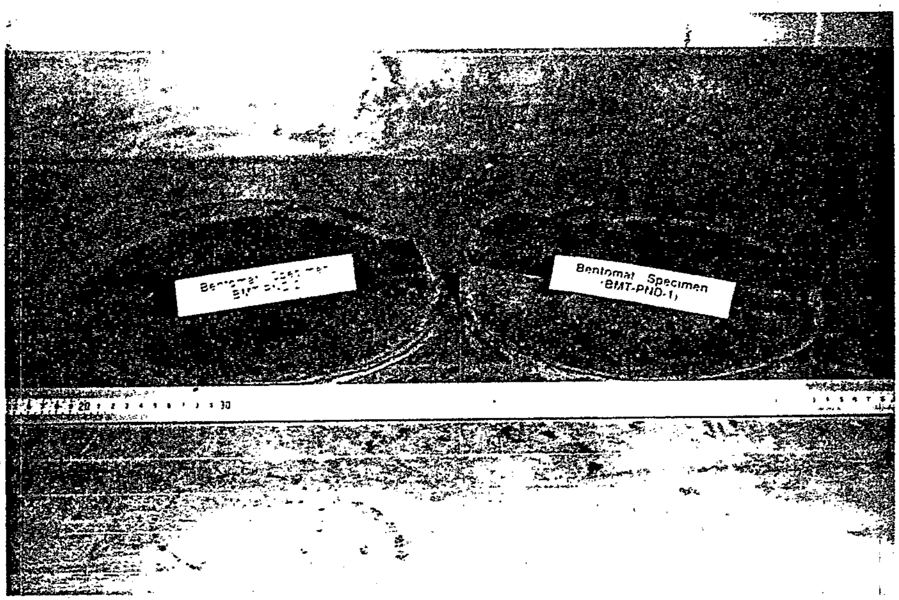


Figure 7.2. Photograph of the two Bentomat® specimens removed from the GCL test ponds at the COLDICE field site.

saturation of the specimens required 3 to 4 weeks. During this period, the hydraulic conductivity decreased and the ratio of outflow to inflow increased, both slowly, as the bentonite hydrated. Hydraulic conductivity tests conducted after freeze-thaw required about 1 to 2 weeks before the termination criteria were met. In contrast to the tests performed before freezing, the hydraulic conductivity was essentially steady from the onset for the GCLs exposed to freeze-thaw and the outflow/inflow ratio fell between 0.75 and 1.25 immediately following initiation of the tests.

Results of the hydraulic conductivity tests are summarized in Figs. 7.3-7.5 and Table 7.3. All of the hydraulic conductivities are low, ranging between 2.9×10^{-11} m/s and 4.9×10^{-11} m/s for the initial condition and 1.7×10^{-11} m/s and 3.3×10^{-11} m/s for the specimens exposed to 20 cycles of freeze-thaw. In the initial condition, the Bentomat® GCLs had slightly lower hydraulic conductivity (3.0×10^{-11} m/s), on average, relative to the Bentofix® (4.5×10^{-11} m/s) and Claymax® (4.0×10^{-11} m/s) GCLs. After 20 cycles of freeze-thaw, the Bentomat® GCLs still had slightly lower hydraulic conductivity (1.8×10^{-11} m/s), relative to the Bentofix® (2.6×10^{-11} m/s) and Claymax® (2.8×10^{-11} m/s) GCLs. Furthermore, for all three GCLs, a small decrease in hydraulic conductivity apparently occurred as a consequence of freeze-thaw (Figs. 7.3-7.5). This decrease in hydraulic conductivity is likely the result of thaw consolidation (Chamberlain and Gow 1979) or rearrangement of the bentonite particles.

The slight decrease in hydraulic conductivity that occurs is evident in the ratio K_{20}/K_0, which is defined as the hydraulic conductivity of a specimen after 20 cycles of freeze-thaw divided by its initial hydraulic conductivity (Table 7.2). The ratio varies between 0.55 to 0.66 for the Bentomat® GCLs, 0.45 to 1.10 for the Bentofix® GCLs, and 0.57 to 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 cycles of freeze-thaw. The one specimen that exhibited an increase in hydraulic conductivity after 20 freeze-thaw cycles (Bentofix®-1) showed a decrease in hydraulic conductivity after 1, 3, and 5 freeze-thaw cycles, relative to its initial hydraulic conductivity.

To determine if the apparent decrease in hydraulic conductivity was statistically significant, a t-test was conducted to compare the mean initial hydraulic conductivity and the mean hydraulic conductivity after 20 cycles of freeze-thaw for each GCL. The comparison was made at a significance level of 0.05, with a corresponding critical t (t_{cr}) of 1.96. Results of the test indicate that the reduction in hydraulic conductivity is significant for each GCL, with t-statistics of 14.7 (Bentomat®), 3.2 (Bentofix®), and 2.2 (Claymax®); i.e., $t > t_{cr}$ for each GCL.

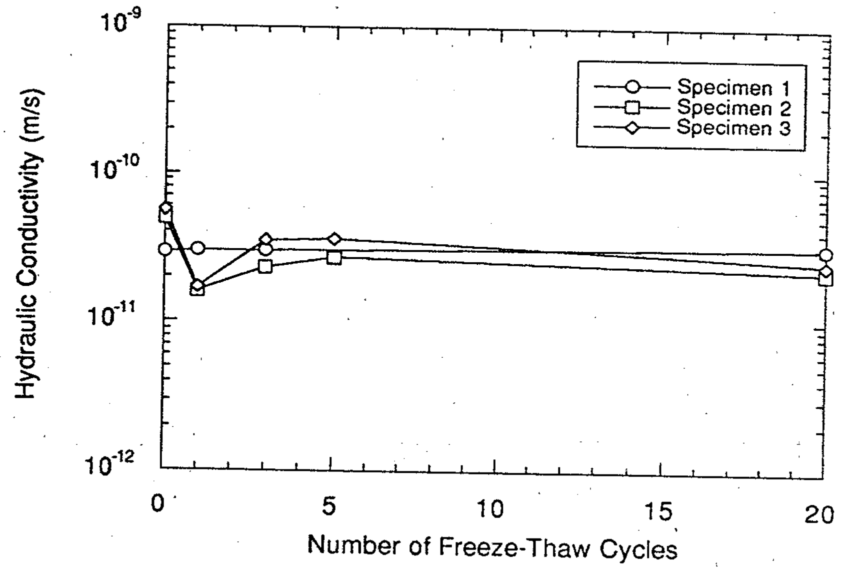


Figure 7.3. Results of freeze-thaw tests on specimens of Bentofix® frozen and thawed in the laboratory.

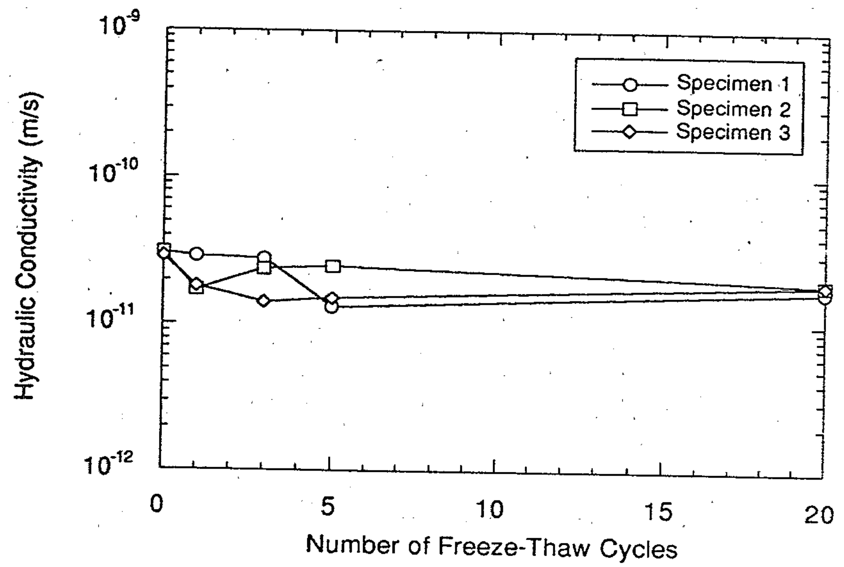


Figure 7.4. Results of freeze-thaw tests on specimens of Bentomat® frozen and thawed in the laboratory.

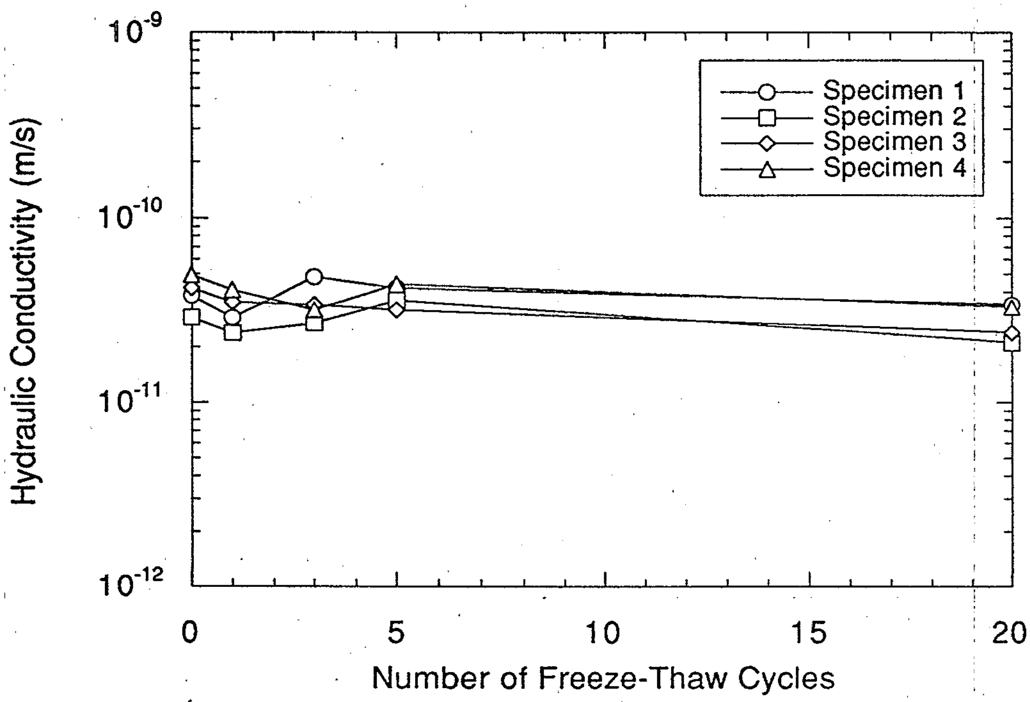


Figure 7.5. Results of freeze-thaw tests of specimens of Claymax® frozen and thawed in the laboratory.

Table 7.3. Summary of freeze-thaw tests on GCL laboratory specimens.

Sample Number	Initial Hydraulic Conductivity, K_0 (m/s)	Hydraulic Conductivity After n Freeze-Thaw Cycles, K_n (m/s)				$\frac{K_{20}}{K_0}$
		K_1	K_3	K_5	K_{20}	
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

7.2.2 Structure of Frozen Specimens

The structure of the GCLs was examined to determine why the hydraulic conductivity of GCLs does not change when they are frozen and thawed, whereas an increase in hydraulic conductivity is generally observed for compacted clays subjected to freeze-thaw. The increase in hydraulic conductivity occurring in compacted clays is attributed primarily to cracking (e.g., Fig. 5.10) that occurs during freezing (Chamberlain et al. 1990, 1994, Othman and Benson 1993).

A band saw was used to cut open hydrated specimens of each GCL 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, the second cut was made parallel to the geosynthetic layers to obtain a horizontal cross-section. A razor blade was used to remove smeared soil that formed during sawing. The exposed frozen faces were examined and photographed.

Small ice crystals in a random orientation existed in the face of each specimen (Fig. 7.6). However, large ice lenses and distinct cracks, such as those observed in frozen compacted clays by Othman and Benson (1993) and Chamberlain et al. (1990, 1994), did not exist in the GCLs. The lack of such cracks is consistent with the low hydraulic conductivity measured after thawing.

Figure 7.7 is a photograph of two hydrated GCL specimens. One of the specimens has been exposed to 20 cycles of freeze-thaw and the other has never been exposed to any freeze-thaw (initial saturation condition). Both specimens in Fig. 7.7 have similar structure. Their nearly identical structure, which is devoid of cracks, is consistent with the similarity of their hydraulic conductivities. Apparently, the voids containing ice lenses collapse as the bentonite returns to its soft, highly plastic condition during thawing.

7.2.3 Bentonite in Effluent

Bentonite was observed in the graduated cylinders used to collect effluent during hydraulic conductivity testing. Bentonite appeared from the Bentofix® specimens after 3 freeze-thaw cycles, from the Bentomat® specimens after 5 freeze-thaw cycles, and from the Claymax® specimens after 20 freeze-thaw cycles. Migration of bentonite from Claymax® and Bentomat® GCLs has also been reported by Estornell and Daniel (1992) in large bench-scale tests. In this study, migration of the bentonite probably occurred as a consequence of particle movement that occurred during freezing and thawing.

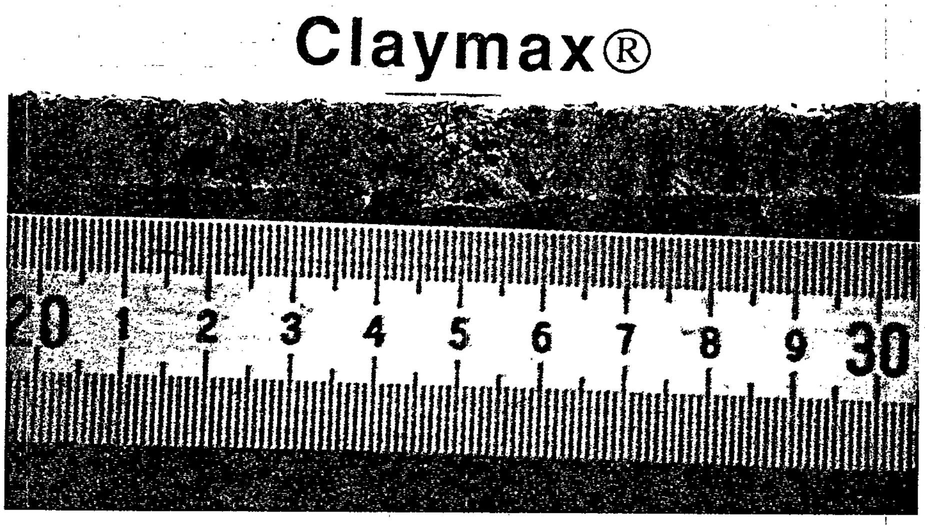


Figure 7.6. Photograph of section of frozen Claymax® GCL.

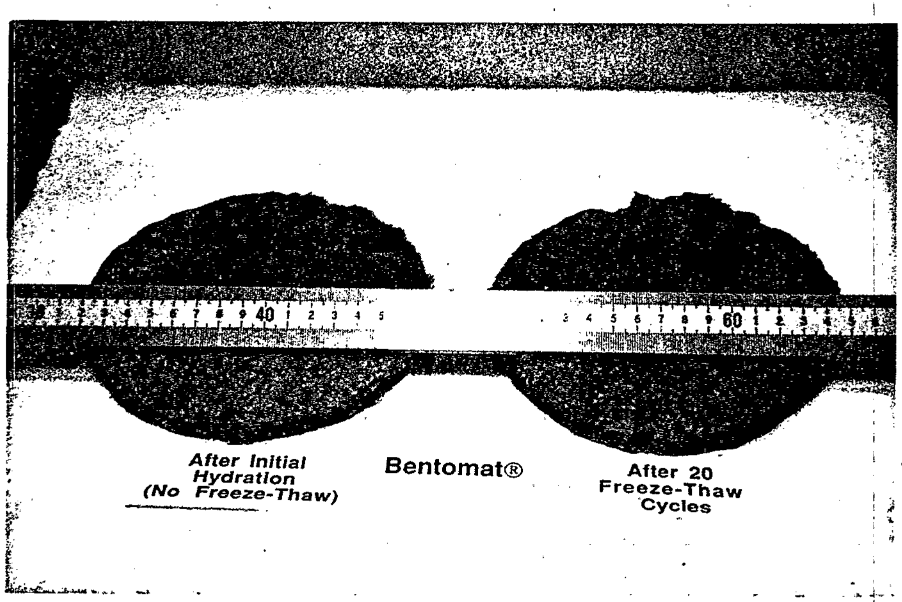


Figure 7.7. Photograph of hydrated Bentomat® specimens before and after freeze-thaw.

The presence of the bentonite in the effluent was a concern, because if a sufficient quantity of bentonite was lost, an increase in hydraulic conductivity could result. However, the quantity of expelled bentonite was small (about 0.4% of the mass of the effluent, <0.01% of the mass of the GCL specimen) and had no influence on the overall hydraulic integrity of the GCLs (Figs. 7.3-7.5).

7.3 COMPARISON OF FIELD AND LABORATORY TEST RESULTS

In general, the hydraulic conductivities measured in the field (or in the laboratory with specimens removed from the field) were greater than those measured in the laboratory, regardless of whether the tests were conducted before or after freezing. The higher hydraulic conductivities observed in the field were likely the result of different test conditions. For example, the effective stress and hydraulic gradient were lower in the field, which has been shown to result in higher hydraulic conductivity of GCLs (Estornell and Daniel 1992). These conditions are difficult to simulate in flexible-wall permeameters. More important, however, is that no significant increase in hydraulic conductivity was observed in the field or laboratory tests. The lack of change in hydraulic conductivity is consistent with the lack of change in structure observed in the field and laboratory specimens (Figs. 7.2 and 7.7). That is, no cracks were present in any of the GCLs that had been subjected to freeze-thaw.

The GCL specimens tested in the field that contained seams had slightly higher hydraulic conductivities than the GCLs without seams, both before and after freeze-thaw. The higher hydraulic conductivity of the seamed specimens may have been caused by the construction methods that were used or freeze-thaw. Additional research regarding how freeze-thaw affects GCL seams should be conducted.

SECTION 8

RESULTS
PAPER MILL SLUDGES

8.1 FIELD TESTS

8.1.1 Compaction of Pipe Specimens

Pipe specimens were constructed by compacting paper mill sludge in large PVC pipes (diameter = 0.35 m, length = 0.6 m). Six specimens were constructed (two specimens per sludge) using a compactive energy equal to standard Proctor effort (592.5 kJ/m^3). Molding water contents of 90, 120, and 130% were used for sludges A, B, and C, respectively. These water contents correspond to the water contents yielding the lowest hydraulic conductivities for specimens used to determine the hydraulic conductivity-water content relationship for each sludge (see Sec. 8.2.1).

Ensuring uniform water content within each specimen was difficult. The paper mill sludges were dried to the molding water contents from their as-received water contents in a large, forced-air walk-in oven in the Structures and Materials Testing Laboratory at the University of Wisconsin-Madison. The oven temperature was approximately 70°C. Approximately 100 kg of each sludge was dried at one time using large pans. Mixing of the sludge to ensure uniform drying was difficult because of the volume of sludge being dried. To alleviate this problem, the partially dried sludge was homogenized in sealed high density polyehtylene (HDPE) drums for 48 hours prior to compaction. This ensured a more uniform distribution of water in the sludge; however, the water content still varied within each specimen by up to 20%. Nonetheless, the water content of each lift was greater than the target water content corresponding to low hydraulic conductivity of the laboratory-compacted specimens (see Sec. 8.2.1), which also results in low hydraulic conductivity ($\leq 1 \times 10^{-9}$ m/s).

8.1.2 Freeze-Thaw Monitoring of Field Specimens

The field specimens were buried in the ground outside the Environmental Geotechnics Laboratory at the University of Wisconsin-Madison on December 1, 1993. Air temperature, relative humidity, and temperatures within the specimens were recorded every hour throughout the winter of 1993-94 using a Campbell Scientific CR10 Datalogger. A photograph of the monitoring system is shown in Fig. 4.18. The other three specimens (control specimens) were permeated in the laboratory using the procedure described in Sec. 4.4.1.3.

Freezing began in mid-December 1993 and was steady later that same month. Thawing began in early February 1994 and complete thaw of the specimens had occurred by mid-March 1994. Figures 8.1-8.3 show the temperature distribution in each of the sludge specimens over time. One freeze-thaw cycle occurred in each specimen, and frost penetrated the entire thickness of each specimen (Figs. 8.1-8.3). The pipe specimens were removed from the ground immediately after thaw was complete in spring 1994.

8.1.3 Hydraulic Conductivity of Pipe Specimens

Two methods were used to measure the hydraulic conductivity of each pipe specimen (field and control specimens). First, the specimens were permeated in the PVC pipes, as if the pipes were rigid-wall permeameters. Permeation of the control specimens was conducted immediately following compaction, whereas permeation of the field specimens was conducted soon after they were removed from the ground. Second, after permeation, specimens were removed from the pipes in slices and permeated in flexible-wall permeameters. Details of the testing procedures are described in Sec. 4.4.1.3. Results of hydraulic conductivity tests performed on the pipe specimens are summarized in Table 8.1.

8.1.3.1 Hydraulic Conductivity Measured in Pipes

For each sludge, higher hydraulic conductivities were measured for the control specimens than for the specimens exposed to freeze-thaw. The control specimens had hydraulic conductivities ranging from 1.2×10^{-9} to 8.2×10^{-9} m/s, whereas the field specimens exposed to one cycle of freeze-thaw had hydraulic conductivities ranging from 3.0×10^{-10} to 4.1×10^{-10} m/s. That is, the hydraulic conductivity of each sludge decreased by at least one-half order of magnitude after exposure to freeze-thaw. These results suggest that the hydraulic integrity of these paper mill sludges is not deleteriously affected by freeze-thaw.

8.1.3.2 Hydraulic Conductivity Measured in Flexible-Wall Permeameters

After permeation, each pipe specimen was sliced horizontally so that two specimens were obtained for hydraulic conductivity testing in flexible-wall

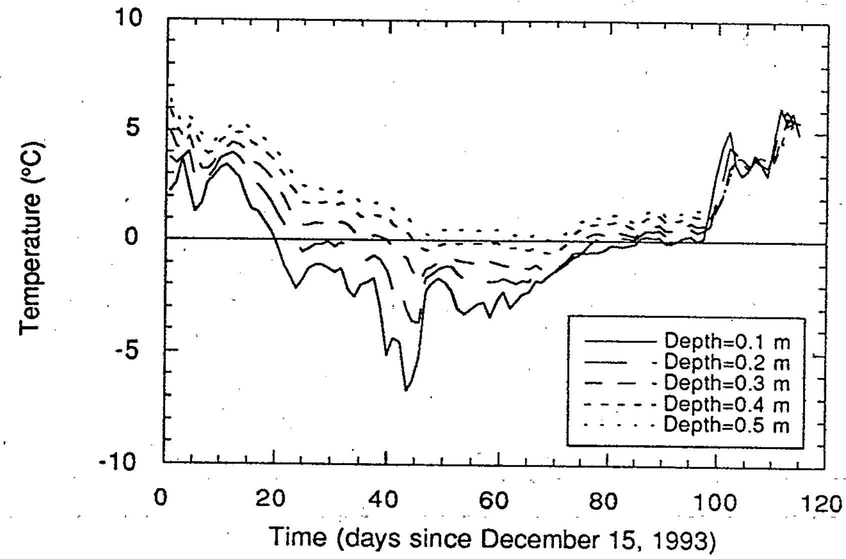


Figure 8.1. Temperature vs. time at various depths within field specimen consisting of paper mill sludge A.

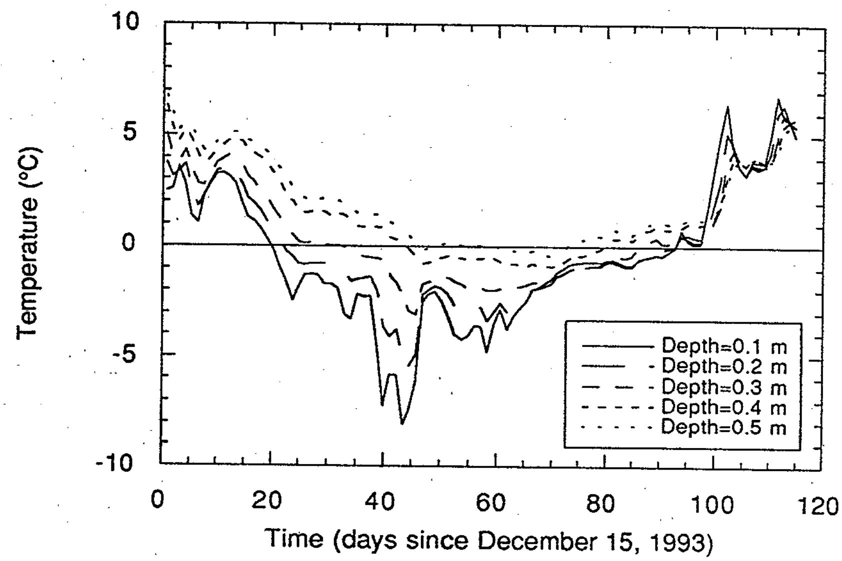


Figure 8.2. Temperature vs. time at various depths within field specimen consisting of paper mill sludge B.

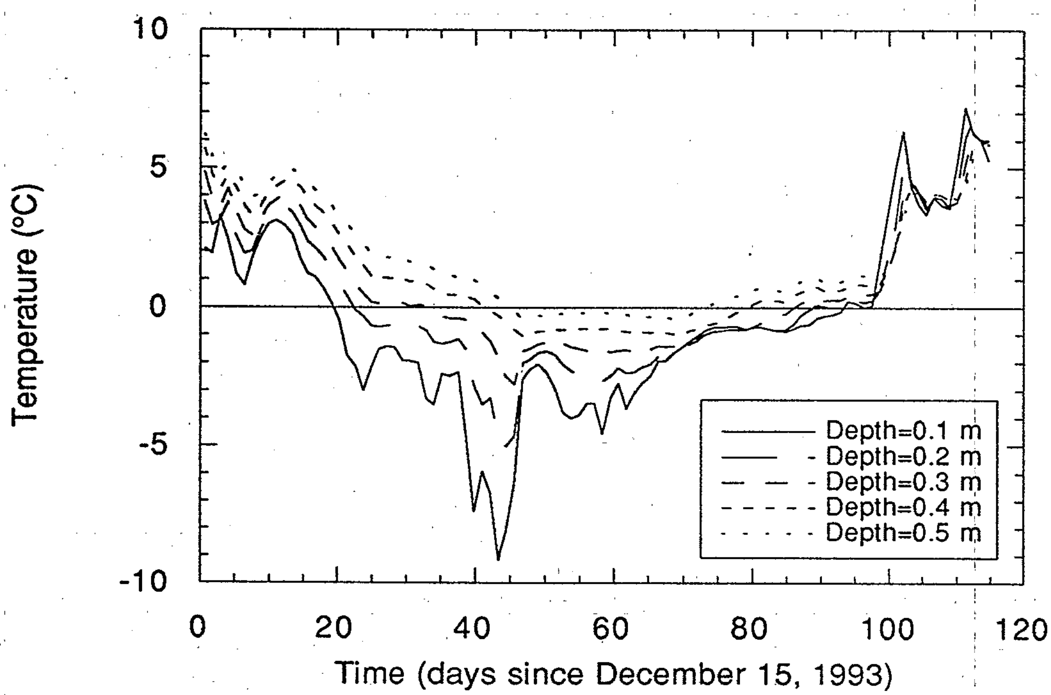


Figure 8.3. Temperature vs. time at various depths within field specimen consisting of paper mill sludge C.

permeameters. The specimens were either 0.30 m or 0.15 m in diameter (Table 8.2). Details of the testing procedure are summarized in Sec. 4.4.1.4.

Results of the hydraulic conductivity tests are summarized in Table 8.2. The hydraulic conductivities varied widely, ranging from 7.3×10^{-11} m/s (sludge A, no exposure to freeze-thaw) to 6.2×10^{-9} m/s (sludge A, exposed to freeze-thaw). Furthermore, the hydraulic conductivities of the specimens exposed to freeze-thaw are higher than those for the corresponding control specimens, which is in direct contrast to results of the hydraulic conductivity tests performed directly on the pipe specimens (Sec. 8.1.3.1). Also, all of the control specimens tested in flexible-wall permeameters have lower hydraulic conductivities than the hydraulic conductivities measured directly in the pipes, whereas the hydraulic conductivities of the specimens exposed to freeze-thaw that were tested in flexible-wall permeameters are higher than the hydraulic conductivities measured directly in the pipes from which they were removed. The only exception is sludge C, where the hydraulic conductivities are essentially the same.

Two hypotheses are provided for this behavior. First, disturbance may have occurred when pipe specimens exposed to freeze-thaw were removed from the ground or sliced for testing in flexible-wall permeameters. That is, cracks or other macroscopic defects may have been opened when the specimens were transported inside the laboratory or when specimens were removed from the pipes. Second, the effective stress in the pipes (1.6 kPa) was lower than the effective stresses in the specimens tested in the flexible-wall permeameters (18 kPa). Thus, the pipe specimens should have higher hydraulic conductivity (see Sec. 8.2.3). However, this second hypothesis only explains the behavior of the control specimens.

As a result of these ambiguities, the results of the small-scale field tests are inconclusive, in that exposure to freeze-thaw resulted in a decrease in hydraulic conductivity for the pipe specimens and resulted in an increase in hydraulic conductivity for specimens tested in flexible-wall permeameters. The results of the tests conducted directly in the pipes are probably more representative of the field condition. Nonetheless, a larger field study is needed to adequately address how freeze-thaw affects the in situ hydraulic conductivity of paper mill sludges.

Table 8.1. Results of hydraulic conductivity tests on paper mill sludge conducted in the pipes.

Sludge	Hydraulic conductivity of Control Specimen (no exposure to freeze-thaw), K_c (m/s)	Hydraulic Conductivity of Field Specimen (exposure to freeze-thaw), K_f (m/s)	Change in Hydraulic Conductivity(1) $\frac{K_f}{K_c}$
A	1.2×10^{-9}	3.5×10^{-10}	0.29
B	8.2×10^{-9}	3.0×10^{-10}	0.037
C	1.2×10^{-9}	4.1×10^{-10}	0.34

Note:
1. Change in hydraulic conductivity is defined as the hydraulic conductivity of the field specimen (K_f) divided by the hydraulic conductivity of the control specimen (K_c).

Table 8.2. Results of hydraulic conductivity tests on sludge specimens tested in flexible-wall permeameters.

Specimen(1)	Specimen Diameter (m)	Hydraulic Conductivity, K_{flex} (m/s)	Hydraulic Conductivity of Parent Pipe Specimen, K_p (m/s)	$\frac{K_{flex}}{K_p}$ (2)
SLA-Control-T	0.30	8.9×10^{-11}	1.2×10^{-9}	0.07
SLA-Control-B	0.30	7.3×10^{-11}		0.06
SLB-Control-T	0.30	2.8×10^{-10}	8.2×10^{-9}	0.03
SLB-Control-B	0.30	3.1×10^{-10}		0.04
SLC-Control-T	0.30	1.0×10^{-10}	1.2×10^{-9}	0.08
SLC-Control-B	0.30	1.6×10^{-10}		0.13
SLA-Field-T	0.15	6.2×10^{-9}	3.5×10^{-10}	18
SLA-Field-B	0.15	5.0×10^{-9}		14
SLB-Field-T	0.30	1.1×10^{-9}	3.0×10^{-10}	3.7
SLB-Field-B	0.15	1.2×10^{-9}		4.0
SLC-Field-T	0.30	5.5×10^{-10}	4.1×10^{-10}	1.3
SLC-Field-B	0.30	1.8×10^{-10}		0.4

Notes:
1. SLA = Sludge A; SLB = Sludge B; SLC = Sludge C; Control = Specimen taken from control pipe specimen (no freeze-thaw exposure); Field = Specimen taken from field pipe specimen (exposure to freeze-thaw); T= Specimen was taken from top of pipe specimen (depth < 0.3 m); B = Specimen was taken from bottom of pipe specimen (depth > 0.3 m).
2. K_{flex}/K_p = Hydraulic conductivity of specimen tested in flexible-wall permeameter divided by hydraulic conductivity of parent pipe specimen (taken from Table 8.1)

8.2 LABORATORY TESTS

8.2.1 Hydraulic Conductivity-Water Content Relationships

Hydraulic conductivity tests were performed on the specimens compacted to obtain the compaction curves described in Sec. 3.3.2. Figures 8.4-8.6 show the relationship between hydraulic conductivity and molding water content for sludges A, B, and C, respectively. Individual results of the hydraulic conductivity tests are tabulated in Appendix A. The tests required up to 45 days to reach steady conditions.

The hydraulic conductivity of each sludge is sensitive to molding water content (Figs. 8.4-8.6); i.e., the specimens compacted at molding water contents dry of optimum have high hydraulic conductivities, whereas specimens compacted wet of optimum have low hydraulic conductivities. Furthermore, wet of optimum water content, hydraulic conductivities less than 1×10^{-9} m/s were obtained for each sludge. This behavior was also observed for the two clays used in this study (Sec. 5.2.1) and is characteristic of most clayey soils. The high percentage of fines in paper mill sludge (Sec. 3.3.1) is likely responsible for the similarity in hydraulic behavior of paper mill sludge and compacted clay.

8.2.2 Standard Freeze-Thaw Tests

Hydraulic conductivity tests were performed on six specimens of sludge A and five specimens of sludges B and C after a various number of freeze-thaw cycles. Specimens of each sludge were compacted using standard Proctor effort at water contents yielding the lowest hydraulic conductivities ("low-K" water content) and at the water contents at which the sludges were received at the University of Wisconsin-Madison ("as-received" water contents). Four specimens of sludge A and three specimens of sludges B and C were compacted at their low-K water contents and two specimens of each sludge were compacted at their as-received water contents. Results of the hydraulic conductivity tests on these specimens are summarized in Table 8.3 and Figs. 8.7-8.9.

8.2.2.1 Low-K Molding Water Contents

Some of the low-K specimens of sludge A showed an increase in hydraulic conductivity after exposure to freeze-thaw, whereas others did not (Fig. 8.7). The two low-K specimens of sludge A frozen and thawed five times without permeation after each freeze-thaw cycle showed an increase in average hydraulic conductivity hydraulic conductivity (27 times), whereas the two identical specimens permeated

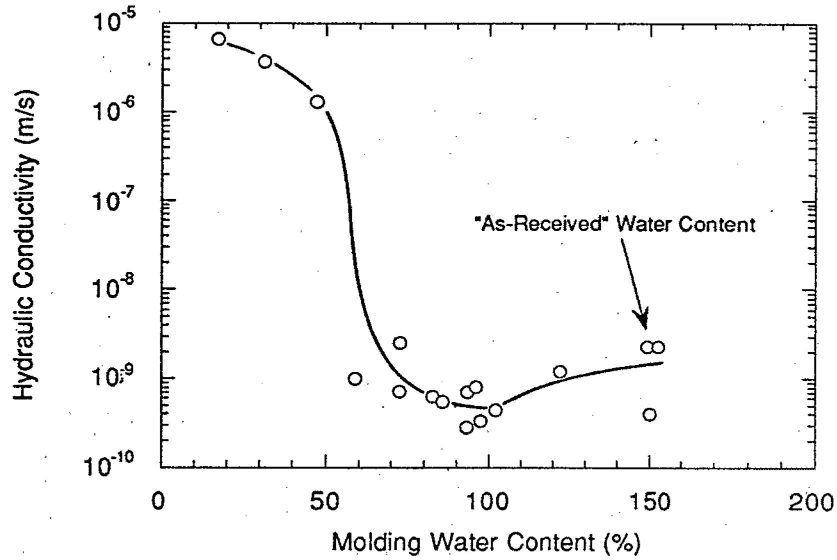


Figure 8.4. Hydraulic conductivity vs. molding water content for paper mill sludge A.

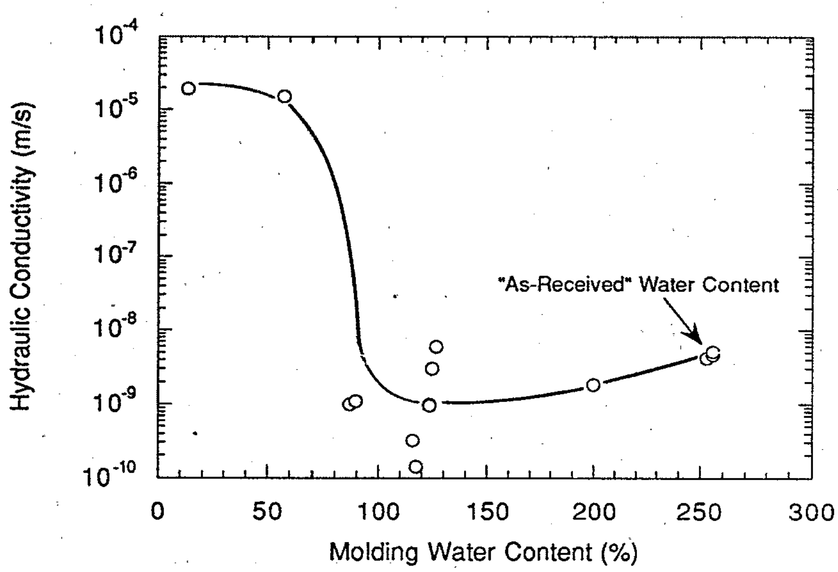


Figure 8.5. Hydraulic conductivity vs. molding water content for paper mill sludge B.

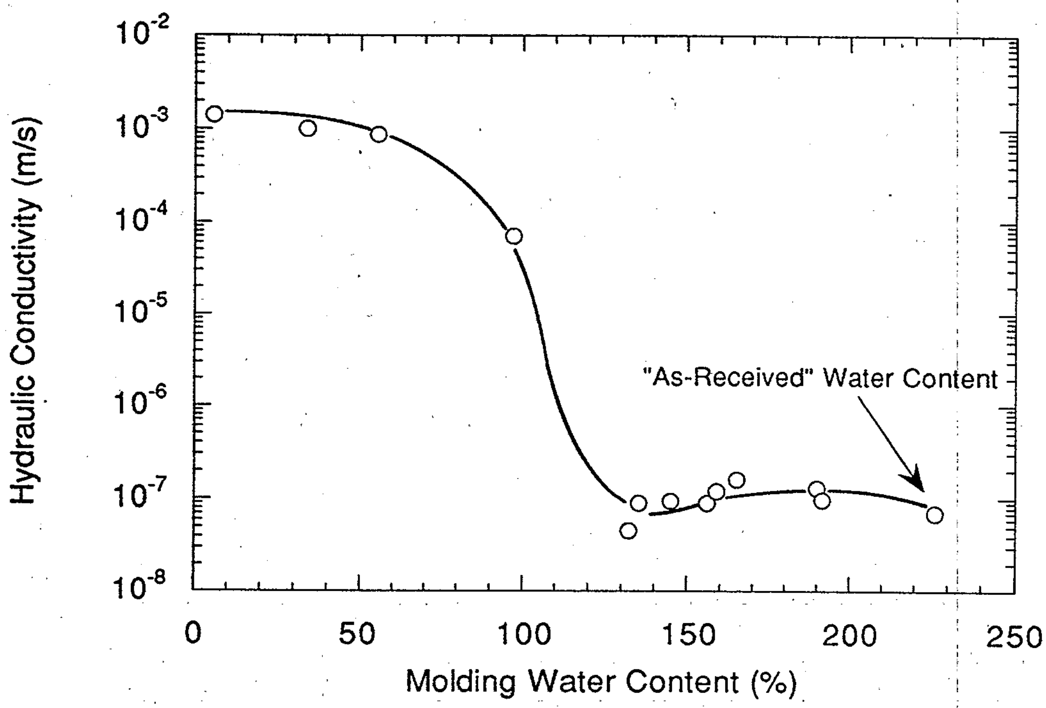


Figure 8.6. Hydraulic conductivity vs. molding water content for paper mill sludge C.

Table 8.3. Summary of freeze-thaw test results.

Sample Number(1)	Initial Hydraulic Conductivity, K_0 (m/s)	Hydraulic Conductivity After n Freeze-Thaw Cycles, K_n (m/s)					$\frac{K_f}{K_0}$ (2)
		K_1	K_2	K_3	K_4	K_5	
SLA-LK-1	7.2×10^{-11}	3.9×10^{-9}	1.2×10^{-9}	3.9×10^{-10}	2.7×10^{-10}	TNP(3)	3.8
SLA-LK-2	8.4×10^{-10}	4.9×10^{-10}	1.6×10^{-9}	4.1×10^{-10}	3.0×10^{-10}	TNP	0.36
SLA-LK-3	2.8×10^{-10}	TNP	TNP	TNP	TNP	8.3×10^{-9}	30
SLA-LK-4	3.3×10^{-10}	TNP	TNP	TNP	TNP	8.3×10^{-9}	25
SLA-AR-1	2.3×10^{-9}	4.8×10^{-9}	5.0×10^{-10}	5.5×10^{-10}	4.1×10^{-10}	2.9×10^{-10}	0.12
SLA-AR-2	4.0×10^{-10}	1.5×10^{-10}	TNP	TNP	TNP	6.3×10^{-10}	1.6
SLB-LK-1	9.6×10^{-10}	5.9×10^{-9}	1.5×10^{-8}	1.2×10^{-8}	TNP	3.8×10^{-8}	40
SLB-LK-2	1.0×10^{-9}	TNP	TNP	TNP	TNP	7.1×10^{-8}	71
SLB-LK-3	9.6×10^{-10}	6.4×10^{-9}	1.4×10^{-8}	1.2×10^{-8}	TNP	4.7×10^{-8}	49
SLB-AR-1	4.6×10^{-9}	6.2×10^{-9}	1.8×10^{-8}	2.4×10^{-8}	6.5×10^{-8}	4.5×10^{-8}	9.8
SLB-AR-2	4.1×10^{-9}	3.9×10^{-9}	1.1×10^{-8}	2.6×10^{-8}	3.5×10^{-8}	3.9×10^{-8}	9.5
SLC-LK-1	1.3×10^{-9}	1.4×10^{-8}	2.7×10^{-8}	2.5×10^{-8}	2.1×10^{-8}	1.2×10^{-8}	9.2
SLC-LK-2	1.6×10^{-9}	1.0×10^{-8}	2.7×10^{-8}	1.7×10^{-8}	1.3×10^{-8}	2.1×10^{-8}	13
SLC-LK-3	8.9×10^{-10}	3.9×10^{-9}	1.3×10^{-8}	TNP	4.9×10^{-9}	9.1×10^{-9}	10
SLC-AR-1	9.8×10^{-10}	2.5×10^{-9}	2.5×10^{-9}	7.6×10^{-9}	1.3×10^{-8}	2.8×10^{-8}	29
SLC-AR-2	1.3×10^{-9}	7.8×10^{-9}	2.5×10^{-8}	2.3×10^{-8}	3.1×10^{-8}	2.4×10^{-8}	18

Note:
1. SLA = Sludge A; SLB = Sludge B; SLC = Sludge C; LK = Specimen was compacted at the low-K water content; AR = specimen was compacted at the as-received water content; -1, -2, -3, -4 = Specimen number.
2. K_f/K_0 = Hydraulic conductivity after final number of freeze-thaw cycles (typically 5) for a specimen divided by the initial hydraulic conductivity of that specimen (before exposure to freeze-thaw).
3. TNP = Test not performed.

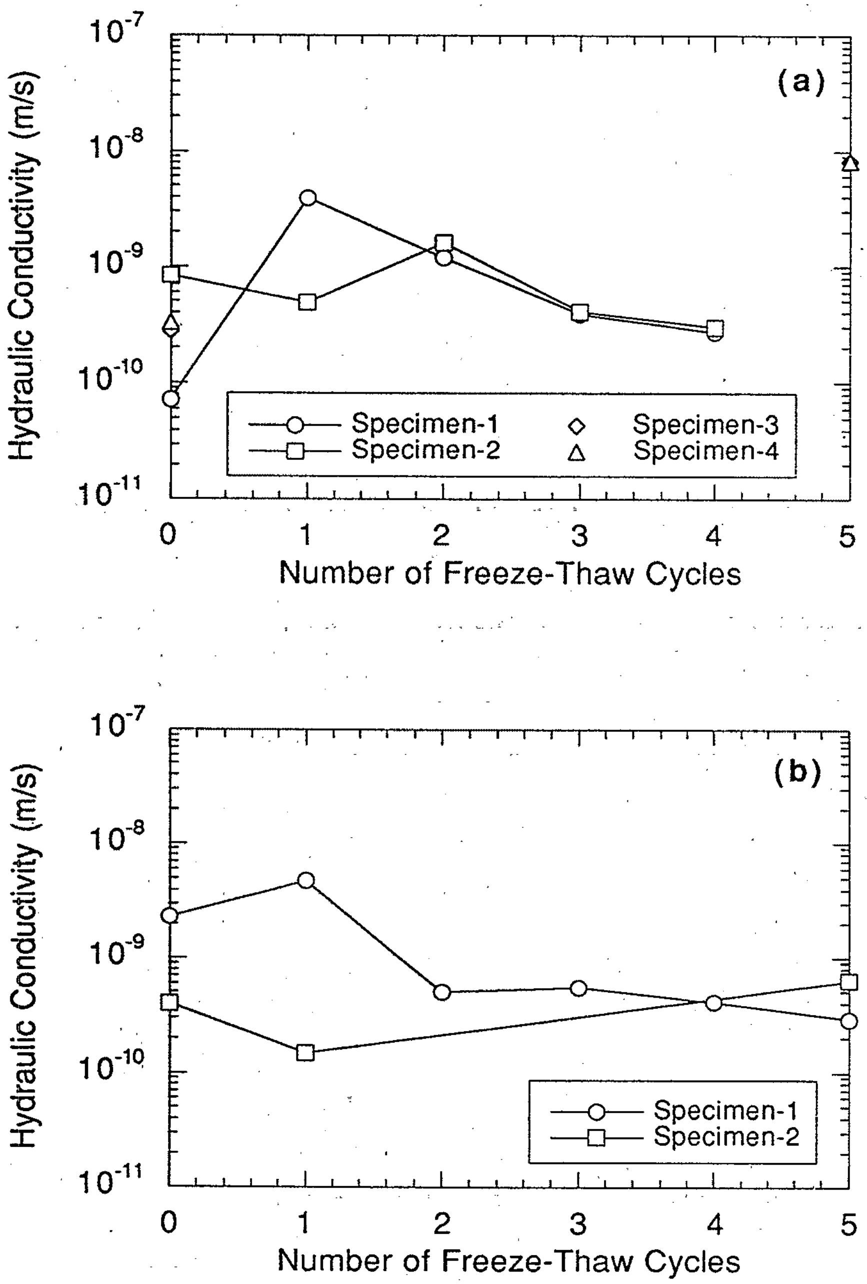


Figure 8.7. Hydraulic conductivity vs. number of freeze-thaw cycles for low-K specimens (a) and as-received specimens (b): paper mill sludge A.

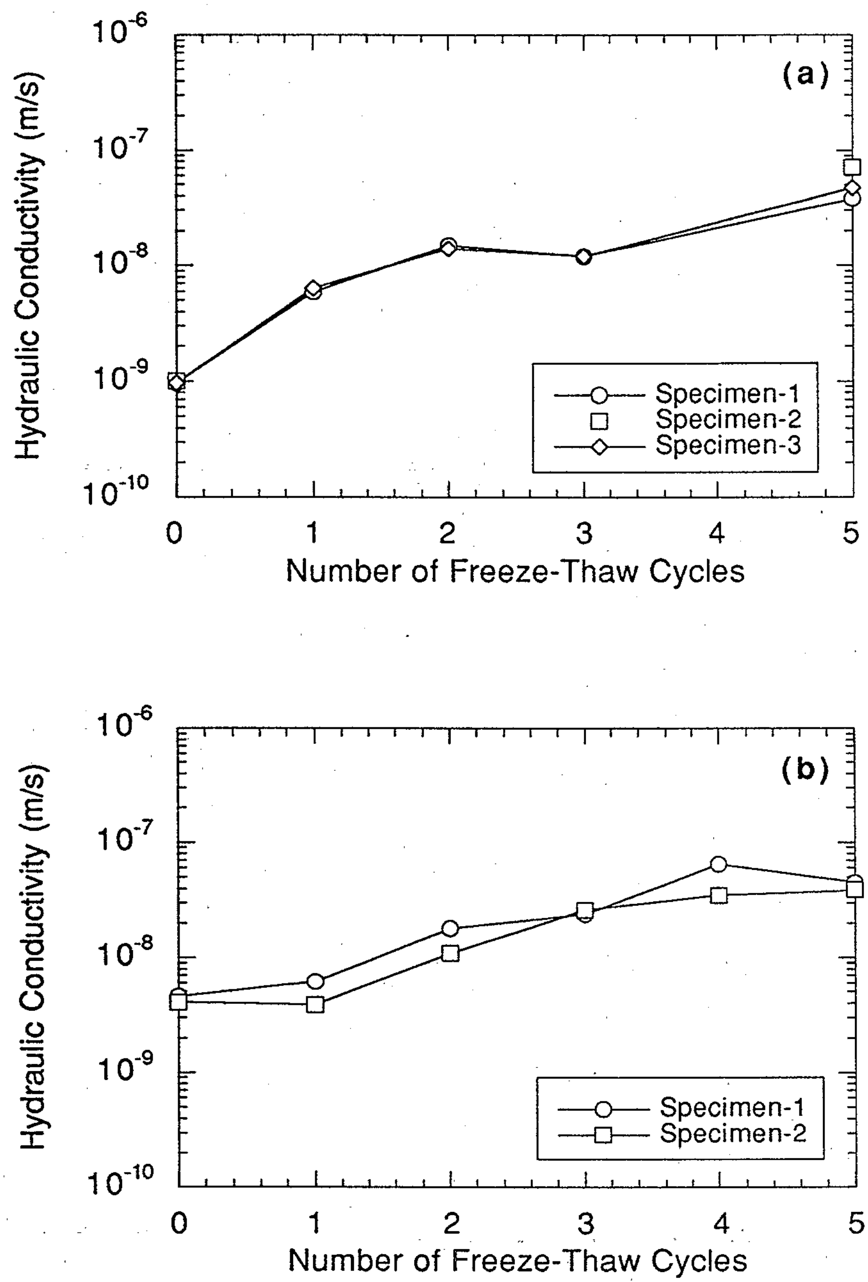


Figure 8.8. Hydraulic conductivity vs. number of freeze-thaw cycles for low-K specimens (a) and as-received specimens (b): paper mill sludge B.

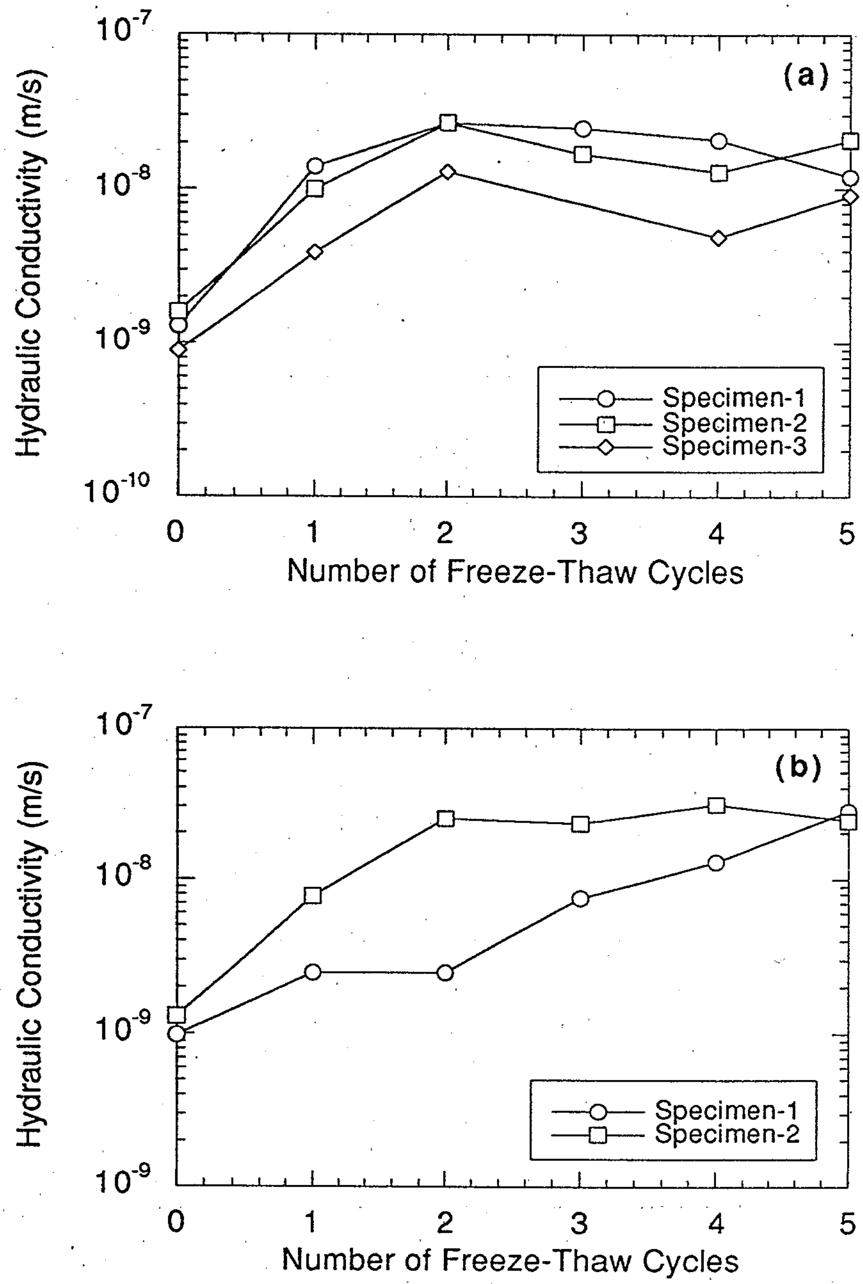


Figure 8.9. Hydraulic conductivity vs. number of freeze-thaw cycles for low-K specimens (a) and as-received specimens (b): paper mill sludge C.

after each freeze-thaw cycle showed a slight decrease in average hydraulic conductivity after exposure to freeze-thaw.

All of the low-K specimens of sludge B showed an increase in hydraulic conductivity of approximately 2 orders of magnitude after being exposed to freeze-thaw (Fig. 8.8). One of the low-K specimens was frozen and thawed five times without intermediary permeation. The hydraulic conductivity of this specimen also increased approximately two orders of magnitude. Similar results were obtained for the other two low-K specimens of sludge B that were permeated after 0, 1, 2, 3, and 5 freeze-thaw cycles.

All of the low-K specimens of sludge C showed an increase in hydraulic conductivity after exposure to freeze-thaw (Fig. 8.9). All of the low-K sludge C specimens were permeated after each freeze-thaw cycle, up to five, except for one specimen which was not permeated after its third cycle. The average hydraulic conductivity of the three low-K sludge specimens increased approximately one order of magnitude as a result of freeze-thaw.

8.2.2.2 As-Received Molding Water Contents

One of the specimens of sludge A compacted at its as-received water content showed a decrease in hydraulic conductivity after exposure to freeze-thaw. This specimen was permeated after each freeze-thaw cycle. The other specimen of sludge A was permeated after 0, 1, and 5 freeze-thaw cycles and showed a slight (1.6 times) increase in hydraulic conductivity as a result of freeze-thaw.

The two specimens of sludge B compacted at the as-received water content were permeated after each freeze-thaw cycle. These specimens had a higher average initial hydraulic conductivity than the low-K specimens, but had a similar hydraulic conductivity ($\approx 4.0 \times 10^{-8}$ m/s) after five freeze-thaw cycles.

Both of the specimens of sludge C compacted at the as-received water content were permeated after each freeze-thaw cycle. The initial hydraulic conductivity and the hydraulic conductivity after five freeze-thaw cycles was essentially the same. However, at an intermediate number of freeze-thaw cycles (1, 2, 3, and 4) the hydraulic conductivities of the specimens varied; i.e., one specimen showed an increase in hydraulic conductivity after two freeze-thaw cycles and no increase after subsequent cycles, whereas the other specimen showed a steady increase in hydraulic conductivity with each freeze-thaw cycle (Fig. 8.9).

8.2.3 Effective Stress Tests

Hydraulic conductivity were performed on one specimen of each sludge compacted with standard proctor effort at the low-K water content (Sec. 8.2.1). The specimens were placed in flexible-wall permeameters and permeated at effective stresses of 7, 35, 46, and 81 kPa. Approximately one week of consolidation occurred between each stage of permeation. Results of the effective stress tests are summarized in Fig. 8.10.

The hydraulic conductivity of all three sludges decreased as a result of increasing the effective stress. However, after an effective stress of 46 kPa, the subsequent decrease in hydraulic conductivity was small (Fig. 8.10). Similar behavior (decreasing hydraulic conductivity with increasing effective stress) was observed for a paper mill sludge tested by Zimmie et al. (1994).

The hydraulic conductivities of sludges A and C were essentially the same at each effective stress, whereas the hydraulic conductivity of sludge B was slightly higher. The hydraulic conductivity of each sludge was less than 1 x 10^{-9} m/s at every effective stress tested, except for the specimen of sludge B permeated at an effective stress of 7 kPa.

8.2.4 Long-Term Hydraulic Conductivity Tests

Hydraulic conductivity was measured on two specimens of each paper mill sludge compacted at standard Proctor effort over a period of at least 90 days to determine whether or not biological decay of the paper mill sludge would adversely impact hydraulic conductivity. One specimen of each sludge was compacted at the low-K water content and the other was compacted at the as-received water content (Sec. 4.4.2.2). Results of the long-term hydraulic conductivity tests are shown in Figs. 8.11-8.13.

The two specimens of sludge B had higher hydraulic conductivity than the specimens of sludges A and C compacted at their respective low-K and as-received water contents. Examination of Figs. 8.11-8.13 shows that the hydraulic conductivity of each specimen decreased slightly over the time interval during which the tests were performed. Thus, biological decay appears to have no adverse impact on hydraulic conductivity, at least for the test period used in this study.

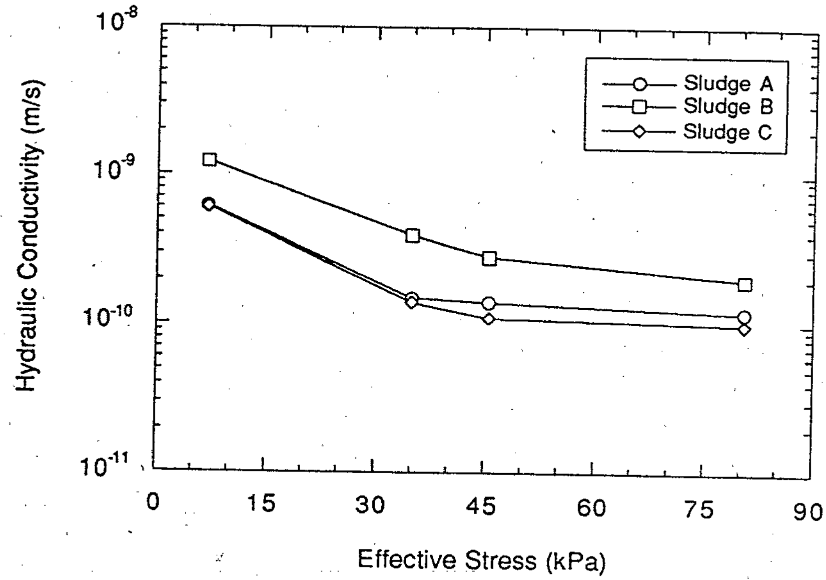


Fig. 8.10. Hydraulic conductivity vs. effective stress for paper mill sludges A, B, & C.

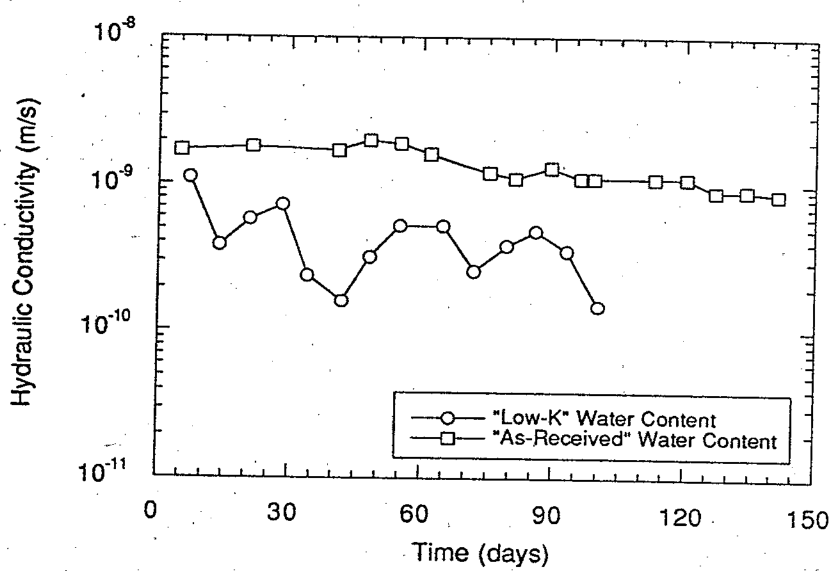


Figure 8.11. Hydraulic conductivity vs. time for paper mill sludge A.

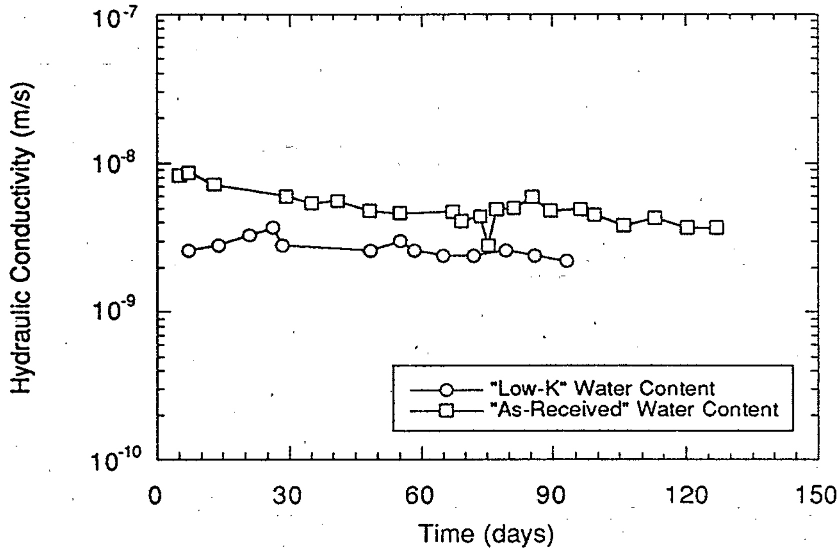


Figure 8.12. Hydraulic conductivity vs. time for paper mill sludge B.

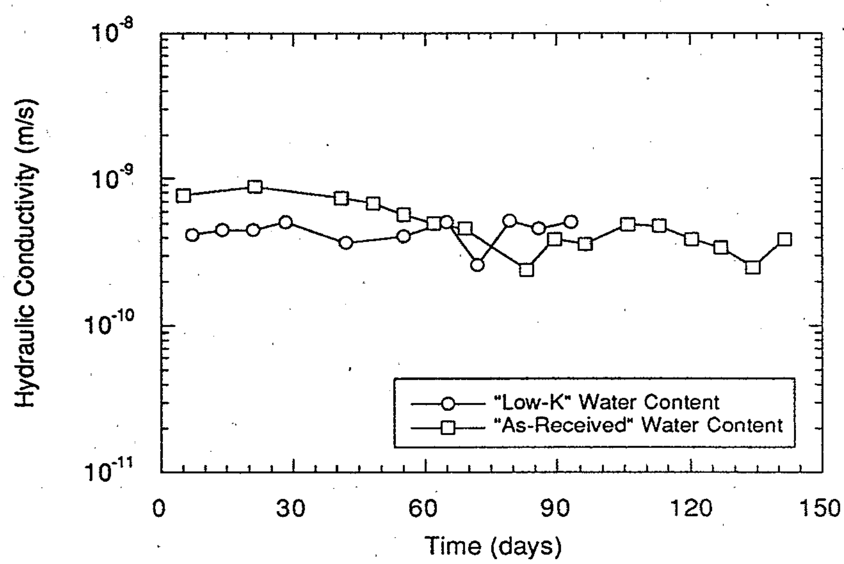


Figure 8.13. Hydraulic conductivity vs. time for paper mill sludge C.

Hydraulic conductivity tests performed on specimens compacted in compaction molds to construct the compaction curves for each sludge indicate that low hydraulic conductivities (< 1×10^{-9} m/s) can be achieved for each sludge. Based on this behavior, paper mill sludge could be used as an alternative to compacted clays for use in landfill final covers. However, results of the hydraulic conductivity tests performed on the specimens compacted and frozen in the laboratory indicate that the hydraulic conductivity of some paper mill sludges (e.g., sludges B and C) can be affected by exposure to freeze-thaw. Nevertheless, it appears that some sludges (e.g., sludge A) may be frost resistant, depending on the hydrologic conditions to which they are exposed. For example, the hydraulic conductivity of sludge A depends on whether or not it is permeated after each freeze-thaw cycle. That is, a decrease in hydraulic conductivity occurs when the specimen is permeated, whereas an increase in hydraulic conductivity occurs if it is not permeated.

Effective stress tests performed on the three paper mill sludges indicate that the hydraulic conductivity of the sludges decreases with increasing effective stress up to a certain effective stress, after which no significant decrease in hydraulic conductivity occurs. Hydraulic conductivities as low as 1×10^{-10} m/s were observed for specimens of sludges A and C at effective stresses greater than 46 kPa. Thus, extra overburden placed to protect paper mill sludge from frost penetration used in final covers may also reduce the hydraulic conductivity of the sludge substantially.

Long-term hydraulic conductivity tests performed on the three sludges compacted at two different water contents indicate that the hydraulic conductivity slightly decreased over the test period. The decrease in hydraulic conductivity is likely the result of consolidation under the 7 kPa overburden stress induced by the lead weight. Maltby and Eppstein (1994) observed consolidation and a decrease in hydraulic conductivity over time in their large-scale field study. Based on the results obtained in this project and the experiments of others, paper mill sludges are likely to perform well for a long period of time provided they are protected against detrimental stresses such as freeze-thaw.

8.3 COMPARISON OF FIELD AND LABORATORY TEST RESULTS

Because the results of the hydraulic conductivity tests performed on the pipe specimens and the specimens removed from the pipes were inconclusive, no direct comparison between field and laboratory test results can be made. However, the results of the field and laboratory tests performed on the paper mill sludges warrant discussion.

The structure of the sludge within the pipe specimens was noted during slicing and trimming of the specimens for hydraulic conductivity testing in flexible-wall permeameters. All of the sludges that were exposed to freeze-thaw (field specimens) were less homogeneous and had a more gravel-like structure than the sludges that had not been exposed to freeze-thaw (control specimens). The specimens would fall apart when being trimmed for flexible-wall tests. Thus, based on visual observation, freeze-thaw had affected the structure of the compacted paper mill sludges. However, given the results of the hydraulic conductivity tests performed in the pipes after freeze-thaw, it is not clear whether these structural changes, which were observed during trimming, had adversely affected hydraulic conductivity. Thus, to ascertain the true impact of freeze-thaw on the field hydraulic conductivity of paper mill sludges, field tests similar to the one described by Maltby and Eppstein (1994) need to be conducted.

SECTION 9

SUMMARY AND CONCLUSIONS

The objective of this study was to evaluate and compare the effect that freezing and thawing has on the hydraulic conductivity of two clays and three alternative barrier materials (a sand-bentonite mixture, three geosynthetic clay liners (GCLs), and three paper industry sludges) under field and laboratory conditions. A battery of hydraulic conductivity tests was performed on specimens prepared in the laboratory under conditions which yield low hydraulic conductivity. The hydraulic conductivity of each specimen was measured before and after exposure to a number of freeze-thaw cycles. Results from the laboratory tests on the clays, sand-bentonite mixture, and GCLs were then compared to hydraulic conductivities measured during the COLDICE/CPAR project, a recent large-scale field study conducted by the U. S. Army Corps of Engineers Cold Regions Research and Engineering Laboratory (CRREL), CH2M Hill, Inc. and a suite of industrial partners. Results of hydraulic conductivity tests performed on the paper mill sludges were compared to results obtained from a small-scale field study performed as part of this project.

9.1 COMPACTED CLAYS

Increases in hydraulic conductivity of two orders of magnitude were observed for clay specimens compacted and frozen and thawed in the laboratory, whereas increases in hydraulic conductivity up to four orders of magnitude were observed for specimens removed from the COLDICE test pads after winter. The observed increase in hydraulic conductivity of the field and laboratory specimens was attributed to a macroscopic network of cracks caused by the formation of ice lenses and desiccation induced by freezing. Extensive cracking of the soil was observed in the field and laboratory experiments. In contrast, no increase in hydraulic conductivity was observed for specimens removed from the tests pads after winter using thin-wall sampling tubes. Apparently, disturbance during sampling and extrusion masked the crack structure caused by freeze-thaw.

Two factors that potentially could have caused the increase in hydraulic conductivity to be larger in the field than in the laboratory were: (1) the dimensionality of freezing (e.g., one-dimensional vs. three-dimensional) and (2) that the in situ freezing rate was smaller than that used in the standard (three-dimensional) laboratory tests. Thus, specimens were frozen in the laboratory one-dimensionally at controlled freezing rates to assess whether dimensionality of freezing or freezing rate affected the increase in hydraulic conductivity. Results of the tests showed that there was no relationship between hydraulic conductivity and freezing rate. Also, the freezing rates occurring in the field were smaller than the lowest freezing rates that could be simulated in the laboratory, whereas the increase in hydraulic conductivity measured in the field was two orders of magnitude greater than the increase in hydraulic conductivity measured on specimens frozen in the laboratory. Thus, dimensionality of freezing and freezing rate were probably not the cause of the discrepancy between the laboratory- and field-measured hydraulic conductivities. Differences in soil structure prior to freezing may have been responsible for the differences in the field and laboratory behavior. However, sufficient data were not available to evaluate this hypothesis.

9.2 SAND-BENTONITE MIXTURE

No increase in hydraulic conductivity was observed for the specimens of sand-bentonite compacted and frozen three-dimensionally in the laboratory. Low post-winter hydraulic conductivities were also observed in the field and measured in the laboratory for specimens removed from the test pad using thin-wall sampling tubes. The field hydraulic conductivity and the hydraulic conductivities of the specimens collected in sampling tubes were slightly higher than the hydraulic conductivity of the laboratory-compacted specimens. The difference in hydraulic conductivity was attributed to heterogeneities in the sand-bentonite mixture and, for the specimens collected in tubes, to disturbance during extrusion.

In contrast, high hydraulic conductivities were measured for all but one of the block specimens removed from the sand-bentonite test pad before winter and on all of the block specimens removed after winter. Examination of the structure of the block specimens revealed bentonite-rich zones. Based on this observation, the high hydraulic conductivities of the block specimens were attributed to insufficient mixing and not to environmental stresses, such as freeze-thaw.

Examination of the soil within the box infiltrometer installed in the sand-bentonite test pad showed that the soil had retained water and that a network of cracks was non-existent. Similarly, examination of the internal structure of specimens removed from the test pad after winter using tubes and the laboratory-compacted specimens exposed to freeze-thaw revealed none of the cracks typically observed in compacted clays exposed to freeze-thaw. The absence of cracks is consistent with the low hydraulic conductivities measured for the sand-bentonite specimens.

9.3 GEOSYNTHETIC CLAY LINERS (GCLs)

Laboratory tests performed on three GCLs (Bentofix®, Bentomat®, and Claymax®) showed that their hydraulic conductivity was low (typically about 2 x 10^{-11} m/s) and that the hydraulic conductivity decreased slightly as a result of freeze-thaw. Results of t-tests indicated that the slight decrease in hydraulic conductivity was statistically significant.

Low hydraulic conductivity was also measured on large undisturbed specimens removed from the COLDICE GCL test ponds after exposure to two winters of freeze-thaw. Hydraulic conductivities less than 1 x 10^{-9} m/s were measured for all but one specimen. The high hydraulic conductivity of that specimen was attributed to disturbance during handling. Similar results were reported by Erickson et al. (1994) for the GCLs tested in the COLDICE test pans. For each of the COLDICE tests, hydraulic conductivities less than 1 x 10^{-9} m/s were measured before and after exposure to freeze-thaw. Erickson et al. (1994) did report, however, that the field hydraulic conductivities of the seamed GCLs were slightly higher than those for the unseamed GCLs. No seamed specimens were tested in this study. Additional study of the hydraulic integrity of GCL seams exposed to freeze-thaw is recommended.

9.4 PAPER MILL SLUDGES

Results of hydraulic conductivity tests performed on paper mill sludges showed that conductivities less than 1 x 10^{-9} m/s can be achieved for each type of sludge when compacted wet of optimum water content. Slightly lower hydraulic conductivities were obtained for sludges A and C (the two combined sludges) relative to sludge B (a primary sludge). The lower hydraulic conductivities of sludges A and C were attributed to the existence of additional biological material from secondary wastewater treatment processes.

Freeze-thaw affected each sludge differently. For specimens of sludge A compacted at the low-K water content, no change in hydraulic conductivity was observed for specimens permeated after each freeze-thaw cycle, whereas an increase in hydraulic conductivity was observed for specimens that were not permeated between freeze-thaw cycles. Also, for specimens of sludge A compacted at the as-received water content, no increase in hydraulic conductivity was observed after exposure to freeze-thaw.

Increases in hydraulic conductivity of approximately one order of magnitude were observed for all specimens of sludge B, regardless of the molding water content or whether the specimen was permeated between freeze-thaw cycles. This increase in hydraulic conductivity is similar to the increase measured for the compacted clays studied in this project. Similar behavior was observed for sludge C.

Results of the hydraulic conductivity tests conducted on the pipe specimens were inconclusive; a decrease in hydraulic conductivity after freeze-thaw was observed when the sludges were permeated in the pipes, whereas an increase in hydraulic conductivity was observed in the slices tested in flexible-wall permeameters. Examination of the sludge in the pipes revealed that exposure to freeze-thaw resulted in a blocky structure that fell apart easily during trimming. Nevertheless, it could not be determined whether formation of the blocky structure had an adverse impact on the hydraulic conductivity of the sludges. Large-scale field tests including morphological investigations are recommended to fully assess the impact of freeze-thaw on the hydraulic conductivity of paper mill sludges.

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APPENDIX A

RESULTS OF COMPACTION AND HYDRAULIC CONDUCTIVITY TESTS PERFORMED ON LABORATORY-COMPACTED SPECIMENS

Table A.1. Results of compaction and hydraulic conductivity tests performed on Parkview clay.

Specimen(1)	Molding Water Content (%)	Dry Unit Weight (kN/m³)	Hydraulic Conductivity (m/s)
PV-S-1	10.5	17.06	2.1×10^{-7}
PV-S-2	10.6	17.30	7.6×10^{-7}
PV-S-3	10.7	16.81	1.7×10^{-7}
PV-S-4	12.1	17.37	2.1×10^{-7}
PV-S-5	13.4	18.52	2.0×10^{-8}
PV-S-6	13.4	18.69	2.1×10^{-8}
PV-S-7	15.3	18.25	4.5×10^{-9}
PV-S-8	16.1	18.34	2.4×10^{-10}
PV-S-9	16.3	18.33	2.6×10^{-10}
PV-S-10	17.7	17.72	4.9×10^{-10}
PV-S-11	19.6	17.07	1.1×10^{-9}
PV-S-12	20.1	17.01	3.9×10^{-10}
PV-M-1	4.1	19.45	TNP(2)
PV-M-2	4.5	19.27	TNP
PV-M-3	5.3	19.63	5.1×10^{-9}
PV-M-4	7.4	20.70	TNP
PV-M-5	7.9	20.47	1.4×10^{-9}
PV-M-6	10.9	20.63	5.7×10^{-11}
PV-M-7	12.8	19.73	TNP
PV-M-8	13.9	19.37	5.1×10^{-10}
PV-M-9	14.0	19.63	TNP
PV-M-10	18.3	17.48	TNP
PV-M-11	19.1	17.34	3.1×10^{-10}

Notes:
1. PV = Parkview clay; -S = Compacted at standard Proctor effort; -M = Compacted at modified Proctor effort; -1..-12 = Specimen number.
2. TNP = Test not performed.

Table A.2. Results of compaction and hydraulic conductivity tests performed on Valley Trail clay.

Specimen[(1)]	Molding Water Content (%)	Dry Unit Weight (kN/m^3)	Hydraulic Conductivity (m/s)
VT-S-1	10.4	16.18	1.6×10^{-8}
VT-S-2	12.9	15.77	9.5×10^{-8}
VT-S-3	14.4	16.37	3.4×10^{-8}
VT-S-4	14.7	16.66	6.9×10^{-8}
VT-S-5	16.1	17.12	7.5×10^{-8}
VT-S-6	16.1	16.71	1.4×10^{-8}
VT-S-7	19.0	16.87	1.6×10^{-9}
VT-S-8	19.3	16.82	1.8×10^{-9}
VT-S-9	19.4	17.18	7.2×10^{-11}
VT-S-10	20.2	17.04	7.6×10^{-11}
VT-S-11	20.2	17.03	8.3×10^{-11}
VT-S-12	20.7	16.54	1.2×10^{-10}
VT-S-13	20.8	16.68	2.2×10^{-10}
VT-S-14	22.7	16.13	2.5×10^{-10}
VT-S-15	23.3	15.85	3.9×10^{-10}
VT-M-1	7.8	18.39	4.8×10^{-9}
VT-M-2	11.3	18.63	2.6×10^{-9}
VT-M-3	11.4	18.69	TNP[(2)]
VT-M-4	13.4	18.97	TNP
VT-M-5	13.5	19.01	TNP
VT-M-6	13.7	19.05	2.1×10^{-10}
VT-M-7	17.0	18.20	8.1×10^{-11}
VT-M-8	17.8	18.22	TNP
VT-M-9	18.9	17.86	TNP

Notes:
1. VT = Valley Trail clay; -S = Compacted at standard Proctor effort; -M = Compacted at modified Proctor effort; -1..-15 = Specimen number.
2. TNP = Test not performed.

Table A.3. Results of compaction and hydraulic conductivity tests performed on sand-bentonite.

Specimen(1)	Molding Water Content (%)	Dry Unit Weight (kN/m^3)	Hydraulic Conductivity (m/s)
SB-S-1	7.9	17.05	1.7×10^{-10}
SB-S-2	8.1	16.88	TNP(2)
SB-S-3	8.4	16.99	TNP
SB-S-4	11.4	17.17	TNP
SB-S-5	12.7	17.06	TNP
SB-S-6	13.9	17.26	1.7×10^{-10}
SB-S-7	15.1	17.23	TNP
SB-S-8	15.9	17.09	TNP
SB-S-9	16.5	17.31	1.2×10^{-10}
SB-S-10	16.7	17.50	TNP
SB-S-11	16.7	17.26	TNP
SB-S-12	16.7	17.31	TNP
SB-S-13	16.7	17.37	TNP
SB-S-14	16.7	17.47	TNP
SB-S-15	16.7	17.28	TNP
SB-S-16	16.7	17.39	TNP
SB-S-17	16.7	17.50	TNP
SB-S-18	19.3	16.81	1.0×10^{-10}
SB-S-19	19.7	16.70	TNP
SB-S-20	20.3	16.62	TNP
SB-M-1	7.1	18.01	TNP
SB-M-2	7.1	18.71	TNP
SB-M-3	7.3	18.57	5.3×10^{-8}
SB-M-4	10.0	18.79	TNP
SB-M-5	10.6	18.75	TNP
SB-M-6	10.7	18.63	6.9×10^{-11}
SB-M-7	12.3	18.85	TNP
SB-M-8	12.4	18.85	TNP
SB-M-9	13.4	18.68	5.9×10^{-11}
SB-M-10	15.4	18.13	TNP
SB-M-11	16.3	17.84	4.3×10^{-11}
SB-M-12	16.5	18.09	TNP
SB-M-13	17.9	17.36	TNP
SB-M-14	18.4	17.14	TNP

Notes:
1. SB = Sand-bentonite; -S = Compacted at standard Proctor effort; -M = Compacted at modified Proctor effort; -1..-20 = Specimen number.
2. TNP = Test not performed.

Table A.4. Results of compaction and hydraulic conductivity tests performed on paper mill sludge A.

Specimen(1)	Molding Water Content (%)	Dry Unit Weight (kN/m^3)	Hydraulic Conductivity (m/s)
SLA-S-1	17.0	8.32	6.6×10^{-6}
SLA-S-2	31.4	8.68	3.7×10^{-6}
SLA-S-3	43.6	8.66	TNP(2)
SLA-S-4	47.2	8.54	1.3×10^{-6}
SLA-S-5	58.7	8.41	1.0×10^{-9}
SLA-S-6	72.4	7.53	7.2×10^{-10}
SLA-S-7	72.8	7.61	2.5×10^{-9}
SLA-S-8	82.8	7.22	6.2×10^{-10}
SLA-S-9	85.6	7.25	5.5×10^{-10}
SLA-S-10	88.3	6.73	TNP
SLA-S-11	89.0	6.68	TNP
SLA-S-12	89.6	6.67	TNP
SLA-S-13	90.4	6.68	TNP
SLA-S-14	91.2	6.62	TNP
SLA-S-15	92.3	6.60	TNP
SLA-S-16	93.1	6.56	2.8×10^{-10}
SLA-S-17	93.3	6.54	7.0×10^{-10}
SLA-S-18	94.8	6.48	TNP
SLA-S-19	95.9	6.63	8.0×10^{-10}
SLA-S-20	97.4	6.41	3.3×10^{-10}
SLA-S-21	102.1	6.41	4.4×10^{-10}
SLA-S-22	122.1	5.61	1.2×10^{-9}
SLA-S-23	149.2	4.78	2.3×10^{-9}
SLA-S-24	150.0	4.78	4.0×10^{-10}
SLA-S-25	152.8	4.72	2.3×10^{-9}
SLA-S-26	185.1	3.98	TNP
SLA-S-27	185.3	3.96	TNP

Notes:
1. SLA = Paper mill sludge A; -S = Compacted at standard Proctor effort; -1..-27 = Specimen number.
2. TNP = Test not performed.

Table A.5. Results of compaction and hydraulic conductivity tests performed on paper mill sludge B.

Specimen(1)	Molding Water Content (%)	Dry Unit Weight (kN/m^3)	Hydraulic Conductivity (m/s)
SLB-S-1	13.3	5.60	1.9×10^{-5}
SLB-S-2	57.3	5.83	1.5×10^{-5}
SLB-S-3	86.7	5.91	1.0×10^{-9}
SLB-S-4	89.8	5.94	3.2×10^{-9}
SLB-S-5	115.9	5.77	TNP(2)
SLB-S-6	116.9	5.67	1.4×10^{-10}
SLB-S-7	117.7	5.74	TNP
SLB-S-8	119.0	5.60	TNP
SLB-S-9	121.1	5.56	TNP
SLB-S-10	121.7	5.58	TNP
SLB-S-11	123.7	5.49	1.0×10^{-9}
SLB-S-12	123.9	5.47	9.6×10^{-10}
SLB-S-13	124.1	5.47	TNP
SLB-S-14	124.5	5.49	TNP
SLB-S-15	124.7	5.52	3.0×10^{-9}
SLB-S-16	126.8	5.45	TNP
SLB-S-17	126.8	5.41	5.9×10^{-9}
SLB-S-18	200.1	3.73	1.8×10^{-9}
SLB-S-19	239.5	3.27	TNP
SLB-S-20	252.9	3.13	4.1×10^{-9}
SLB-S-21	255.9	3.11	4.6×10^{-9}
SLB-S-22	256.0	3.16	5.0×10^{-9}
SLB-S-23	259.7	3.10	TNP
SLB-S-24	259.9	3.11	TNP
SLB-S-25	262.7	3.10	TNP

Notes:
1. SLB = Paper mill sludge B; -S = Compacted at standard Proctor effort; -1..-25 = Specimen number.
2. TNP = Test not performed.

Table A.6. Results of compaction and hydraulic conductivity tests performed on paper mill sludge C.

Specimen(1)	Molding Water Content (%)	Dry Unit Weight (kN/m^3)	Hydraulic Conductivity (m/s)
SLC-S-1	5.8	5.64	1.4×10^{-5}
SLC-S-2	33.9	6.24	1.0×10^{-5}
SLC-S-3	55.4	6.13	8.7×10^{-6}
SLC-S-4	97.3	5.31	7.0×10^{-7}
SLC-S-5	120.9	5.49	TNP(2)
SLC-S-6	121.0	5.47	TNP
SLC-S-7	121.7	5.47	TNP
SLC-S-8	124.4	5.36	TNP
SLC-S-9	126.4	5.30	TNP
SLC-S-10	132.2	5.22	4.6×10^{-10}
SLC-S-11	135.2	5.00	8.9×10^{-10}
SLC-S-12	135.5	5.12	TNP
SLC-S-13	135.9	5.11	TNP
SLC-S-14	145.0	4.78	9.4×10^{-10}
SLC-S-15	156.0	4.51	8.9×10^{-10}
SLC-S-16	159.0	4.64	1.2×10^{-9}
SLC-S-17	165.0	4.37	1.6×10^{-9}
SLC-S-18	189.9	3.84	1.3×10^{-9}
SLC-S-19	191.6	3.77	9.8×10^{-10}
SLC-S-20	207.5	3.54	TNP
SLC-S-21	226.2	3.40	7.0×10^{-10}
SLC-S-22	227.9	3.36	TNP

Notes:
1. SLC = Paper mill sludge C; -S = Compacted at standard Proctor effort; -1..-22 = Specimen number.
2. TNP = Test not performed.

APPENDIX B

GRAPH OF AIR TEMPERATURE VS. TIME FOR THE WINTER OF 1993-94 FOR THE BURIED SMALL-SCALE FIELD PIPE SPECIMENS

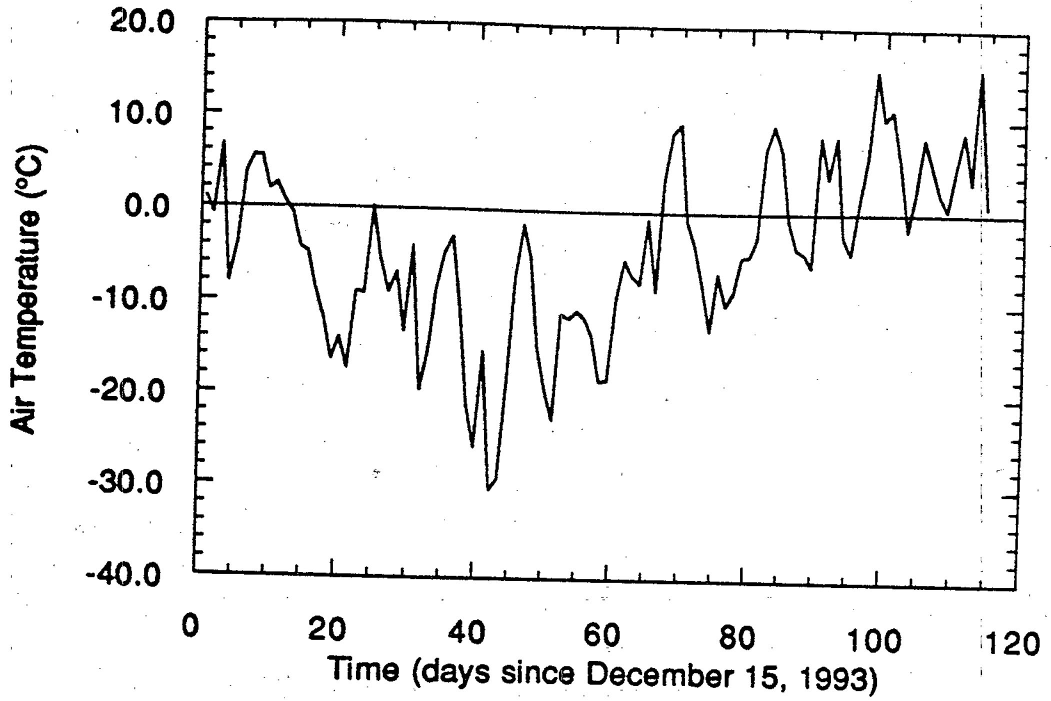

Figure B.1. Air temperature vs. time during freezing of buried small-scale field pipe specimens.