# Effect of Freeze-Thaw on the Hydraulic Conductivity of Three Compacted Clays from Wisconsin

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A laboratory testing program that was conducted to evaluate how freeze-thaw affects the hydraulic conductivity of three compacted clays is described. A parametric study was conducted to evaluate how the rate of freezing, temperature of freezing, dimensionality of freezing, and number of freeze-thaw cycles affect changes in hydraulic conductivity. The influence of molding water content, compactive effort, and state of stress has also been evaluated. Although the soils used in this study are of different mineralogical composition and geologic origin, the results show that freeze-thaw has a similar effect on their hydraulic conductivity. In particular, an increase in hydraulic conductivity of one to two orders of magnitude occurs because of freeze-thaw. Physical observations have shown that freeze-thaw causes cracks that act as conduits for flow and hence results in increased hydraulic conductivity. The study has shown that changes in hydraulic conductivity are independent of molding water contents in excess of optimum, but that increases in compactive effort reduce, albeit slightly, the increase in hydraulic conductivity. Results of the study also show that a single freeze-thaw cycle can result in large increases in hydraulic conductivity, but increases in hydraulic conductivity cease after three cycles of freeze-thaw. Conditions during freeze-thaw have also been found to influence the change in hydraulic conductivity. In particular, greater changes in hydraulic conductivity occur at greater rates of freezing and lower freezing temperatures.

Engineers are often confronted with remediating sites contaminated with hazardous materials such as chemical compounds from tank-truck or railroad car spills, mixed wastes generated by maintenance facilities, or hydrocarbons that have leaked from underground storage tanks. Because they have low hydraulic conductivity, earthen barriers constructed with compacted clay are often used as caps at contaminated sites to control infiltration and prevent the spread of pollutants. Earthen barriers are also used in waste containment structures. For example, they are used as liners for landfills, storage ponds, and sewage lagoons.

In cold regions, unprotected earthen barriers are subjected to freeze-thaw in the winter months. During freeze-thaw, the growth of ice lenses and the development of pore water suctions result in changes in soil structure that can have a deleterious effect on the ability of the soil to act as a hydraulic barrier. In particular, the hydraulic conductivity can increase one to two orders of magnitude (*1*,*2*). An investigation by Chamberlin et al. (*1*) has shown that freeze-thaw causes cracking and degradation of the soil fabric, which results in the increase in hydraulic conductivity.

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Numerous factors can affect the freeze-thaw process and the resultant changes in hydraulic conductivity. In this paper, a parametric study is described that was conducted to evaluate how compaction conditions (water content and compactive effort), freezing variables (freezing rate and ultimate temperature), and state of stress affect changes in hydraulic conductivity. Tests were conducted on three soils of different plasticity index to determine whether the changes were dependent on soil type.

## BACKGROUND

When a soil freezes, free water in the pores and water adsorbed on soil particles change to ice. During this process, the water expands approximately 9 percent because of the opening of the lattice of its hexagonal crystal structure. Redistribution of water may also occur in the soil as a result of suctions developed during the growth of ice lenses. More details regarding the freezing process can be found elsewhere (*3*,*4*).

The expansion occurring during the phase change and the redistribution of water can exert considerable pressures on adjacent soil particles. As a result, the peds consolidate and ice-filled cracks form in the soil mass (*5*,*6*). When the ice melts, pores and cracks that were filled with ice become large voids filled with water. If these voids are continuous throughout a soil, then its hydraulic conductivity may increase substantially.

### Experiments on Natural Soils

The formation of cracks during freeze-thaw in naturally deposited soils has been observed by Chamberlin and Gow (*7*). They examined thin sections of frozen sedimented silt and clay and found horizontal ice lenses perpendicular to the direction of freezing and vertical ice-filled shrinkage cracks that were linked to form columns with polygonal cross sections. Chamberlin and Gow conducted hydraulic conductivity tests on these soils in specially prepared consolidometers. They found that the hydraulic conductivity increased 10 to 100 times after freeze-thaw and attributed the increase in hydraulic conductivity to the cracks formed during freeze-thaw.

### Experiments on Compacted Clays

Recently, two experimental studies have been published that were conducted to evaluate the effect of freeze-thaw on the hydraulic conductivity of compacted clays (*1,2*). Chamberlin et al. (*1*) compacted five days at optimum water content and measured their hydraulic conductivity in a consolidometer. The specimens were frozen from bottom to top with free access to water (an "open system" for freeze-thaw). Freeze-thaw was continued for 15 cycles and hydraulic conductivity was measured after thawing at selected cycles.

For four of the clays, the hydraulic conductivity increased one to two orders of magnitude. The increases were larger during the first few cycles and ceased after about nine cycles. Chamberlin et al. (*1*) attributed the increases in hydraulic conductivity to macroscopic horizontal and vertical cracks that were formed during freeze-thaw. Each of these clays was classified as CL in the Unified Soil Classification System (USCS). The fifth clay, which was classified as CH, did not show an increase in hydraulic conductivity when frozen and thawed.

Zimmie and La Plante (*2*) investigated the effect of freeze-thaw on the hydraulic conductivity of compacted Niagara clay (also a CL). The specimens had no access to water; hence freeze-thaw occurred in a "closed system." After a specified number of cycles of freeze-thaw, the specimens were thawed in a flexible-wall permeameter and then permeated. Like Chamberlin et al. (*1*), Zimmie and La Plante measured increases in hydraulic conductivity of one to two orders of magnitude. They also found that similar hydraulic conductivities were obtained with one- and three-dimensional freeze-thaw and suggested that drier soils undergo greater changes in hydraulic conductivity.

### Implications for Earthen Barriers

The findings of Chamberlin et al. (*1*) and Zimmie and La Plante (*2*) suggest that the performance of an earthen barrier may be compromised if it is exposed to freeze-thaw. It is not clear, however, whether their findings are representative of field conditions. Differences between conditions in the laboratory and in the field, such as rate of freezing, temperature of freezing, and state of stress may magnify or reduce the change in hydraulic conductivity. In this paper, a study is described that was conducted to evaluate these factors.

## SOIL CHARACTERISTICS

Three clayey soils excavated from sites in southern Wisconsin were used in the study. Table 1 is a summary of pertinent index properties of the three soils. Soils A and B are glacial clays of low to moderate plasticity. Soil C is a residual clay of high plasticity. All of the soils have a particle size distribution with at least 71 percent passing the No. 200 sieve and clay contents (5μm fraction) exceeding 58 percent.

Compaction tests were conducted on each soil. Before compaction, the soil was air dried and broken down to particle sizes smaller than the No. 4 sieve. Tap water was then added to the soil to achieve the desired water contents. The soils were then sealed in plastic bags and allowed to hydrate for 3 days. Compaction curves corresponding to standard (ASTM D698) and modified Proctor (ASTM D1557) compactive efforts are shown in Figure 1.

The compacted specimens were permeated in flexible-wall permeameters in accordance with ASTM D5084. However, backpressure was not used. The permeant was deaired 0.005 N $CaSO_4$. Tests were conducted at an effective stress of 21 kPa and a hydraulic gradient in the range of 13 to 18. Tests were terminated after the hydraulic conductivity became steady and inflow equaled outflow. Graphs of hydraulic conductivity as a function of water content and compactive effort are shown in Figure 1. For each soil, hydraulic conductivities less than $1 \times 10^{-7}$ cm/sec were obtained when compacted wet of optimum.

## PROCEDURES FOR FREEZE-THAW

### Closed Versus Open System

Because increases in hydraulic conductivity induced by freeze-thaw appear to be caused by cracks formed during freezing, it is plausible to expect that greater access to water may result in more ice lensing and greater changes in hydraulic conductivity. However, the studies by Chamberlin et al. (*1*) and Zimmie and La Plante (*2*), conducted in open and closed systems, respectively, show similar changes in hydraulic conductivity. Apparently, at high water contents (and degree of saturation) ordinarily used to compact earthen barriers, sufficient water is available to form ice lenses that crack the soil and cause increases in hydraulic conductivity. Hence, from a practical perspective, the difference between open and closed systems does not appear significant. For the study described herein, tests were conducted in a closed system.

**TABLE 1 Characteristics of Soils Used in Study**

| Soil | USCS Classification | LL (%) | PI (%) | Optimum Water Content (%)[a] | Maximum Dry Unit Wt (kN/m$^3$)[a] | $P_{200}$[b] (%) | 5μm Clay Fraction (%) | Activity (PI/2μm) |
|---|---|---|---|---|---|---|---|---|
| A | CL | 34 | 16 | 16.0 | 18.0 | 85 | 58 | 0.36 |
| B | CL | 42 | 22 | 18.5 | 16.8 | 99 | 77 | 0.41 |
| C | CH | 84 | 60 | 26.0 | 14.7 | 71 | 58 | 1.43 |

[a] Standard Proctor
[b] Percentage Passing No. 200 Sieve

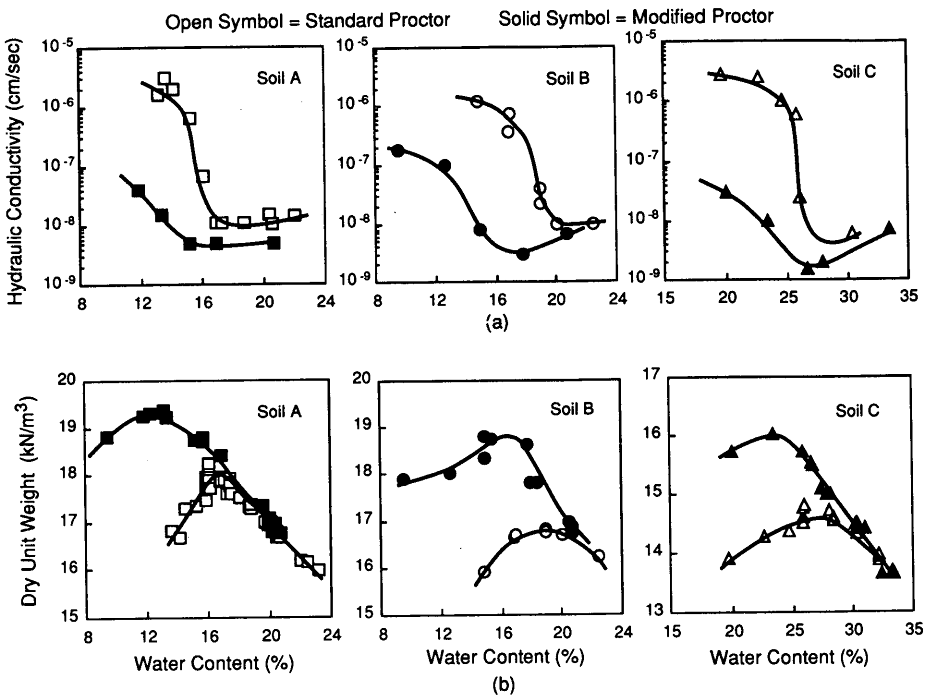


**FIGURE 1 Hydraulic conductivity-water content curves (*a*) and compaction curves (*b*) for Soils A, B, and C.**

### Three-Dimensional Freeze-Thaw

Specimens were subjected to one- and three-dimensional freeze-thaw to determine whether simpler three-dimensional tests result in the same hydraulic conductivities as more realistic one-dimensional tests. Specimens subjected to three-dimensional freeze-thaw were sealed with two layers of plastic wrap to prevent desiccation. For rapid freeze-thaw, specimens were placed in a freezer with only the plastic wrapping. If the freezing rate was to be reduced, fiberglass insulation was wrapped around the specimen.

Multiple specimens compacted under essentially identical conditions were frozen concurrently. One of the specimens was instrumented with thermocouples to monitor temperature. The other specimens were used for hydraulic conductivity measurements. Thermocouples were also placed in the freezer to ensure that the air temperature was uniform. A specimen was subjected to a freeze-thaw cycle by cooling it from room temperature ($\approx$ 20°C) to the ambient temperature of the freezer and then warming it back to room temperature.

### One-Dimensional Freeze-Thaw

Specimens subjected to one-dimensional freeze-thaw were sealed in the same manner that was used for specimens frozen three-dimensionally. To promote one-dimensional freezing, the specimens were wrapped in a cylinder of fiberglass and subjected to a temperature gradient. The temperature gradient was created by placing a source of heat at the bottom of the specimen as shown in Figure 2. A heating pad sandwiched between two 0.05-m-thick sheets of Styrofoam was used to provide the source of heat.

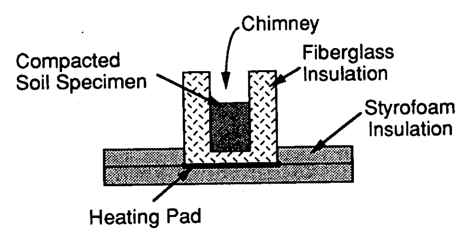


**FIGURE 2 Apparatus for one-dimensional freeze-thaw.**

Finite element analyses of heat transfer and several preliminary experiments were used to determine the thickness of insulation and temperature of the heating pad that would yield one-dimensional freeze-thaw for a wide variety of temperatures in the freezer. From these experiments, the insulation thickness was selected as 7 cm and the initial temperature of the heating pad was 37°C.

Figure 3 shows a typical temperature profile obtained by monitoring thermocouples at the top, bottom, and center of a specimen of Soil A. The thermocouples placed at the "middle-center" and "middle-out" of the specimen show that freezing occurs one-dimensionally, whereas the thermocouples located at the top and bottom show that a vertical gradient in temperature exists.

### Comparison of One- and Three-Dimensional Tests

To compare one- and three-dimensional freeze-thaw, specimens were compacted 4 percent wet of optimum water content with standard Proctor effort. This water content and effort

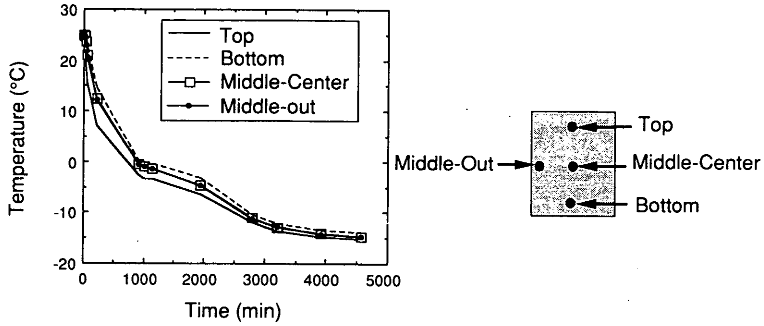


**FIGURE 3 Freezing curve and schematic showing location of thermocouples in a specimen during one-dimensional freeze-thaw.**

are typically used for compaction of earthen barriers (*8*). Specimens were then subjected to one- and three-dimensional freeze-thaw. To eliminate confounding effects, the rate and temperature of freezing were held constant. The rate of freezing, $R_f$, was defined as

$$R_f = \frac{L_{max}}{\Delta t} \quad (1)$$

where $L_{max}$ is the greatest distance the freezing front must travel and $\Delta t$ is the time required to lower the temperature at this point from 0°C to the ambient temperature of the freezer ($T_f$).

The hydraulic conductivity of the specimens is shown in Figure 4; the median of five replicate tests was used to determine each point on the graph to avoid ambiguities caused by scatter. Figure 4 shows that one- and three-dimensional freeze-thaw result in essentially the same hydraulic conductivity. Because the hydraulic conductivities for one- and three-dimensional freeze-thaw are essentially the same, the simpler and faster procedures for three-dimensional freeze-thaw were used in the remainder of the study.

Figure 4 also shows that large changes in hydraulic conductivity occurred when the soil was frozen and thawed. Visual observations of the compacted specimens revealed a network of cracks that formed throughout the specimens (Figure 5b). When the specimens were split open after permeation, the surfaces of the cracks were laden with water. Similar free water was not observed in the matrix between the cracks. On the basis of these observations, the writers believe that the formation of cracks during freeze-thaw is the primary cause of the increase in hydraulic conductivity.

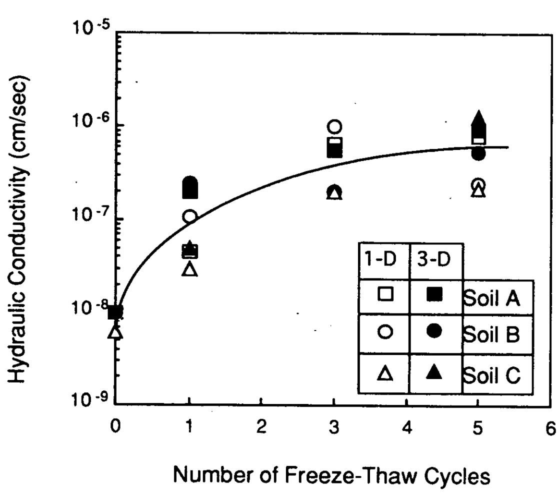


**FIGURE 4 Comparison of hydraulic conductivities for one- and three-dimensional freeze-thaw.**

## RESULTS OF PARAMETRIC STUDY

### Comparison of Soils A, B, and C

Chamberlin et al. (*1*) found that changes in hydraulic conductivity were large for four clays of low plasticity and nonexistent for a clay of high plasticity. One explanation of this behavior is that highly plastic clays tend to have a greater amount of adsorbed water because of the presence of more active clay minerals and hence have less water available for the formation of ice lenses. This explanation is supported in concept by experiments conducted by Tsytovich (*3*). By changing pore fluid chemistry, Tsytovich (*3*) showed that increasing the amount of adsorbed water can significantly reduce the amount of cracking and frost heave in clays.

Soils A, B, and C, which differ in composition (e.g., PI, activity), were compared to determine whether clays of different composition exhibit different changes in hydraulic conductivity when frozen and thawed. Specimens were compacted 3 to 4 percent wet of optimum and then subjected to three-dimensional freeze-thaw. Figure 6 shows hydraulic conductivity as a function of number of freeze-thaw cycles for the three soils. For all three soils, the hydraulic conductivity increased by a factor of 100 or more, with the greatest change occurring in the first cycle. Furthermore, changes ceased after three cycles.

Soil C, a CH, underwent the greatest change in hydraulic conductivity, but its final hydraulic conductivity was essentially the same as the final hydraulic conductivities of Soils A and B ($\approx 2 \times 10^{-6}$ cm/sec). This is in direct contrast to the results obtained by Chamberlin et al. (*1*). The CH soil they tested showed no change in hydraulic conductivity. Apparently, for the soils used in this study, the differences in composition did not have a significant effect on the hydraulic conductivity after freeze-thaw.

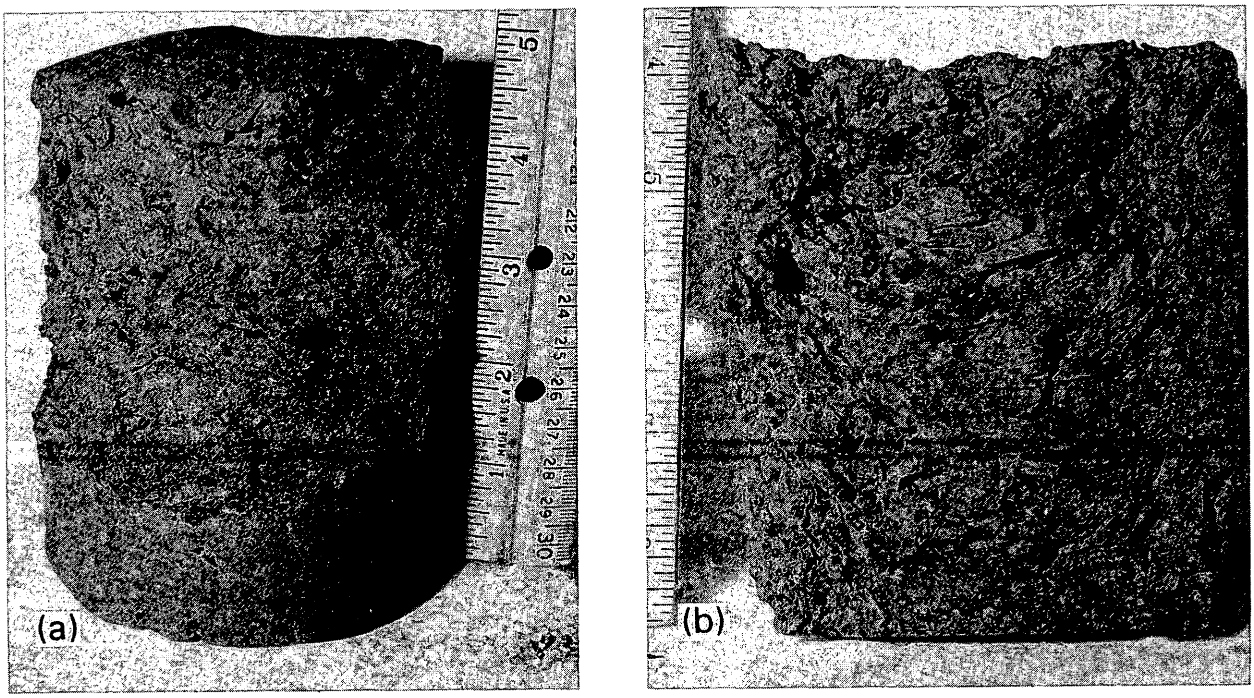


**FIGURE 5** Specimen (*a*) before and (*b*) after freeze-thaw.

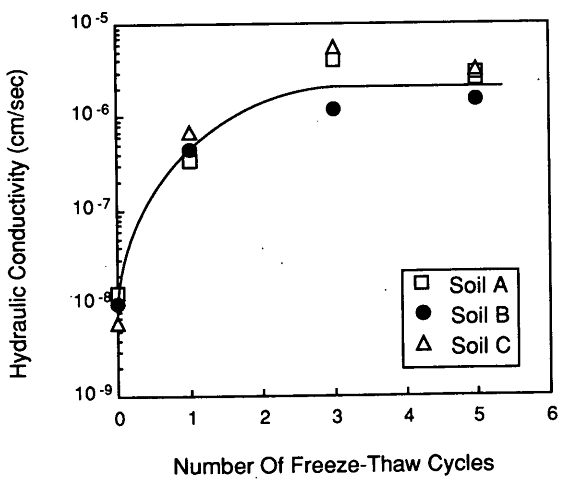


**FIGURE 6** Comparison of hydraulic conductivities of Soils A, B, and C after freeze-thaw.

## Molding Water Content

Zimmie and La Plante (*2*) found greater hydraulic conductivities after freeze-thaw for specimens compacted at lower water contents. To determine whether a similar effect occurred for the soils used in this study, specimens were compacted at optimum water content and 4 percent wet of optimum to bracket molding water contents typically specified for construction of earthen barriers (*8*). The specimens were then subjected to three-dimensional freeze-thaw.

Table 2 summarizes the hydraulic conductivities of Soils A, B, and C compacted at optimum and 4 percent wet of optimum water content before and after freeze-thaw. For all three soils, the hydraulic conductivity after freeze-thaw was essentially the same for both water contents ($\approx 4 \times 10^{-6}$ cm/sec). For typical molding water contents, it appears that differences in water content are not large enough to cause significant differences in the effects of freeze-thaw for these soils.

## Compactive Effort

The effect of compactive effort on the increase in hydraulic conductivity was also evaluated to determine whether increases in density achieved with higher compactive effort would prevent increases in hydraulic conductivity. Broderick and Daniel (*9*) have shown that modified Proctor effort can be

**TABLE 2** Comparison of Effect of Freeze-Thaw on Hydraulic Conductivity at Two Molding Water Contents

| | Hydraulic Conductivity (cm/sec)[a] | |
|---|---|---|
| Soil | Optimum Water Content | 4% Wet of Optimum |
| A | $3.5 \times 10^{-6}$ | $4.0 \times 10^{-6}$ |
| B | $5.0 \times 10^{-6}$ | $1.2 \times 10^{-6}$ |
| C | $3.0 \times 10^{-6}$ | $5.5 \times 10^{-6}$ |
| Average | $3.8 \times 10^{-6}$ | $3.6 \times 10^{-6}$ |

[a] Note: $R_f = 2 \times 10^{-6}$ m/s; $T_f = -18°C$

**TABLE 3 Comparison of Hydraulic Conductivities for Standard and Modified Proctor Effort**

| | Hydraulic Conductivity (cm/s)[a] | | | |
|---|---|---|---|---|
| | Water Content = 16.5% | | Water Content = 20% | |
| Soil A | Std. Proctor | Mod. Proctor | Std. Proctor | Mod. Proctor |
| No Freeze-Thaw | $1 \times 10^{-8}$ | $5 \times 10^{-9}$ | $1 \times 10^{-8}$ | $5 \times 10^{-9}$ |
| 3 Cycles of Freeze-Thaw | $4 \times 10^{-6}$ | $6 \times 10^{-7}$ | $4 \times 10^{-6}$ | $1 \times 10^{-6}$ |
| | Water Content = 18.5 % | | Water Content = 20.5% | |
| Soil B | Std. Proctor | Mod. Proctor | Std. Proctor | Mod. Proctor |
| No Freeze-Thaw | $4 \times 10^{-8}$ | $3 \times 10^{-9}$ | $1 \times 10^{-8}$ | $7 \times 10^{-9}$ |
| 3 Cycles of Freeze-Thaw | $6 \times 10^{-6}$ | $1 \times 10^{-6}$ | $1 \times 10^{-6}$ | $1 \times 10^{-6}$ |
| | Water Content = 26 % | | Water Content = 30% | |
| Soil C | Std. Proctor | Mod. Proctor | Std. Proctor | Mod. Proctor |
| No Freeze-Thaw | $2 \times 10^{-8}$ | $2 \times 10^{-9}$ | $8 \times 10^{-9}$ | $6 \times 10^{-9}$ |
| 3 Cycles of Freeze-Thaw | $3 \times 10^{-6}$ | $3 \times 10^{-7}$ | $6 \times 10^{-6}$ | $2 \times 10^{-7}$ |

[a] Note: $R_f = 2 \times 10^{-6}$ m/s; $T_f = -18°C$

used to prevent cracking and increases in hydraulic conductivity of compacted clays that often occur during permeation with strong organic chemicals. They concluded that particles are unable to move at increased densities, and therefore cracks are unable to form.

To determine whether compactive effort had a similar beneficial effect for freeze-thaw, specimens were compacted with modified Proctor effort at molding water contents corresponding to standard Proctor optimum and 2 to 4 percent wet of standard Proctor optimum. The specimens were then subjected to three cycles of three-dimensional freeze-thaw and afterwards permeated in flexible-wall permeameters.

Table 3 gives the results of the hydraulic conductivity tests. Specimens compacted with modified Proctor effort had slightly lower hydraulic conductivity after freeze-thaw than samples compacted with standard Proctor effort. Apparently, specimens compacted with modified Proctor compactive effort are slightly more resistant to changes in hydraulic conductivity than the specimens compacted using standard Proctor effort. Nevertheless, the change in hydraulic conductivity was still large (≥ two orders of magnitude) even when modified Proctor effort was used.

## Rate of Freezing

As ice lenses nucleate in the pores of a freezing soil, suctions develop that draw water toward the growing ice crystal (*10*). At greater rates of freezing, the rate of growth of ice lenses increases, larger suctions develop, and, as a result, more frost damage occurs. These effects have been documented in research on frost heaving. For example, Penner (*11*) has shown that the rate and magnitude of heave increase as the rate of freezing increases because larger ice lenses are formed. Thus, it might be expected that the change in hydraulic conductivity depends on the rate of freezing.

To evaluate the effect of rate of freezing, specimens were frozen three-dimensionally at various rates of freezing. The rate of freezing was controlled by varying the thickness of insulation. Specimens were subjected to rates of freezing of $2 \times 10^{-6}$ m/sec (fast), $4 \times 10^{-7}$ m/sec (moderate), and $2.6 \times 10^{-7}$ m/sec (slow). For the slow rate, tests were conducted only on Soil A because of the number of specimens and length of time required to conduct the tests.

Figure 7 shows hydraulic conductivity for fast, moderate, and slow freezing as a function of number of freeze-thaw cycles. The rate of freezing has a significant effect on how freeze-thaw changes hydraulic conductivity. For fast freeze-thaw, the hydraulic conductivity increased by a factor of 300, whereas for moderate freeze-thaw the increase was only about a factor of 60. No difference was observed, however, between moderate and slow freezing. Visual observations of the specimens showed that rapid freezing resulted in a more dense network of cracks than slow freezing and hence had greater hydraulic conductivity.

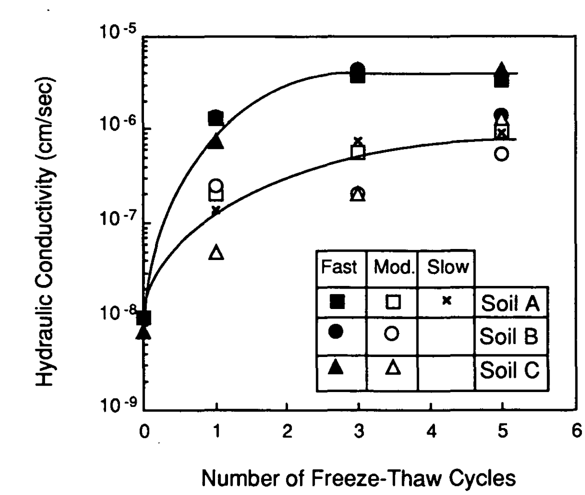


**FIGURE 7 Effect of rate of freezing on hydraulic conductivity.**

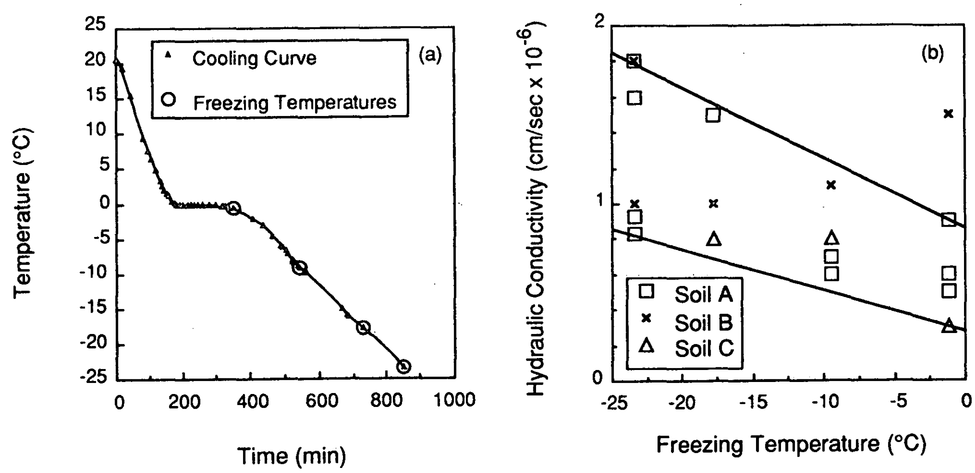


**FIGURE 8 Freezing curve (*a*) and hydraulic conductivity as a function of temperature of freezing (*b*).**

A practical implication of these results is that tests used to evaluate the effects of freeze-thaw should be performed at rates of freezing that are expected in the field. Tests conducted at rates that are too fast will probably yield conservative hydraulic conductivities but may also lead to incorrect conclusions regarding the actual performance of an earthen barrier.

## Temperature of Freezing

When the temperature of soil drops below 0°C, the water in the pores begins to freeze. Because of the thermodynamic equilibrium between the solid, water, ice, and air, unfrozen water still exists at temperatures below 0°C (*10,12*). As the temperature is lowered further, more of the water becomes ice. Hence, if the formation of cracks caused by the growth of ice lenses is the primary cause of increases in hydraulic conductivity, then it is expected that hydraulic conductivity depends on the temperature of freezing.

To examine the influence of temperature of freezing, specimens of Soils A, B, and C were subjected to three-dimensional freeze-thaw. At temperatures of −1°C, −9°C, −18°C, and −23°C, specimens were removed from the freezer and allowed to warm at room temperature. Figure 8a shows these temperatures on the freezing curve. The highest temperature (−1°C) corresponds to near complete freezing of free water; lower temperatures correspond to increasing amounts of freezing of adsorbed water (*4*).

Figure 8b is a graph of hydraulic conductivity as a function of temperature of freezing. It shows that hydraulic conductivity increases slightly as temperature of freezing is lowered. However, the difference between hydraulic conductivities of specimens frozen at −1°C and −23°C is small. Furthermore, the change in hydraulic conductivity due to temperature of freezing is very small compared with the change in hydraulic conductivity that occurs when the free water simply undergoes a change of phase. Apparently, the freezing of free water causes the most significant change in soil structure.

## State of Stress

If the changes in hydraulic conductivity that occur because of freeze-thaw are caused by the formation of cracks and reorientation of particles, it is expected that the state of stress imposed on the soil may affect hydraulic conductivity. Boynton and Daniel (*13*) observed significant decreases in hydraulic conductivity with increasing levels of effective stress for compacted clays that were cracked by desiccation.

To examine whether hydraulic conductivity after freeze-thaw is affected by effective stress, a specimen of Soil B was subjected to five cycles of three-dimensional freeze-thaw ($R_f = 2 \times 10^{-6}$ m/sec, $T_f = -18$°C). Afterwards, the specimen was placed in a flexible-wall permeameter and consolidated to effective stresses of 14, 70, and 210 kPa. After each increment of effective stress, the hydraulic conductivity was measured.

Figure 9 shows hydraulic conductivity as a function of effective stress for Soil B. Two curves are shown. The upper

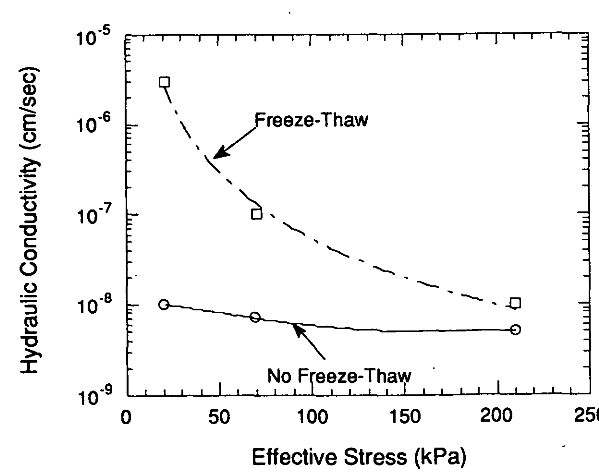


**FIGURE 9 Influence of effective stress on hydraulic conductivity.**

curve corresponds to a specimen subjected to five cycles of freeze-thaw; the lower curve corresponds to an identical specimen that was not subjected to freeze-thaw. Figure 9 shows that hydraulic conductivity decreases as the effective stress increases for both specimens. For the specimen exposed to freeze-thaw, however, much larger reductions in hydraulic conductivity occurred. The likely cause of this greater reduction in hydraulic conductivity is the closing of cracks (such as those shown in Figure 5b) that act as conduits for rapid flow. At high effective stress, however, the specimen subjected to freeze-thaw still had larger hydraulic conductivity than the specimen never frozen.

The sensitivity of hydraulic conductivity to effective stress has important ramifications. For earthen barriers used for liners in landfills, exposure to freeze-thaw will result in only temporary increases in hydraulic conductivity, provided a sufficient depth of waste is placed on the liner. For conditions where lower stress occurs, such as caps, liners for lagoons, and side slopes of landfill liners, changes in hydraulic conductivity are likely to be permanent.

## SUMMARY

From the parametric study described in this paper, the following conclusions can be drawn:

1. For the clays used in this study, freeze-thaw resulted in an increase in hydraulic conductivity of one to two orders of magnitude. Similar changes have been observed by other investigators.
2. Significant changes in hydraulic conductivity (an order of magnitude or more) can occur in a single cycle of freeze-thaw. Increases in hydraulic conductivity cease after three to five cycles.
3. For the soils in this study, which range in plasticity index from 16 to 60 and differ in geologic origin, nearly identical hydraulic conductivities ($\approx 3 \times 10^{-6}$ cm/sec) were obtained after three to five cycles of freeze-thaw.
4. Hydraulic conductivity after freeze-thaw did not depend on molding water content in the range of typical water contents used for compacted earthen barriers (0 to 4 percent wet of optimum). Increases in compactive effort reduced the increase in hydraulic conductivity caused by freeze-thaw. The reduction was small, however, and hydraulic conductivities in excess of $1 \times 10^{-7}$ cm/sec still occurred at high effort.
5. The rate and temperature of freezing affect the change in hydraulic conductivity. Faster rates and lower temperatures resulted in greater increases in hydraulic conductivity.
6. State of stress has a significant influence on how freeze-thaw affects hydraulic conductivity. As the effective stress is increased, the hydraulic conductivity decreases substantially, an effect probably caused by the closing of cracks. However, even at high stress (200 kPa), the hydraulic conductivity was greater for soil frozen and thawed than for soil never frozen.

## ACKNOWLEDGMENT

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## REFERENCES

1. E. J. Chamberlin, I. Iskander, and S. E. Hunsiker. Effect of Freeze-Thaw on the Permeability and Macrostructure of Soils. *Proc., International Symposium on Frozen Soil Impacts on Agricultural, Range, and Forest Lands*, Spokane, Wash., March 21–22, 1990, pp. 145–155.
2. T. F. Zimmie and C. La Plante. The Effect of Freeze-Thaw Cycles on the Permeability of a Fine-Grained Soil. *Proc., 22nd Mid-Atlantic Industrial Waste Conference*, Philadelphia, Pa., July 24-27, 1990, pp. 580–593.
3. N. A. Tsytovich. *The Mechanics of Frozen Ground*. McGraw-Hill, New York, 1975.
4. N. A. Lundarini. *Heat Transfer in Cold Climates*. Litton Educational Publishing, New York, 1981.
5. E. J.Chamberlin and S. E. Blouin. *Freeze-Thaw Enhancement of the Drainage and Consolidation of Fine-Grained Dredged Material in Confined Disposal Areas*. CRREL Final Report, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, N.H., 1976.
6. B. D. Alkire and J. M. Morrison. Changes in Soil Structure due to Freeze-Thaw and Repeated Loading. In *Transportation Research Record 918*, TRB, National Research Council, Washington, D.C., 1982, pp. 15–22.
7. E. J. Chamberlin and A. J. Gow. Effect of Freezing and Thawing on the Permeability and Structure of Soils. *Engineering Geology*, No. 13, 1979, pp. 73-92.
8. D. E. Daniel and C. H. Benson. Water Content-Density Criteria for Compacted Soil Liners. *Journal of Geotechnical Engineering*, ASCE, Vol. 116, No. 12, 1990, pp. 1811–1830.
9. G. Broderick and D. Daniel. Stabilizing Compacted Clay Against Chemical Attack. *Journal of Geotechnical Engineering*, ASCE, Vol. 116, No. 10, 1990, pp. 1549–1567.
10. R. Koopmans and R. Miller. Soil Freezing and Soil Water Characteristic Curves. *Proc., Soil Science Society of America*, Vol. 30, No. 6, 1966, pp. 680–685.
11. E. Penner. The Importance of Freezing Rate in Frost Action in Soils. *Proc., American Society for Testing and Materials*, Vol. 60, 1960, pp. 1151–1165.
12. P. B. Black and A. R. Tice. Comparison of Soil Freezing Curve and Soil Water Curve Data for Windsor Sandy Loam. *Water Resources Research*, Vol. 25, No. 10, 1989, pp. 2205–2210.
13. S. Boynton and D. Daniel. Hydraulic Conductivity Tests on Compacted Clay. *Journal of Geotechnical Engineering*, ASCE, Vol. 111, No. 4, 1985, pp. 465–478.

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