New Experiments To Simplify Frost Susceptibility Testing of Soils

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Experiments conducted in recent years indicate that frost susceptibility testing of soils can be shortened considerably from the 2 weeks or so previously required. Results of experiments show that useful frost-heaving data can be obtained in a matter of 2 or 3 days by a more rapid freezing technique. Results of experiments whereby soil specimens are exposed to a constantly maintained temperature are presented. Data show that heave rate in laboratory experiments is a variable and not a constant of a soil and is strongly dependent upon the heat extraction rate. The important role of frost susceptibility testing and soil evaluation for highway design is discussed. Comments are provided on suitability of equipment for use in conducting frost-heaving tests.

•THE selection of suitable soils for use in earth construction under conditions where they will be exposed to freezing temperatures is an important function of design. This is especially true and critical in the construction of modern airfields and high-speed highways where any surface roughness due to frost heaving might be detrimental to property and safety. Another very important economic consideration for selection of a suitable material is the prevention of thaw-weakening damage to the costly runway or roadway itself during the spring melting period.

Our present experience with soils permits us to recognize quickly the obviously frost-susceptible soils, such as the silts and clays, strictly by visual means. However, when it comes to the selection of a non-detrimental material for use as subbase and base course from the assortment of borrow materials that may be available, visual means become inadequate.

PRESENT FROST SUSCEPTIBILITY EVALUATION TEST PROCEDURE

It appears that a reliable evaluation of the frost-susceptible characteristics of a soil must come from some kind of a laboratory performance test during freezing. A test has been developed for the U. S. Army Corps of Engineers (5, 8) and has been most useful in the evaluation of soils proposed for use as base course material at many of the major airfield construction projects in the United States and overseas areas. The main control in the tests has been the rate of frost penetration, and the observed effect is the measure of the rate of heaving or ice lens growth.

The test has undeniably proven its effectiveness and is prescribed by the Corps of Engineers (15) whenever any doubt exists about the potential frost susceptibility of a soil proposed for use. The major objection to the test has been the total length of time required for the freezing procedure. Initially (1951), a freezing procedure was adopted requiring that a 6-in. high specimen be frozen slowly at a rate of $\frac{1}{4}$ in. a day in an open system and with the bottom temperature at about 38 F. The 24 days necessary to completely freeze a 6-in. high specimen were subsequently reduced to 12 days or less by increasing the freezing rate to $\frac{1}{2}$ in. per day (5). This reduction in testing time is still inadequate to make the test attractive in our "need-it-today" society.

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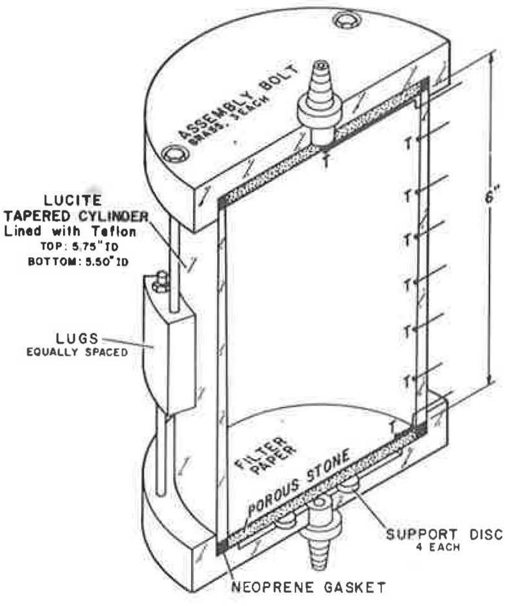


Figure 1. Inside-tapered freezing cell.

Description of Technique and Freezing Cell

The laboratory technique, which has been used for a number of years as a procedure for evaluating the relative frost susceptibility of soils for the U.S. Army Corps of Engineers, is patterned after techniques used earlier by Taber (12), Beskow (2), Casagrande (4), Winn and Rutledge (16) and others, except that larger (6-in. diameter) specimens were used by the Corps. The large diameter size was essential for evaluation tests on base course type soils used in airfield pavement construction. The specimen containers initially adopted for these tests were waxed cardboard cylinders and later straight-walled polyacrylate (Lucite) tubes because of problems encountered with the cardboard. Subsequently, a completely new Lucite soil cell with a number of improvements was developed (Fig. 1). This new cell contains a slight vertical taper on the inside (¼-in. greater diameter at top) to permit the heaved portion to enter into a wider area and thus reduce wall-friction or adfreeze resistance to heaving.

Even though empirical, the results obtained from freezing tests have been useful in several ways:

1. For selection of the least frost-susceptible material for construction use when several choices are available;
2. For evaluation of frost potential of in situ soil or soil previously used for construction;
3. For evaluation of effectiveness of soil additives and treatments in studies of frost inhibitors or modifiers; and
4. For conducting laboratory studies on soils to determine effect of various soil parameters on their frost behavior.

Thus, the test is undoubtedly only a first step toward an ultimate rational test procedure that will evolve from the research now in progress at USA CRREL and other laboratories, since the basic controlling factors responsible for ice segregation have not been incontrovertibly established.

APPROACHES TOWARD FREEZING TEST SIMPLIFICATION

For a number of years considerable thought has been given to various ways and means to speed up the frost susceptibility evaluation test of soils by a simplified freezing procedure, which would produce visual results easily comprehended and interpreted in terms of heaving rate and ice segration.

Freezing at Controlled Penetration Rates

This procedure as initially adopted requires a daily manual adjustment of a thermostat to reduce the air temperature above the specimen in decrements to obtain the desired rate of freezing. This technique was not always satisfactory and large variations in the freezing rate occurred. It was then observed that in most cases a faster rate of freezing resulted in a slightly faster rate of heaving, thus suggesting a possible speedup in freezing time. Experiments were subsequently performed on several typical soils with still more rapid freezing rates (6).

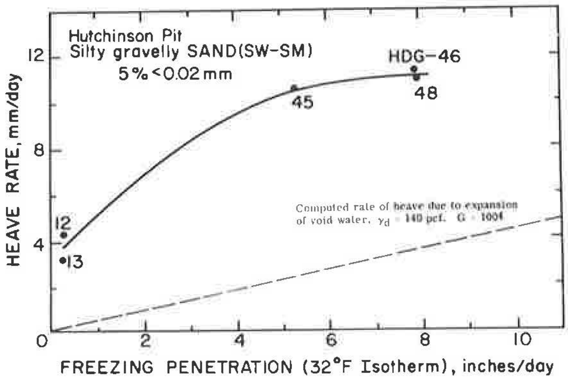


Figure 2. Effect of freezing rate on heave (ice segregation) rate. Tests were performed in freezing cabinet with manually controlled decreasing temperature schedule and specimens in inside-tapered containers.

The effect of faster freeze penetration rate on the heave rate for a typical gravelly sand is shown in Figure 2. From the curve shown it appears that there may be a maximum rate corresponding to a critical freezing rate, beyond which the curve may be expected to drop off until it intersects the theoretical heave-rate line computed for expansion of void water present in a saturated soil.

The results of rapid-freezing experiments indicate that freezing rates might possibly be as high as 6 in. per day in some soils and still produce useful freezing-rate results for frost evaluation purposes. At a freezing rate of 6 in. per day, useful heave-rate data would be available in 24 hours for a 6-in. specimen. However, such rapid rates of freezing are not recommended without further knowledge of the heave-rate vs freezing-rate behavior.

Major Problem Encountered With Freezing Cell—The major problem in the freezing tests as conducted is believed due to the development of sidewall resistance to heaving either by adfreeze of specimen to the wall of the container or by frictional resistance of the particle contact or a combination of both. Efforts have been made to reduce or eliminate this frictional (or adfreeze) resistance, which has the effect of an added load on the specimen. Special silicone grease and lapped strips of acetate paper were introduced and finally a tapered cylinder was evolved with a 3-mil thick, one-piece, adhesive-backed Teflon liner on the inside. Data collected on the force required to eject specimens from the cylinders after freezing indicated that the sidewall resistance problem was considerably reduced by use of the tapered cylinder with silicone grease and lapped acetate strips, but the resistance was not always eliminated.

Other modifications to the tapered freezing cell consisted of improvements to insure unrestricted water supply to the base of the specimen. This was done by using coarser porous stones and supporting them on small disc supports to provide a comparatively large reservoir beneath, so that one large air bubble would not be able to block the water supply as was previously possible.

The presence of sidewall resistance was suspected, particularly on the coarser type sandy and gravelly soils, because the heave vs time plots frequently exhibited a flattening out with time; for example, specimen HDG-63 in Figure 9. However, this flattening out was not usually observed in the higher heaving finer grained soils such as silts. In computing heave rates for tests where heave curves had started to flatten out, the flattened portions were disregarded and useful test results were obtained from the earlier portion of the curve.

Multi-Ring Freezing Cell—The presence of some restraining force to heaving was verified recently when, during a cooperative effort between the University of New Hampshire, the New Hampshire Department of Public Works and Highways and USA CRREL, UNH reverted to use of specimen containers made of 1-in. wide ring segments, such as used by Taber (12), Beskow (2), LaRochelle (7) and others to compare results with those obtained using the solid-wall tapered cylinders. The UNH investigators (3) found that, for the coarse-grained base course type soils they used, higher heave rates were measured in the ring type containers for the same test conditions than in solid-wall tapered containers.

Similar tests performed under the author's supervision at USA CRREL also gave generally similar results on coarse-grained soils. It appears that any freezing test

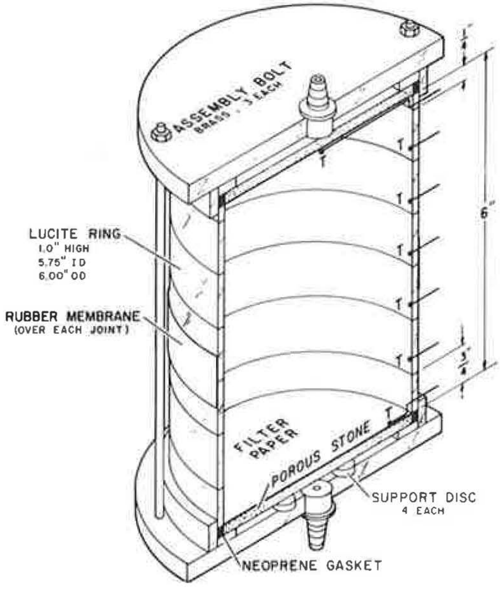


Figure 3. Multi-ring freezing cell.

results based on ice segregation rates in rigid-walled containers may give lower values, influenced by either adfreeze or frictional restraint or both. For a more reliable test, means must be found to eliminate the friction problem. The use of multiple-ring containers is a definite improvement, but it has certain drawbacks that for research purposes may be difficult to overcome, such as the achievement of complete or even uniform saturation prior to test; the difficulty of ring removal to permit splitting of the specimen for photographing and determination of water content distribution; and the difficulty in performing other supplementary tests, such as determining the coefficient of permeability during the saturation procedure. However, the use of the rings offers a simple, practical, relatively low-friction specimen container for frost susceptibility tests on gravelly type soils. A sketch of a multi-ring cell made at USA CRREL from $^{1}/_{8}$-in. thick acrylic tubes and flat plates is shown in Figure 3. Other less expensive materials could be used. The use of a top cap and outside rubber sleeve permits application of some vacuum to the system if desired for better control of degree of saturation in some soils. The use of the caps and rubber sleeve facilitates the handling of the specimen. The top cap is removed during freezing, while the bottom one remains as a water reservoir.

Freezing at Constant Surface Temperature

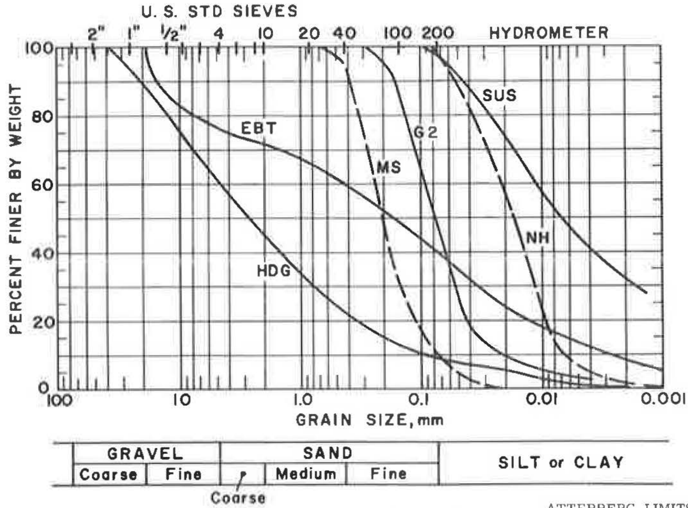
To overcome some of the objections raised against the controlled penetration rate type of freezing test and some of the nonuniformities of control associated with it, it has been suggested that perhaps all soil specimens should be exposed to some freezing temperature maintained at a constant level, and the frost heaving behavior of each soil might then be a useful indicator of its relative frost susceptibility. An argument in favor of freezing under a constant temperature is that the imposed boundary conditions in such a procedure would make the test results more readily amenable to mathematical analysis. Such an analysis is now being conducted at USA CRREL by Takagi (13). The application of a constant-level freezing temperature would certainly simplify the control problem and would insure a precise duplication of test conditions for each and every soil.

Experimentation with this procedure indicated that useful frost-heave data for frost susceptibility evaluation might be obtained in a few days with a much simpler, easily controllable, and reproducible freezing procedure.

A more complete series of freezing experiments was subsequently made by using the constant temperature method on a number of soils at different temperatures. Some preliminary experimentation was also made along these lines using thermoelectric cooling, i.e., a Peltier battery. Both methods will be discussed in following sections.

STUDY OF FROST HEAVING OF SOILS UNDER CONSTANT TEMPERATURE FREEZING

As a result of the encouraging results from preliminary freezing tests using a constant freezing temperature, a small program of freezing tests was set up to explore several factors:



MATERIAL	SYMBOL	UNIFIED SOIL CLASSIFICATION (14)	ATTERBERG LIMITS LL	PL	PI
Hutchinson Pit gravelly sand	HDG	SW-SM	Nonplastic		
-3/4 in. East Boston till	EBT	SC	23	16	7
New Hampshire silt	NH	ML	Nonplastic		
Suffield clay	SUS	CL	35	20	15
Grantham sand No. 2	G2	SP-SM	Nonplastic		
Manchester fine sand	MS	SP	Nonplastic		

Figure 4. Soils used in studies.

1. Effect of type of specimen container,
2. Effect of different constant freezing temperatures, and
3. Effect on several different soil types.

Because of the problems of frictional or adfreeze restraint indicated to be present in solid-wall specimen containers, tests were set up to compare results from both the multi-ring container and the solid-wall, Telfon-lined tapered containers. A few tests were also made to compare results of ring width in the multi-ring containers. Ring widths used were 1/2 in. and 1 in.

The scheduled constant temperatures planned for this series were 25, 20, 15 and 10 F. Time did not permit all of these temperature conditions to be applied to all soils, but sufficient data were obtained to show some interesting results.

Soils Selected for Tests

Six soils were selected for the comparison tests between the Teflon-lined tapered cylinders and the multi-ring cylinders. The six soils were (a) Manchester fine sand; (b) Grantham silty sand; (c) Hutchinson gravelly sand; (d) East Boston glacial till; (e) New Hampshire (Goff's Falls) silt; and (f) Suffield clay. The gradations and other physical properties are shown in Figure 4.

Soil Preparation Procedure

For the tapered specimens the soils were molded in special tapered steel molds and placed into the polyacrylate cylinders. For the multi-ring specimens the compaction was performed in the rings, which were first placed and firmly held in a standard CBR cylinder. The multi-ring containers consisted of either 1-in. or 1/2-in. wide polyacrylic rings, except for the uppermost ring which was 1/4 in. wide and the bottommost ring which was 3/4 in. wide. The 1/4-in. wide upper ring was designed so that contact between the ring below would be quickly broken by the frost-heave forces occurring near the top and thus prevent heat conduction and possible adfreeze problems at some point below.

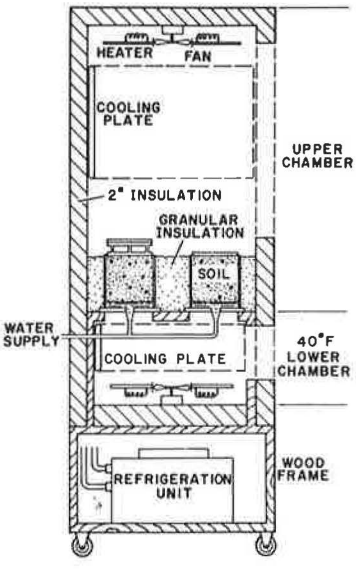


Figure 5. Soil freezing cabinet (2 by 2 by 5 ft) with self-contained refrigeration.

It is believed that high heat conduction through the thicker walled tapered cylinders was a contributing factor to the sidewall resistance observed.

After compaction of the soil in the rings and removal of the CBR cylinder, the ring specimen was placed in its base and wrapped carefully with dental dam rubber to seal the joints prior to saturation. The highly absorptive soils such as New Hampshire silt were allowed to saturate solely by capillarity. For this material, experiments previously performed at ACFEL[1] showed that the initial degree of saturation at preparation did not affect the freezing heave-rate results because fine-grained soils can absorb water overnight by capillarity while tempering. For the more impervious and higher density soils, wetting was promulgated by gradually increasing the hydraulic head from 0 to about 2 ft to induce water to enter the specimen. Small heads were used to minimize the possibility of internal rearrangement of fines as might occur by application of vacuum and the establishment of a resulting head of 33 ft of water pressure. During freezing all specimens were loaded with a lead weight to give an overburden pressure of 1/2 lb/sq in.

Freezing Procedure

After saturation specimens were placed in groups of four in a special freezing cabinet similar to that shown in Figure 5. The base of the specimen was carefully attached to a constant level, de-aired water supply, as shown, taking great care to prevent air bubbles from entering the system. A 1/4-in. copper plate with the same surface area as the specimen was placed on the specimen surface to prevent drying and to maintain good thermal contact. Four raised lugs on this plate support the additional weights used to place an overburden load of 1/2 psi. The space between specimens was filled with a dry granular insulation. The specimen was allowed to temper overnight at a cabinet temperature of about 40 F. The following morning the cabinet temperature was lowered to the desired constant temperature. Heaving was measured by dial gages mounted over each specimen.

In these tests two multi-ring specimens were paired with two tapered specimens for a given run. A number of duplicate specimens were prepared to observe replicability. The duplicate pairs were never tested together but always independently under the same test conditions.

Results of Tests

Typical plots of heave vs time for two of the soils at different temperatures are shown in Figures 6 through 9. In most of these tests the slope of the heave vs time plot was quite uniformly linear, except for some of the gravelly sand specimens, with the multi-ring specimens showing a steeper slope, i.e., a larger rate of heave. The results also indicated that there was no consistent difference in favor of the 1/2-in. rings, and subsequently they were eliminated in the remaining tests.

Figure 10 shows the maximum heave rates vs the applied surface air temperatures for four of the soils where more than one constant temperature was applied. Here, too, it can be observed that the specimens in tapered cylinders exhibited lesser heave rates under the same temperature conditions than the multi-ring specimens. It should be

[1]Arctic Construction and Frost Effects Laboratory, New England Division, U.S. Army Corps of Engineers, Waltham, Massachusetts. Merged with the Snow, Ice and Permafrost Research Establishment, C.E., in 1961 to form USA CRREL.

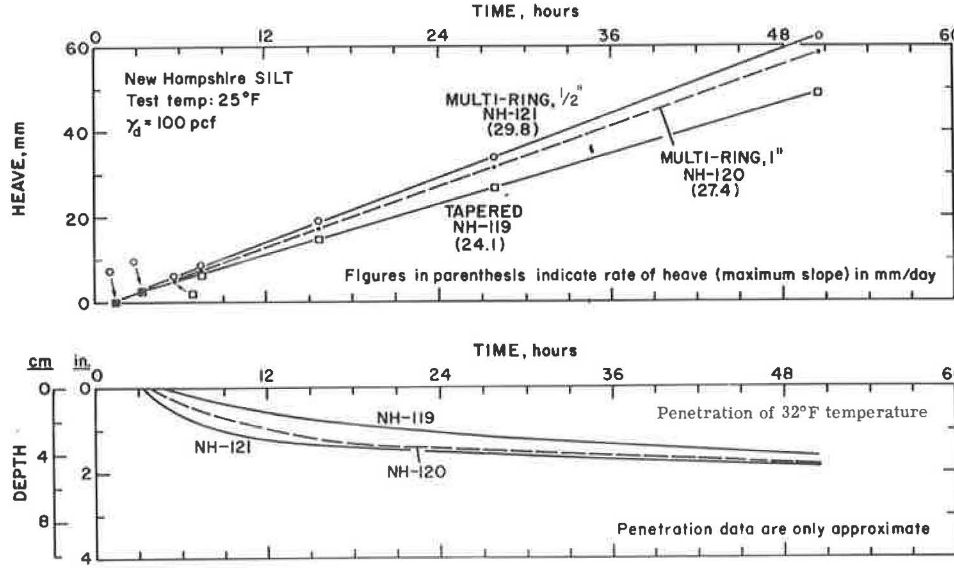


Figure 6. Heave and frost penetration data for constant temperature tests vs container type.

noted that when duplicate specimens were used, the replicate results obtained were in good agreement for both the tapered containers and the multi-ring containers.

A summary plot of measured heave rates vs the applied surface temperature for all soils and specimens used in this series in multi-ring containers is shown in Figure 11. The data thus obtained from this series are sufficiently well defined to permit a curve to be drawn relating the rate of heaving to the constant temperatures being supplied to the surface.

Figure 12 shows a summary of heave vs time for New Hampshire silt for each of the four temperatures used. The similar freezing depths as shown in the lower figure for

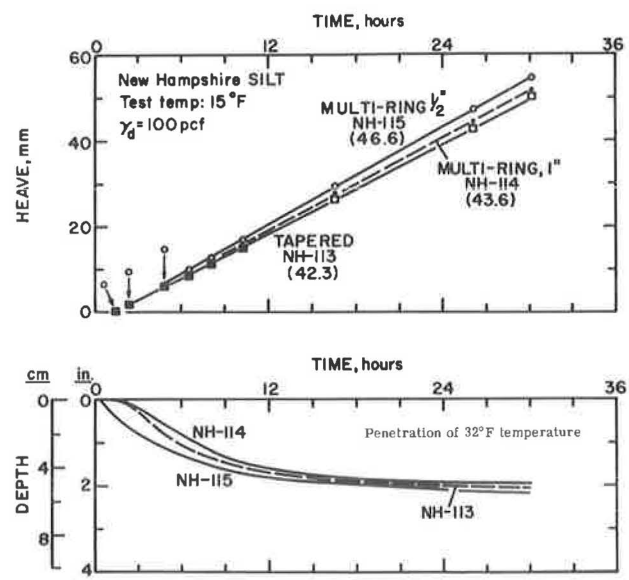


Figure 7. Heave and frost penetration data for constant temperature tests vs container type.

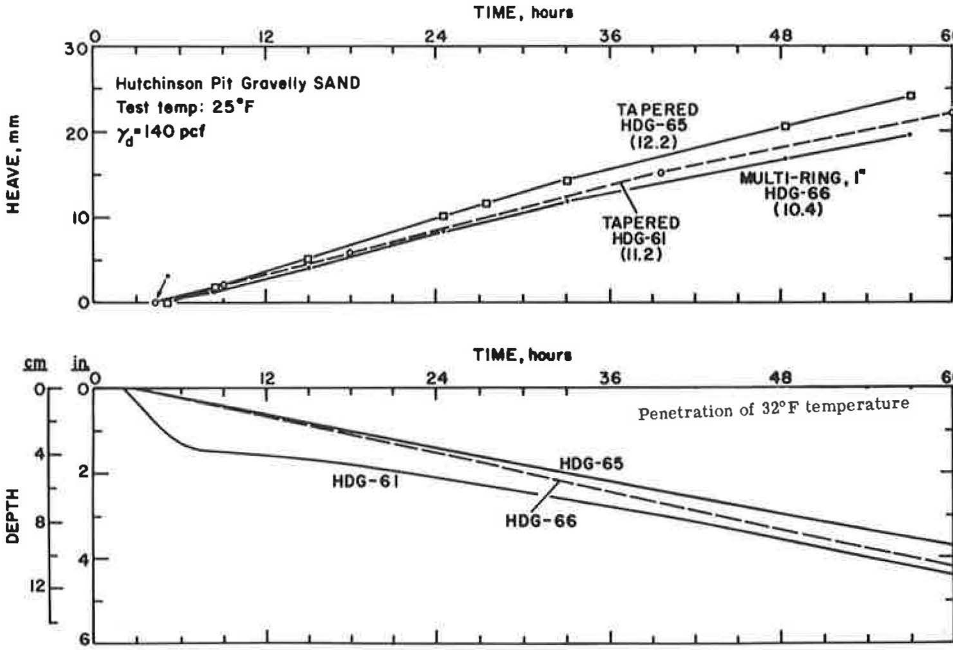


Figure 8. Heave and frost penetration data for constant temperature tests vs container type.

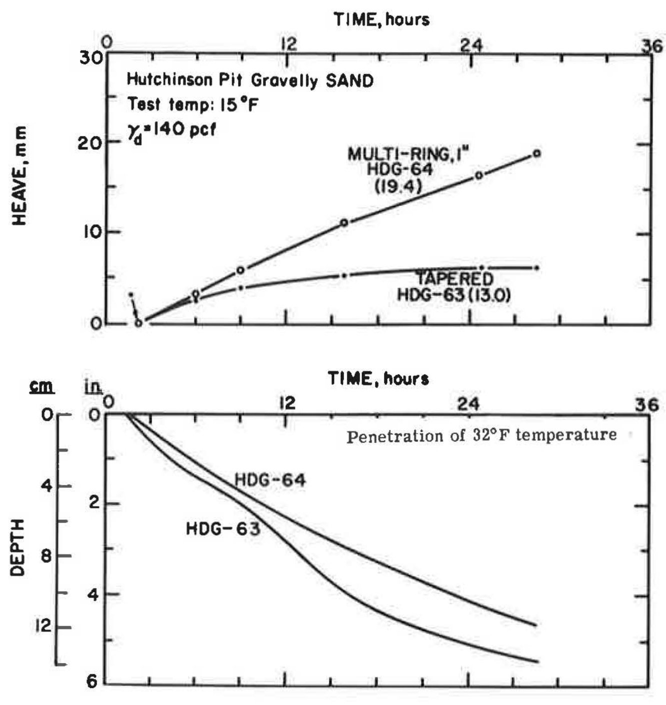


Figure 9. Heave and frost penetration data for constant temperature tests vs container type.

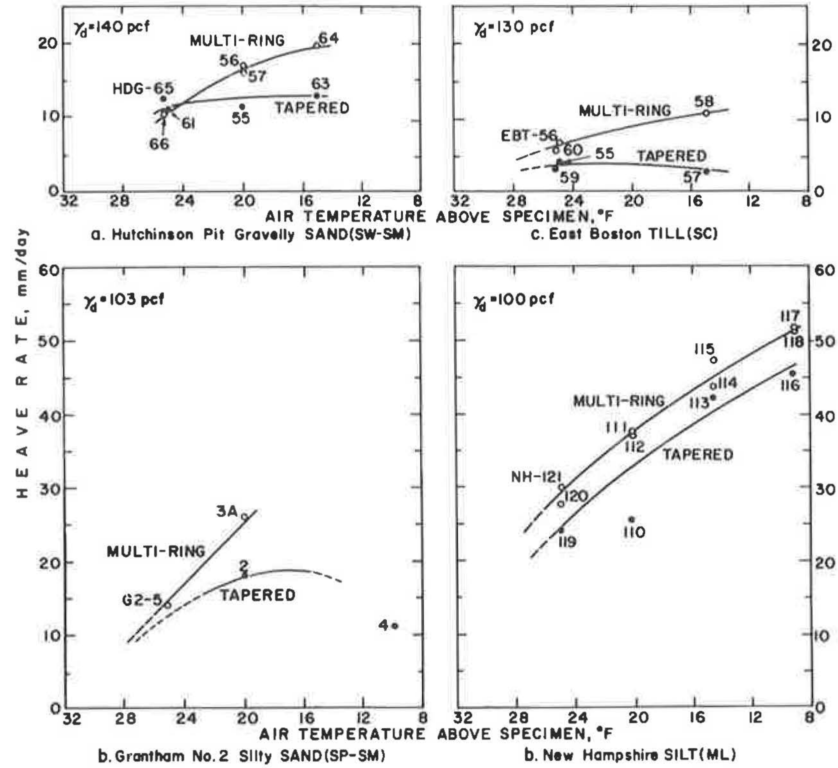


Figure 10. Rate of heave vs cabinet air temperature.

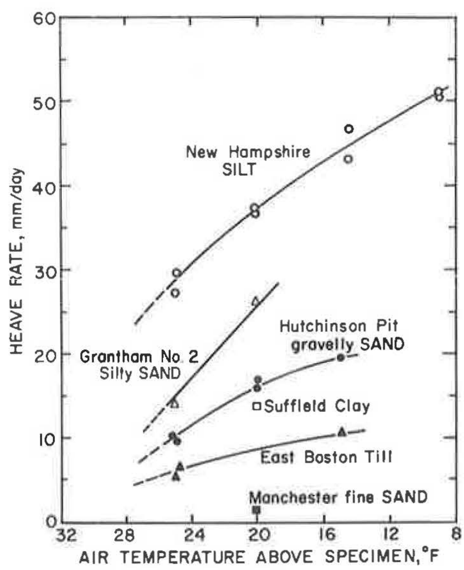


Figure 11. Summary of multi-ring freezing tests.

these specimens are attributed to the increased heat energy (latent and sensible heat) supplied at the freezing front by the increased water flow rates.

The data presented in this paper demonstrate that the heave rate is dependent on or controlled by the rate of heat extraction (up to some unknown critical rate dependent upon the availability of water and the capability of the soil to conduct the water). Penner (11) observed a similar relationship between heat extraction rate and heave rate for several soils. Ultimately the ice segregation rate must be dependent upon the geometric characteristics of the combined soil particles insofar as they provide the necessary medium in which freezing water occurs and heave forces are generated within the postulated moisture films (9, 10).

These tests demonstrate that useful data for evaluation of the relative frost susceptibility of soils can be obtained in a much shorter period of time (two days or less freezing time) by application of a constant

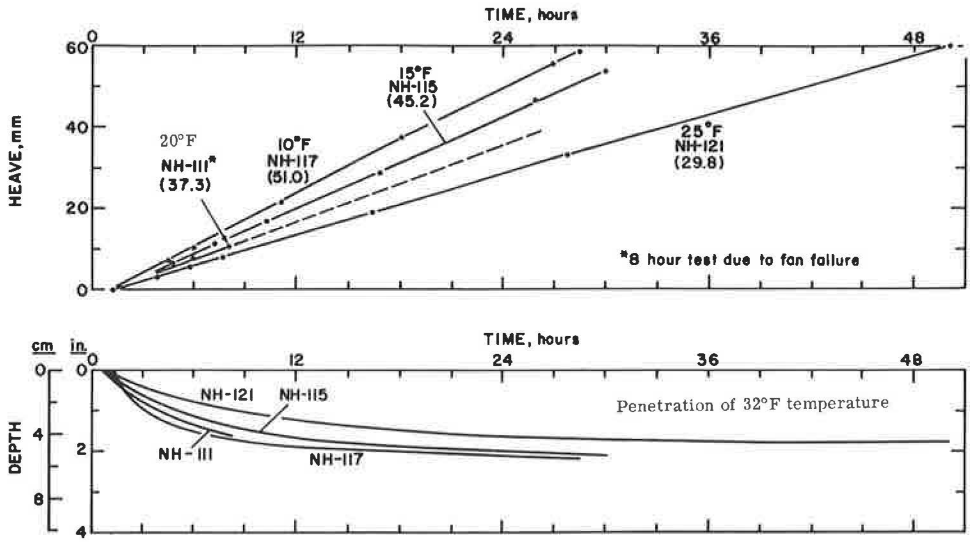


Figure 12. Relationship of heave rate and test temperatures for N.H. silt in multi-ring containers.

subfreezing temperature to properly prepared representative specimens in friction-free containers.

THERMOELECTRIC FREEZING—PELTIER BATTERY

One of the approaches made at USA CRREL for frost susceptibility freezing test procedure simplification has been in the area of equipment simplification as well as in reduction of testing time. When the Peltier battery was introduced in a suitable form and size for use in a soils laboratory, a number of exploratory experiments were initiated to determine the battery's capability for freezing of soils. Results of a brief study performed in early 1964 indicated that these exhibit considerable potential, which needs further development. Studies have been continued intermittently since then in this area as time permits to develop a bench-type automatic system complete with specimen container, temperature and heave sensors together with miniature recorders. A number of different bench setups were tried and discarded.

The application of the Peltier battery to freezing experiments has some very interesting possibilities and should be utilized to full advantage for whatever purposes it is best adapted. It is not considered that it will economically displace all of the functions that a simply constructed freezing cabinet can perform, such as applying the same temperature environment for a group (four 6-in. diameter specimens) or tray of specimens, or for freezing very large specimens, and for many other special conditions for which the freezing cabinets will most likely be most suitable.

The Peltier battery's greatest potential is due to its portability, mechanical simplicity and constant rate of heat removal and, therefore, promises to be an important tool in conducting small-scale bench-type freezing experiments.

Some of the disadvantages of a Peltier battery, in the author's experience, may be of interest to some potential users:

1. The high cost (about $500) of a single unit of battery and constant power supply for use on one specimen at a time.

2. The possibility of uneven temperature distribution across the face plate due to quality control problems in the manufacturing process, thus causing uneven heaving and heave measurement problems.

3. It requires a temperature controlled room (not always available).

4. It has limited capability. Observations at USA CRREL revealed that it was impossible to freeze a highly frost-susceptible silt more than a fraction of an inch with a

90-watt capacity cell at ambient temperature in a controlled temperature environment (air conditioned room) even though the specimen was completely insulated. It was necessary to place the freezing unit with the soil specimen into a 40 F cold room before substantial freezing of the silt could be accomplished.

5. Indeterminate durability or life expectancy. Experience at USA CRREL has shown that some thermoelectric cooling units have burned out and have had to be replaced within a year's time.

The author believes that for general purposes a freezing cabinet that can hold four or more specimens at a time offers greater advantages of economy, reliability, and versatility at less cost than an equal capability by means of thermoelectric cooling. An economical freezing cabinet containing its own refrigeration unit for cooling both the upper and lower chambers is currently being redesigned by the author so that it may be constructed at a cost of materials of less than $700, exclusive of labor (Fig. 5). Such a freezing cabinet should be well within reach of most state testing laboratories and larger project laboratories.

SUMMARY AND CONCLUSIONS

Laboratory studies indicate that frost susceptibility evaluation testing by freezing can be speeded up considerably from the slower procedures previously used. Experimental data on several different soil types reveal that ice segregation rate is a function of the rate of heat extraction as governed by the surface temperature.

Observations of heave-rate data in different soil containers indicate that the problem of sidewall friction is likely to be present in rigid containers of any type. Useful and repeatable results were obtained with multi-ring containers. Unless means can be found to eliminate the friction or adfreeze problem on rigid-wall containers, frost heaving evaluation by freezing should be performed in some kind of friction-free containers.

Observations and results obtained from freezing tests at constant temperatures indicate that frost testing time can now be reduced to not more than a few days, including specimen preparation time, to produce useful relative information. The freezing cabinets with a capability of holding four 6-in. diameter specimens are deemed as the most suitable and economical means for batch output required for engineering support. Testing in duplicate pairs is recommended in view of the importance of decisions to be made on the basis of test results.

ACKNOWLEDGMENTS

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