FREEZE/THAW EFFECTS ON THE HYDRAULIC CONDUCTIVITY OF COMPACTED CLAYS

Specimens of clay were molded at water contents dry of optimum, optimum, and wet of optimum and subjected to freeze thaw cycles. The hydraulic conductivity of the specimens was then measured with respect to the number of freeze/thaw cycles the clay had experienced. Permeability testing was also performed at various pressures to determine the relationship between permeability and effective stress.

Test data shows that permeability changes due to the effects of freezing and thawing are greater at low effective stresses. This can have important implications when designing clay landfill covers and liners. Results indicate that the permeability of clay can increase by two orders of magnitude as a result of freezing and thawing. If clay were used in a landfill cap design, test results indicate that it is highly important to protect the clay from freeze/thaw cycles.

Clay molded at dry of optimum appears to exhibit the largest changes in permeability due to freeze/thaw cycles. This can be attributed to the cracks and clods of clay that are present in specimens when molded dry of optimum. Based on these results, it is evident that the moisture content of clay is very important when constructing a clay hydraulic barrier system. With changes in weather conditions on a project, moisture content of clay can be difficult if not impossible to control.

Data also shows that the permeability of a clay layer can increase by two orders of magnitude as a result of freezing and thawing when subjected to an effective stress of 2 psi (14kPa). This is consistent to the overburden stress a clay layer would experience when used in a cap system with 2 feet of soil.

TR-202
Revised 1/01

TR-202

FREEZE/THAW EFFECTS ON THE HYDRAULIC CONDUCTIVITY OF COMPACTED CLAYS

by

Christine M. LaPlante[1]

and

Thomas F. Zimmie[2]

submitted for the Symposium on

"Physical and Chemical Aspects of Soil Freezing"

at the

Seventy–first Annual Meeting of the

Transportation Research Board
Washington, D.C.

January 1992

[1]Graduate Student and [2]Associate Professor, Civil and Environmental Engineering Dept., Rensselaer Polytechnic Institute, Troy, NY 12180, (518)276–6939, FAX (518)276–4833.

ABSTRACT

A series of clay samples molded at differing water contents were 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 changes in permeability of about one order of magnitude (a factor of ten) increase in permeability from 10^{-8} cm/sec to 10^{-7} cm/sec. The maximum permeability changes occurred in less than ten 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 a permeability change of about two orders of magnitude can be expected due to 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 prior to 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 is placed on the clay liner, the permeability can decrease to an acceptable value.

INTRODUCTION:

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 to minimize or eliminate 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. Environmental Protection Agency (EPA) Advanced Landfill Design, Construction and Closure Publication (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.

TEST PROGRAM:

Two distinctly different clay soil types were subjected to a varied number of freeze/thaw cycles. Table 1 lists 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 employed. Although a detailed comparison of 1D versus 3D freezing is beyond the scope of this paper, the results appear to indicate that for all practical purposes the end results (change 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 utilizing 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%), optimum (16% to 17%), and wet of optimum (18.5% to 19.5%). Figure 1 illustrates the Proctor results for the Niagara clay. Specimens were molded at dry densities representing 95% compaction and moisture contents of approximately 3% wet or dry of optimum. Also illustrated in the figure is the natural (before freezing) permeability with 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 utilized for specimen preparation were 30.5% to 31.5% for the optimum specimens and 34.5% to 35.5% 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 in Zimmie, LaPlante and Bronson (4); and a more extensive discussion of equipment details and experimental procedures can be found in LaPlante and Thomas (5).

Further permeability tests were performed on the Niagara clay to evaluate the effect of effective stress on the permeability, and also as a result, the effect of effective stress onthe 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 nineteen freeze/thaw cycles were tested. The nineteen freeze/thaw cycles ensured that the maximum permeability change due to freeze/thaw conditions was reached. Based on this research as well as that of Chamberlain, et al.(6) it has been observed that the maximum permeability changes due to freeze/thaw effects occur within the first ten cycles.

RESULTS/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 to two orders of magnitude (4)(6). As shown on Figures 2 and 3 the two clays depicted in this study exhibit between one and one and one–half 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 also 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 (1 1/2 orders of magnitude). The optimum and wet of optimum samples exhibited approximately one (1) 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 samples. 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 one–dimensional consolidometer permeameters in their research, which did not allow for the application of backpressure. Thus, the larger apparent changes in permeability may be due to saturation effects. However, the applied effective stresses utilized in both studies differed, and this may be the most important reason for observed differences in permeability changes. This will be discussed further in the conclusion section. Chamberlain utilized an effective stress of about 14kPa (2 psi) representing about 0.6 meters (2 ft) of overburden, a reasonable stress for cover material. The applied effective stress (which shall be referred to as chamber pressure, although it is actually the difference between chamber pressure and back pressure in the triaxial apparatus) utilized in this study for the testing of the Niagara and Brown clays was 69kPa (10 psi) representing about 3 meters (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, generally exhibits a linear relationship when presented on a semi–logarithmic plot (3) (9).

Figure 4 shows the results of permeability tests performed on the Niagara clay utilizing 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 in 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, or a smooth curve through the test points, or a series of straight lines connecting the test points, in Figure 4.

CONCLUSIONS:

Clays molded at dry of optimum water contents generally exhibit a large amount of cracks and clods compared to 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 appear premature. Further research appears warranted to quantify the magnitude of the change in permeability due to freezing and thawing with respect to molding water content.

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 quite consistent with the results found by 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 meters (2 ft) of soil. A minimum two foot 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). Based on 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 ten 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, if the integrity of the cover is to be maintained. Similar concerns exist for landfill liners which are subjected to freezing conditions during construction and initial waste placement. Prior to waste placement, overburden pressures can vary due to landfill liner design. Standard design practices usually place a minimum of twenty–four inches 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 ten (10) freeze/thaw cycles.

In contrast to landfill covers, liners undergo increased overburden pressures due to waste placement, and eventually cover installation. Based on 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 greater than about ten freeze/thaw cycles). This pressure is equivalent to about 21 feet of soil material or 60 feet 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). In highly populated areas this depth of waste can easily be reached within a year. Thus, based on 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 Edition. State University of NY at Albany, Albany, N.Y., August, 1990.

2. U.S. Environmental Protection Agency. Geosynthetic Design Guidance for Hazardous Waste Landfill Cells and Surface Impoundments. EPA/600/2–871097, 1987.

3. W.T. Lambe and R.V. Whitman. Soil Mechanics. John Wiley and Sons, Inc., New York, N.Y., 1969, p. 286.

4. T.F. Zimmie, C.M. LaPlante and D.L. Bronson. The Effects of Freezing and Thawing on Landfill Covers and Liners. Proceedings, Third International Symposium on Cold Regions Heat Transfer, Fairbanks, Alaska, June, 1991, pp. 363–371.

5. C.M. LaPlante and M.B. Thomas. The Effect of Freeze/Thaw Cycles on the Permeability of Niagara Clay. Masters of Engineering Thesis, Rensselaer Polytechnic Institute, Troy, NY, 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, Washington, March, 1990.

7. T.W. Lambe. Soil Stabilization, Chapter 4 of 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. J. 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. Proceedings, Tenth International Conference on Soil Mech. and Foundation Engineering, Stockholm, Sweden, June, 1981.

10. New York State Department of Environmental Conservation. 6 NYCRR Part 360 Solid Waste Management Facilities. New York State Department of Environmental Conservation, Albany, N.Y., December, 1988.

11. G.F Sowers. Introductory Soil Mechanics and Foundations; Geotechnical Engineering. Fourth Edition. 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, chapter 4.

LIST OF TABLES

LIST OF FIGURES

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

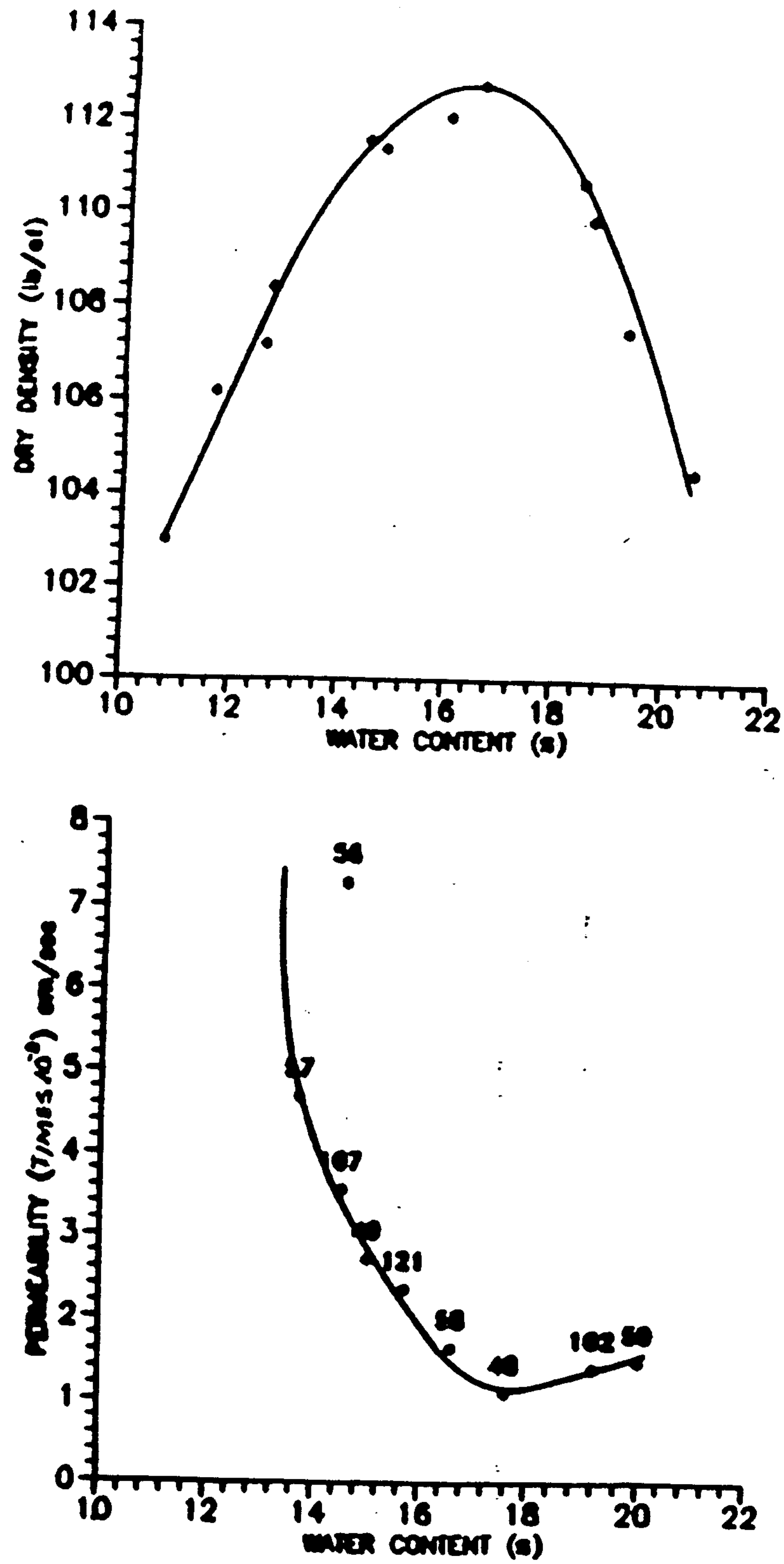

Figure 1 Natural Permeability and Dry Density Versus Water Content.

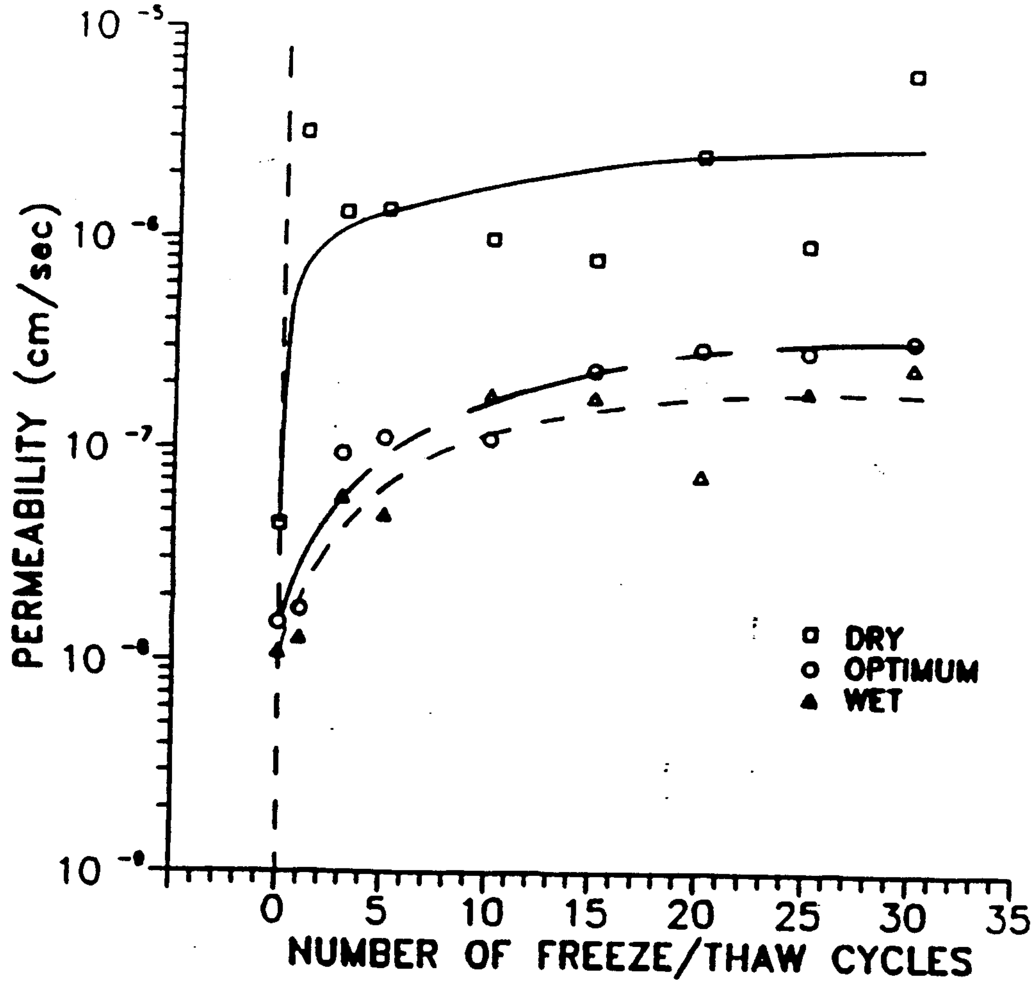

Figure 2 Summary of the 1D Freeze/Thaw Cycle Effects on Niagara Clay.

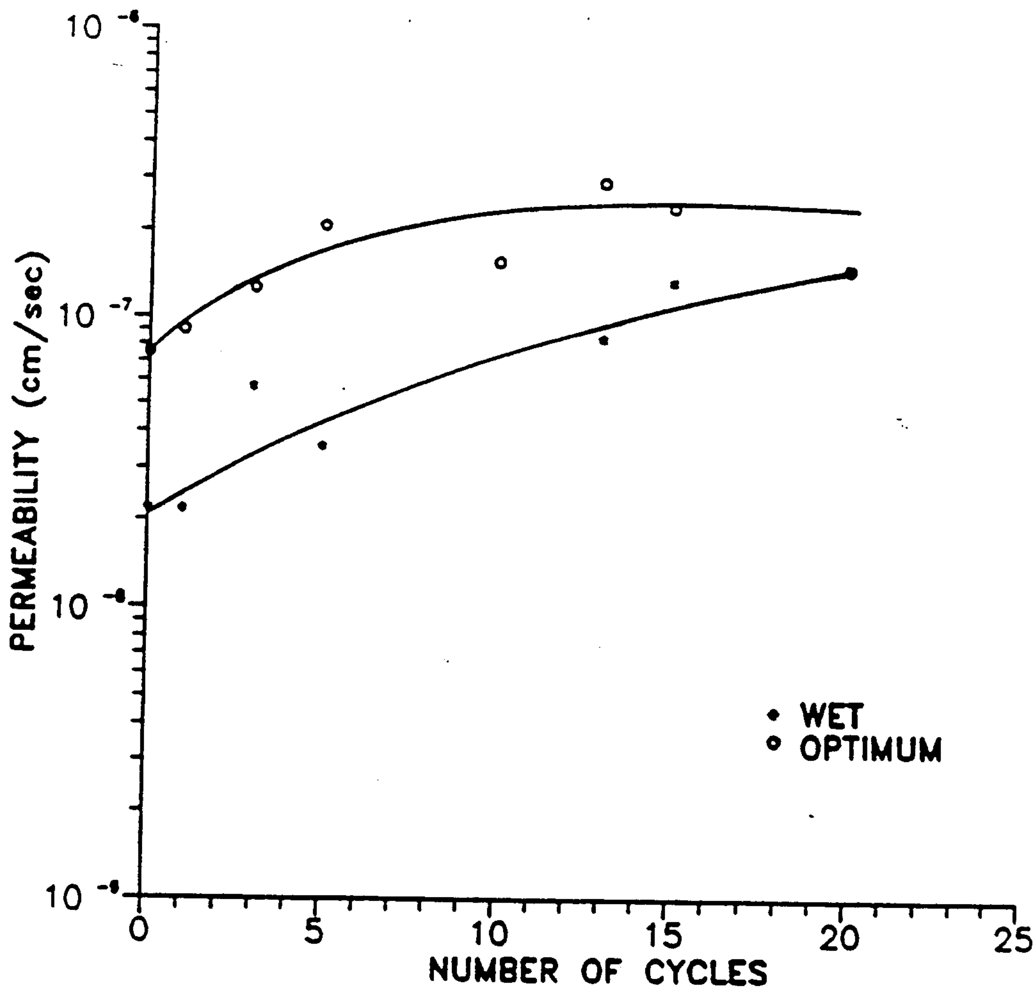

Figure 3 Summary of the 1D Freeze/Thaw Cycle Effects on Brown Clay.

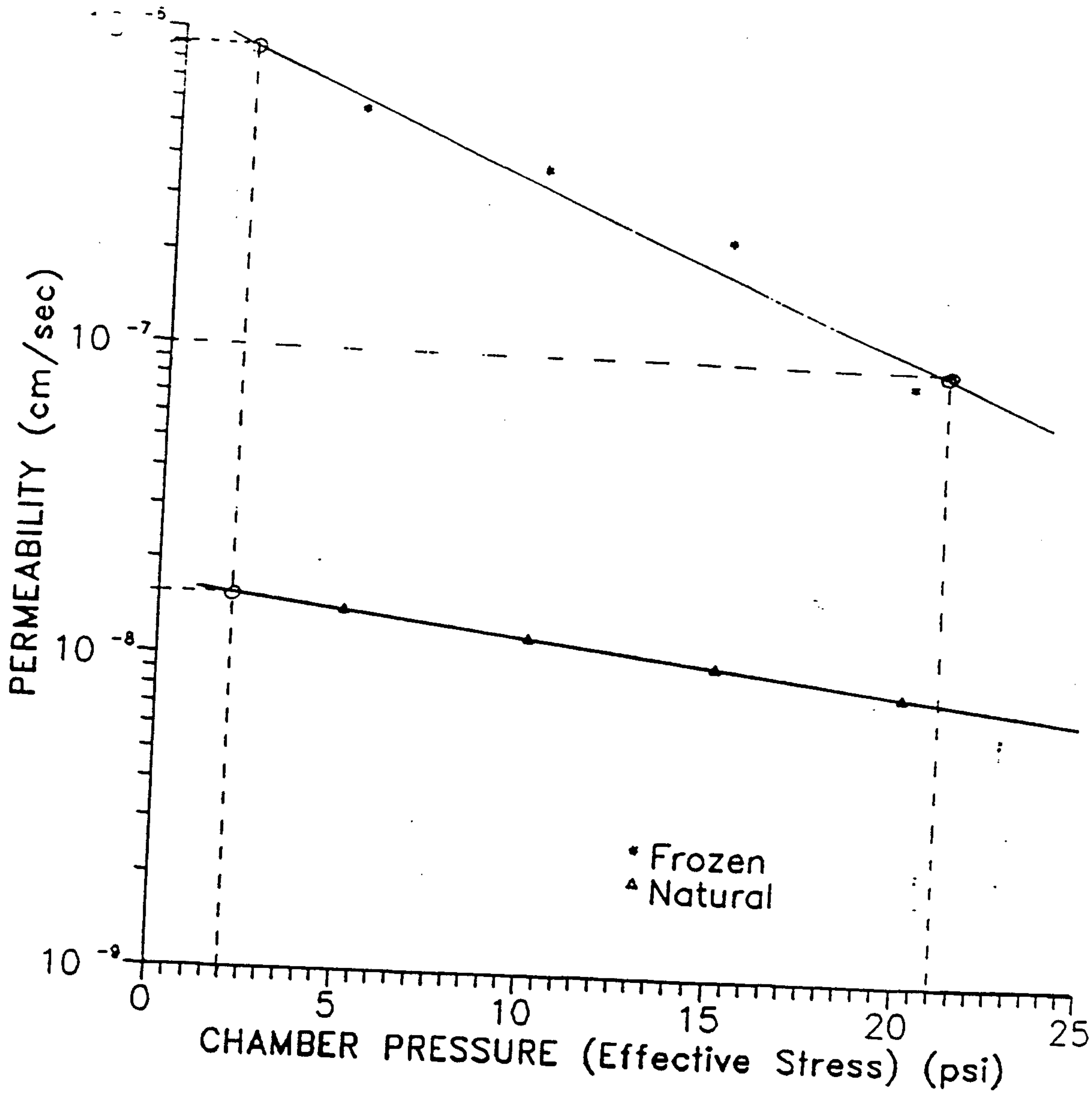

Figure 4 Effect of Freeze/Thaw Cycling on the Permeability of Niagara Clay Molded Wet of Optimum in the Permeability vs. Chamber Pressure Plane.