INFLUENCE OF FREEZING RATE ON FROST HEAVING

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The major thermal influences on the frost-heaving process in soils are reviewed. Laboratory experiments that are designed to predict the frost susceptibility of soil in the field are shown to be strongly influenced by the freezing procedure. It is believed to be misleading to compare the frost susceptibility of different soils based on freezing tests that are carried out at the same rate of frost line penetration. Applying the same rate of heat removal is thought to give more meaningful comparisons of frost susceptibility. In general, increasing the rate of heat removal causes the heaving rate to rise to a maximum followed by a reduction that intercepts the in-place pore water phase change expansion line. Arakawa's concept of ice segregation efficiency is introduced, and its usefulness for assessing frost susceptibility is discussed. The ice segregation efficiency ratio, E, gives the fraction of the heat removed from the freezing front in the soil that is directly attributable to ice lens formation. When $E = 1$, the total heat evolved is from the phase change involved in ice lens formation; when when $0 < E < 1$, only a part of the heat evolved is derived from ice lens formation; and when $E = 0$, no ice lensing occurs. Finally, suggestions are made for the improvement of frost-susceptibility tests in the laboratory.

•A SATISFACTORY laboratory test method has not yet been devised that serves as a reliable basis for the assessment of frost susceptibility of soils for all conditions. The variability of the natural environment complicates simulation of the conditions. The procedure up to the present has been to create favorable conditions for frost heaving in the laboratory, where it has not been possible to simulate the desired conditions effectively. However, by using this method, soils can be distinguished that are borderline with respect to frost susceptibility and that may cause unexpected frost action problems in the field.

The nature of the porous media, water supply, and thermal conditions are the three principal frost action factors and, of these, the first factor is probably the easiest to simulate. Representative samples may be taken from the site in question, pretreated, and compacted to simulate the field condition. This can be done easily when the freezing zone is confined within earth structures such as fills and embankments but may be more difficult for undisturbed soils.

Because the amount and rate of lensing is dependent on water supply, the most favorable condition for heaving is normally simulated. Laboratory specimens are usually presaturated before freezing, and in the case of open systems additional moisture is made available at the base of the soil sample. The ice lensing system in the field may operate as an open system from a high water table or as a closed system if the water table is at great depth. These are the extremes, which can be created easily in the laboratory, but the ordinary cases are more difficult to simulate.

This paper is particularly concerned with the third frost action factor—thermal conditions. The importance of the rate at which the soil specimen is frozen and its effect on mobilizing moisture flow is an essential factor that influences frost-susceptibility assessments for field conditions. This is supported by many experiments carried out recently in various laboratories. Finally, a method for quantifying the influence of heave rate with respect to the thermal condition imposed is discussed. This method is based on an efficiency ratio concept recently introduced by Arakawa (1).

The dependency of heave rate on the freezing rate has not always been recognized. Beskow (2) found that, for a constant pressure (load on the soil), "the rate of heaving is independent of the rate of freezing." He further stated that "it should be noted, however, that this is completely valid only for relatively permeable soil." Beskow recognized that, for soils where the frost line was stationary, various heave rates were possible and dependent on heat flow (a relatively unique condition), thus this dependence did not hold for a penetrating frost line (more common in the field). Similarly, the U. S. Army Corps of Engineers (9) stated that "rate of heave has been found to be relatively independent of rate of freezing over a range of freezing rates employed in the investigation." This was the basis for their frost-susceptibility classification that is valid for freezing rates between ¼ and ¾ in. of frost penetration per day.

Higashi (4) studied the rate of heaving in the laboratory and found an inverse relation with frost-line penetration, a result quite contradictory to previous findings. Although this is difficult to understand, the author believes that the highly restrictive water supply influenced the results attributed to thermal conditions by Higashi. In more recent laboratory expeiments by Penner (7) and Kaplar (5, 6), the heaving rate was found to be directly dependent on heat flow, i.e., increasing net heat flow and frost-penetration rate increased the heave rate.

Haas (3) concluded from results of field studies that, when the frost line was not penetrating, the heave rate was essentially proportional to the heat conduction difference between the frozen zone and the unfrozen zone. This observation is similar to Beskow's findings. Field data were also presented for the case when the frost line was actively penetrating, and the heave rate was found to be inversely proportional to the frost penetration rate. In a published discussion to the paper by Haas, Penner (8) was able to show that no statistical significance existed between the two variables, frost-penetration rate and heave rate, because of scatter in the data.

HEAT FLOW AND FROST PENETRATION STUDIES

The method used by Penner (7) to study the influence of the rate of heat flow on the heave rate was to measure heat in and heat out with calibrated heat transducers placed at opposite ends of a 3-in. long and 6-in. diameter specimen. At the same time, heave rate and moisture-influx rate were also measured under conditions of unidirectional heat flow. The relevant aspects of this investigation are summarized as follows.

Three soils were studied: a clay (Leda clay) with 64 percent clay-size particles and 36 percent silt-size particles; a silt (PFRA silt) with 9 percent clay-size particles, 43 percent silt-size, and 48 percent sand-size; and a sandy soil (Lindsay sand) with 7 percent clay-size particles, 13 percent silt-size, and 80 percent sand-size, based on the MIT grain-size classification. The dry densities were 91, 110, and 137 lb/ft^3 respectively; all the samples were presaturated before freezing. The saturated moisture contents averaged 33.2 percent, 19.2 percent, and 8.2 percent respectively.

The prefreezing procedure was to impose a thermal gradient of about 0.35 C/in. across the water-saturated specimen with the cold end near 0 C. When thermal equilibrium was established, the temperature of the cold end was reduced to just below 0 C and crystallization of the water was artificially induced. The heat flow was then controlled to give a constant rate by manual adjustment of the temperature on the cold side. When a constant heave rate was established, the thermal gradient was increased to give a different rate of heat extraction by lowering the cold-side temperature.

Figure 1 (from a previous paper by the author, 7) shows the results of three rates of heat removal from one of the soils, Lindsay sand. The figure shows the net heat removal (difference between heat in and heat out) and the moisture influx values expressed in terms of the heat released upon freezing. All three soils showed a positive increase in heaving rate when the heat flow was increased.

The results shown in Figure 2 (from a previous paper by the author, 7) were obtained somewhat differently but lead to the same conclusions. In this series of experiments, a new sample was prepared for each heat flow rate; at the same time, the moisture flow rates into the sample were also measured. As before, moisture flow was plotted in terms of latent heat of fusion by using standard values of 80 cal/g of water or 144

Figure 1. Cumulative values of net heat flow and moisture flow versus time.

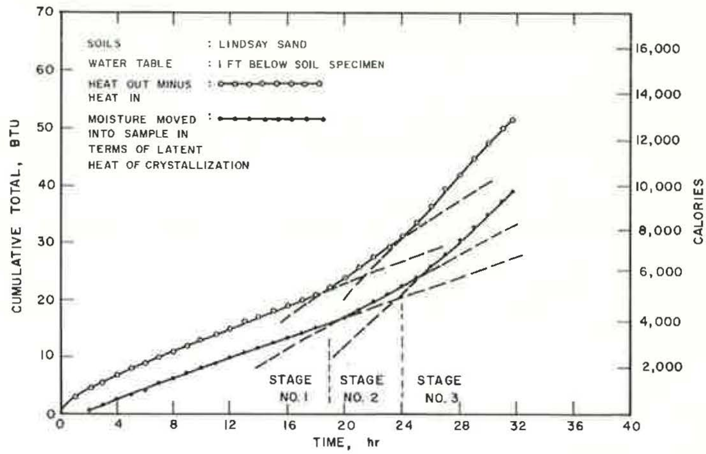
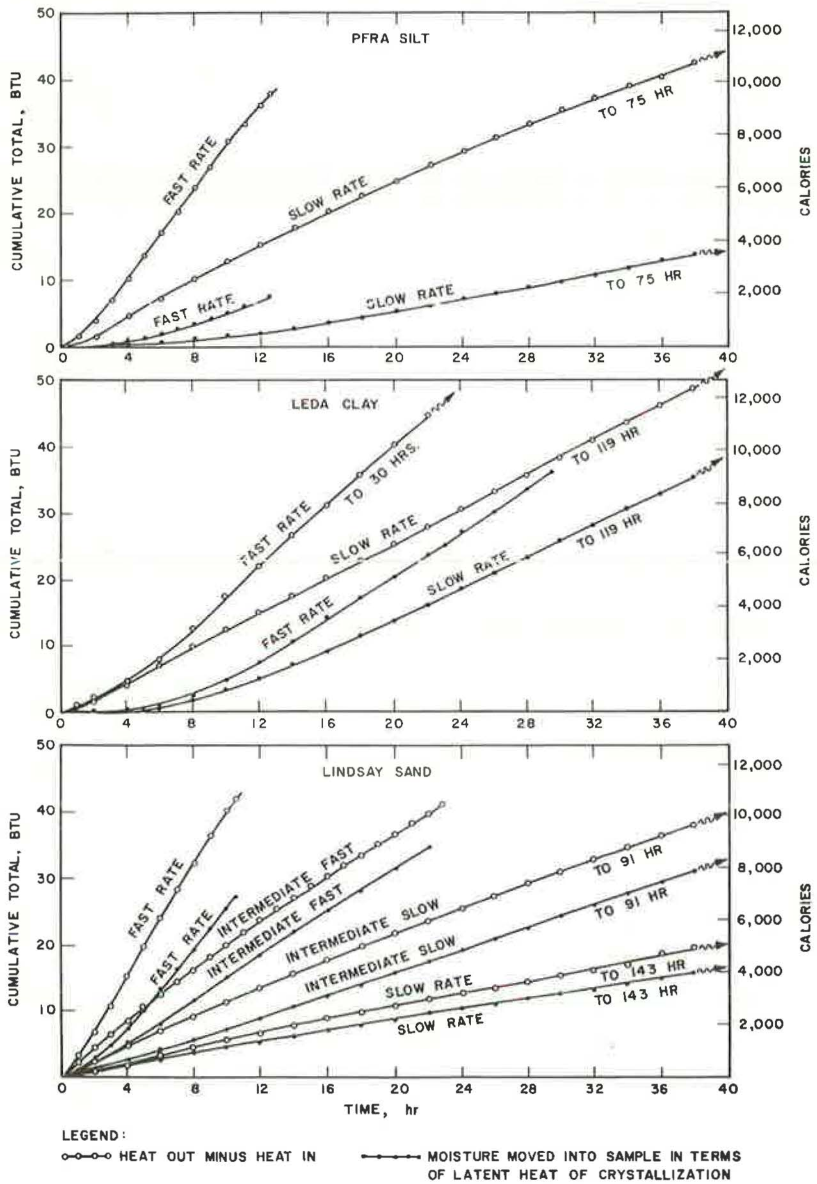


Figure 2. Cumulative value of net heat flow and moisture flow versus time.



Btu/lb of water. It was possible to establish and maintain a constant heat extraction rate after a short period, as may be seen from Figure 2. The apparatus was dismantled, and the thickness of the frozen layer was measured to calculate the average frost-penetration rate.

The influence of rate of frost-line penetration on heave rate has been summarized for these studies in Figure 3. The upper curves show the total heave due to (a) the expansion of the in situ water as the frost line penetrated and (b) the additional water moved into the freezing zone. The lower curves give the heave rates that can be assigned to the in-place expansion of in situ water when it freezes.

Kaplar's (5) recent studies support the positive influence of frost-penetration rate on frost-heave rate (Fig. 4; from Kaplar, 6) in laboratory-conducted experiments. Experiments were also carried out by Kaplar (6) where the frost-heaving rate was measured for different but constant freezing temperatures in the freezing cabinet above the samples. Summary results are shown in Figure 5 (from Kaplar, 5) for four different soils, from which Kaplar concludes "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)."

The frost-line penetration rate is, therefore, an important consideration when deciding on the freezing procedure to be used for determining the frost susceptibility of soils in the laboratory. Figures 3, 4, and 5 show, however, that the dependence of the heave rate on heat extraction rate (or frost-line penetration rate) is different for each soil. This dependence cannot as yet be predicted and must apparently be determined experimentally. Yet the criterion currently used exclusively to evaluate quantitatively frost susceptibility is the rate of heaving. It is unfortunate that this important criterion is so sensitive to the rate at which freezing is carried out. Some effort has been made to understand the degree of frost susceptibility in terms of other factors such as heaving pressures, but further work is necessary before these can be applied with confidence to field problems.

ICE SEGREGATION EFFICIENCY RATIO

The author, in previous studies (7), measured the induced water flow into the sample during ice lensing as well as the net heat flow (heat out minus heat in). Arakawa (1) termed the ratio of these quantities the ice segregation efficiency ratio, which is defined by the following equation:

$$E = \sigma L / [K_1(\partial T_1/\partial x) - K_2(\partial T_2/\partial x)] \tag{1}$$

where σL gives the heat evolved at the freezing front based on the moisture flow rate (ice lens growth rate) and the denominator is the net heat flow out of the sample, that is, heat out minus heat in. The symbols in the equation are defined as follows:

- σ = ice segregation rate, mass of ice per unit area per unit time at the frost line;
- L = latent heat of fusion;
- K_1 = thermal conductivity, frozen layer;
- K_2 = thermal conductivity, unfrozen layer;
- $\partial T_1/\partial x$ = thermal gradient in frozen layer; and
- $\partial T_2/\partial x$ = thermal gradient in unfrozen layer.

The ice segregation efficiency ratios have been calculated from the results shown in Figure 2. In the first instance, the efficiency ratio has been plotted as a function of net heat flow (Fig. 6). In Figure 7, the ratio has been plotted as a function of rate of frost penetration for the same experiments with the aid of Figure 3. Figures 6 and 7 both show the same tendency for the ice segregation efficiency ratio to decrease as the rate of heat removal or frost penetration rate increases. Within the range of rates of heat extraction of 0 to 20 Btu/hr ft^2 or frost penetration rates of 0 to 3 in./day, the rate of moisture flow into the sample (hence the heaving rate) increased when the rate of heat

Figure 3. Heave rate versus frost-penetration rate.

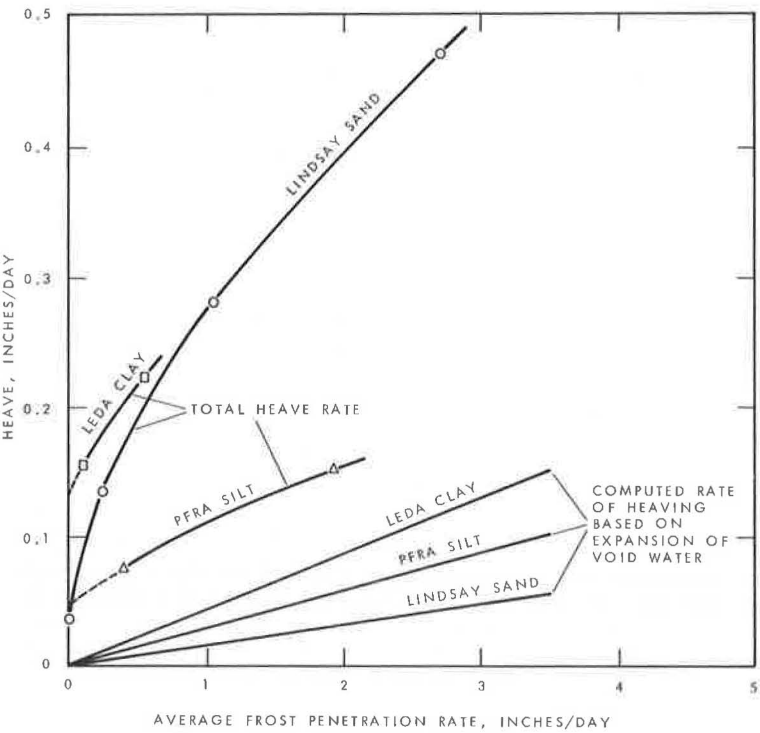


Figure 4. Heave rate versus rate of frost penetration.

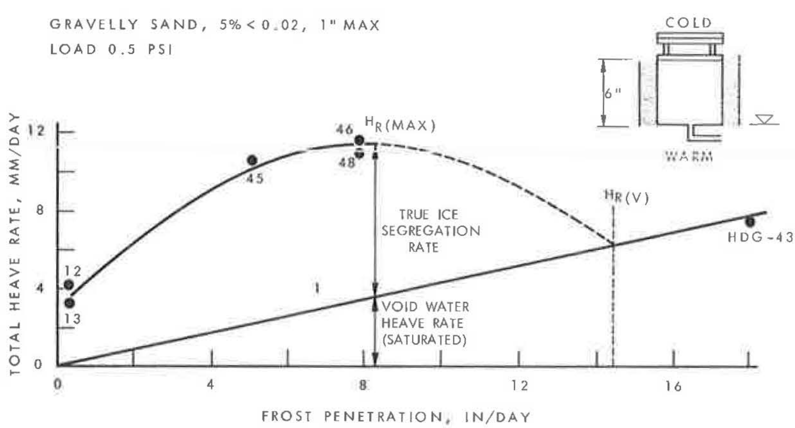


Figure 5. Summary of multi-ring freezing tests.

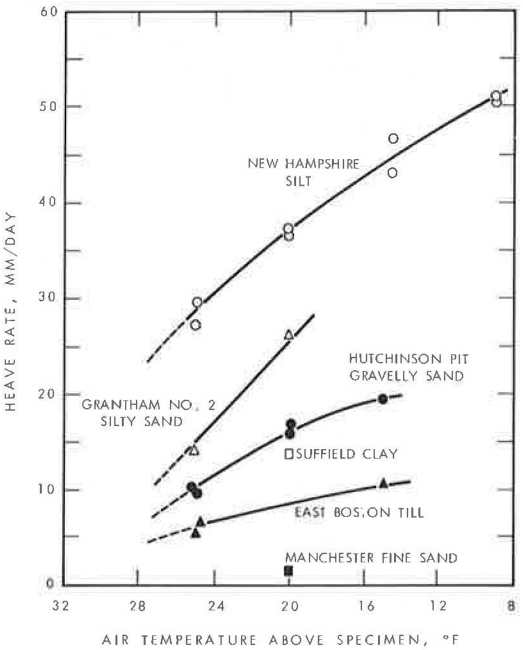


Figure 6. The ice segregation efficiency ratio as a function of net heat flow (heat out minus heat in).

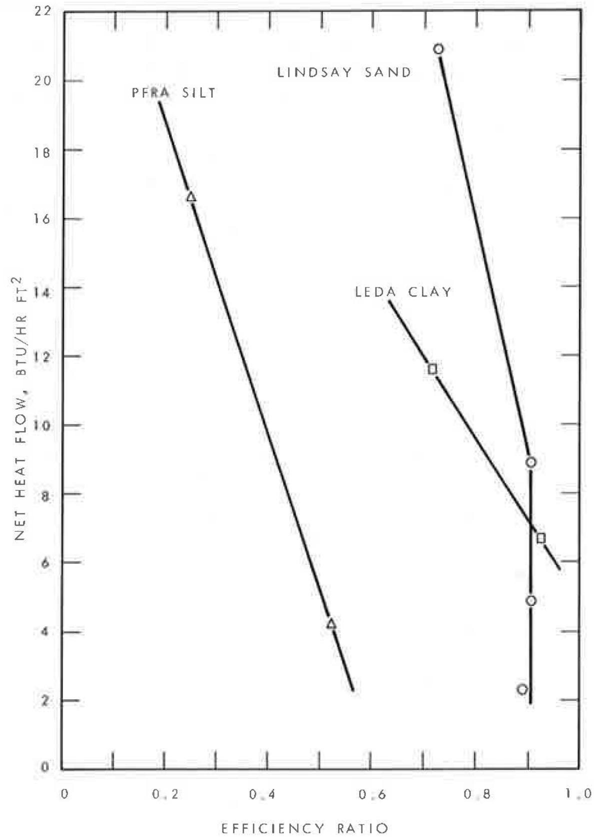


Figure 7. The ice segregation efficiency ratio as a function of frost-penetration rate.

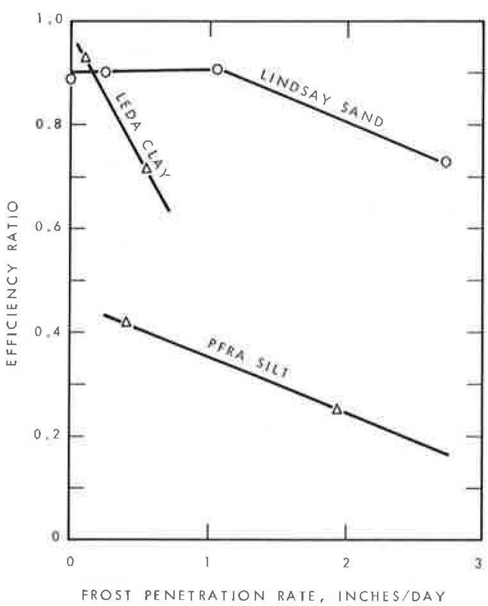
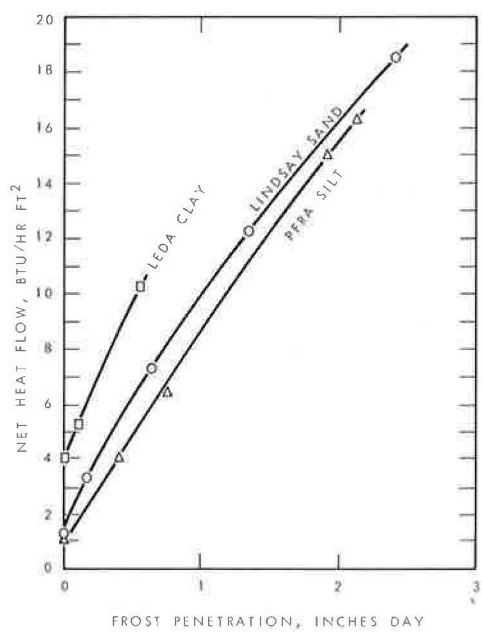


Figure 8. The influence of net heat flow on frost penetration.



removal was increased (Fig. 2). Doubling the rate of heat removal, however, does not double the heave rate. This decrease in ice lensing efficiency is depicted in the ice segregation efficiency ratio and is an indication that the moisture permeability, even in saturated samples, is too low to hold the efficiency ratio constant for some soils as the freezing rate is increased. In Lindsay sand it appeared to remain relatively constant up to 1 in./day of frost penetration (in this case equivalent to about 9 Btu/hr ft^2) and then decreased. Sufficient data are not available for the other soils to determine whether this trend applies more generally.

There is a special case of frost heaving with a stationary frost line and, as pointed out by Haas (3) and others, it may occur over a range of values of net heat flow. If we ignore the small amount of heat extraction due to cooling of the water as it moves in the thermal field, $\partial T_2/\partial x$, the efficiency ratio E equals 1, that is,

$$K_1(\partial T_1/\partial x) - K_2(\partial T_2/\partial x) = \sigma L \tag{2}$$

despite the fact that the heaving rate may vary depending on the net heat flow. Arakawa calls it perfect segregation when $E = 1$ and imperfect segregation when $0 < E < 1$. For a soil that does not heave, E equals 0 because σ is zero when no ice segregation occurs.

There is one component of the total heave that is not taken into account in the ice segregation efficiency. In a frost-susceptible soil, the expansion of the existing pore or void water adds to the total heave if the frost line is penetrating. The amount of heave in this case results simply from the phase change of pore water to ice, which gives about a 9 percent volume increase. Kaplar and Penner have both shown the amount this contributed to the total heave (Figs. 4 and 3). The calculation of heave response to the expansion of the void water when it freezes has been based on all the water freezing at 0 C. This is known to introduce an error in the total heave, but other experiments would have to be undertaken to evaluate this correctly for all three soils. Although the latent heat of fusion is the same for both the void water and "outside" water moved to the freezing zone, the amount of heave resulting is vastly different. The amount of heave resulting simply from phase change expansion of the void water may be, in some soils, a considerable portion of the total heave. For Lindsay sand at a frost penetration rate of 3 in./day, it amounts to about 9.5 percent as shown in Figure 3. At present there does not seem to be a satisfactory way of incorporating this contribution into the ice segregation efficiency ratio. Nonetheless, it should not be overlooked in the total assessment of frost susceptibility.

The heave rate tends to increase to a maximum as the rate of freezing is increased and then falls off and intersects the heave-rate curve, which results solely from the void water phase change. This trend is shown in Figure 4. Under very high rates of frost penetration, mobilization of water apparently is not possible. It is also unlikely that under field conditions the frost penetration rate would be high enough to produce the maximum heave rate attainable in the laboratory. The average frost penetration rate is more likely to be less than 1 in./day in areas of seasonal frost in Canada.

Finally, it is misleading to compare the frost susceptibility of various soils based on freezing tests carried out at the same rate of frost-line penetration. Different soils exposed to the same freezing conditions will freeze at different rates. This is shown for three soils (Fig. 8) for which heat flow data and frost-penetration rates were available. As an example, for a heat extraction rate of 10 Btu/hr ft^2, the average frost penetration in the laboratory was 0.5 in./day for Leda clay, 1 in./day for Lindsay sand, and 1.20 in./day for PFRA silt. The samples were fully saturated and had a mositure content of 33.2 percent, 8.2 percent, and 19.2 percent respectively. Under similar thermal conditions, the main factors that determine the frost penetration rate in frost-susceptible soils are the in situ moisture content and the ice segregation rate. Other lesser influences placed on the foregoing samples are such factors as density and the thermal conductivity and specific heat of the soil solids.

DISCUSSION AND SUMMARY

The major influences on frost heaving that have been stressed in this paper can be attributed directly to the thermal aspect of freezing tests conducted in the laboratory for frost-susceptibility evaluation. It has been shown that, for saturated soils studied in an open system, the following apply:

1. The heat-removal rate influences the heaving rate (Figs. 1 and 2).
2. With increasing heat-removal rates, the heaving rate increases (Figs. 3, 4, and 5) and appears to rise to a maximum; it then decreases and intersects the heave rate based on the phase change expansion of the pore water (Fig. 4).
3. The rate of frost penetration is not the same for different soils at the same rate of heat extraction (Fig. 8).
4. The concept of the ice segregation efficiency ratio, E, is a useful indicator of the frost susceptibility of a soil; as the rate of frost penetration and heat removal is increased, the ratio is reduced (Figs. 6 and 7).
5. The heave-rate response to increasing heat-removal rates is not the same for all frost-susceptible soils (Figs. 3, 4 and 5).
6. A considerable portion of the measured heave may be due to the in situ freezing of the pore water (Figs. 3 and 4), but the present concept of the ice segregation efficiency ratio does not take this into account.

CONCLUSIONS AND SUGGESTIONS

The work reviewed in this paper suggests that the thermal conditions imposed on laboratory samples during laboratory frost-susceptibility experiments are an important element of the testing procedure. These studies indicate that the rate of freezing used should be related to the thermal conditions in the field for which the tests are being performed. Because thermal conditions will vary from year to year in the field, it would be helpful to carry out the freezing tests at two rates, one at less than the minimum rate of freezing and the other at somewhat faster than the maximum rate of freezing expected. One test conducted with an arbitrary rate of freezing is not sufficient to evaluate the response to a different freezing rate because this varies with soil type.

The use of heat meters at both ends of the soil sample (along with measurements of moisture influx, in situ moisture content, and depth of freezing) allows the calculation of a thermal balance. The ice segregation efficiency ratio can be calculated from these results. Such a test procedure, although desirable, may be too costly, and the information obtained from exposing the soil samples to different surface temperatures to impose different rates of freezing may be sufficient. If rates of frost penetration are both slower and faster than the expected field values, the results should permit a good evaluation of frost susceptibility of the material under test.

There does not seem to be a need to carry the freezing experiments beyond a 24-hr (or even shorter) period. It can be seen from the data in Figure 2 that relatively constant flow and heaving conditions are established in a few hours. More useful information can be obtained by spending extra time and effort on conducting heaving experiments at various rates rather than relying on prolonged measurements at one rate.

Finally, the heaving response to different thermal conditions has been evaluated for only a few soils under relatively simple conditions of in situ moisture, moisture supply, and sample density. This work does indicate, however, that improvements can be effected in frost-susceptibility testing procedures used in the laboratory.

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REFERENCES

1. Arakawa, K. Theoretical Studies of Ice Segregation in Soil. Jour. Glaciology, Vol. 6, No. 44, 1966, pp. 255-260.
2. Beskow, G. Soil Freezing and Frost Heaving With Special Application to Roads and Railroads. Swedish Geological Society, Series C, No. 375, 26th Year Book No. 3, 1935, (Osterberg, J. O., Trans), Technological Institute, Northwestern Univ., Evanston, Ill., 1947, pp. 14-21.
3. Haas, W. M. Frost Action Theories Compared With Field Observations. HRB Bull. 331, 1962, pp. 81-95.
4. Higashi, A. Experimental Study of Frost Heaving. U. S. Army, Corps of Engineers, Snow, Ice, and Permafrost Research Establishment, Res. Rept. 45, 1958.
5. Kaplar, C. W. New Experiments to Simplify Frost Susceptibility Testing of Soils. Highway Research Record 215, 1968, pp. 48-59.
6. Kaplar, C. W. Phenomenon and Mechanism of Frost Heaving. Highway Research Record 304, 1970, pp. 1-13.
7. Penner, E. The Importance of Freezing Rate on Frost Action in Soils. Proc. ASTM, Vol. 60, 1960, pp. 1151-1165.
8. Penner, E. Discussion of paper by Haas, W. M., HRB Bull. 331, 1962, pp. 95-97.
9. Cold Room Studies—Third Interim Report. U. S. Army, Corps of Engineers. Tech. Rept. 43, 1958.