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Project Summary

Effect of Freeze-Thaw on the Hydraulic Conductivity of Barrier Materials: Laboratory and Field Evaluation

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Laboratory tests were conducted on barrier materials to determine if their hydraulic conductivity changes as a result of freezing and thawing. Results of the tests were compared to data collected from a field study. Tests were conducted on two compacted clays, one sand-bentonite mixture, three geosynthetic clay liners, and three paper mill sludges.

Analysis of the data showed that compacted clays undergo large increases in hydraulic conductivity in the field and laboratory when exposed to freeze-thaw, with the increase in hydraulic conductivity being larger in the field. In contrast, both the laboratory and field tests showed that sand-bentonite mixtures and geosynthetic clay liners are not affected by freeze-thaw. The sludges behaved similar to the clays, that is, they show large increases in hydraulic conductivity when frozen and thawed. However, the hydraulic conductivity of one of the sludges increased only if it was not permeated between freeze-thaw cycles.

This Project Summary was developed by the EPA's National Risk Management Research Laboratory, Cincinnati, OH, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction and Objectives

Laboratory studies conducted by several investigators have shown that freezing and thawing causes compacted clays to crack. Consequently, their hydraulic conductivity increases dramatically. These findings suggest that compacted clay barriers used in liners and covers for waste containment facilities may be damaged if not protected from frost. However, because the data collected to date have been generated from laboratory testing, it cannot be confirmed whether similar increases in hydraulic conductivity do in fact occur in the field. In addition, it is not known whether alternative barrier materials increase in hydraulic conductivity after freezing and thawing. Thus, the objectives of this study were (1) to determine if the results of laboratory tests are representative of field conditions and (2) to determine if alternative barrier materials are deleteriously affected by frost.

To meet these objectives, tests were performed in the laboratory to assess how freeze-thaw affected 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.

Compacted Clays

Typical results obtained from the field study are shown in Figure 1. The graph shows hydraulic conductivity vs. depth in a test pad constructed with Parkview clay, a low plasticity glacial till from the Milwaukee, WI area. The hydraulic conductivity tests were conducted on large undisturbed block specimens (diameter = 0.3 m) removed from the test pad. Before freezing, the test pad had low hydraulic conductivity at all depths tested. After freeze-thaw, however, the hydraulic conductivity increased as much as four orders of magnitude in soil located above the maximum depth of frost penetration. Below the maximum depth of frost penetration, the hydraulic conductivity was unaltered.

Results of the laboratory freeze-thaw tests on Parkview clay show that an increase in hydraulic conductivity of approximately two orders of magnitude occurred as a result of freeze-thaw (Figure 2). This increase in hydraulic conductivity is two orders of magnitude smaller than the increase in hydraulic conductivity occurring in the field. Comparison of the structure of the laboratory specimens to the structure existing in the field showed that cracks in the laboratory were more closely spaced and had a smaller aperature.

These findings demonstrate that the hydraulic conductivity of compacted clays increases as a result of exposure to freeze-thaw regardless of whether freezing and thawing occurs in the laboratory or field. Cracks that form due to desiccation (induced by freezing) and formation of ice lenses are responsible for the increase in hydraulic conductivity. However, 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.

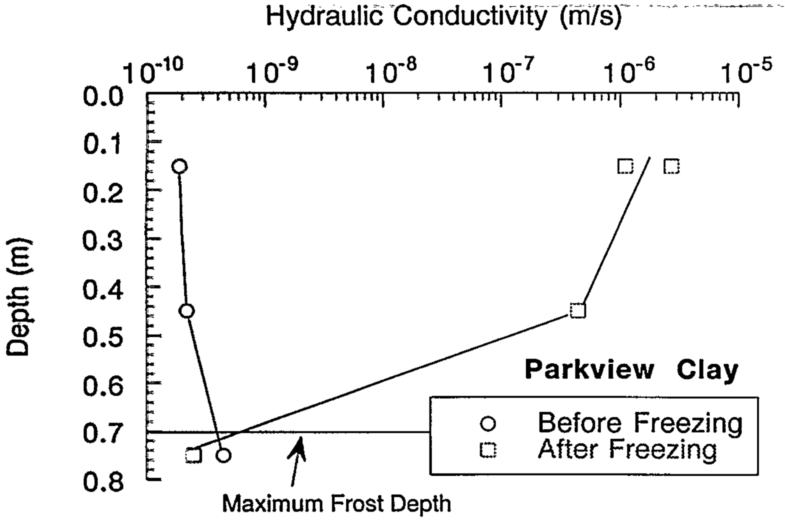

Figure 1. Hydraulic conductivities before and after freeze-thaw

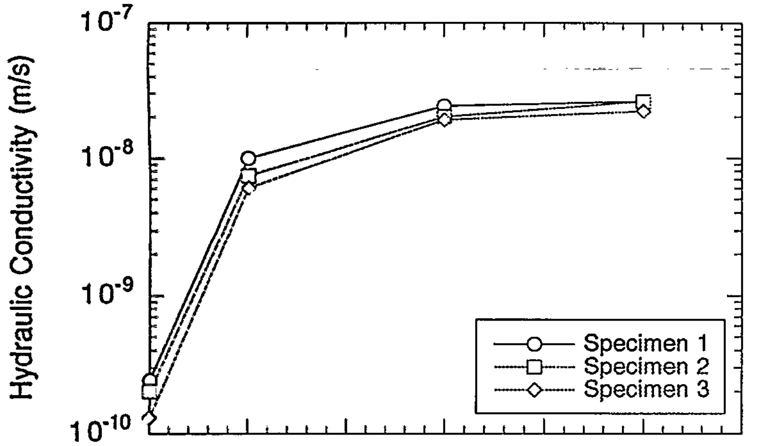

Figure 2. Hydraulic conductivity of specimens of Parkview clay frozen and thawed in the laboratory.

Testing was also conducted to show that frost damage can be difficult to detect if the assessment is based on hydraulic tests performed on specimens collected in thin-wall sampling tubes. Results of tests conducted on specimens collected after freezing and thawing from the test pad constructed with Parkview clay are shown in Table 1. The specimens were collected as blocks (diameter = 0.3 m) and with sampling tubes having an inside diameter of 0.071 m. The specimens collected in sampling tubes have much lower hydraulic conductivities, which are similar to the hydraulic conductivities measured on the specimens removed as blocks prior to freeze-thaw (Figure 1). Examination of the specimens collected in sampling tubes showed that they did not contain the cracks observed in the field and in the block specimens. Apparently, the sampling tubes were too small to capture the cracks existing in the field or caused sufficient disturbance to remold the soil and eliminate the cracks. These findings suggest that frost damage should not be assessed by testing specimens collected in sampling tubes.

Bentonitic Barriers

Results of the laboratory and field tests on the bentonitic barrier materials (sand-bentonite mixture, GCLs) showed that these materials are insensitive to freeze-thaw (e.g., see Tables 2 and 3 for tests on GCLs, Figure 3 for tests on sand-bentonite). The laboratory tests were conducted on disks of GCLs (diameter = 0.15 m) that were permeated in flexible-wall permeameters. The field tests were conducted using large test pans that con-

Table 1. *Summary of Hydraulic Conductivity Tests on Specimens from Parkview Test Pad*

Type of Specimen(1)	Sample Depth (m)	Initial Hydraulic Conductivity (m/s)	Final Hydraulic Conductivity(1) (m/s)	$\frac{K_f}{K_i}$ (2)
Block	0-0.3	1.9×10^{-10}	1.9×10^{-6}	10,000
Block	0.3-0.6	2.2×10^{-10}	4.4×10^{-7}	2,000
Block	0.6-0.9	4.5×10^{-10}	2.5×10^{-10}	0.56
Tube	0.10	2.9×10^{-10} (3)	1.0×10^{-9}	0.35
Tube	0.15	2.9×10^{-10} (3)	1.0×10^{-9}	0.35
Tube	0.25	2.9×10^{-10} (3)	4.5×10^{-10}	1.6
Tube	0.45	2.9×10^{-10} (3)	1.6×10^{-10}	0.55
Tube	0.52	2.9×10^{-10} (3)	1.6×10^{-10}	0.55

Notes:

1. *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)*
2. *Change in hydraulic conductivity (K_f/K_i) is defined as the final hydraulic conductivity divided by the initial hydraulic conductivity.*
3. *No specimens collected before winter in thin wall tubes; thus average hydraulic conductivity is reported as the average hydraulic conductivity for the block specimens collected before winter.*

Table 2. *Summary of Field Hydraulic Conductivity Tests for the GCLs used in the COLDICE project (courtesy Allan Erickson, CH2M Hill, Inc.)*

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*

tained a double-ring underdrain to collect effluent from the GCLs

Examination of both frozen and thawed specimens of the sand-bentonite showed that ice lenses do not form in sand-bentonite and thus the structure of the sand-bentonite is unchanged by freezing and thawing. Consequently, the hydraulic conductivity does not change. In contrast, ice lenses do form in hydrated GCLs when they freeze, but the resulting cracks in the soft bentonite close during thawing. 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.

Paper Mill Sludges

The paper mill sludges behaved similarly to the clays. They exhibited compaction curves having a distinct optimum water content and maximum dry unit weight. Their hydraulic conductivity was also sensitive to water content, with hydraulic conductivities less than 1 x 10^{-9} m/s occurring wet of optimum water content.

Two of the sludges behaved nearly the same as compacted 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.

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 re-

Table 3. *Hydraulic Conductivity of GCLs Frozen and Thawed in the Laboratory*

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

moved 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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The complete report, entitled "Effect of Freeze-Thaw on the Hydraulic Conductivity of Barrier Materials: Laboratory and Field Evaluation," (Order No. PB95-253928; Cost: $27.00, subject to change) will be available only from:
National Technical Information Service
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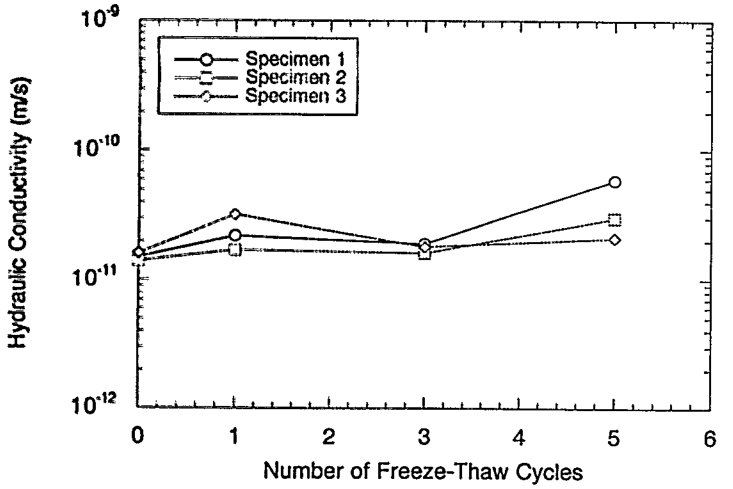

***Figure 3.** Hydraulic conductivity of sand-bentonite frozen and thawed in the laboratory.*

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