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BY

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FROST-HEAVING IN SOILS

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A literature survey shows that present interest in frost action research is focused on thermodynamic properties of the ice-water interface. This aspect of the freezing process is a fascinating field for research and much progress is being made, but there are many other equally important aspects, when ice-lensing is involved in the freezing process, that have not been investigated since the studies of Taber [1] and Beskow [2].

To draw attention to a much wider field in the problem of frost-heaving, this conference may be an appropriate occasion to summarize some work carried out since 1955 by the Division of Building Research, National Research Council of Canada. These studies have included changes in soil structure from ice segregation, characteristics of moisture flow and potentials induced, heaving pressures produced by frost action, dependence of unfrozen water content on temperature and soil type, ice proliferation rates in water and in growth retarder solutions, heat and moisture balance during ice-lensing, some observations on the structure of ice in lenses, and the freezing process in porous systems.

ICE-LENSING

The formation of ice-lenses as a major cause of frost-heaving in soils is well established, although the 10% phase change expansion also adds significantly to the total heave. In providing space for ice as the lens grows, work must be done to lift overburden and any surface surcharges. The necessary supply of water is obtained from surrounding soil or ground water, and so further work is done to establish and maintain a potential gradient in soil water. The available work by the freezing process must be divided therefore between these two processes which occur simultaneously.

Ice-lenses usually form parallel to the soil surface along an isothermal freezing plane so that the expansion and heaving pressures are always in the direction of heat flow. The lateral extent of one lens depends on the homogeneity of solid material and the uniformity of water supply and temperature gradient. The thickness of the lens, however, is a rate-dependent phenomenon that varies between soils but is always contingent on the balance between moisture supply and heat flow.

When, therefore, potential water supply is equal to or exceeds the existing heat removal rate, the lens will continue to grow at one site indefinitely. When heat removal rate temporarily exceeds moisture supply, temperature at the lower face of the ice-lens decreases; a new location for growth may be established when a more favorable water supply is encountered by the freezing front. As these events are repeated, they result in rhythmic ice banding.

Heat removal rate can be increased to a point where a uniform distribution of ice occurs throughout the frozen soil behind a continuously penetrating frost line, but at the same time, water is being moved to the freezing zone so that heaving still occurs. Finally, in the case of a quick freeze, heaving is reduced to the 10% expansion when freezing is too rapid for the movement of soil moisture, and hence only the in situ water freezes.

STRUCTURE OF ICE IN LENSES

It is of considerable interest to note the conformation of ice-lenses. When grown in soil with a carefully controlled environment of temperature, pressure, and water supply, the structure of the lenses were not as uniform as anticipated [3]. Ice grains were elongated in the direction of heat flow, but different optical orientations were often observed in adjacent crystals. Optical orientation was determined by etching a freshly polished ice surface. Fig. 1 shows soil structure formed, ice distribution, and shape of the freezing front in an ice-lens. Fig. 2 shows the disorder of the etch pits on the horizontal face of the ice-lens. In Fig. 2 the heat flow is perpendicular to the plane of the paper. The c-axis (crystal axis), lower crystal is almost parallel to the heat flow; the upper crystal is at about a 45° angle to the heat flow. Although randomness is apparent in all lenses examined, the studies were not statistical enough to establish firmly the degree of disorder.

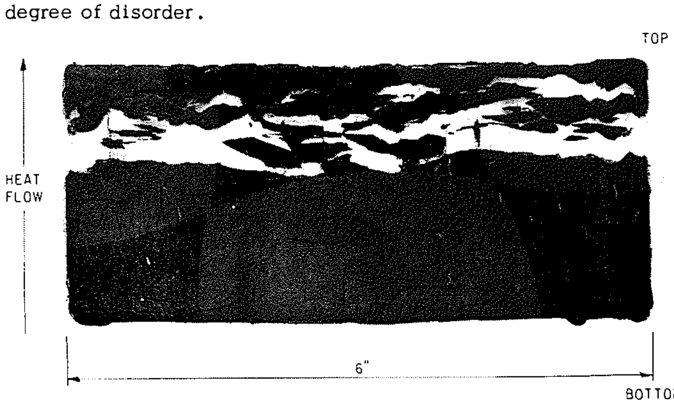

Fig. 1. Vertical slice of clay specimen after unidirectional freezing

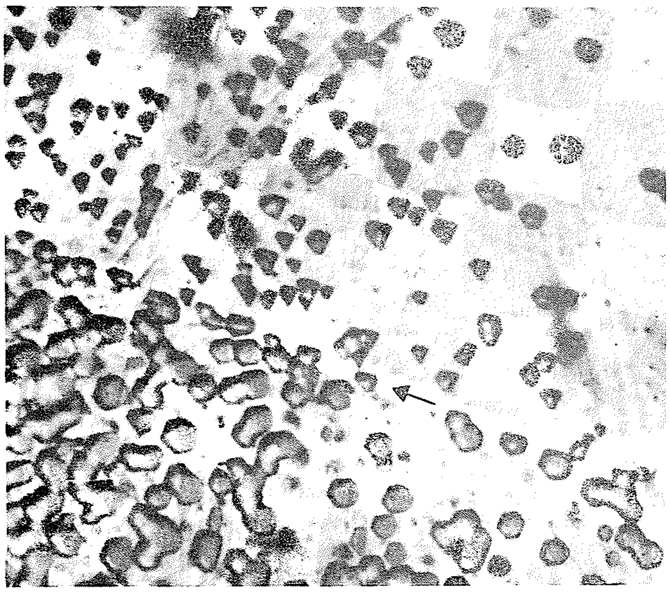

Fig. 2. Crystal boundary of ice-lens indicated by arrow

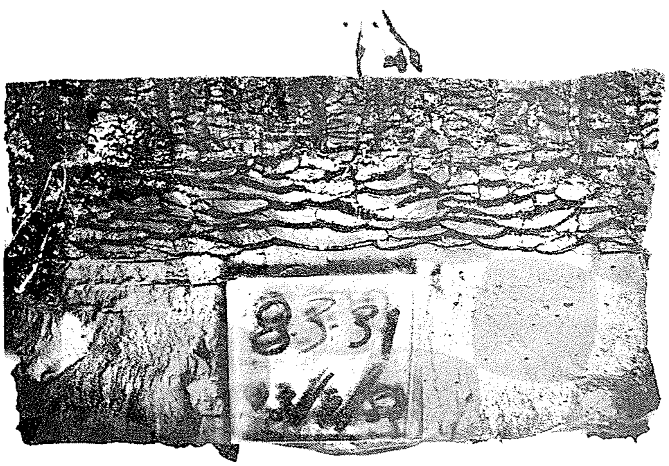

Fig. 3. Laboratory-produced ice-lensing in silty clay

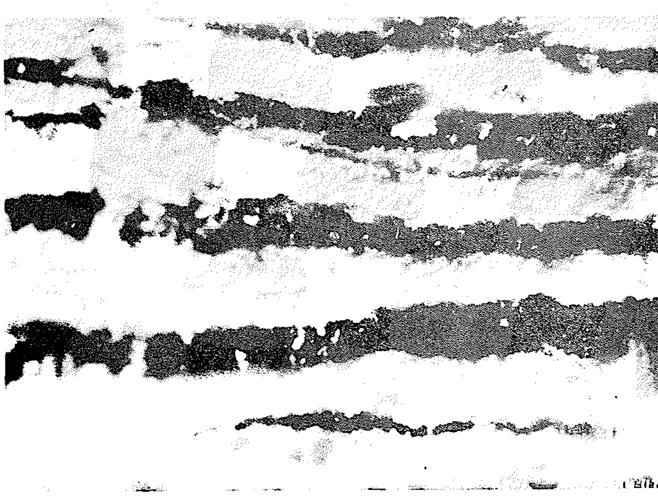

Fig. 4. Ice-lenses (dark) in silt (light)

Crystal orientation was usually different above and below the soil occluded in the ice-lens. Non-unidirectional heat flow around occluded soil, may have contributed to the randomness observed.

Growth rate of ice in a pure melt is greatest in the direction normal to the c-axis during free growth [4]. This may be responsible for the change in structure with depth of unidirectionally frozen ice starting with random nucleation at the water surface. The grains oriented with the c-axis normal to direction of heat flow gained preference at the expense of all other directions of orientation [5]. This preference was not observed in the ice formed by lensing in soil.

SOIL STRUCTURE FORMATION

There are important differences in the structure of frozen soil and in the disposition of ice and soil resulting from the ice segregation processes in different soil types [6]. The convex shapes of the lower face of occluded structures and the undulating freezing front in clays (Fig. 3) are in sharp contrast to the more uniform size of soil strata between ice-lenses common in coarser frost-susceptible soils (Fig. 4) [7]. When the frost line is advancing in clays, the shrinking process, due to local water removal by ice growth, appears to dominate the shape of the particle plucked away from the freezing front and occluded in the ice. The lower face, which is normally convex, is thought to be a result of uneven shrinking, leaving an irregular freezing front even though unidirectional heat flow conditions are carefully maintained for the sample as a whole. Suction potential developed in clays is high, but the permeability is low; this accounts for the local shrinkage and hence the kind of structure observed.

INDUCED SUCTION, HEAVING PRESSURES, AND MOISTURE FLOW

Moisture in the liquid phase can flow through constrictions between adjacent pores more easily than ice can proliferate through the same porous system in the temperature range normally encountered during soil freezing. This is the basic reason why ice crystals grow in pores. If the pores are small enough, the crystals develop into ice-lenses, although water in pores directly beneath may be below 0°C. This water would crystallize if seeded, but is not cold enough for spontaneous nucleation.

Soils have a low strength in tension and unless there are confining pressures due to overburden or superimposed surcharges, the crystal is almost free to grow within the restrictive limits of water supply assuming appropriate thermal conditions. Transfer of water from the film surrounding the soil particle to the ice crystal appears to remove the molecule from the sphere of attraction by the particle. This changes the moisture potential and sets up a suction gradient in soil water.

If induced suction is of sufficient magnitude to overcome capillary pressures, it may empty larger pores and thus the soil desaturates. This decreases the cross-sectional area of the flow path and reduces the permeability coefficient below the value for full flow. The characteristics of change in the unsaturated permeability depend on the properties of the material such as pore-size range, pore-size distribution, and nature of the solid. In view of the suction-permeability interdependence it is obviously not correct to use saturated permeability coefficients for predicting heaving rates.

Development of suction during freezing in a closed system containing Potter's flint at almost no overburden pressure is shown in Fig. 5. In the same material the development of heaving pressures was followed while the system was kept fully saturated. When heaving ceased, the suction in the soil water was zero. In both cases, the system was initially saturated and a small ice-lens was allowed to develop before the experiment was started. The importance of this is accounted for by Everett [8].

The final moisture content in the suction experiment (Fig. 5) was much below the saturated conditions maintained in the heaving pressure experiment; that is, as a suction developed, the flint samples desaturated, a phenomenon not uncommon in the field.

Thus, Fig. 5 demonstrates two methods for reducing ice-lensing to zero—of course, heaving can be stopped also by the simultaneous application of suction and overburden pressure. It is believed that forces responsible for heaving and induced suction can be accounted for by considering only the geometry of the porous material, provided it is hydrophilic in nature.

UNFROZEN WATER CONTENT OF FROZEN SOILS

Ice-lensing activity in soils is generally assumed to be restricted to the plane separating the completely unfrozen soil and the lowest ice-lens. Although this may be the plane of greatest heaving activity, since in heavier soils layers between successive lenses are frequently soft and apparently unfrozen, it lends weight to the conclusion that several ice-lenses, one above the other, may be increasing in thickness concurrently but at different temperatures. It is obvious from Fig. 6 and from similar results given elsewhere [9] that simultaneous growth of several lenses, one above the other, may be quite general since the water in natural soils freezes over a temperature range, but the simultaneous growth of several lenses is probably most pronounced in clays. During the season of heat loss from the soil—when frost-heaving occurs—the temperature in the soil increases with depth. Hence, other things being equal, the smallest unfrozen moisture content would be near the surface.

The process whereby successive ice-lenses become established has not been determined, but there are at least two possibilities: (1) "Seeding" of the new location occurs by ice proliferation through the larger pores until a stable balance of heat and moisture flow is reached; or (2) as the temperature drops at the ice-soil interface due to natural processes, spontaneous nucleation may occur ahead of the previous ice-lens in larger water filled pores leaving a layer of unfrozen soil between successive ice-lenses. It is, therefore, of some interest to look briefly at some aspects of ice proliferation in its own melt.

ICE PROLIFERATION RATES IN SOLUTION

Dentritic ice proliferation rates have been measured in pure water and various aqueous solutions [10]. The growth rate in a particular solution is not predictable, except that it is known in a general way that aqueous organic solutions are more effective retarders of growth of ice than inorganic solutions.

Ice proliferation rates were measured in small, thin-walled glass capillaries filled with solutions of various concentration [11, 12] to study how injecting solutions into the pore water of soils affects frost-heaving. Within the heat-dissipation limits, rates were realized to be relative rather than absolute [13]. The majority of experiments were in solutions of calcium lignosulfonate, a byproduct of wood pulping by the sulfite process. The attenuation of proliferation rate is shown in Fig. 7 as a function of supercooling for water and aqueous solutions of sulfite liquor up to 50% concentration.

Although ice proliferation in these experiments was by dentritic growth and therefore not entirely similar to ice-lens growth in soil, the effectiveness of field injections with this product agrees with the results of the laboratory experiment. Some conclusions based on these results are: (1) That altering the ice growth characteristics of soil water may be a useful approach to pursue for diminishing frost-heave rates; (2) the effectiveness of the retarder is not related to its "antifreeze" characteristics since the sulphite liquor (50% concentration) lowered the freezing point by less than 3°C (this is also substantiated by freezing point and proliferation studies in both high and low molecular weight fractions in the liquor [12]); (3) the character of ice proliferation rates studied in the presence of large molecules should be extended to channels between solid particles and the pores of porous solids.

HEAT AND MOISTURE BALANCE DURING SOIL FREEZING

Simultaneous measurement of heat flow, moisture movement, and heave during freezing has been useful in identifying some of the significant factors that should determine a realistic laboratory frost susceptibility test for soils [14]. The apparatus was designed to ensure unidirectional heat flow that could be measured by heat transducers at both ends of the specimen. It has, therefore, been useful also in measuring the thermal conductivity of soils [14, 15].

The dominating influence of heat flow on the heaving rate was evident for all soils. Three distinctly different rates of heat extraction from specimens were imposed during one experiment. The response in moisture flow closely followed changes in net heat flow. Three soils, varying widely in many characteristics, responded similarly (Fig. 8). The conclusion is that it is misleading to assess frost susceptibility of different soils (for field use) in the laboratory with the same frost line penetration rate. Different soil types would not freeze at the same rate under similar climatic conditions because of differences in thermal conductivity, water supply, in situ water content, etc.

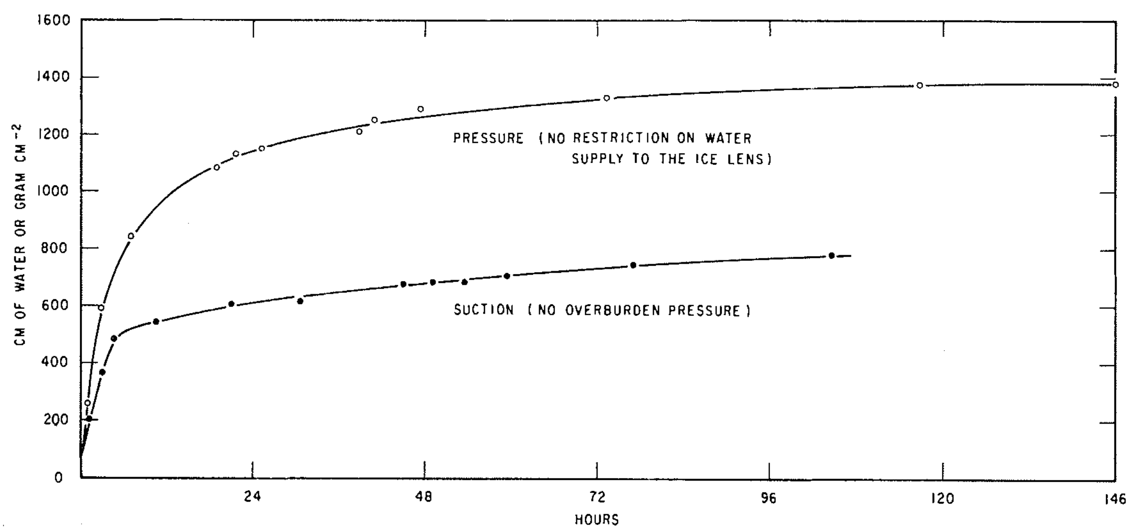

Fig. 5. Development of suction and heaving pressure in Potter's flint

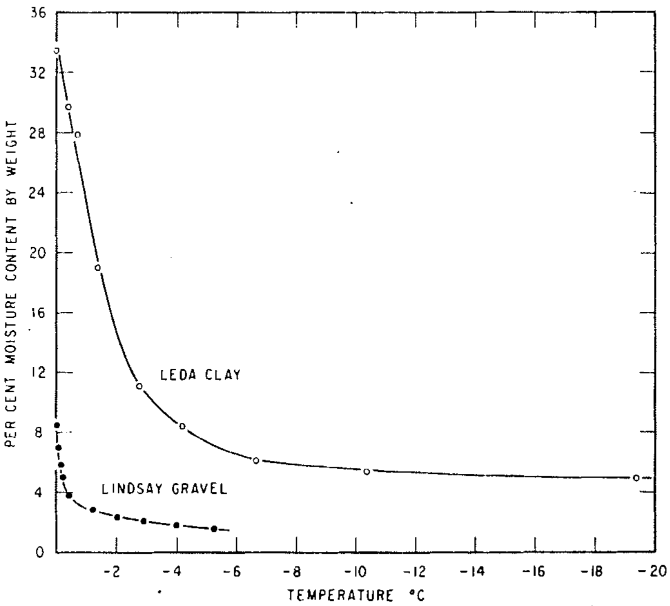

Fig. 6. Unfrozen moisture content versus temperature

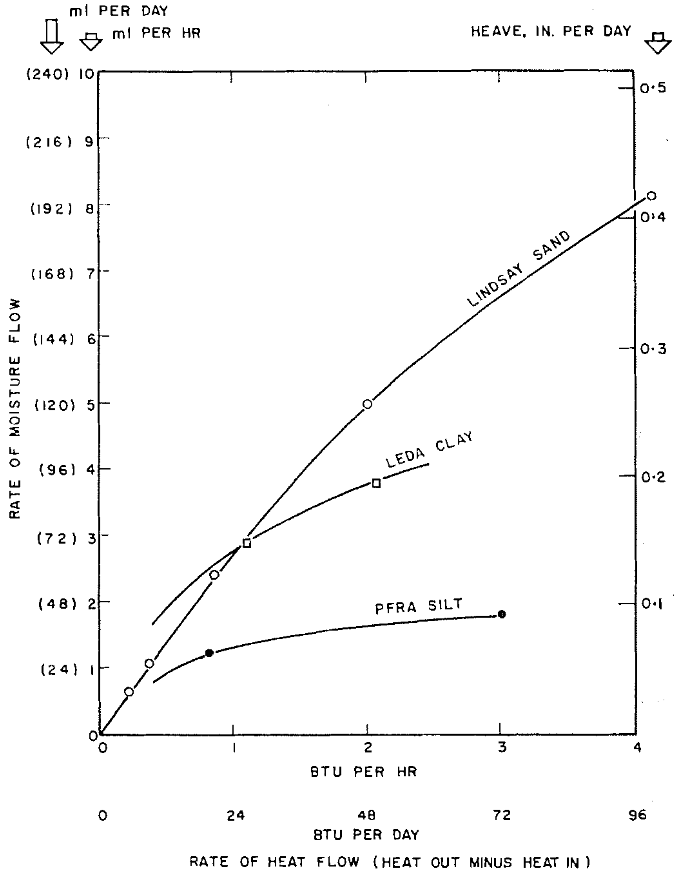

Fig. 8. Rates of moisture flow and heave versus net heat flow

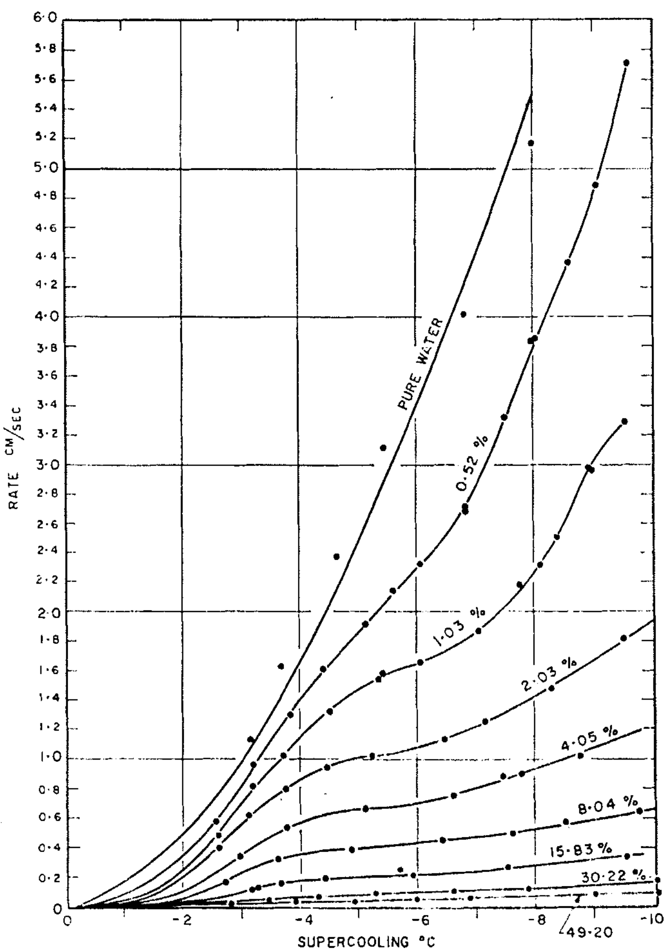

Fig. 7. Rate of linear ice crystallization versus supercooling at different concentrations of sulfite liquor

A uniform heat extraction rate consistent with the average field condition appears to be the more realistic approach for evaluating the frost susceptibility of different soils in the laboratory. Further, these experiments showed that freeze-thaw cycles are not a requirement for ice-lensing [16], as some still believe. Confusion arises from the fact that freeze-thaw cycles do have the effect of "pumping" water in successive steps to one plane in the soil. This wider separation at one plane can be particularly destructive to plant root systems.

FREEZING OF WATER IN PORES: EXPERIMENT AND THEORY

Thermodynamic properties of water freezing in pores and causing frost-heaving have been discussed at length by Gold [17], Jackson and Chalmers [18], Everett [8], and in less specific terms by the author [19, 20, 21]. There is agreement on the nature of the process, but the treatment by Everett has been generally preferable. It states the problem simply and precisely, yet it is sufficiently comprehensive to be applicable to both unconsolidated and solid porous materials. It is of interest, however, to review some of the experimental facts on which the theory is based.

Earlier work [19] established that, starting from saturation, the amount of water available for ice-lensing and the maximum suction induced in a closed soil system below the zone of freezing was a function of the state of subdivision in granular material; both were greater for a clay than for coarser soils.

Measurements of the maximum heaving pressure, suction, and combinations of these in Potter's flint [20] at various densities do not appear to satisfy completely a self consistent theory. These experiments showed that the maximum heaving pressure in a fully saturated material was greater by a factor of approximately two than the maximum suction when heaving stopped. Such comparisons are of practical importance since soils in the field desaturate under suction as did the Potter's flint.

The active area at the ice water interface is now thought to decrease as desaturation takes place, emptying the larger pores. This may account for the suctions being lower than heaving pressures. As desaturation occurs the permeability is also greatly reduced, making equilibrium difficult to evaluate. In light of this, valid comparisons would seem to be possible only so long as the material stays fully saturated; nonetheless, in the field, desaturation cannot be avoided.

At equilibrium the rate of melting equals the freezing rate. Thus the free energy of ice equals the free energy of water at the ice water interface. It follows that the reversible condition is

$$v_i \, dP_i - s_i \, dT = v_w \, dP_w - s_w \, dT \qquad (1)$$

where i and w are the ice and water phases, v is specific volume, s is specific entropy, P is pressure, and T is temperature.

Rearranging and substituting Q_f/T for $s_w - s_i$, where Q_f is the latent heat of fusion per gram and considering finite changes, the expression becomes

$$\frac{v_w \, \Delta P_w - v_i \, \Delta P_i}{\Delta T} = \frac{Q_f}{T} \qquad (2)$$

Considering the freezing plane to be in a porous material [15] apparently permits three possible cases in the physical application of pressure to the two phases of atmospheric pressure: The pressure is on the ice only, thus the pressure change in water is zero and hence, $v_w \, \Delta P_w$ is zero; or the pressure is on the water only and the pressure change on the ice is zero and hence, $v_i \, \Delta P_i$ is zero; or the same pressure is applied equally to both phases, which was the case preferred previously by the author [21]. Hence,

$$\Delta P_{total} \, (v_w - v_i) = \frac{Q_f \, \Delta T}{T} \qquad (3)$$

Assuming that heaving pressures resulting from ice-lensing do not influence the pressure in the water phase, then $v_w \, \Delta P_w$ equals zero. Combining the resultant equation with the well-known form of the Thomson equation [22] leads to Everett's relationship which gives the limiting heaving pressure in terms of pore radius.

$$\Delta P_i = \frac{2\sigma_{iw}}{r} \qquad (4)$$

where r is the radius of the smallest constriction of the pore, and σ_{iw} is the interfacial energy. In the same way, in the case for zero pressure on the ice and negative pressures in the water, the limiting suction (ΔP_w is negative) is given by

$$\Delta P_w = \frac{2\sigma_{iw}}{r\rho_i v_w} = \frac{2.22 \, \sigma_{iw}}{r} \qquad (5)$$

where ρ_i is the density for ice.

Everett has made some estimates using the author's published results for Potter's flint. Based on this, along with other substantiating evidence for porous solids, he claims the theory to be consistent with experimental results at least for heaving pressures. A large pore-size range in the material is, however, a drawback in making rigorous comparisons of heaving experiments with theory.

Pressure measurements were made during early work on frost action in a frost cell apparatus [19] on two different size fractions of Potter's flint. The predominant pore sizes were determined by water release curves (Fig. 9). Fixing the pore radius of the finer material at 1.47 μ and at 25 erg/sq cm for σ_{iw}, (4) predicts a maximum heaving pressure of 350g/sq cm, whereas the actual measurement at saturation gave 400 g/sq cm. Taking 9μ as the predominant pore radius for the coarser fraction, the predicted value is 55 as against the measured value 23 g/sq cm. More substantiating evidence is still required but these results are of the right order.

As refinements are developed in measuring pressures and suctions associated with ice-lensing in porous material, a reliable value for σ_{iw} and how it is influenced by temperature and foreign matter will be of great assistance. At present, values from 10 to 45 erg/sq cm may be found in the literature. The difference between ice-water and air-water interfacial energy accounts for the lower pressure pore entry by ice, provided that the temperature is consistent with (2).

Finally, a point by Everett [8] should be stressed regarding the difference in pressure exerted by an ice-lens and that of an ice crystal confined in a pore. The value for 1/r in the equations above should be replaced by 1/r - 1/R where r is the radius of the constriction leading from the pore and R the largest radius of the pore. After the lens is established, R is large and the term 1/R may be neglected. Thus, the potential heaving pressures are always greater after the lens has formed—a point to remember in the study of deterioration of porous solids by frost action, which must break in tension before an ice lens can be established.

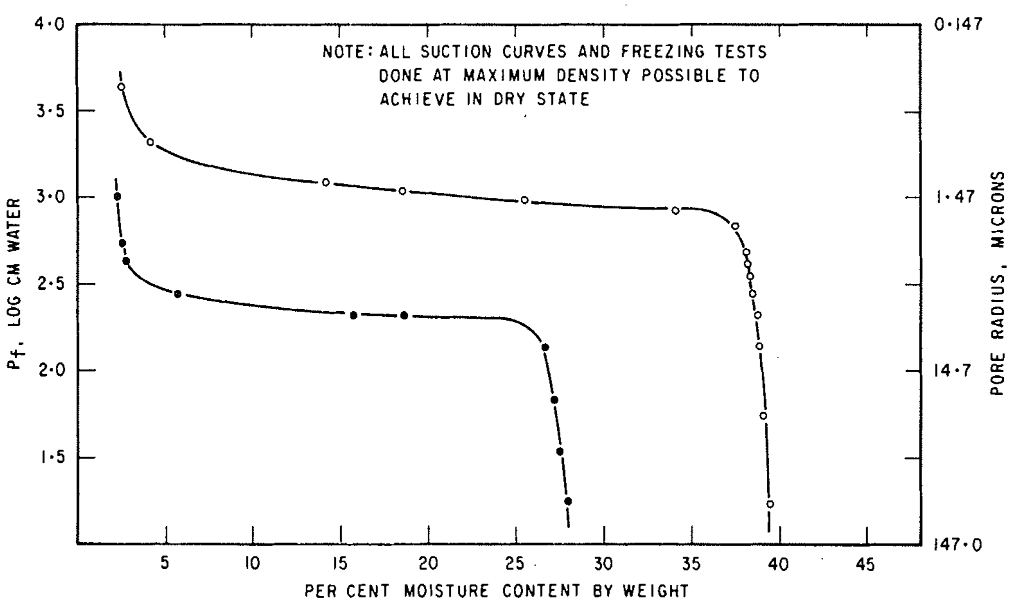

Fig. 9. Moisture release curves to determine the predominant pore radius of two fractions from Potter's flint

ACKNOWLEDGMENT

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