

Frost-Heaving Pressures

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Considerable pressure develops on freezing a saturated soil in an open system from the top down. The pressure is the result of the surface energy of a curved ice-water interface. The curvature of the interface is necessary for ice to proliferate through the soil pores and is related to the pore size distribution of the soil.

The test chamber used is designed to minimize the friction of the soil with the wall. An accurate control of heat removal is obtained by thermoelectric cooling. A load cell placed on top of the sample is used to measure the pressure developed and at the same time prevents heaving of the sample. Measurement of the pressure on a layered sample shows that the pressure develops at the freezing front. Results on several soils indicate that each soil develops a characteristic maximum pressure. For each soil used, the water content vs tension curve is given and the maximum pressure is related to this curve.

•A SOIL frozen from the top down can lift a considerable load. This phenomenon is not related to the crystallization pressure that water develops on being frozen in a closed container (e.g., a motorblock) because the soil is essentially an open system. Therefore, when the water in the upper layers of the soil freezes, the water can move freely to and from the freezing front. The pressure a soil develops on freezing is the result of the surface energy between ice and water. In this paper an attempt is made to relate the maximum pressure a soil develops to the pore size distribution of a soil.

REVIEW OF THE LITERATURE

Several studies, both in the laboratory and the field, have been made on the origin and magnitude of the heaving pressure (1, 2, 9, 14, 16).

Taber (16) found that a maximum pressure of 105 psi developed on freezing a clay. Since his system developed large friction forces, he estimated a total pressure of 200 psi. More significant, however, was his observation that the pressure not only develops in an ice-water system, but is common to all growing crystals.

Heaving pressure measurements in a cylindrical sample in the laboratory were made by Balduzzi (1). The heaving pressure and the pore water pressure were measured simultaneously. He found that tension in the pore water reduced the heaving pressure.

The influence of rate of heave under fixed loads has been determined by several other researchers. Actual measurements of the force required to prevent heaving were not made in these cases. For example, Beskow (2) found that the curves of rate of heave vs surcharge were hyperbolic, the rate of heave decreasing with increasing load. He also noted that finer grained soils were less affected by surface load. Linell and Kaplar (10) conducted the same experiments. Like Beskow, they did not measure the load required to prevent heaving, but determined the relationship between rate of

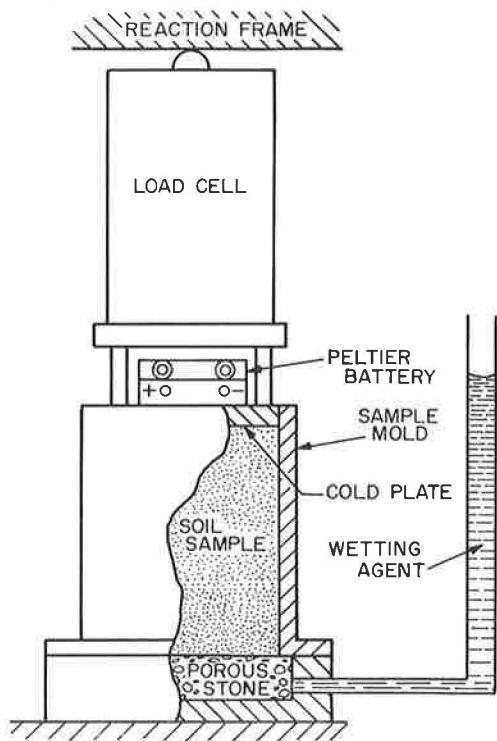


Figure 1. Schematic drawing of freezing chamber.

baseplate is sealed against the mold by an O-ring. A thermoelectric element is attached to the cold plate at the top of the mold. The cold plate is sealed against the mold by a U-cup. Above and bearing the thrust of the cold plate is a Baldwin load cell which in turn bears against a reaction frame.

A thermoelectric element (Pt 47/5, Ferroxcube Corp. of America) was used to cool the sample. The principle used is the same as that of thermocouples. When the two junctions of a thermocouple are at different temperatures, a potential difference or a current can be measured. In a thermoelectric element a potential difference is applied across the junctions of two dissimilar semiconductors and, as a result, heat is removed at one junction and dissipated at the other junction. The rate of heat removal is controlled by the current through the element (7).

The thermoelectric element used has a cooling capacity of 54 BTU/hr. For our sample this corresponds to a frost penetration of approximately 1 in./hr. The low voltage d. c. power supply for the thermoelectric element was a Sorensen Model QB68. The warm side of the thermoelectric element was cooled by circulating tap water. To minimize friction, the walls of the cylinder were given a 2° taper and coated with Teflon. Water was provided through the water inlet and the porous stone. The load was measured by Baldwin SR-4 load cells and recorded on a Leeds and Northrup Speedomax G. millivolt recorder. The recorder was calibrated with a Keithley differential voltmeter, Model 660.

Copper-constantan thermocouples were placed at 1-in. intervals of depth to obtain a temperature profile.

SAMPLE PREPARATION

The sample was wet to optimum moisture content to give maximum compaction using the modified Proctor method. The sample was de-aired and saturated with

heave and surcharge. Penner (15) used a closed system; that is, after his samples were saturated, the water supply was cut off and the freezing was conducted without a free supply of water. By extrapolating Penner's data, a heave pressure of approximately 25 psi might be expected for powdered quartz with particle size 0.001 to 0.03 mm.

Several researchers (3, 4, 12, 14) have drawn attention to the importance of pore size in frost heaving. Miller et al. (11) showed that ice penetration into soil pores filled with water could be predicted by equilibrium thermodynamics if the geometry of the ice-water interface was taken into account.

Although pore size was known to be a governing parameter, no systematic study relating pore size and heaving pressure has so far been reported.

EXPERIMENTAL APPARATUS

From experience gained by Kaplar and others in our laboratory a test chamber was designed, as shown in Figure 1. The cylinder is a stainless steel mold, 4 in. in diameter and 5 1/4 in. in depth, tapered and coated on the inside with Teflon. A stainless steel baseplate, housing a porous

de-aired water or, in the case of one series of tests, with benzene. The sample was then frozen from the top down. The ambient temperature was 5.5 C and the heave force was measured as discussed previously. On completion of a test, the water content vs tension curve was determined on the sample.

A very uniform and flat interface was formed on freezing; the difference in depth of penetration across the sample was less than $\frac{1}{8}$ in. Due to volume expansion, water was observed to flow out of the sample when a soil saturated with water was frozen. When a sample saturated with benzene was cooled, there was a flow of benzene into the sample, due to the contraction of benzene on solidification.

THEORETICAL

It was mentioned in the introduction that the pressure developed on freezing a saturated soil in an open system is due to the surface energy between ice and water. A better understanding of this phenomenon may be arrived at by considering the test chamber in Figure 1 filled with water with a constant head maintained in the standpipe. On freezing the water in the chamber a flat ice-water interface forms. As a result of the expansion of the water-ice phase change, some water flows out of the chamber through the porous stone; no pressure develops.

When there is saturated soil in the mold, the water is contained in pores. On freezing this system again, an ice-water interface forms, in this case at the boundary of frozen and unfrozen soil. However, this interface cannot be flat. For ice to proliferate through the soil pores, the interface has to be irregular. This causes the surface area of the interface in a porous system to be larger than that of a flat interface. An increase in surface area of an interface is always associated with an increased surface energy of the system.

For an interface of regular curvature thermodynamic equations can be written. The relation between the chemical potential of a flat interface μ_p to that of a curved interface μ_c is given by:

$$\mu_c - \mu_p = \frac{2 \bar{v}_i \sigma}{r} \quad (1)$$

where

σ = surface tension,
 \bar{v}_i = partial molal volume, and
 r = radius of interface.

Although this concept can be readily applied to liquid-vapor systems, it has been questioned if these principles also apply to solid-liquid interfaces. In this paper it is assumed that the surface tension theory applies also to solid-liquid interfaces. The conditions under which these assumptions are valid are extensively discussed by Herring and Kingery (5, 8).

Since there is a temperature gradient maintained in our system, it is also necessary to consider whether or not the usual thermodynamic variables and properties are still valid. When a steady state is obtained, the properties of the system do not change with time, but there can be an irreversible flow of heat, matter, or electricity through the system. The theory of irreversible thermodynamics postulates that for a non-equilibrium steady-state process, the equilibrium thermodynamics applies, so that Eq. 1 has been presented by several authors (4, 12, 15) in the form

$$\Delta P = \frac{2 \sigma}{r} \quad (2)$$

Although ΔP should truly present a hydrostatic pressure, the one-dimensional heaving pressure has been substituted for P . Thus far there is no justification other than that it is far more convenient to use the heaving pressure than to consider the anisotropy in the pressure distribution.

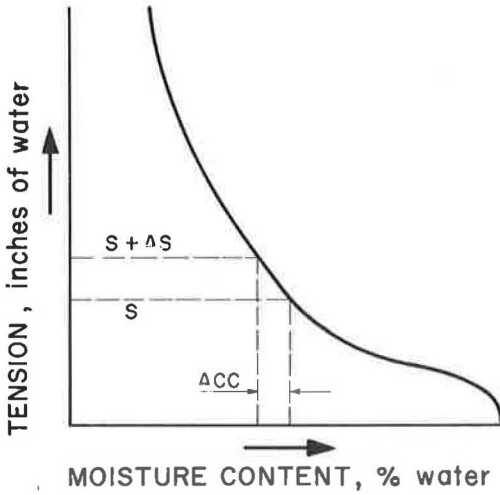


Figure 2. Typical water content vs tension curve of soil.

PORE SIZE DISTRIBUTION OF SOIL

If the radius of curvature of the interface in Eq. 2 is equated with the radius of the pores in the soil, the heaving pressure can be related to the pore size distribution of the soil. Penner (15) already pointed out that a large pore size range in the material is a drawback in making a rigorous comparison of the heaving experiment with the theory. The pore size distribution of a soil can be calculated from the water content vs tension curve of a soil. In Figure 2 a water content vs tension curve is shown. For an increment of tension, Δs , the water content changes (Δcc). This is interpreted to mean that Δcc of water is held in pore sizes defined by the equation

$$\frac{s}{2\sigma_w} < r < \frac{s + \Delta s}{2\sigma_w} \quad (3)$$

where

r = effective pore radius,
 s = tension in pore water, and
 σ_w = surface tension air-water.

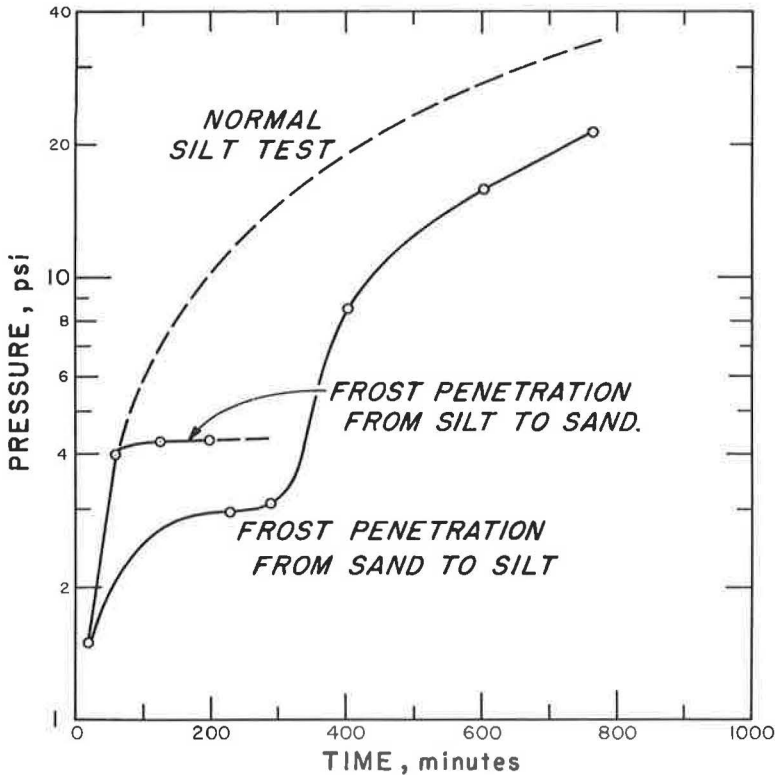


Figure 3. Pressure vs time for layered samples.

This procedure can be carried out for the entire curve so that a pore size distribution curve can be obtained. To relate the heaving pressure of a soil to the pore size distribution, a characteristic pore size will have to be determined empirically. The determination of a characteristic pore size will be discussed. Another point that needs to be discussed is the entry of ice into a pore filled with water. Once ice grows into a large pore, it will not grow all the way down because it will reach a region of higher temperature and growth will stop. An ice-water interface forms somewhere in the pore. This is different from air entry into a pore filled with water. When air entry takes place in a pore filled with water, all water is forced out of that pore. No air-water interface forms in the pore.

RESULTS AND DISCUSSION

If the pressure developed on freezing a soil is the result of the surface energy between ice and water, then this pressure should originate at the freezing front. This hypothesis was tested on a stratified sample with layers of sand and silt packed in the test chamber. Since the pores in a sandy soil are larger than in a silt soil, the pressure should increase faster when the freezing front moves from the sand to the silt. Figure 3 shows that the experiments verify the hypothesis. The movement from sand to silt shows the reverse effect.

If the pressure developed is the result of the surface energy of a solid-liquid interface in a porous system, the pressure should not be a property of the ice-water system only, but should also occur when, e. g., benzene solidifies in the system. This was verified on Richfield silt (Fig. 4). The pressure developed in the same manner for a benzene-saturated soil as for a soil saturated with water. The difference in pressure

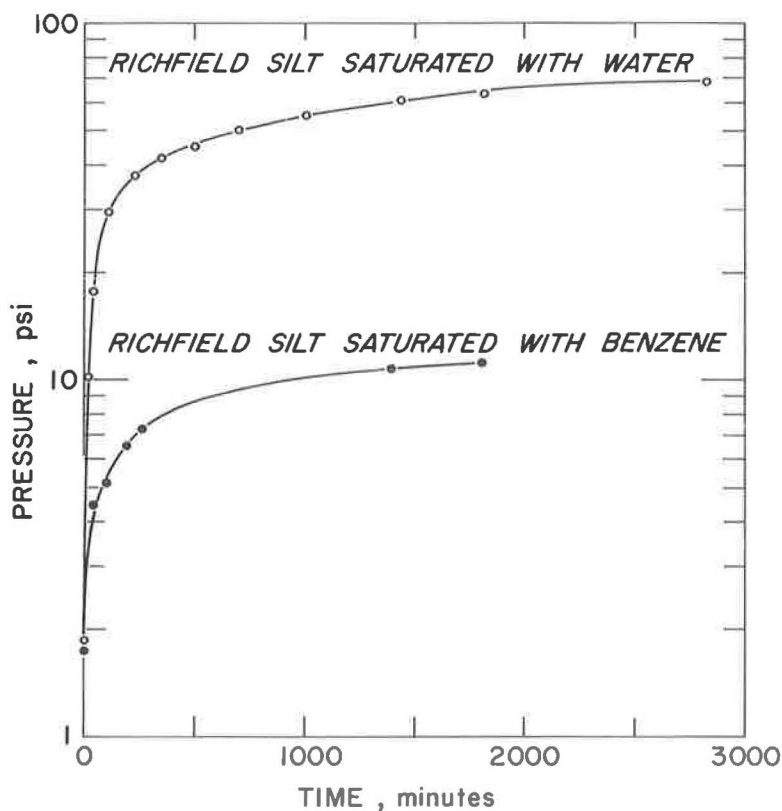


Figure 4. Pressure vs time for Richfield silt saturated with benzene.

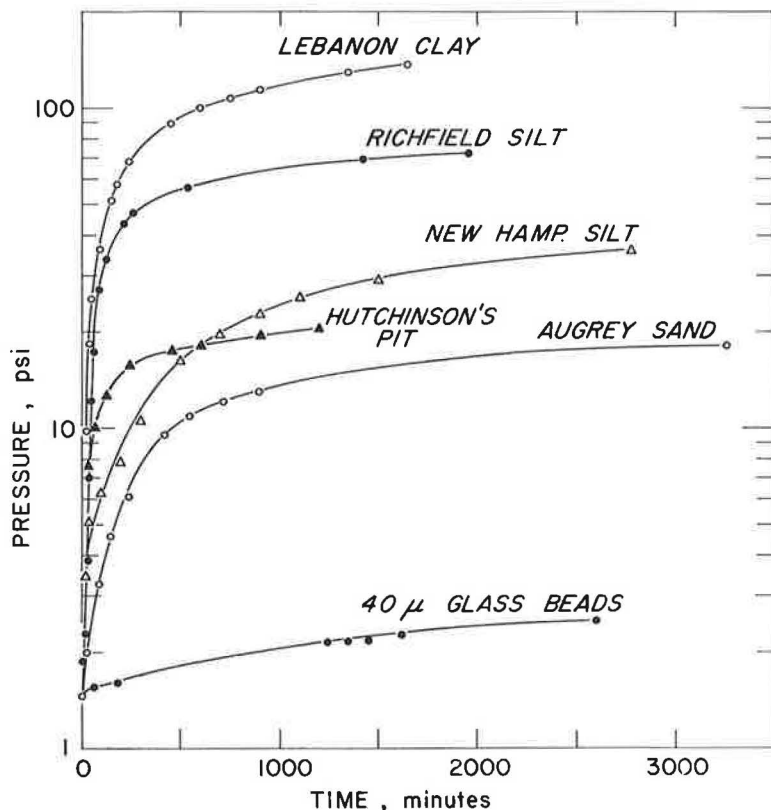


Figure 5. Pressure vs time for several soils.

is due to the different values of the surface tension of ice-water and liquid-solid benzene. This experiment has another important implication. Not all water freezes in a soil at temperatures close to 0 C. The "unfrozen water" freezes gradually at lower temperatures. It is conceivable that the pressure is due to expansion on freezing of the unfrozen water. Since benzene contracts on solidification, the pressure developed must be due to the surface energy of the liquid-solid interface.

In Figure 5, the increase in load with time is plotted for several soils. Several runs were performed on each soil. The maximum pressure that develops is reproducible to within 10 percent. This is an important observation since it means that the pressure can probably be used as a criterion to indicate the behavior of soils on freezing. The maximum pressure is developed when the position of the freezing front becomes stable in the soil. To show that the pressure cannot increase beyond a maximum value even when further penetration occurs, an initial load slightly higher than the expected maximum load was placed on the sample, and the sample was frozen. Figure 6 shows that the pressure never increases beyond the expected maximum load. The increase in pressure with time can be described by:

$$P = A [1 - \exp (-a \sqrt{t})] \quad (4)$$

where

A = maximum pressure,

a = constant,

P = pressure (psi), and

t = time (min).

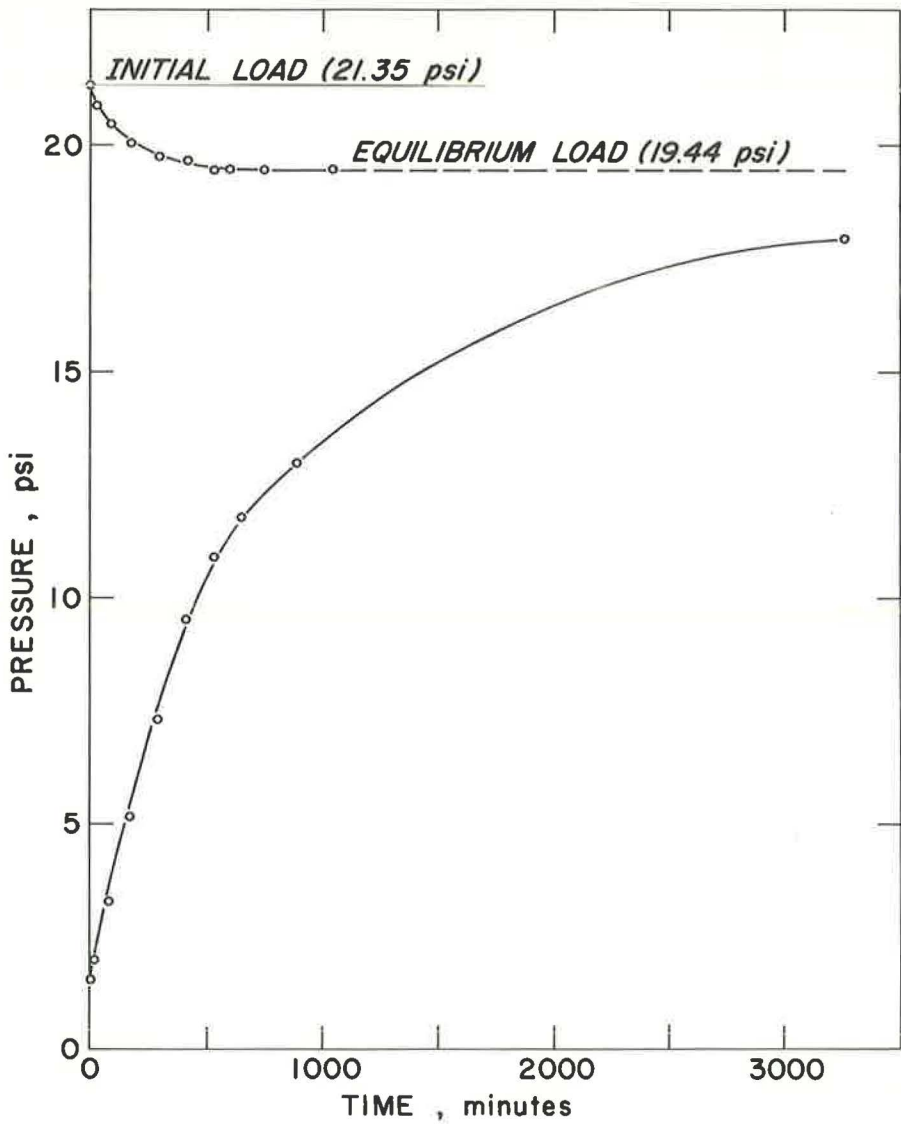


Figure 6. Pressure vs time for augrey sand with and without an initial load.

When $t \rightarrow \infty$, $\exp(-a\sqrt{t}) \rightarrow 0$, and $P \rightarrow A$. This relation can be written as:

$$\ln(A - P) = \ln A - a\sqrt{t}$$

If the maximum value is estimated from Figure 5, A_{est} , can be inserted in Eq. 4 in the form:

$$\ln(A_{est} - P) = \ln A - a\sqrt{t} \quad (5)$$

This relation is plotted for several soils in Figure 7. This shows that Eq. 4 adequately describes the increase in pressure with time. From the intercept at time zero, $\ln A$ is obtained. If A differs from A_{est} , A and A_{est} can be made to coincide by successive

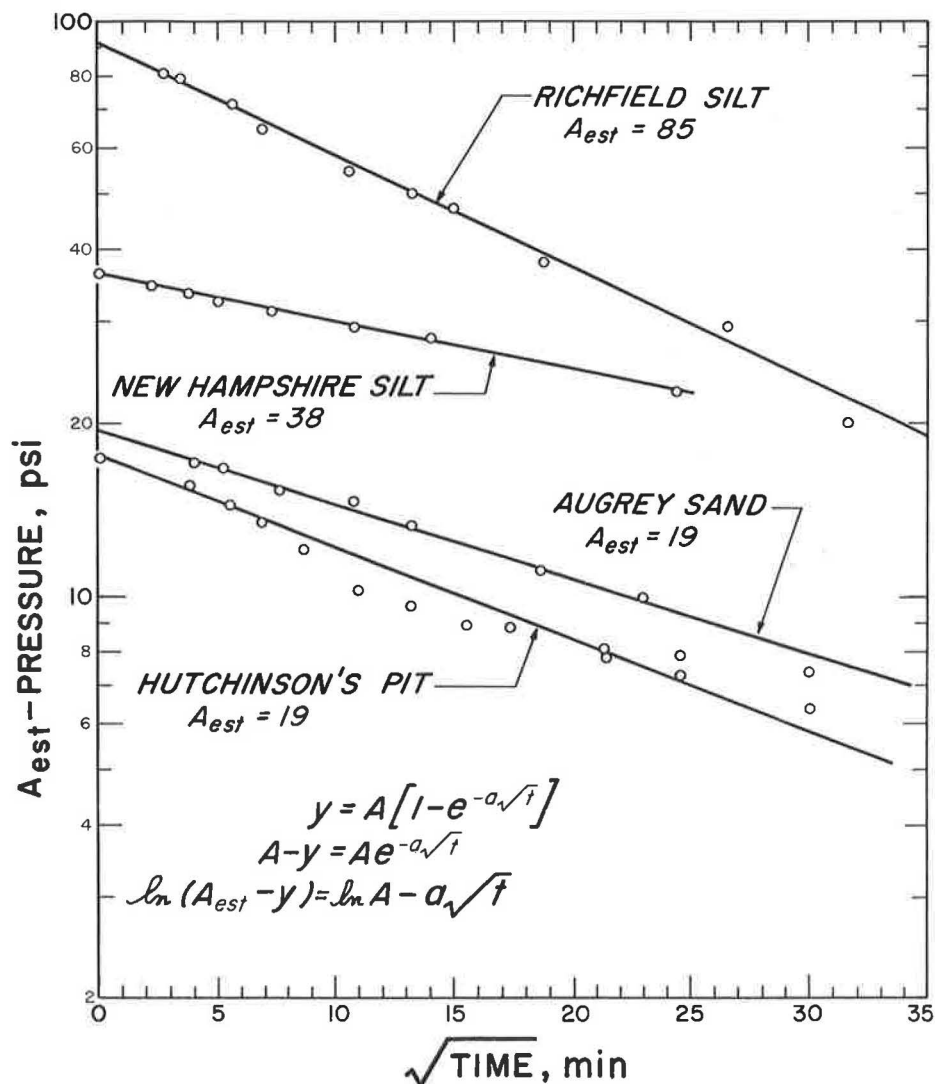


Figure 7. Difference between estimated maximum pressure and pressure at time t vs root of time.

approximations. However, it was found that near agreement was obtained on the first approximation. The maximum pressure can thus be evaluated from a 24-hr test.

In Figure 8 the percent saturation vs tension curves of the soils used are given. An empirical criterion has to be established to correlate the pressure developed with the percent saturation vs tension curve of the soil. In establishing an empirical criterion, the following reasoning was used. The maximum pressure will be developed so that the ice interface can proliferate through the smallest pores. However, this cannot be the only criterion; the number of small pores present is another. If there were only a few pores of a small size present, the freezing front could bypass these pores. The amount of water held in pores of a particular size range is given by the slope of the curves in Figure 8; the point where the slope of the line decreases rapidly is indicated. In Figure 9 the tension at this point is plotted vs the pressure developed. There is a consistent relationship between the tension at the points indicated in Figure 8 and the pressure.

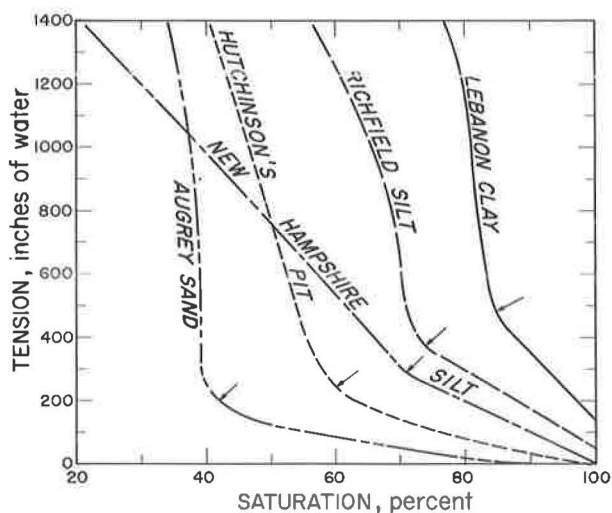


Figure 8. Percent saturation vs tension curves for several soils.

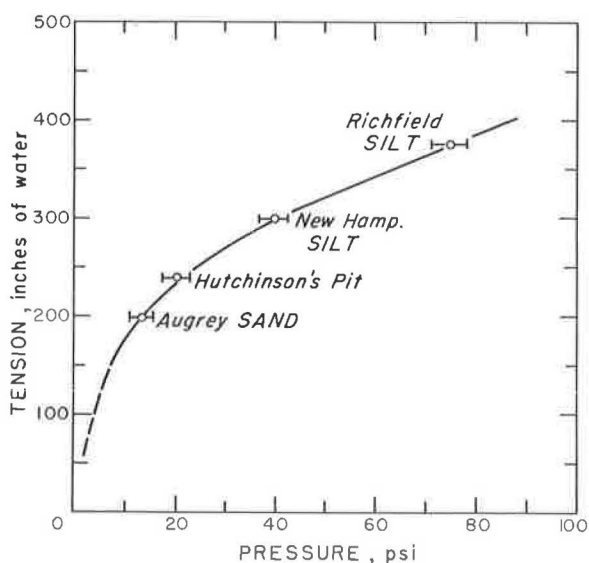


Figure 9. Pressure vs tension at points indicated in Figure 8.

CONCLUDING REMARKS

All present criteria for frost susceptibility are based on the grain size distribution of the soil. A close look at the frost-heaving process reveals that pore size is a more fundamental soil parameter than grain size. The grain size distribution is partly successful in predicting frost susceptibility because grain sizes and pore sizes are somewhat related. However, particle shape and gradation obscure the relationship between grain sizes and pore sizes. In Figure 10 the grain size distributions of the soils used are given. The Richfield silt and augrey sand have different degrees of frost susceptibility. The soils would, however, both be classified as SM in the Unified System. The maximum heaving pressure differentiates between these soils (Fig. 5)

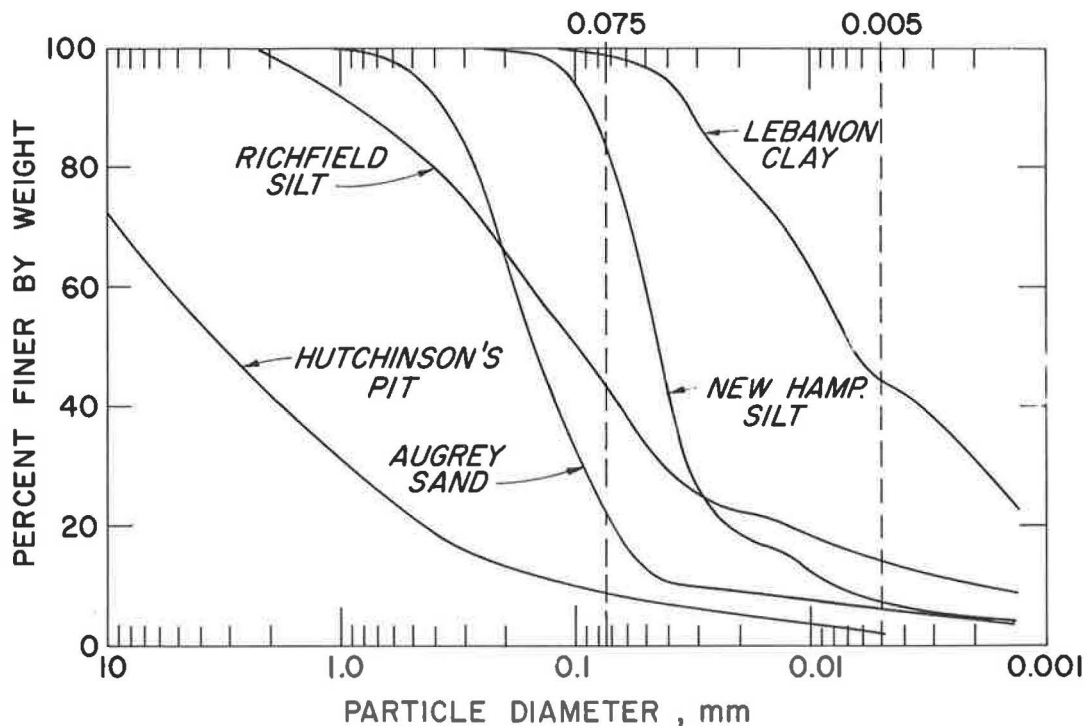


Figure 10. Grain size distributions of several soils.

and there is a consistent relation (Fig. 9) between heaving pressure and the pore size distribution of the soil. Additional research is being undertaken to test more soils and to determine if the heaving pressure provides a reliable criterion for frost susceptibility.

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