Freeze/Thaw Effects on the Hydraulic Conductivity of Compacted Clays

CHRISTINE M. LAPLANTE AND THOMAS F. ZIMMIE

A series of clay samples molded at differing water contents was subjected to one-dimensional freezing and thawing, and the changes in permeability (hydraulic conductivity) were determined with respect to the number of freeze/thaw cycles. Triaxial permeability tests were performed at chamber pressures of 69 kPa (10 psi), resulting in observed increases in permeability of about one order of magnitude (a factor of 10), from 10^{-8} cm/sec to 10^{-7} cm/sec. The maximum permeability changes occurred in less than 10 freeze/thaw cycles. Permeability tests were also performed at various chamber pressures to determine the permeability–effective stress relationship. Permeability changes due to freezing and thawing are greatest at low effective stresses and decrease with increasing effective stress. The results can have important implications for landfill cover and liner design. The clay barrier for a cover system remains at a relatively low effective stress. Test results indicate that a permeability change of about two orders of magnitude can be expected because of freezing and thawing. Thus, the clay barrier in the cover system must be protected from freezing and thawing. Clay liners subjected to freezing and thawing, for example after construction and before waste placement, will show the same increase in permeability as for cover material. However, as the waste is placed, and hence the effective stress increased, the clay permeability will decrease. If sufficient waste, cover, and overburden material are placed on the clay liner, the permeability can decrease to an acceptable value.

Safe solid waste disposal methods are a major environmental concern. Disposal of waste in specially designed landfills appears to be a necessary and feasible way to deal with solid waste. However, many unanswered questions exist with respect to the reliability of landfill liners and cover systems in minimizing or eliminating leachate entering the environment (i.e., escaping from the landfill).

Many factors influence proper landfill liner and cover system operations. Several of these factors can be controlled with proper construction and design considerations. Suggested liner and cover system designs can be found in numerous publications [e.g., that of the Environmental Protection Agency (EPA) (*1*)]. An important area of concern is the performance of the impermeable barrier layer located within both the cover and liner systems. This layer consists of a low permeability soil material, most commonly clay. Current design guidelines state that this layer must have a maximum permeability of 1×10^{-7} cm/sec (*2*). This paper is concerned with maintaining the required permeability in the barrier layer after it has been subjected to freeze/thaw cycling effects.

Civil and Environmental Engineering Department, Rensselaer Polytechnic Institute, Troy, N.Y. 12180.

TEST PROGRAM

Two distinctly different clay soil types were subjected to a varied number of freeze/thaw cycles. Table 1 gives the results of typical soil classification tests. The Niagara clay is from western New York State in the vicinity of Niagara Falls, and the Brown clay is from eastern New York State near Albany. The Niagara clay is a fine-grained silty clay classified as CL, and the Brown clay is a high-plasticity fat clay classified as CH [Unified Soil Classification System (*3*)].

The soil samples were frozen and thawed one-dimensionally (1D) as well as three-dimensionally (3D). Since the freezing front penetrates soil in the field from the surface downward (i.e., 1D), fundamental research dealing with freeze/thaw effects must duplicate the in situ 1D freeze/thaw process. The 1D freezing process is time-consuming when simulated in the laboratory relative to 3D freezing; therefore, 3D freezing was also used. Although a detailed comparison of 1D with 3D freezing is beyond the scope of this paper, the results indicate that for all practical purposes the end results (changes in permeability) are similar (*4*). This has important implications for routine testing, standardization of test procedures, and similar activities, since 3D testing is much faster and simpler than 1D testing.

All soil specimens tested were 10.2 cm (4 in.) long and 7.6 cm (3 in.) in diameter. The specimens were prepared using the standard Proctor compaction technique. Each specimen was prepared in the 10.2 cm (4 in.) polyvinyl chloride (PVC) mold. For the Niagara clay the specimens were prepared at molded water content ranges of dry of optimum (13.5 to 14.5 percent), optimum (16 to 17 percent), and wet optimum (18.5 to 19.5 percent). Figure 1 shows the Proctor results for the Niagara clay. Specimens were molded at dry densities representing 95 percent compaction and moisture contents of approximately 3 percent wet or dry of optimum. Also shown in Figure 1 is the natural (before freezing) permeability with

TABLE 1 Soil Characteristics

	NIAGARA CLAY	BROWN CLAY
Plastic Limit:	19.8	26.0
Liquid Limit:	38.6	60.0
Plasticity Index:	18.8	34.0
Optimum Water Content:	16.5	31.0
Clay Content:	50%	NA
Silt Content:	40%	NA

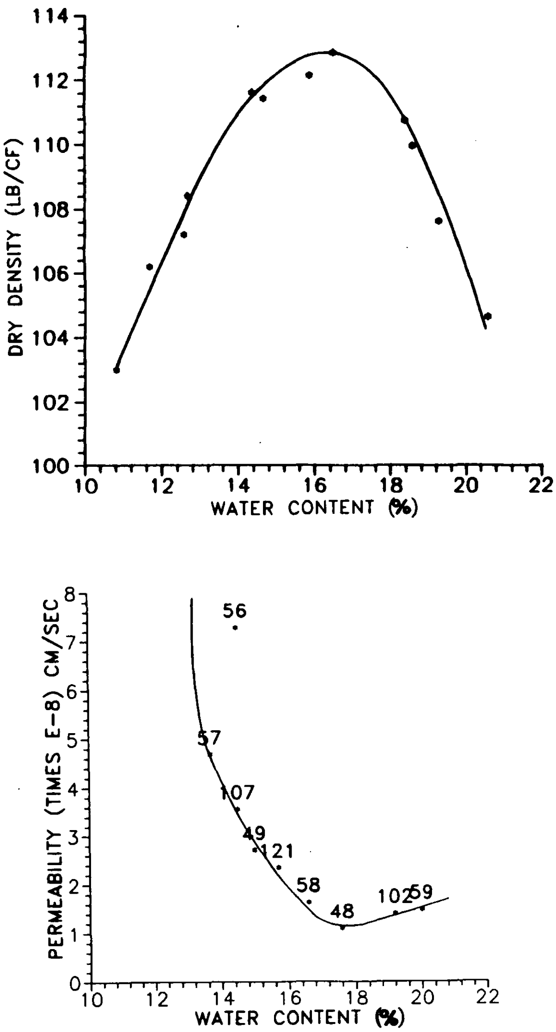

FIGURE 1 Natural permeability and dry density versus water content.

respect to water content curve. All specimens had natural permeabilities in the 10^{-8} cm/sec range. The Brown clay exhibited similar results. For the Brown clay, water content ranges used for specimen preparation were 30.5 to 31.5 percent for the optimum specimens and 34.5 to 35.5 percent for the wet of optimum specimens. The dry of optimum state was not tested. The decreased workability, large clods, and cracks of the material molded dry of optimum prevented the formation of intact test specimens (i.e, the specimens collapsed).

Permeability tests were performed using flexible wall, backpressure, triaxial permeability apparatus. Additional testing details, test results, and procedures can be found elsewhere (*4*); a more extensive discussion of equipment details and experimental procedures is given by LaPlante and Thomas (*5*).

Further permeability tests were performed on the Niagara clay to evaluate the effect of effective stress on the permeability, and as a result, the effect of effective stress on the observed changes in permeability due to freezing and thawing. Samples of the Niagara clay were tested and subjected to various chamber pressures typical for liners and covers. Test conditions were chosen to represent typical landfill construction practices for liners and covers. The samples were molded wet of optimum, and both unfrozen soil and soil subjected to 19 freeze/thaw cycles were tested. The 19 freeze/thaw cycles ensured that the maximum permeability change due to freeze/thaw conditions was reached. This research as well as that of Chamberlain et al. (*6*) indicates that the maximum permeability changes due to freeze/thaw effects occur within the first 10 cycles.

RESULTS AND DISCUSSION

Previous research studies indicate a definite increase in the permeability of compacted clays due to the freezing and thawing process. Observed permeability changes vary between one and two orders of magnitude (*4,6*). As shown in Figures 2 and 3 the two clays depicted in this study exhibit between 1 and 1½ orders of magnitude increases in the natural permeability due to freeze/thaw cycling effects. The amount of increase appears to be correlated with the molding water content, which in turn can be related to the soil dry density. Extensive research has been done correlating permeability and molded water content for unfrozen soil. Increases in compacted moisture content result in marked decreases in permeability until the minimum value of permeability occurs at a moisture content slightly wet of the optimum water content (*7,8*). Both the Niagara clay and the Brown clay tested in this study exhibited this typical behavior. The Niagara clay molded dry of optimum, and thus at the lowest dry density, exhibited the largest change in permeability (1½ orders of magnitude). The optimum and wet of optimum samples exhibited approximately one order of magnitude change in increased permeability due to freeze/thaw effects, relative to the natural unfrozen permeability. A similar relationship is shown in Figure 3 for the Brown clay optimum and wet of optimum sam-

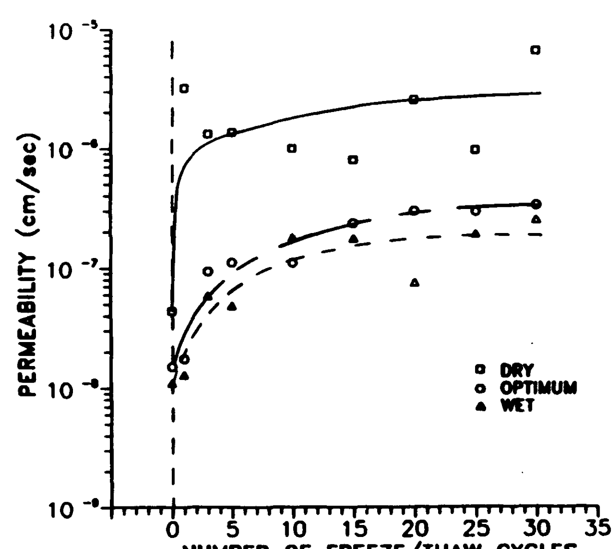

FIGURE 2 Summary of the 1D freeze/thaw cycle effects on Niagara clay.

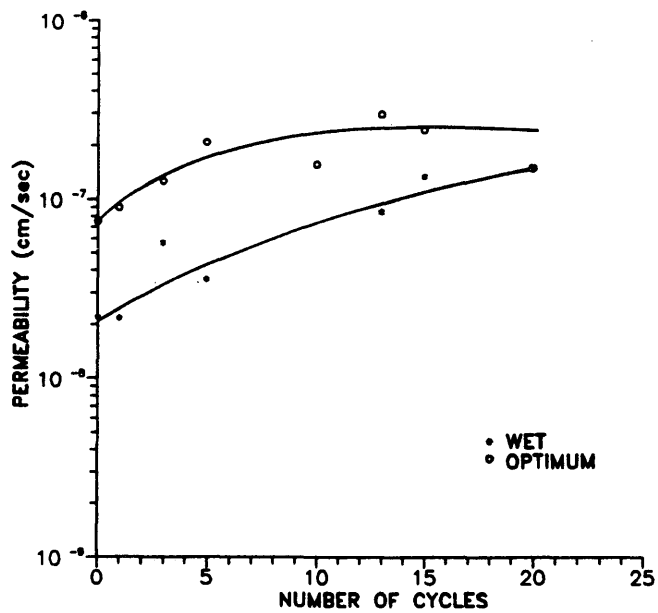

FIGURE 3 Summary of the 1D freeze/thaw cycle effects on Brown clay.

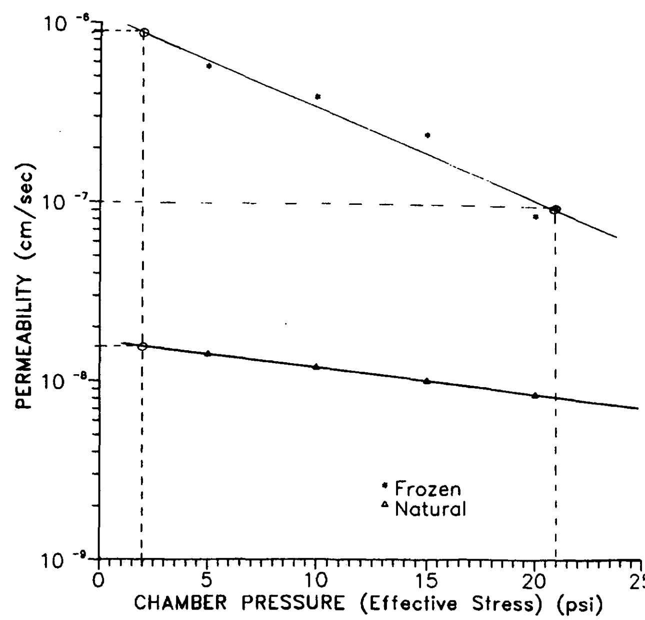

FIGURE 4 Effect of freeze/thaw cycling on the permeability of Niagara clay molded wet of optimum in the permeability versus chamber pressure plane.

ples. Research performed on uranium mill tailings covers by Chamberlain et al. (*6*) indicated permeability increases for the compacted clays tested of approximately two orders of magnitude due to freeze/thaw effects. All samples tested were molded at about their optimum water contents.

The clays in both studies were different, and thus the differences may simply be due to clay type. In addition, Chamberlain et al. used 1D consolidometer permeameters in their research, which did not allow for the application of back-pressure. Thus, the larger apparent changes in permeability may be due to saturation effects. However, the applied effective stresses used in both studies differed, and this may be the most important reason for observed differences in permeability changes. This will be discussed further later. Chamberlain used an effective stress of about 14 kPa (2 psi) representing about 0.6 m (2 ft) of overburden, a reasonable stress for cover material. The applied effective stress (referred to as chamber pressure, although it is actually the difference between chamber pressure and back pressure in the triaxial apparatus) used in this study for the testing of the Niagara and Brown clays was 69 kPa (10 psi), representing about 3 m (10 ft) of overburden material, a rather large effective stress for landfill cover soil.

It is well known that permeability is dependent on void ratio or effective consolidation stress. The relation between permeability and void ratio, or between permeability and effective stress, is generally linear when presented on a semi-logarithmic plot (*3*,*9*).

Figure 4 shows the results of permeability tests performed on the Niagara clay using varied effective stresses. Both the frozen and nonfrozen soil exhibit a linear relationship between chamber pressure and permeability, as expected. As the chamber pressure increases the permeability decreases.

These results are consistent with the void ratio–permeability plots of soils depicted by Lambe and Whitman (*3*) discussed previously.

The frozen soil exhibits a bit more scatter than the unfrozen soil. However, this appears to be due to normal test deviation. The conclusions are not altered whether one fits a straight line to the test results, a smooth curve through the test points, or a series of straight lines connecting the test points (Figure 4).

CONCLUSIONS

Clays molded at dry of optimum water contents generally exhibit a large amount of cracks and clods compared with samples molded at optimum or wet of optimum water contents. Thus, one may wish to conclude that dry of optimum clays will exhibit the largest permeability changes due to freezing and thawing, as observed with the Niagara clay (Figure 2). One may also conclude that since dry of optimum clays contain less water than clays at optimum moisture content, and are less saturated, they should show a lower increase in permeability due to freezing and thawing. However, with the limited amount of data available at this time, any such generalizations are premature. Further research to quantify the magnitude of the change in permeability due to freezing and thawing with respect to molding water content appears warranted.

As already noted, Chamberlain et al. (*6*) observed about two orders of magnitude change in permeability for the clays tested, using about 14 kPa (2 psi) effective vertical stress. In this research, about one order of magnitude increase in permeability was observed, using an effective stress (chamber pressure) of 69 kPa (10 psi). If the straight lines for both the frozen and unfrozen Niagara clay (Figure 4) are extended back to 14 kPa (2 psi), a permeability change of almost two orders of magnitude is indicated. These results are consistent with the results of Chamberlain et al. (*6*). It is clear that the effective stress must be considered when discussing absolute

values of permeability as well as changes in permeability due to freeze/thaw effects. This can have important implications when dealing with landfill cover and liner design.

An effective stress of 14 kPa (2 psi) is representative of about 0.6 m (2 ft) of soil. A minimum 2-ft barrier protection layer is often required over the clay cover layer for municipal landfills (*10*). Also, regulation and guidance documents usually stipulate that the impermeable barrier layer must not exceed a maximum permeability of 1×10^{-7} cm/sec for covers and liners (*2,10*). On the basis of the results shown in Figure 4, the permeability of the Niagara clay soil cover could become unacceptable within the first winter season. The choice of a winter season is based on the Northeast region, where well over 10 freeze/thaw cycles can typically be experienced (*11*).

It appears that low-permeability clay barriers used for landfill covers must be protected from deleterious freezing and thawing effects to maintain the integrity of the cover. Similar concerns exist for landfill liners that are subjected to freezing conditions during construction and initial waste placement. Before waste placement, overburden pressures can vary because of landfill liner design. Standard design practices usually place a minimum of 24 in. of material over the low-permeability soil (i.e., clay) layer for single and double composite liner systems (*1*). As mentioned previously, this overburden material represents an effective stress of approximately 2 psi and a permeability increase of about two orders of magnitude when subjected to at least 10 freeze/thaw cycles.

In contrast to landfill covers, liners undergo increased overburden pressures due to waste placement and eventually cover installation. On the basis of the results shown in Figure 4, one might say that a healing process takes place with respect to permeability as the effective stress increases. With the introduction of waste materials the clay liner will regain a portion of its lost permeability (i.e., the permeability decreases). For the Niagara clay shown in Figure 4, a chamber pressure of approximately 21 psi would be required to restore the clay liner to an acceptable permeability of 1×10^{-7} cm/sec after it has been subjected to a winter season (or more than about 10 freeze/thaw cycles). This pressure is equivalent to about 21 ft of soil material or 60 ft of waste. The calculation for depth of waste is based on a waste density of 50 lb/cf of well-compacted residential landfilled waste (*12*, chapter 4). In highly populated areas this depth of waste can easily be reached within 1 year. Thus, on the basis of this example, the effects on the liner due to freeze/thaw conditions could be eliminated within the first year of landfill operation.

REFERENCES

1. U.S. Environmental Protection Agency. *Advanced Landfill Design, Construction and Closure Seminar* (2nd ed.). State University of New York at Albany, Albany, Aug. 1990.
2. *Geosynthetic Design Guidance for Hazardous Waste Landfill Cells and Surface Impoundments*. EPA/600/2-871097. U.S. Environmental Protection Agency, 1987.
3. W. T. Lambe and R. V. Whitman. *Soil Mechanics*. John Wiley and Sons, Inc., New York, 1969.
4. T. F. Zimmie, C. M. LaPlante, and D. L. Bronson. The Effects of Freezing and Thawing on Landfill Covers and Liners. *Proc., Third International Symposium on Cold Regions Heat Transfer*, Fairbanks, Alaska, 1991, pp. 363–371.
5. C. M. LaPlante and M. B. Thomas. *The Effect of Freeze/Thaw Cycles on the Permeability of Niagara Clay*. Master of Engineering thesis. Rensselaer Polytechnic Institute, Troy, N.Y., 1989.
6. E. Chamberlain, I. Iskandar, and S. E. Hunsicker. Effects of Freeze/Thaw Cycles on the Permeability and Macrostructure of Soils. Frozen Soil International Symposium, Spokane, Wash., March 1990.
7. T. W. Lambe. Soil Stabilization. In *Foundation Engineering* (G. A. Leonards, ed.), McGraw Hill, New York, 1962, pp. 351–437.
8. J. K. Mitchell, D. R. Hooper, and R. G. Campanella. Permeability of Compacted Clay. *Journal of the Soil Mechanics and Foundation Engineering Division*, ASCE, Vol. 91, No. SM4, July 1965, pp. 41–65.
9. T. F. Zimmie, J. S. Doynow, and J. T. Wardell. Permeability Testing of Soils for Hazardous Waste Disposal Sites. *Proc., Tenth International Conference on Soil Mechanics and Foundation Engineering*, Stockholm, Sweden, June 1981.
10. *6 NYCRR Part 360 Solid Waste Management Facilities*. New York State Department of Environmental Conservation, Albany, 1988.
11. G. F. Sowers. *Introductory Soil Mechanics and Foundations; Geotechnical Engineering* (fourth ed.). MacMillan Publishing Co., Inc., New York, 1979, pp. 137–143.
12. G. Tchobanoglous, H. Theisen, and R. Eliassen. *Solid Wastes: Engineering Principles and Management Issues*. McGraw-Hill, Inc., New York, 1977.

Publication of this paper sponsored by Committee on Physicochemical Phenomena in Soils.