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SOIL FREEZING CHARACTERISTICS VERSUS HEAT EXTRACTION RATE

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RÉSUMÉ

Les phénomènes agissant lors du gel des sols fins non soumis à une surcharge sont décrits et reliés au taux d'extraction nette de chaleur. Des expériences unidimensionnelles de soulèvement dû au gel ont été faites au Canada sur un sol limoneux pour différentes conditions limites de température. Il a été établi que le taux de soulèvement dû à la formation de lentilles de glace est fortement dépendant du taux d'extraction de la chaleur. Aucun écoulement d'eau n'a été observé à des taux d'extraction situés entre 0,35 et 0,45 mW/mm^2. Les taux de soulèvement ségrégationnel maximums sont survenus à environ 0,1 mW/mm^2. Toutefois, pour le même sol, des variations importantes du soulèvement ségrégationnel ont été relevées pour un taux d'extraction de chaleur donné au cours d'un gel transitoire. Les prédictions du soulèvement dû au gel enregistrées lors d'essais effectués à des taux d'extraction de chaleur représentatifs des conditions in situ sont également examinées.

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Soil Freezing Characteristics Versus Heat Extraction Rate

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ABSTRACT

The processes that are operative during fine-grained soil freezing with no applied surcharge are described and related to the rate of net heat extraction. One-dimensional frost heave experiments were carried out on a Canadian silty soil under various freezing conditions. It was established that the segregational heave rate is strongly dependent on the rate of heat removal. No water flow was observed at heat extraction rates between 0.35 and 0.45 mW/mm^2. Maximum segregational heave rates occurred at rates of about 0.1 mW/mm^2. For the same soil, however, significant variations in segregational heave rates were measured for a given heat removal rate during transient freezing. Frost heave predictions using freezing tests at rates of heat extraction representative of field conditions are also discussed.

INTRODUCTION

The propensity for heave of a soil under freezing conditions is mainly affected by factors such as grain size, pore size distribution, availability of water, applied loads and the rate of freezing.

This paper is concerned with the influence of the thermal boundary conditions in a frost heave test. Therefore, it is restricted to a fully saturated soil with the same grain size distribution at a given porosity, subjected to zero external loading and frozen with free access of water from an external source, i.e., an open system freezing.

Attempts to establish a relationship between the rates of heat extraction, frost penetration and heave have been made by several investigators. The conclusions of these studies are contradictory. Beskow [1] demonstrated, with experiments in which the air temperature above the specimen varied between -2°C and -10°C, that the heaving rate is not always influenced significantly by the rate of frost penetration. He concluded that, at constant load on the soil, the rate of heave is independent of the rate of freezing. The U.S. Army Corps of Engineers [2] stated the same conclusion, but specified that it was only valid for the range of freezing rates employed in its investigation. Loch [3] found no dependence between the rates of heave and heat extraction in many of the soils tested in his study. He emphasized that his conclusion was only valid for the range of heat extraction rates used in his experiments.

Kaplar [4], on the other hand, concluded that the heave rate is dependent on, or controlled by, the rate of heat extraction. Kaplar's conclusion was supported by experiments performed by Penner [5] establishing that the ice segregation efficiency ratio proposed by Arakawa [6] (the segregational heave rate) was strongly dependent on the rate of heat extraction.

Horiguchi [7] presented data for powder materials that showed that the total heave rate is strongly dependent on the rate of heat removal. Furthermore, different forms of this relationship were obtained for different types of powdered zeolites depending on the particle size. Finally, Loch [8] studied five Norwegian silty soils and found that the rate of heave obtained by freezing saturated, unloaded soil does depend on the net rate of heat extraction. He also established that a maximum heave rate is obtained at a certain value or range of heat extraction rates.

HEAT TRANSFER IN FREEZING SOILS

When a sudden step temperature below freezing is applied to the surface of a soil sample, unsteady heat flow is initiated. The progress of frost front into the soil is a function of the imbalance of the heat supplied to the heat removed. Heat associated with cooling is negligible compared to that associated with the latent heat of freezing water.

When a wet soil is subjected to freezing, the liquid-solid phase change involves two simultaneous processes. Pore water in the soil freezes in situ at the "in situ" freezing temperature, T_i, and water supplied from the unfrozen soil, or possibly an external source, is sucked to the freezing front where it freezes at the segregation freezing temperature, T_s. The second process usually leads to the development of ice lenses in saturated soils. For fine grained soils, depending on their frost susceptibility, T_s may range from about $-0.05°C$ to $-0.50°C$. In some clays, T_s can eventually be below $-0.5°C$. For many soils the in situ freezing temperature is close to 0°C and is primarily affected by pore size, as T_i refers to the warmest temperature at which ice can penetrate a pore. Both T_s and T_i are also dependent on solute concentration.

Satisfying both continuity of temperature and heat flux at each boundary results in Equation (1) at the T_i isotherm and Equation (2) at the T_s isotherm:

$$\left(\frac{\partial T}{\partial z}\right)_{fr^-} K_{fr}^- - \left(\frac{\partial T}{\partial z}\right)_u K_u = wL \frac{dX}{dt} \qquad (1)$$

$$\left(\frac{\partial T}{\partial z}\right)_f K_f - \left(\frac{\partial T}{\partial z}\right)_{fr^+} K_{fr}^+ = \nu L \qquad (2)$$

where K_f, K_{fr}, K_u represent respectively the thermal conductivities of the frozen layer, the frozen fringe between T_s and T_i and the unfrozen soil. w is the initial volumetric moisture content of the soil, T is the temperature, $\frac{dX}{dt}$ is the frost penetration rate, z is the depth, L is the latent heat of fusion of water and ν is the water intake rate.

Since the abovementioned freezing processes are operative simultaneously and continuously, and considering continuity of heat flux in the frozen fringe, Equations (1) and (2) can be combined as:

$$\left(\frac{\partial T}{\partial z}\right)_f K_f - \left(\frac{\partial T}{\partial z}\right)_u K_u = \nu L + wL\frac{dX}{dt} \qquad (3)$$

The left-hand term in Equation (3) is the net heat extraction rate, and represents the heat flow out of the sample minus the heat flow into the sample.

FROST HEAVE VERSUS HEAT EXTRACTION RATE

Total heave rate, $\dot{h}$, is the sum of the segregational heave rate, $\dot{h}_s$, and the heave resulting from the volume expansion of pore water by in situ freezing. The latter is related to the frost penetration rate. Segregational heave rate, $\dot{h}_s$, is related to the water intake rate as:

$$\dot{h}_s = \frac{V_i}{V_w} \nu \qquad (4)$$

where V_i and V_w represent respectively the specific volumes of ice and water.

Combining Equations (3) and (4):

$$\dot{h}_s = \frac{V_i}{V_w} \left[\frac{\dot{q}}{L} - w \frac{dX}{dt}\right] \qquad (5)$$

where $\dot{q}$ is the net heat extraction rate.

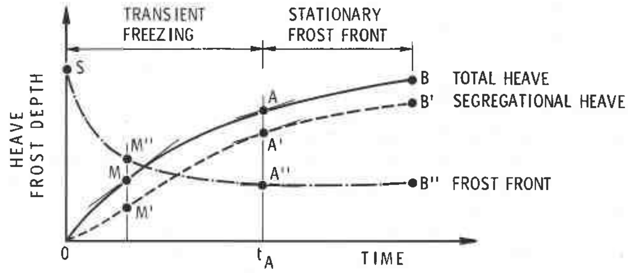
Total heave rate is obtained as:

$$\dot{h} = \frac{V_i}{V_w} \left[\frac{\dot{q}}{L} - w \frac{dX}{dt}\right] + (V_i - V_w)\, w \frac{dX}{dt} \qquad (6)$$

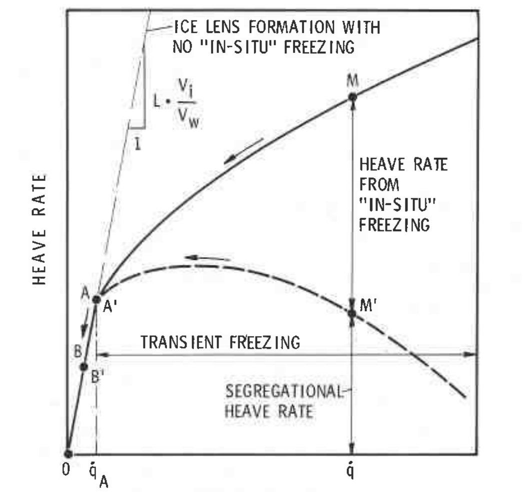
When conducting freezing tests in the laboratory, it is standard procedure to measure temperatures within the sample, water movement to the freezing front and total heave versus time. Any freezing test can therefore be characterized adequately at any time t by total heave, segregational heave and position of the 0°C isotherm. Figure 1(a) represents a typical result of a freezing test under constant thermal boundary conditions. Unsteady heat flow persists as long as the frost front continues to penetrate, i.e., from S to A". A period of stationary position of the 0°C isotherm follows, during which a major ice lens grows until testing is stopped at points B, B' and B".

For a given soil and temperature boundary conditions, it is also possible to characterize the entire freezing process by the relationship between the net heat extraction rate, total heave rate and segregational heave rate, as shown by Equations (5) and (6). Using the example given in Fig. 1(a), this particular freezing test will be characterized at any time t by the net heat extraction rate $\dot{q}$ obtained from Equation (3) and by the slope of the tangent at points M and M' of the total and segregational heave curves respectively. For fixed thermal boundary conditions, the net heat extraction rate decreases steadily with time. Therefore, points M and M' in Fig. 1(b) move respectively on two loci from the right to the left during transient freezing. During this phase the rate of water migration affects the thermal balance within the soil as latent heat is released during freezing. Thermal balance at any time t then determines the rate of in situ water freezing. The vertical distance between the two loci may be viewed as a measure of the frost penetration rate at the various heat extraction rates.

At point A, thermal balance is such that no further in situ water freezing is required. In Fig. 1(b), the two curves representing total and segregational heave rates merge, and dX/dt is then equal to zero. For $\frac{dX}{dt} = 0$, Equations (5) and (6)



a) CONVENTIONAL GRAPH



b) HEAVE RATE VS NET HEAT EXTRACTION RATE

FIGURE 1

CHARACTERIZATION OF A FREEZING TEST WITH RESPECT TO THE NET HEAT EXTRACTION RATE indicate that the total heave rate and segregational heave rate are equal and that they are linearly related to the net heat extraction rate. The slope of this particular line is $(V_i/V_w)(1/L)$. At point A the frost front reaches its maximum penetration in the soil. If the rate of heat extraction obtained at this point is maintained constant, by changing the cold step temperature for example, the rate of heave will also remain constant. Furthermore, the frost front will remain stable. The representative point of this freezing condition, then, is still point A.

On the other hand, if the temperature boundary conditions are maintained constant with time, water migration and growth of the final ice lens contribute to changes in height of the specimen. The temperature gradients decrease slowly but steadily with a concomitant decrease in net heat extraction rate. The representative point of such freezing will move along the straight line towards the origin. For the test represented by Fig. 1(a), the freezing is stopped at point B. It is noteworthy to stress that all representative points located on this line correspond to the growth of a single ice lens, its formation rate being dictated by the rate of heat removal. Another ice lens will only be generated as a result of a change in net heat extraction larger than $\dot{q}(A)$ that would only be possible with a change in thermal boundary conditions.

If sufficient freezing time is available, the representative point of the freezing condition (fixed temperature boundary conditions) may ultimately reach the origin where both the net heat extraction rate and the heave rates are zero. In the case of a solute free, saturated, unloaded soil, the above condition means that the temperature at the base of the ice lens is 0°C and the pressure in the liquid-like water film adjacent to it is atmospheric, i.e., no more driving potential for mass transfer, and the sample reaches true thermal steady state. It must be emphasized that increasing solute concentrations beneath the ice lens by solute rejection could produce a condition of no water flow to the current ice lens at a positive net heat removal rate. This, in turn, may result in slight temperature adjustments without freezing in order to attain true thermal steady state.

TESTING PROCEDURE

The freezing cell used during this investigation has been described by Konrad [9]. Thermistors were placed in the side of the wall of the cylindrical cell to measure the temperature distribution in the soil sample. The cell was heavily insulated and placed in a cold room at +0.5°C. Testing was carried out using Devon silt, which is highly frost- susceptible. The properties of Devon silt are as follows:
liquid limit = 46%; plastic limit = 2%; specific gravity = 2.70; percentage passing #200 = 95%; and percentage clay size (≤0.002 mm) = 28%.

The samples were prepared by consolidating a slurry to a pressure of 210 kPa. After primary consolidation was complete, each sample was placed in the freezing cell where it rebounded under zero load. The saturated samples were frozen in the axial direction either from the top down or from the bottom up. Water was supplied freely at the warm end. When a sample froze downwards, the top plate was maintained at a constant temperature below 0°C and the bottom plate was held at a particular temperature above 0°C. Freezing progressed in each case to steady state condition, i.e., a stationary frost front. Thus a period of decelerating frost penetration was obtained during each test, followed by a period of stationary frost front, during which a major ice lens could grow. The temperature profile, water movement into the sample, and total heave versus time were monitored with a data acquisition system.

RESULTS

Freezing Tests with Constant Thermal Boundary Conditions

Table 1 summarizes the thermal and geometrical conditions of different freezing tests with no externally applied load. Figures 2 to 5 illustrate typical results obtained from this test series. As shown in Figs. 3 and 5, the measured temperatures were linear through the samples for the steady state condition, confirming one-dimensional heat flow. Owing to the small height of the samples, the temperature distribution during transient heat flow was also linear in both frozen and unfrozen soil layers as shown in Fig. 3. Net heat extraction rates were readily obtained from the thermal conductivities of the unfrozen and frozen silt, which were respectively 1.47 mW/(mm°C) and 1.76 mW/(mm°C).

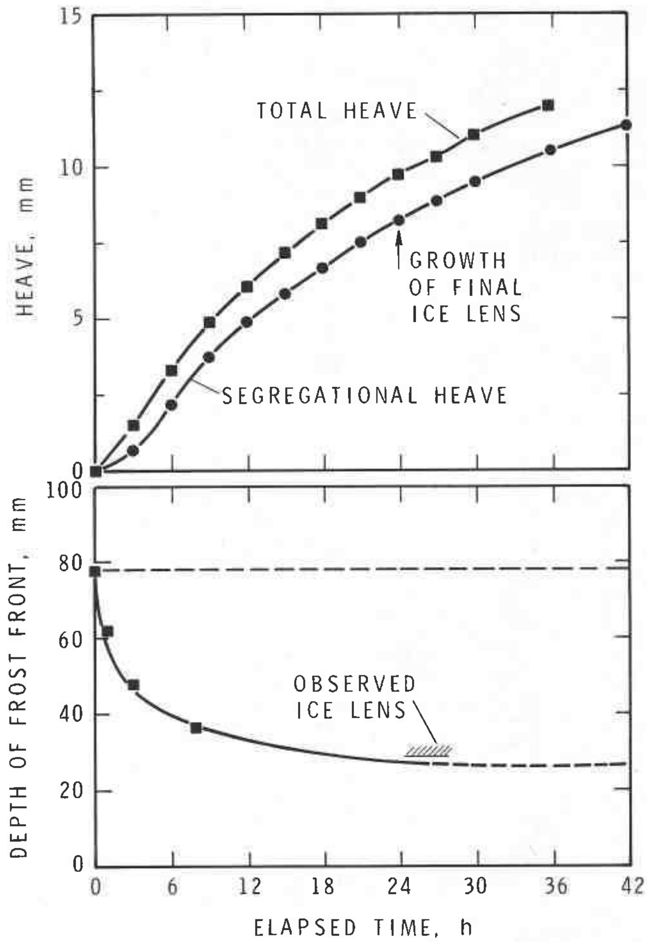


FIGURE 2

EXPERIMENTAL RESULTS FROM TEST E4

Table 1. Summary of Freezing Test Conditions

Test	T_W (°C)	T_C (°C)	Initial Height (cm)
NS-1	+ 1.1	- 3.4	10.4
NS-4	+ 1.1	- 2.5	7.6
NS-5	+ 1.1	- 6.2	10.0
NS-7	+ 1.1	- 3.5	12.0
NS-9	+ 1.0	- 6.0	28.0
E2	+ 3.5	- 3.6	13.5
E4	+ 3.0	- 5.5	7.8
E6	+ 0.4	- 3.5	7.1
E7	+ 2.0	- 3.5	7.0

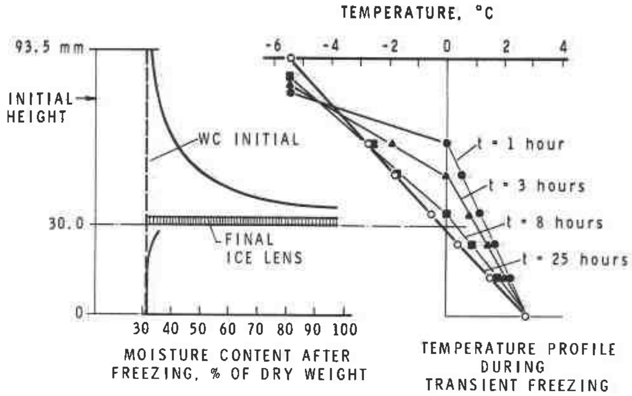


FIGURE 3

RESULTS FROM TEST E4

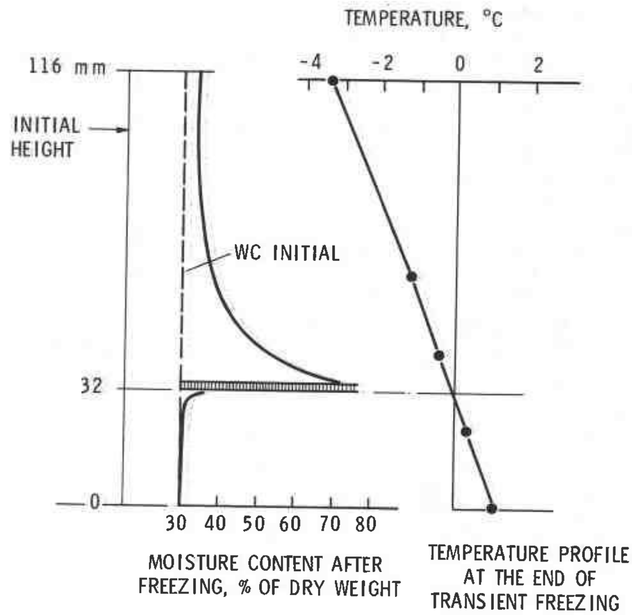


FIGURE 5

RESULTS FROM TEST NS-1

Figure 6 summarizes the curves of net heat extraction rate versus water intake flux and Fig. 7 presents total heave rate versus net heat extraction rate.

Figure 6 shows that each sample experienced a wide range of heat extraction rates during each freezing test. Furthermore, it is striking that a limiting rate of heat removal exists at which no water flow to the freezing front is possible. For Devon silt, this limiting rate of heat extraction is approximately between 0.35 and 0.45 mW/mm^2. Within the range of heat extraction rates of 0.5 to 0.1 mW/mm^2, the rate of

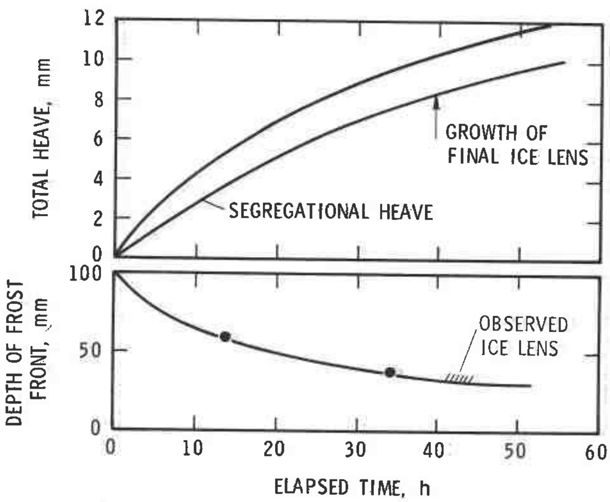


FIGURE 4

EXPERIMENTAL RESULTS FROM TEST NS-1

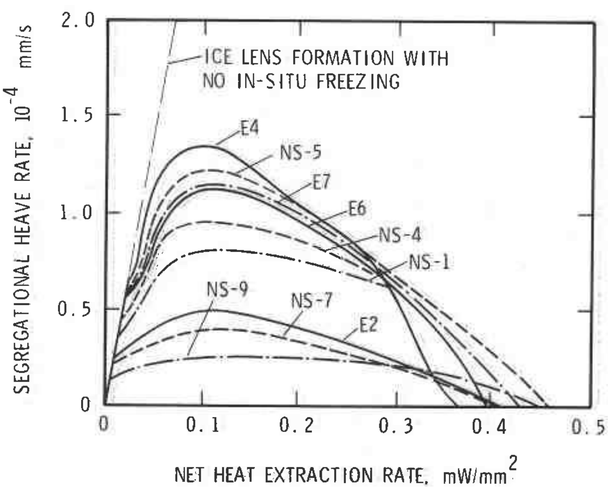


FIGURE 6

SEGREGATIONAL HEAVE RATE VERSUS NET HEAT EXTRACTION RATE FOR DEVON SILT

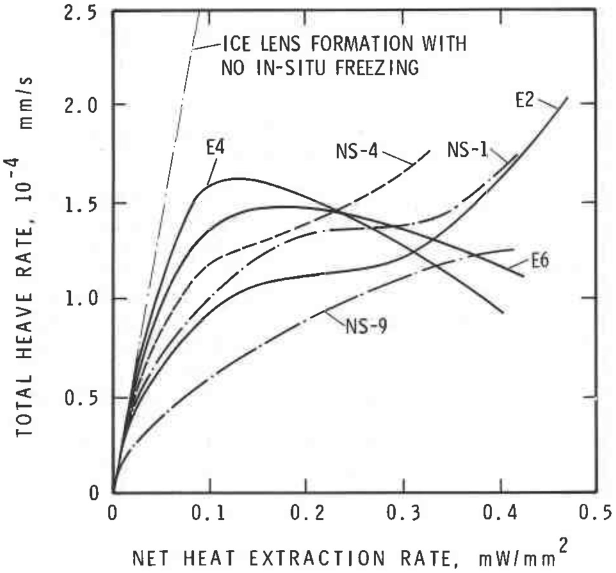


FIGURE 7

TOTAL HEAVE RATE VERSUS NET HEAT EXTRACTION RATE FOR DEVON SILT

moisture flow into the sample increased as the rate of heat removal decreased. In all freezing tests, a maximum water migration rate was obtained for a rate of heat removal of about 0.1 mW/mm^2. For rates of heat extraction between 0 and 0.1 mW/mm^2, the rate of moisture migration decreased with decreasing rates of heat removal. As no further frost advance occurs, all the curves characterizing each freezing test intersect the straight line corresponding to the final ice lens formation condition. As discussed earlier, the representative point of the freezing soil is then moving on this line toward 0 if the net heat extraction rate still continues to decrease. It is striking that for the same soil, different segregational heave rates were obtained for the same rate of heat removal during the whole phase of transient freezing. Furthermore, the different freezing conditions of the present series resulted in different positions of the representative point when the frost front became stationary. The general shape of these curves, however, is the same for all tests.

Another important feature is the difference in shape of the curves characterizing the dependence on heat extraction rate of the total heave rate and the water intake flux. This arises from the fact that the shape of the total heave rate curves depend on the rate of frost advance and the amount of heat released by the migratory water as it freezes at the segregation freezing level. Particularly, at the beginning of freezing when the water intake flux is relatively small, total heave rates are then mainly dictated by the rate of frost penetration. Therefore, various shapes of total heave rates versus net heat extraction curves will be obtained, depending on the freezing conditions. In some tests the total heave rate decreased steadily with decreasing heat extraction rates. In others, an initial decreasing rate was followed by a relatively constant value for heat removal rate between 0.15 and 0.30 mW/mm^2. The heave rate then decreased until the curve intersected the line corresponding to ice lens formation without further frost advance. Tests which induced high moisture flow rates combined with a relatively small frost penetration rate were characterized by an increasing heave rate to a maximum, followed by a decreasing rate for the remaining phase of transient freezing. The various shapes obtained for Devon silt compare quite well with those obtained by Horiguchi (1978) for various types of zeolites. The above results show a strong dependence of the relative amounts of segregational heave and in situ heave on the way each specimen was frozen. Seeking a relationship between total heave rate and heat extraction rate, as is done by most of the researchers, will inevitably lead to apparently contradictory results.

<u>Freezing Test with Constant Net Heat Extraction Rate</u>

One soil sample was frozen under fixed temperature boundary conditions for about 24 hours. By that time, the frost front was stationary for about 10 hours and the final ice lens was a few millimeters thick. During the following 24 hours, the temperature gradient in the frozen zone was maintained constant by manually lowering the cold-side temperature according to the amount of measured heave. The warm-end temperature was maintained constant during the entire process. Equation 2 shows that the water intake rate, and consequently the heave rate, are constant if the net heat extraction rate is constant. Figure 8 shows that the measured heave rate during that second phase, in which the heat flux out of the sample was approximately constant since the temperature gradient near the cold side was maintained constant, is constant. Moreover, as soon as the temperature boundary conditions are

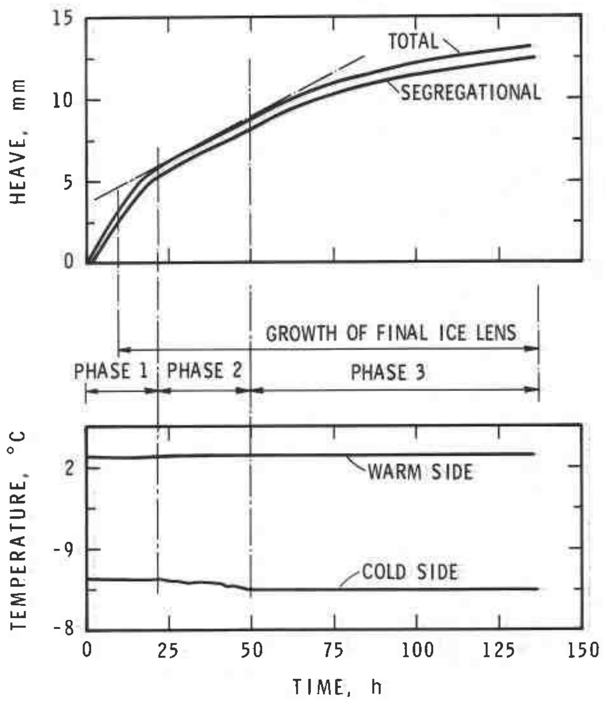


FIGURE 8

EFFECT OF NET HEAT EXTRACTION RATE DURING ICE LENS FORMATION WITH NO IN-SITU FREEZING again constant with time, the representative point moves slowly towards zero and the rate of heaving decreases slowly with time.

DISCUSSION

The results presented in Figures 6 to 8 demonstrate clearly that the rate of frost heave of saturated, unloaded soil depends on the net rate of heat extraction from the soil. However, net heat extraction rate does not appear to be the only variable influencing the heave rate since several values of heave rates have been obtained for the same soil and at a given rate of heat removal. Konrad and Morgenstern [10,11,12] established that frost heave during transient freezing for unloaded soils was also dependent upon the suction at the frost front and the overall temperature gradient in the frozen zone near the freezing front.

Loch [8], considering that the rate of heat extraction is the independent variable in the frost heave process, proposed to perform freezing tests at a standard rate of heat extraction rather than at a standard rate of frost penetration. Because the rate of heat extraction is dependent on the thermal conditions and the thickness of the frozen and unfrozen layers, it cannot be an independent variable in the frost heave process. Therefore, conducting freezing tests at a rate of heat removal consistent with field data, without considering the abovementioned variables, may not result in a proper frost heave simulation. Konrad and Morgenstern [10,11,12] relate the degree of thermal imbalance during transient freezing to the rate of cooling of the frozen layer near the 0°C isotherm. The rate of cooling is defined as the change of temperature per unit time at the frost front as illustrated in Fig. 9. It can be calculated as:

$$dT/dt\ (0°C) = \text{grad}\ T \cdot dX/dt \qquad (7)$$

This variable has the advantage of combining both the geometrical and thermal conditions of the freezing system.

Konrad and Morgenstern [13] also established that a standard freezing test may be carried out with fixed temperature boundary conditions in which the frost heave rate obtained at the onset of a stationary frost front is measured. Because the temperature gradients in the field are significantly smaller than those used in most laboratory tests, the rate of cooling in the field during transient freezing (Equation 7) is very close to that obtained in a laboratory test near steady state. Konrad and Morgenstern [13] showed then that the ratio of segregational heave rate and temperature gradient in the frozen soil near 0°C was the same in both cases.

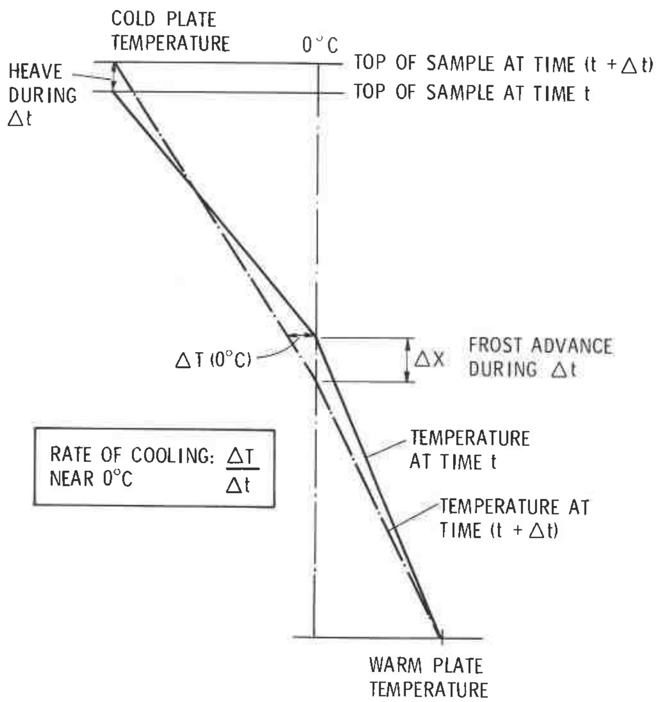


FIGURE 9

RATE OF COOLING NEAR THE CURRENT FROST LINE

CONCLUSION

During transient freezing, i.e., advancing frost front, the rate of heave in an unloaded soil is a function of the net rate of heat extraction. For Devon silt and constant temperature boundary tests, maximum segregational heave rates (heave resulting from freezing of intake water) occurred at net heat extraction rates of about 0.1 mW/mm^2 independently of the initial thermal conditions. A critical rate of net heat extraction rate at which no water flow occurred into the sample was obtained for heat removal rates between 0.35 and 0.45 mW/mm^2 for all the freezing tests.

For the same soil, however, different values of the segregational heave rate was measured for a given net heat extraction rate indicating a dependency of the frost heave variables on the way the soil is frozen. It may not be possible, therefore, to obtain consistent relationships between total heave rate and net heat extraction rate for a given soil.

It can also be concluded from the results of the laboratory study that when the frost line is stationary, the heave rate is essentially proportional to the net heat extraction rate.

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