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Bulletin 225

Highway Pavement Design in Frost Areas, A Symposium: Part 1. Basic Considerations

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Highway Pavement Design in Frost Areas, A Symposium: Part 1. Basic Considerations

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University of Minnesota, Minneapolis

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Foreword

At its Annual Meeting in January 1958, the Highway Research Board Committee on Frost Heave and Frost Action in Soils included in its plans for future activities the sponsoring of a symposium on the subject "Highway Pavement Design in Frost Areas."

The objective of this symposium was to review, summarize and report the state of knowledge concerning the design of highway pavement in frost areas; treating individually the factors of temperatures, water, types of soils and materials, and the freezing mechanisms of soil-water systems; and relating these factors to the design problems associated with pavement surfaces, bases, subbases and subgrades, topography, highway cross-section and grade line, subsurface drainage, climate, and traffic weight and volume.

The purpose of the symposium was to provide for the practicing engineer, who is now confronted with the greatest highway program of history, a digest of current scientific knowledge that he may use as a guide in the solution of highway design problems in frost areas; and to provide for the research engineer and scientist information concerning practical highway design and construction problems in frost areas for use as a guide in experimental and investigational programs.

The information presented herein concerns the basic considerations of the frost action problem; namely, water temperature, soil, and the freezing mechanism of soil-water systems.

It is the intention of the Committee to present Part II of the symposium, dealing with design considerations, at a later date. Papers on this subject will attempt to relate the basic considerations of the frost action subject to design problems encountered in highway work.

George W. McAlpin, Chairman

Committee on Frost Heave
and Frost Action in Soil

The Mechanism of Frost Heaving in Soils

E. PENNER, Division of Building Research, National Research Council, Ottawa, Ontario

The "mechanism of frost heaving" involves the interaction of the three frost action factors: a water supply, a frost-susceptible soil, and below-freezing temperatures.

The propagation of ice between soil particles depends on pore size, that is, the smaller the pores and channels between pores, the lower the temperature necessary before the ice front can advance. This provides a means for supercooling the pore water beneath an actively growing ice lens. The subsequent release of energy in such systems is utilized to create a moisture suction gradient which induces a moisture flow to the ice front and also to develop a positive pressure to raise the overburden and provide a space for the ice lens. Consistent with the theory, it can be shown that compact clay soils, which have the greatest resistance to ice propagation, can develop the largest moisture suction and heaving pressure in a closed system and coarse-grained soils, the lowest.

In the over-all phenomenon of frost heaving the most difficult combination of related processes to treat, even on a semi-quantitative basis, is the heat and moisture flow. This difficulty arises not only from the complexity of the mathematics but also from the lack of experimental measurements of heave rates, heat flow, moisture flow, temperature distributions, and moisture tensions while ice lensing is in progress. In the absence of such information the quantitative treatment of the combined heat and moisture flow appears impossible.

● FROST ACTION in soils consists of two different phenomena. It involves frost heaving resulting mainly from the accumulation of moisture in the form of ice lenses at the freezing plane in the soil and also the decrease of supporting strength when thawing takes place.

Frost action is contingent on the existence of a combination of frost action factors. These factors are a frost-susceptible soil, a moisture supply, and sufficiently low soil temperatures to cause some of the soil water to freeze. The process which results from the interaction of these factors during the freezing period is commonly referred to as the "mechanism" of frost heaving. The other phenomenon involved in frost action, the decrease of supporting strength of the soil during the thawing period, is particularly important in the performance of highways and airports. This problem, however, has not received much attention by research workers.

This paper is devoted to the interaction of the frost action factors in frost heaving and not to the details of any one factor.

Although some basic research has been carried out in the field of frost heaving the mechanism is still not completely understood. This has been and still is a real obstacle to the complete solution of problems of frost damage to engineering structures constructed of soil or other porous material. In recent years a number of research workers have made important contributions on certain aspects of the frost heaving process, but the early published work on the mechanism of frost action by Taber and Beskow still stands as the most complete coverage of the subject.

Since the frost heaving process is extremely complicated and much experimental work is still needed, the theory outlined is tentative and may be changed or modified as more information becomes available. Nevertheless, it is based on the work published by others and the results of research carried out in recent years by the author and his colleagues.

The material in this paper is divided into two sections. The first section deals with the phenomena of soil freezing based on experimental evidence obtained mostly in the laboratory. The second section is mainly concerned with the theory of frost heaving in an attempt to explain the observed phenomena.

PHENOMENA OBSERVED DURING FREEZING

In Soils That Support Ice Lens Growth

Ice Lensing and Frost Heave. The cause of frost heaving can be attributed mainly to the formation of ice lenses in the soil. This was first shown in 1916 by Taber (1) at a time when the popular belief was that frost heaving resulted solely from the volume change of water in changing from a liquid to a solid.

Ice lenses normally grow parallel to the ground surface and perpendicular to the direction of heat flow. The former is not always true since there are a number of different ice forms known; the latter, however, is always true. The thickness of the ice may vary from small hairline lenses to those several inches thick (Fig. 1) depending on a number of factors to be discussed later.

The heave in a saturated non-compressible soil in a closed system originates from the expansion of the water frozen in situ plus the volume of water moved to the freezing zone and its expansion. It is noted that the volume change of water on freezing is in the direction of the heat flow. In a closed system containing a compressible soil which is saturated before freezing the volume increase due to ice segregation is offset, except for the 9 percent expansion, by the consolidation of the soil. This is true in the region where the shrinkage curve is linear. If, on the other hand, additional water is supplied to the specimen from an outside source (open system) the shrinkage may be more than offset.

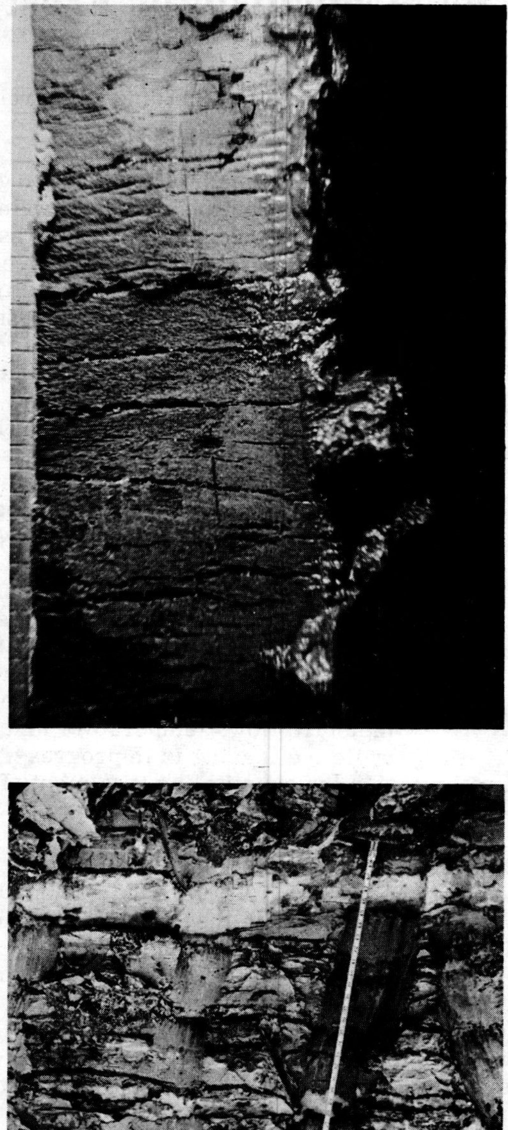

Figure 1. Small hairline ice lenses in silty soil (above). Ice lens, approximately 5 in. thick, in silty soil.

The soil between successive ice lenses is often relatively dry. Whether some of the soil water in these layers is frozen depends on the moisture status of the layers and the temperature. The latter is primarily determined by its position in the frozen soil profile.

Induced Suction and Moisture Flow. The flow of moisture to the freezing zone in relatively moist soils appears to start immediately after crystallization of the water begins. The effect is so pronounced that it can be observed some distance away from

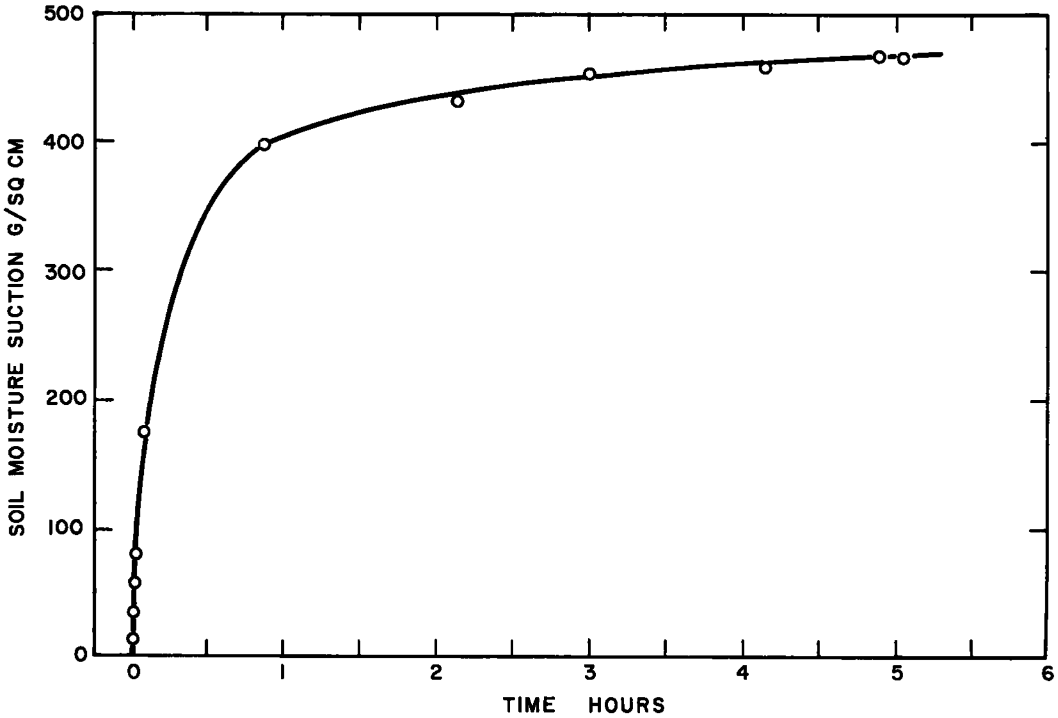

Figure 2. Soil moisture suction increase due to ice lensing as a function of time in a closed system containing Potters flint. Cold side temperature -3 C, warm side temperature 1.5 C.

the freezing zone. This indicates that a suction gradient is set up in the soil water. The phenomenon can be demonstrated by connecting a mercury manometer through a water connection to the soil water in the specimen. Measurements such as this have been made by several observers (2, 3).

The actual rate at which suction increases in a closed system is a function of a number of variables such as the suction-moisture content relationship, moisture permeability, and rate of heat extraction. The results shown in Figure 2 give the time-suction relationships during ice lens growth in a sample of Potters flint. This material is composed of about 6 percent clay-size particles with the remainder in the silt-size range. The temperature on the cold side of the specimen was held at -3 C with the warm side at +1½ C. Crystallization was mechanically induced at the cold end of the specimen at approximately -2 C.

The suction developed at the ice lens induces a suction gradient in the soil moisture. This is the main driving force for water movement to the ice lens. Since the driving force is a suction gradient, as opposed to a positive pressure gradient, the principles of unsaturated permeability apply. This type of flow should not be confused with saturated permeability. The significant difference lies in the fact that the unsaturated permeability coefficient is not a constant but is rather a function of the average suction, decreasing as the average suction increases. This principle is illustrated in Figure 3 showing the unsaturated permeability coefficient and the moisture content as functions of the average moisture suction.

Heaving Pressures. When vertical displacement is prevented in a frost-heaving soil a positive pressure is developed at the ice-water interface. This pressure is known as the heaving pressure. Such pressures can be sufficiently high to destroy foundations and lift buildings.

The author has measured the heaving pressure as a function of dry density for Potters flint. At constant moisture suction the heaving pressure increased with increasing density (Fig. 4). In another experiment using a different preparation of Potters flint the increase in pressure was measured as a function of time with a suitably mounted ring dynamometer. An adequate supply of water was assured by maintaining the water table at the base of a 3-in. specimen throughout the experiment. On the basis of Figure 4 this moisture condition should be potentially the most favorable for the development of maximum pressure. Figure 5 shows the relationship between time and pressure. The pressure eventually terminates the ice lensing process. At this point the heaving pressure is at a maximum.

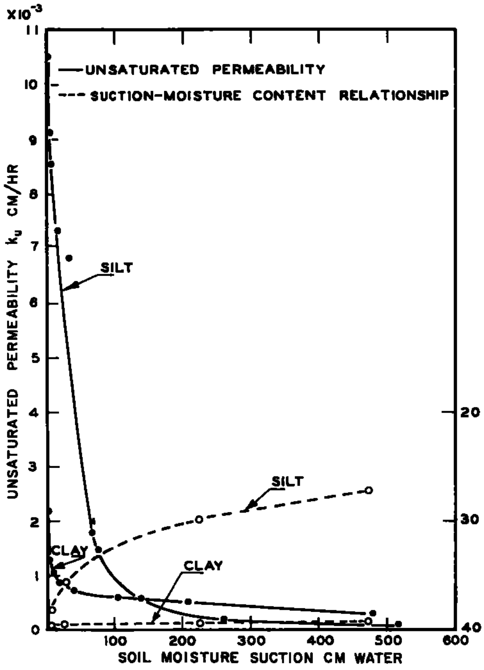

Figure 3. Unsaturated permeability and suction-moisture content relationship.

<u>Rate of Frost Heave</u>. Beskow (<u>4</u>) demonstrated that the heaving rate was not always influenced by the rate of frost penetration as shown by Figure 6. In his experiments the temperature was varied between -2 C and -10 C above the sample without affecting the heave rate. Beskow pointed out that the maximum rate of heave was achieved when the cold side temperature of the specimen was -2 C. Colder temperatures down to -10 C, although increasing the rate of frost penetration, did not increase the heaving rate. It is evident, however, that, over a certain range of temperatures, increasing the rate of frost penetration by applying lower cold-side temperatures does increase the heave rate (Fig. 7). Two different cold-side temperatures were used, -3 and -6 C.

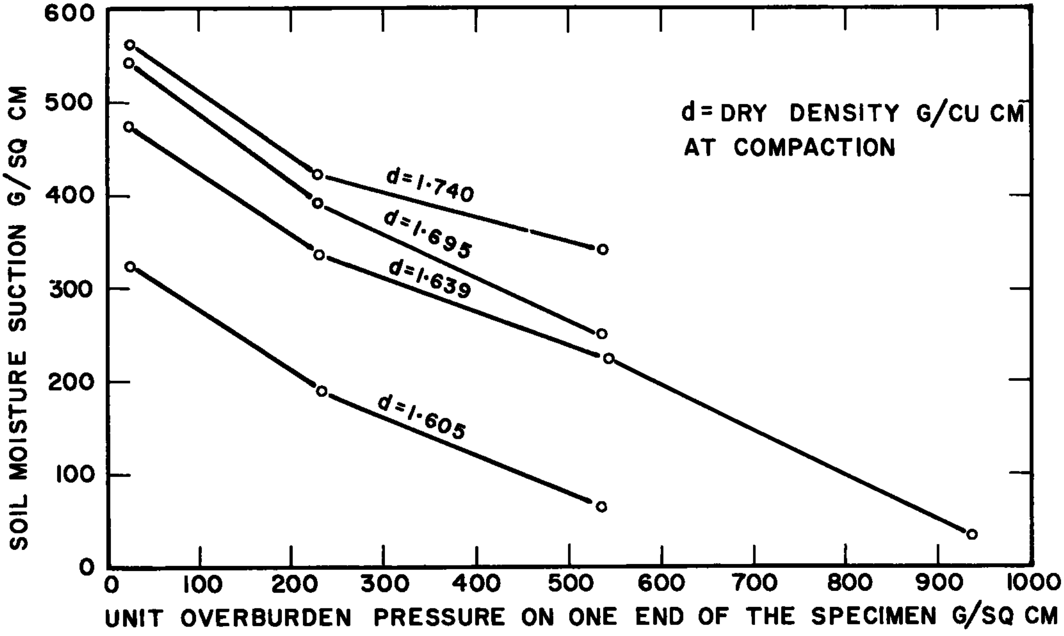

Figure 4. Relationship between soil moisture tension, overburden pressure, and dry density when heaving ceased.

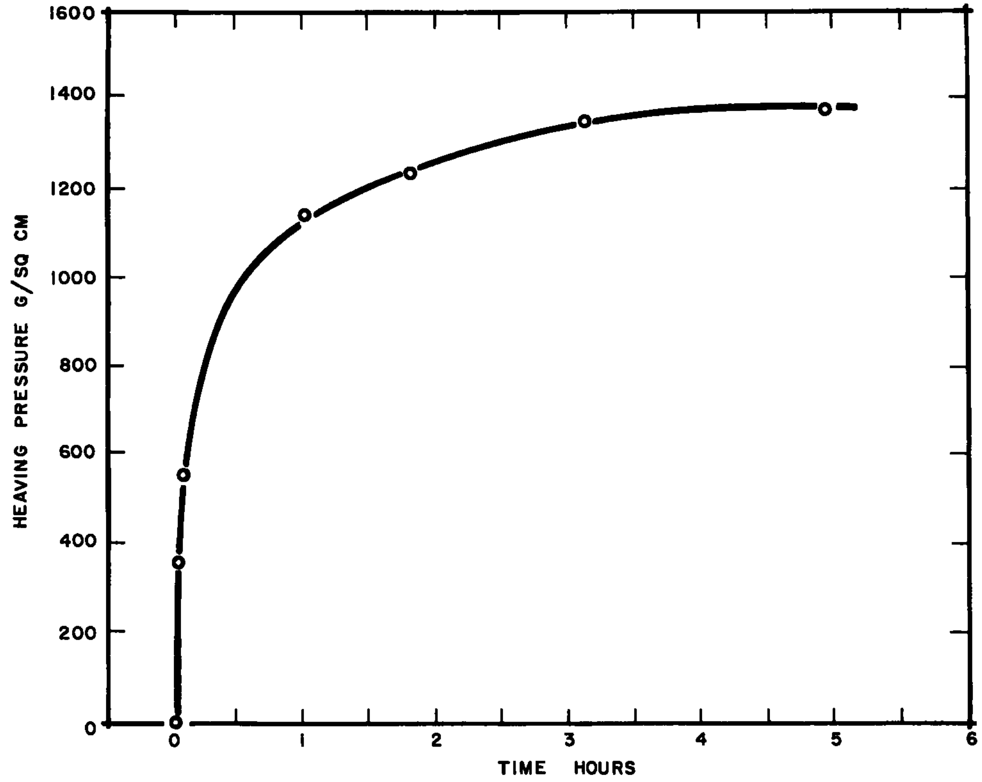

Figure 5. Heaving pressure increase due to ice lensing as a function of time measured with a ring dynamometer in a saturated sample of Potters flint. Cold side temperature -3 C, warm side temperature 1.5 C.

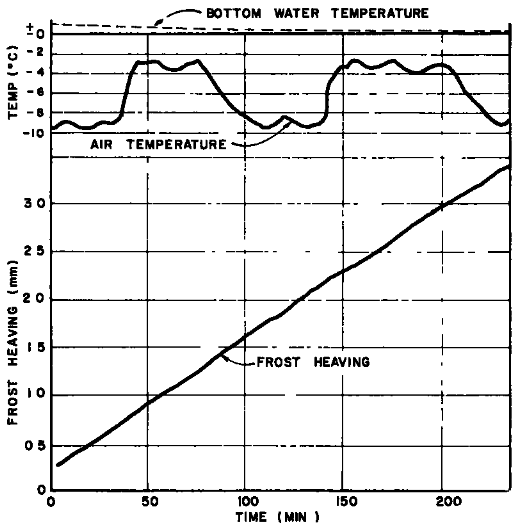

Figure 6. Another example showing that frost heave is independent of rate of freezing. Soil—very fine silt, pressure—410 g/sq cm (4).

The specimen consisted of a homogeneous mixture of 45 percent silt and 55 percent clay compacted to a dry density of 1.26 g/cc. Free water was provided continually at the base of the 3-in. specimen. The rate of heave was a function of the rate of heat removal. Increasing the temperature gradient within a certain range increases the rate of heave. If the heaving rate reaches a maximum value as Beskow suggests, it is still a matter of speculation whether the rate of heave stays constant or decreases as the temperature gradient is still further increased. Such maximum values of heat removal may well lie beyond those encountered under natural conditions.

There appears to be general agreement on the influence of overburden pressure and/or soil moisture suction level on the rate of heaving. Beskow's results (Fig. 8) illustrate what has been generally observed, that is, increasing either the overburden pressure or soil moisture suction simultaneously or independently reduces the rate of heaving.

At this stage it should be pointed out

that the heave rate is dependent not only on the rate of heat removal from the freezing zone but is intimately associated with the unsaturated permeability and the induced suction gradient. This will be discussed more fully later.

In Soils That Do Not Support Ice Lens Growth

There is very little information available on the freezing behavior of soils that do not show ice segregation. Two different phenomena were recognized when saturated specimens of this kind were subjected to unidirectional freezing. Even under rather small loads some laboratory-prepared specimens exuded water from the unfrozen end to accommodate the volume increase as the initial freezing occurred. The amount of water exuded has not been measured. The phenomenon is also mentioned by Beskow (4). In all cases the exudation of water coincided with active penetration of the freezing zone.

Other specimens showed heaving during the initial freezing which terminated when the freezing plane stopped penetrating. Soils that exhibit this second type of phenomenon are thought to be borderline with respect to frost damage. How these soils react to different rates of freezing has not been determined experimentally.

FUNDAMENTAL FEATURES OF THE ICE LENSING PROCESS

The growth of ice lenses in soils is a fascinating subject and has recently caught the attention of a number of research workers who have made useful contributions

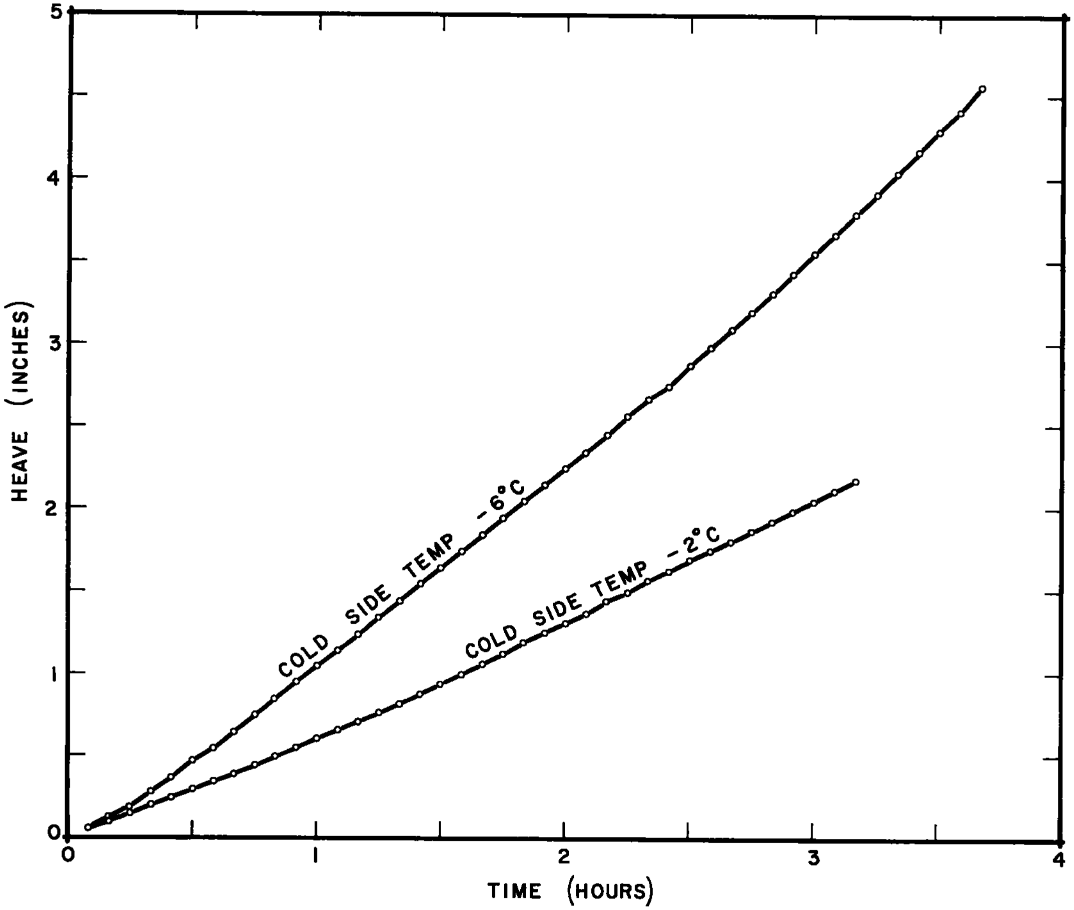

Figure 7. The amount of heave as a function of time for two different cold side temperatures. The specimens were prepared at a dry density of 1.26 g/cc from crushed air dry Leda clay.

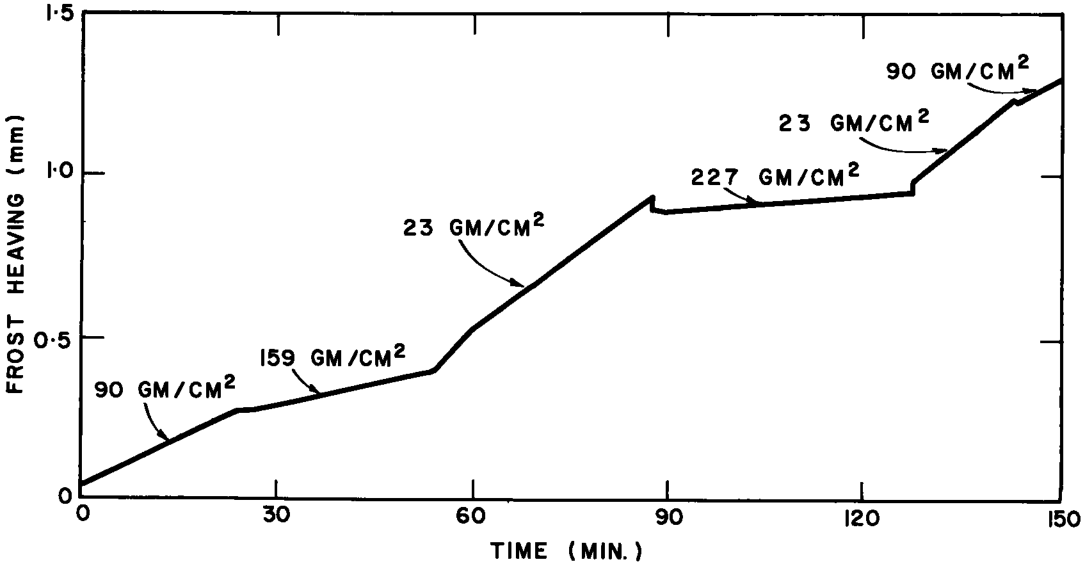

Figure 8. Diagram showing frost heaving rate for different pressures, surface load or capillary pressure. For any given pressure there is a certain slope of the curve, i.e., a definite rate of heave. For each slope the corresponding pressure is given in g/sq cm. Soil pure fractions, 0.01 - 0.005 mm. (4)

(6, 7, 8). As has been pointed out, some disagreement still exists about the mechanism but this stems from a lack of experimental results. Any consideration of the fundamental features of the ice lensing process in nature is therefore somewhat speculative. An attempt has been made in this paper to support the theory by experimental results wherever possible and to include the opinions expressed in the literature particularly where general agreement exists.

Pore Size as a Mechanism for Supercooling

In the unidirectional freezing of a saturated soil the dimensions of the interconnecting channels determine the temperature at which ice propagation may proceed. This effect of channel or pore size provides a means for the supercooling of the soil water below the freezing point near the ice-water interface. The freezing of soil water at supercooled temperatures was suggested by Taber (5) and Jackson et al. (6) as a necessary feature of the ice lensing process, as it provides the energy for the development of heaving pressure and the creation of a suction gradient.

The relationship between the size of a stable spherical crystal in its own melt and the absolute temperature can be shown by:

$$\Delta T = \frac{2T\,\sigma_{iw}}{r\,\rho_i\,Q_f} \qquad (1)$$

in which

r = radius of the crystal (cm);

ρ_i = density of the ice (g/cc);

σ_{iw} = interfacial energy (ergs/sq cm);

Q_f = latent heat of fusion (ergs/g);

T = temperature of melting at zero curvature of the solid-liquid interface (°K); and

ΔT = freezing point depression.

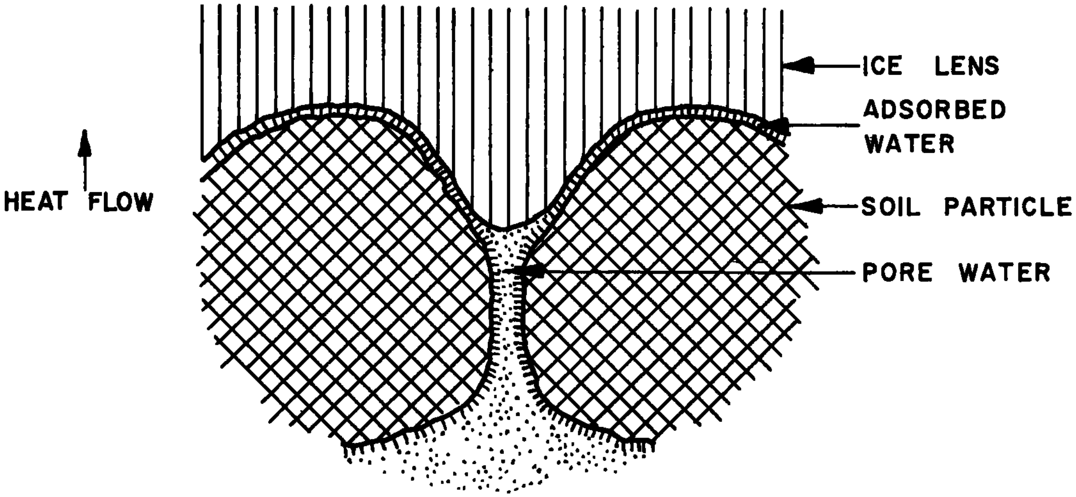

Figure 9. An enlarged schematic diagram showing a section of the ice lens with respect to the soil particle and soil pore.

Eq. 1 recently used by Sill and Skapski (9) for the determination of the surface tension of solids in thin wedges, states that the product of the curvature radius and freezing point depression is a constant determined by the interfacial tension and the bulk properties of the substance.

Assuming that the size of the soil pore determines the size of the advancing ice crystal the quantity r in Eq. 1 may be interpreted as the radius of the pore. A part of the soil pore is occupied by the adsorbed phase which probably places additional size limitations on the ice crystal. This mechanism appears to be responsible for the growing of the ice phase at the supercooled temperatures necessary to release the energy required for the work involved in heaving and moisture movement. Accordingly, the smaller the pore radius, r, the lower the temperature necessary for the ice front to advance, that is, $\Delta T \alpha \frac{1}{r}$. Measurements of heaving pressure and suction pressure indicate that these quantities do increase as the pore size of the porous material is reduced. The difficulty with a more rigid application of Eq. 1, although desirable, is beset with many difficulties since a gradation of pore sizes normally exists in soils.

Pressure Relationships at the Ice-Water Interface

The heaving pressures that are developed at the ice-water interface depend to a large extent on the moisture status of the soil. When the soil system is maintained completely saturated, given sufficient time, the maximum heaving pressure possible for a given soil is developed because under these conditions the suction pressure in the water is essentially zero. According to Figure 4 increasing the suction reduced the ultimate heaving pressure. In the absence of any overburden pressure the maximum suction pressure is possible. An attempt will be made in this part of the paper to justify theoretically this relationship. Figure 9 is a schematic drawing showing the ice phase and water phase in relation to the soil pore and soil particle. Attention is drawn to the intimate contact that exists between the ice and water phases as this is of some importance in developing the theory.

The temperature at which the ice phase grows depends on the pressure imposed. The pressure may be imposed on the water phase, or on both the ice and water phases simultaneously or on the ice phase alone. In each case the equilibrium freezing temperature is different. The complete development of the pressure-freezing point depression equations are given by Edlefsen and Anderson (10). The final equations developed by Edlefsen and Anderson are as follows.

Case 1. The total change in pressure on the ice is always equal to the total change in pressure on the water.

$$\frac{dP_t}{dT} = \frac{Q_f}{(v_w - v_i)T} \qquad (2)$$

in which

dP_t = total change in pressure;

Q_f = latent heat of fusion;

v_w = specific volume of water;

v_i = specific volume of ice;

T = the absolute temperature at which the phase change occurs; and
dT = change in freezing point temperature.

Substitution of the proper values for v_i, v_w, T, and Q_f shows that the freezing point is lowered by 0.00748 C per atmosphere of pressure increase.

Case 2. The pressure on the water remains constant while the pressure on the ice is changed.

$$\frac{dP_i}{dT} = -\frac{Q_f}{Tv_i} \qquad (3)$$

where dP_i is the pressure change on the ice; the other symbols are the same as previously designated. In this case the freezing point is lowered by 0.0899 C per atmosphere of pressure increase.

Case 3. The pressure on the ice remains constant while the pressure on the water is changed.

$$\frac{dP_w}{dT} = \frac{Q_f}{Tv_w} \qquad (4)$$

In this case a positive pressure raises the freezing point temperature by 0.0824 C per atmosphere of pressure, but a decrease in pressure lowers the freezing point.

In the light of the different relationships between pressure and freezing point depression it is necessary to assume the actual disposition of the water relative to the ice phase and soil grains. It is believed that in a saturated system the relationship that applies is given in Case 1. The fact that the characteristics of ice lensing show no abrupt change in going from a completely saturated to a partially saturated system seems to indicate that an intimate contact between the water phase and the ice phase extends into the unsaturated range. One need not exclude the possibility of moisture transfer in the vapor phase to the ice lens but it must be accepted that, at the face of the growing ice lens, the water and ice phases exist in contact with each other.

If pressure is applied to the ice phase the water between the ice and soil particles is placed in a state of compression. The pore water is not affected if a rigid non-compressible material is being considered. Applying suction to the pore water would place the pore ice in a state of tension and consequently Case 1 still seems to apply.

The Mechanism of Ice Lens Growth

The mechanism of ice lens growth together with the development of heaving pressures and suction in the soil moisture can be described as follows, assuming that Eqs. 1 and 2 apply. If the system is saturated, as depicted in Figure 9, the absorption forces are fully satisfied. This means that if it was not inside a soil pore the outermost layer of water around the particle would freeze at nearly the temperature of bulk water. It is believed that the initial crystallization of water begins either in the soil pore at the ground surface of the soil and propagates downward or, in the case of ice lenses separated by relatively dry layers, crystallization begins most easily in large pores or discontinuities in the soil.

After crystallization has occurred its subsequent growth into an ice lens involves the manifestations of heaving pressures and suction pressures that accompany the process. Referring to Figure 9, the ice front will be temporarily prevented from propagating downward between the soil particles until the temperature has been lowered sufficiently to satisfy Eq. 1. Before this occurs part of the adsorbed water above the particle will freeze. As water is being removed from the adsorbed layer into the ice phase it is replaced from below and an equilibrium thickness of water is maintained around the soil particle by continual replacement with supercooled water molecules. This is really no more than film adjustment around the particle and will continue until the temperature drops sufficiently for the ice front to propagate through the soil pore. The mechanism really hinges on the existence of supercooled water in contact with the adsorbed phase and continual replacement of water to the adsorbed phase as more water molecules enter the ice phase. It can also be seen that the existence of the adsorbed phase is a vital link in the movement of water from a supercooled state into the adsorbed phase and hence into the ice phase. Similarly it may be noted that if the propagation of ice occurred at the freezing temperature of bulk water, 0 C, the evolution of energy necessary to cause heaving and moisture movement would not occur. This is well supported by experimental evidence and is the justification for replacing fine-grained soils with gravels when frost heaving cannot be tolerated. In going from porous systems containing small pores to those containing large pores no abrupt change in the heaving tendency is predicted but would be in accordance with the amount of supercooling possible which is proportional to the radius of the pores according to Eq. 1.

The growth of such an ice lens may be halted in two ways. Firstly, if the ice lens is loaded, causing a pressure at the ice-water interface above the soil particle, the freezing point of the water would drop according to Eq. 2. The limiting pressure to stop ice growth would occur when the freezing point of the water above the particle has been lowered (by positive pressures) to the same temperature as is necessary for ice to propagate through the pore constriction. The experimental justification is shown in Figure 5 which shows that ice lens growth can be stopped in a saturated soil by loading the soil.

Ice lensing may also be halted by applying suction to the water in the pore system. A suction or negative pressure in the pore water raises the temperature at which ice can propagate through a pore of given size. This is based on Eq. 2. At the same time application of suction has the effect of drawing the ice-water interface toward the soil particle. This induces a state of compression at the ice-water interface above the soil particle and a lowering of the temperature at which freezing occurs.

Based on these considerations it is thought possible that the maximum overburden pressures to stop ice lensing should be about twice as great as the maximum suction. From limited experimental evidence using Potters flint as the soil media this appears to be the case (11).

Under natural conditions in the field the positive pressures on the ice-water interface are the naturally occurring overburden pressures due to the weight of frozen soil. The suction or negative pressure gradient is induced by the ice lens in the soil water. The induced suction gradient will never be greater than that required to supply the demands of the growing ice lens. When the demand for water is great the suction gradient increases. This tends to lower the unsaturated permeability coefficient, however, resulting in a diminishing water supply. It follows therefore that the most favorable conditions for frost heaving in any frost-susceptible soil is when the frost line is close to the surface (low overburden pressure) and when the water table is high (low suction).

HEAT AND MOISTURE FLOW AS RELATED TO ICE LENSING

In the over-all phenomenon of frost heaving the most difficult combination of related processes to treat, even on a semi-quantitative basis, is the heat and moisture flow. This difficulty arises not only from the complexity of the mathematics but also from the lack of experimental measurements of heave rates, heat flow, moisture flow, temperature distributions, and moisture tensions while ice lensing is in progress. In the absence of such information, the quantitative treatment of the combined heat and moisture flow appears impossible.

Some attempt at a quantitative theoretical treatment for soils was first made by Winterkorn (12). Following Winterkorn's method of reasoning, Powers (13) made some tentative calculations of relative rates of heat flow due to conduction and heat flow arising from the latent heat of fusion in the freezing of green concrete. Although these authors have indicated the type of information that is necessary, the correctness of the computations depends on whether valid coefficients were used. These coefficients are not constants but vary as the system changes. Perhaps all that can be done at this stage is to point out the various factors that are known to be involved and to speculate on the progress of a continually changing system.

As the moisture tension increases in the unfrozen zone beneath the ice lens the unsaturated permeability coefficient may also change. In relatively uniform sands and silts the change is abrupt and occurs at relatively low moisture tensions consistent with the size of the pores. In well-graded sands and silts the change is less abrupt but decreases continuously with increasing moisture tension (Fig. 3). The varying permeability coefficient is known to be related to the desaturation of these systems without any consolidation occurring. In systems consisting of compressible soils the permeability coefficient is also a function of the tension but the rate of change is less abrupt due to the consolidation of the clay. Because the tension or suction gradient is thought to be the driving force for liquid moisture flow in frost-heaving soils, it can be assumed that the unsaturated permeability coefficient will also change during ice lensing if the tension changes.

A portion of the moisture flow during ice lensing is attributable to flow in the vapor phase if some of the voids are air filled. Therefore unsaturated permeability coefficients determined normally under isothermal conditions cannot be strictly applied.

The thermal conductivity of frozen soil is higher than that of unfrozen soil at moisture contents above about 10 percent according to Kersten (14). The ratio for frozen to unfrozen soil increases to values exceeding 1.5 as the moisture content increases. Referring now to the thermal conductivities of a frozen layer of soil above an unfrozen layer it may be correct to assume a constant conductivity for the frozen layer but as the moisture content beneath the ice lens changes so does the thermal conductivity. In addition, the changing dimensions of the specimen due to heaving and the layering of the ice phase with its unique thermal conductivity must also be taken into account. Superimposed on this complicated system is the climate-controlled temperature fluctuation which adds further to the difficulty of unravelling the phenomenon as it occurs under field conditions. Complicated as it may be the consecutive formation of ice lenses is, nevertheless, the product of the combined heat and moisture flow patterns.

Much speculation surrounds the phenomenon of consecutive ice lens formation. The growth of an ice lens is thought to terminate when the rate of heat removal exceeds the total heat arriving at the lens. This can be shown to be the case if a reduced rate of moisture flow, resulting from increased tensions, is postulated. The reduction in flow rate of moisture is not entirely necessary for consecutive ice lens formation. Increasing the rate of heat removal may also drive the freezing zone further into the material until a more favorable heat and moisture flow balance is encountered. An important difference exists between the two cases. When there is a reduced rate of moisture flow and desaturation occurs beneath the ice lens, ice crystal nucleation must precede the formation of a new ice lens. In the case where the rate of heat removal is suddenly increased, ice propagation proceeds through the pore system and the nucleation of ice crystals at the new site is not involved. This has been observed by the author in unidirectional freezing of saturated soil specimens.

Practical Considerations Based on Basic Principles

The amount of guidance that the practicing engineer can obtain from basic considerations is limited at this stage in the understanding of basic phenomenon of frost heaving. In many instances the suggestions which stem from a fundamental approach support the measures that are used in practice based on experience in the field and laboratory freezing experiments.

Frost Susceptibility Based on Grain Size and Grain-Size Distribution. According to theory, grain size is not as important as the resultant pore size but there is a relationship between the two. In relatively uniform soils pore size increases with grain size. The theory predicts that the maximum moisture suctions and heaving pressures should decrease with increasing pore size. The importance of pore size is implicit in the frost action criteria commonly used which permit a larger percentage of fines in uniformly graded material than in well-graded material. The theory therefore supports the practice of using coarse-grained materials with gradation limitations such as the Casagrande criteria. No rigid guidance, however, can be obtained from the theory as to the exact grain size or grain-size distribution above which no frost heaving will occur under favorable moisture supply. It would seem reasonable to categorize soils in practice according to the degree of frost susceptibility recognizing no abrupt delineation based on grain-size considerations between frost-heaving and non-frost-heaving soils. The influence of grain size on the rate of moisture movement must also be taken into account if the rate of heave is considered. Although the maximum moisture suctions possible increase with decreasing grain size, the moisture permeability is decreased. Consequently, as is observed in the field, heavy clays will heave at a much slower rate than silts and the total amount of heave during one winter season would be much less. In coarse-grained soils, the moisture suctions will be low or negligible and the permeability parameter need not be considered. Silts which are notoriously treacherous from a frost action point of view have a combination of moisture suction and permeability which lead to an extremely high frost susceptibility and are avoided when possible in current practice.

Density and Frost Susceptibility. The effect of increasing the density is similar to decreasing the grain size, that is, the soil pores are reduced in size. High densities may be desirable and necessary in achieving the required bearing capacity but at the same time soils which are borderline with respect to frost susceptibility would become more frost susceptible with increasing density.

Homogeneity and Differential Heave. A non-frost-susceptible material containing pockets of silt or clay which are frost susceptible may show characteristic differential heaving when intercepted by the frost line. It has been shown that normally non-frost-susceptible soils can act very effectively in transmitting moisture (3). There are other reasons for differential heaving; variations in soil texture is one of the more important.

Moisture Supply and Frost Susceptibility. Without moisture no soil is frost susceptible. Normally the assessment of frost susceptibility is made under the most favorable moisture supply. It is shown theoretically that the lower the moisture supply (high suctions) the smaller the maximum heaving pressures and the lower the rate of heave (Figs. 4 and 5). An expression of frost susceptibility for a given soil should also be based on the moisture status likely to be encountered at a given site. Drainage and the dissipation of seepage forces is therefore most significant. Hydrostatic pressures which result in the supply of free water to the freezing plane will increase the maximum heaving pressures possible and increase the rate of heaving. This will also lead to differential heaving with the same outward manifestations as non-homogeneous soils. Frost heaving will not occur, however, even with adequate water supply unless the soil pores are sufficiently small to induce some supercooling. When the soil consists of coarse uniform sands and gravels, no amount of water can possible result in heaving.

CONCLUSIONS

The mechanism of frost heaving and all its ramifications are still not completely understood. This is particularly true in resolving the combined heat and moisture flow in frost heaving systems.

In some aspects of the mechanism the process is fairly well known. This applies to the understanding of how heaving pressures and suction potentials develop. The independent role of liquid moisture flow under suction potential gradients and the variation of flow with average suction is also reasonably well understood. In the development of consecutive ice lens formations and the rate of ice growth the mechanism can be only qualitatively described and a more rigid mathematical development would be useful.

The assistance the practicing engineer can expect from basic studies is mostly qualitative in nature. In many instances the theory supports the kind of solutions developed from many years of field experience. At the same time it offers a reasonable tentative working basis and future studies can be more directed toward finding solutions to frost heaving in soils and frost action generally.

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Discussion

R. TORRENCE MARTIN, Research Associate, Soil Engineering Division, Massachusetts Institute of Technology—It is not the purpose of a discusser to introduce new evidence with the aim of either substantiating or refuting the thesis of the author. On the other hand, criticism alone is not sufficient. To admit a competitive hypothesis to the working list is a concrete form of expressing a doubt, while at the same time respecting existing hypotheses, and serves better than abstract criticism toward unravelling the intertwined complexities of nature. In brief the writer accepts T. C. Chamberlain's system of multiple working hypotheses as furnishing the most wholesome conditions for research and that any additional hypothesis not in itself incredible will be welcomed.

In order to keep the discussion within tolerable limits, the remarks shall be confined to possible alternative interpretation regarding the significance of (1) pore size (Eq. 1 in Mr. Penner's paper) and (2) pressure upon freezing point depression (Eq. 2 in Mr. Penner's paper), relative to the theory of ice lens formation. At the outset it must be clearly stated and with emphasis, that the author's hypothesis concerning Eq. 1 and Eq. 2 appears to be completely rational and self-consistent with the experimental data presented. Therefore, the author's arguments must be respected, at least for the present, as one of a group of working hypotheses.

Pore Size

The author attributes to the small pores and the even smaller pore constrictions two vital effects related to the mechanism of ice lens formation: (1) supercooling and (2) retardation of ice front advance.

Supercooling, ΔT, is the temperature difference between the actual temperature at which the ice is forming, T_x, and the equilibrium temperature, T_e, at which the liquid phase under its existing activity could coexist with the solid phase; i. e., $\Delta T = T_e - T_x$. Supercooling is frequently confused with freezing point depression. Freezing point depression, dT, is the temperature difference between the equilibrium temperature for the activity of the liquid in the system under consideration, T_e, and the equilibrium temperature for pure liquid under no restraint, T_o; i. e., $dT = T_o - T_e$. For pure water $T_o = 0.00$ C, water in a clay soil system may have a freezing temperature, T_e, of -5 C; therefore, if the water in such a soil system is being converted to ice at a temperature, T_x, of -6 C, the supercooling for the system is -1 C and the freezing point depression is -5 C.

The full realization conerning the meaning of these definitions is essential. Penner correctly defines dT in Eq. 1 as a freezing point depression; however, he then states "This mechanism (referring to Eq. 1)[1] appears to be responsible for the growing of the ice phase at the supercooled temperatures necessary to release the energy required for the work involved in heaving and moisture movement . . ." which can hardly be true since dT of Eq. 1 is a freezing point depression and not a supercooling.

Futher, very pure water in bulk has been supercooled to at least -39 C; if this be fact, then small pores are not a necessary prerequisite for supercooling. Nevertheless, the pore size has a profound influence upon supercooling because pore size controls the statistical probability of obtaining sufficient ice nucleation to reach a measurable growth rate. To illustrate this concept, the following hypothetical example is given—Case A: ten large water filled pores each pore having one nucleus for ice formation; the temperature is lowered until ice starts to nucleate. Ice growth is rapid because the volume of water at the proper temperature, instantaneously available to each ice nucleus, is very large. Case B: use the same volume, the same water, and the same number of nuclei as in Case A but now with a porous system containing 1,000 pores. Here there is a nucleus in only one pore per 100. The temperature is lowered and at about the same temperature as in Case A ice nuclei form in the 10 pores; however, the volume of water at the proper temperature available to each ice nucleus is now 1/100 what it was in Case A. Total ice growth is very small; therefore, the temperature must be lowered (or additional water supplied) before an appreciable growth rate is reached.

Cooling curves (temperature vs time) on various porous systems with different pore fluids should provide the data necessary in order to decide the proper relationship between pore size and supercooling.

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[1] Parenthetical insert by the writer.

Retardation of ice front advance is clearly demonstrated by Eq. 1; however, there is an equally valid counter-proposal which states that the ice front has no desire to advance through the pore constriction provided that a supply of water can be maintained at the ice front. Then, by the time the ice front wants to advance it is too late, ice formation has already begun further down in the soil.

This additional hypothesis arises from a consideration of crystal growth rate independent of any pore constrictions. The first condition, for a crystal of a given size in its own melt, is that the rate of crystal growth increases at a fantastic rate as the temperature is lowered below the equilibrium temperature (for this case $T_e = T_o$). The second condition, given a fixed amount of supercooling, is that the larger the crystal size the more rapid the growth rate. Returning to a soil system, suppose that a small crystal (a whisker) is attempting to grow perpendicular to a large pore crystal, any water available will go to the large pore crystal rather than the whisker because (a) the pore crystal is larger and thus grows faster, and (b) the pore crystal is colder, thus it grows faster. Both of these situations rob the small whisker in favor of the large pore crystal since the larger crystal is energetically more stable than the whisker.

One may phrase the question another way. Which requires the least expenditure of energy, water transport or ice front advance? A crude calculation from very meager data indicates that water transport requires only a fraction of the expenditure of energy required for ice front advance. This energy consideration is not an additional hypothesis, but should provide a means of testing between different hypotheses when better experimental data become available. Data needed are temperature and pressure measurements in both phases at a freezing ice front. Some way must be devised to differentiate between freezing point depression and supercooling. In fact, Penner's hypothesis and the alternatives herein suggested, both tacitly assume that supercooling does occur. There can be no doubt but that supercooling will provide the energy required; however, if experiments show that there is no supercooling then some other source of energy must be found and any acceptable working hypothesis will have to be modified to include the new information. Since ice lensing is a rate process in which the rate is definitiely finite, there must be some infinitesimal amount of supercooling to provide a gradient in order to prevent the rate from going to zero.

Pressure upon Freezing Point Depression

The author prefers Case 1 where the total pressure change on the ice is always equal to the total pressure change on the water because of ". . . the intimate contact that exists between the ice and the water phases." That there is intimate contact between the phases has been verified by numerous workers since Taber's original work (author's ref. 5). Penner has very carefully measured the tension (-P) in the water phase during ice lensing; if Case 1, Eq. 2, is applicable it seems to imply that the ice phase can withstand no lateral stress.

Does intimate contact necessarily require that the pressure on the two phases be equal? Taber did not think so, he envisioned the adsorbed water film (which may be only a few molecular layers thick) as a two-dimensional liquid able to withstand normal stresses and at the same time retain relative free mobility laterally. In their discussion of pressure effects upon freezing point depression Edlefson and Anderson (author's ref. 10) were of the opinion that Case 2 and Case 3, Eqs. 3 and 4, would be the appropriate solutions for freezing a soil system provided that the percent air voids was greater than zero. It is certainly a rare soil where the voids are 100.0 percent water-filled.

Penner mentions ". . . that the characteristics of ice lensing show no abrupt change in going from a completely saturated[2] to a partially saturated system . . ." Applica-

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[2] It is assumed that Penner is using saturation as previously defined by him (HRB Bull. 135, p. 109) which states, "At saturation the tension is zero, although in the case of light textured soils the soil pores may be partially filled with air."

tion of the combination of Case 2 and Case 3 likewise would provide a perfectly smooth transition. It might also be added that the freezing point depression would be increased 10 times for the same pressure change.

Taber (author's ref. 5) performed freezing experiments with benzene and nitrobenzene where $\frac{dT}{dP}$ from Case 1, Eq. 2 would be positive rather than negative as for water. The organic liquid systems gave marked "ice" lensing and appear to vary with pressure in the same manner as the water systems. By the use of Cases 2 and 3, Eqs. 3 and 4, one would expect similar behavior between the organic liquid and water systems. Because there is appreciable mass transfer, whether the volume change from liquid to solid is positive or negative is probably of no consequence.

From the present data, the pro and con arguments concerning the importance of pressure on freezing point depression are inconclusive; however, the organic liquids may prove advantageous toward obtaining definite data regarding the effect of pressure because the $\frac{dT}{dP}$ coefficients are much larger than for water. The coefficients for benzene and nitrobenzene are compared below with the water coefficients given by Penner.

	$\frac{dT}{dP}$ in C/atm. calculated from		
Fluid	Eq. 2	Eq. 3	Eq. 4
Water	-0.00748	-0.089	+0.0824
Benzene[a]	+0.040	-0.22	+0.25
Nitrobenzene[a]	+0.023	-0.25	+0.27

[a] Temperature of freezing, latent heat, and specific volumes necessary for these calculations were obtained from the International Critical Tables.

In conclusion, one of Penner's major points should be reiterated. Frost heaving is a dynamic unsteady state process; therefore, in any experiment designed to test any portion of any hypothesis concerning ice lensing, one must always keep in mind that all the variables are very strongly interrelated. For example, suppose one were to arbitrarily change the overburden pressure. In order to ascertain what effect this will have on ice lensing one must consider at the very least what happens to (1) the freezing temperature, (2) the nucleation point, (3) water transport, and (4) heat transfer through the soil and ice. Then, in turn, how each of these changes effects and is effected by the induced changes in the other three variables.

A. R. JUMIKIS, Professor of Civil Engineering, Rutgers, The State University, New Brunswick, N. J. —The aim of Penner's paper is, like that of the papers by the other authors partaking in this symposium, the review and assessment of the practical utility of the currently available knowledge as it pertains to the freezing of water in soils, mainly in relation to highway engineering. The author presents his paper in three principal sections, the last of which can be described as follows:

1. Phenomena observed by the author with his soil freezing experiments in the laboratory;
2. A condensed theory of frost heaving which serves here partly for the purpose of explaining the phenomena observed in the author's studies; and
3. Practical considerations based on fundamental principles.

Water, Temperature, Undercooling, Interaction—Important Factors

In general two things strike one immediately upon starting to study a freezing soil system and these are, first, the profound influence of temperature upon the soil moisture, and, second, the observation that the substance water contributes considerably to the performance of the soil, particularly when under freezing conditions. These two factors—temperature, or rather heat exchange with the surroundings of the freezing soil system on the one hand, and soil moisture migration induced by a thermal potential on the other hand—interact mutually, an interaction which endows the freezing soil system with great complexity, and consequently makes it very difficult to study.

In studying frost effects upon soil it must also be remembered that there is something else involved than merely the solid particles of the soil, viz., soil texture (refer to the textural criterion of frost-susceptible soils, for example). As just mentioned, in the soil freezing process an important factor, among others, is the soil moisture and, what seems to be more important, the interaction of physical forces between the surface of soil particles and the soil moisture films surrounding the soil particles. This is of particular significance in studying the soil moisture transfer in the film phase upon freezing.

From what is thus far known from literature, from the research work by the author, the discusser of the author's paper, and others, it seems that the key to the secrets of the freezing soil system lies in the substance water itself and in the understanding of the undercooling phenomenon taking place in the freezing soil system. Thus the liquid phase of the soil is not just an important constituent part of the soil as it concerns the performance of the soil under load, but it also plays an important role when subjected to temperature changes. Temperature, it is known, changes the properties of water. Variation in temperature starts a thermal potential which induces the soil moisture to migrate, and to induce between the ends of the freezing soil system an electrical potential. The influence of the latter on the other processes taking place in a freezing soil system seems at present to be very obscure.

Method of Study

Referring to the contents of the paper under discussion, it can be observed that the author and the discusser both study the freezing soil system in its entirety. The obvious reason for using this method is that unfortunately at present there are no satisfactory scientific tools available for handling all of the interior details of the system. Hence the author's working method is very advantageous for its simplicity and practical applications. This method comprehends all the factors and potentials—although some of them may be masked out—which might contribute to the net amount of the upward flow of soil moisture upon freezing and consequent frost heaving.

The author states, rightly it is felt, that the mechanism of frost heaving is still not completely understood. To this can be added that in the soil freezing system more than one mechanism is operative; besides the frost heaving mechanism there act also simultaneously several moisture transfer mechanisms, some of which are more effective than others, depending upon the degree of porosity of the soil. The details of the moisture transfer, too, are not too well understood. The lack of such knowledge, in the words of the author, is indeed a real obstacle to the complete solution of the frost action problem in highway, foundation and earthwork engineering. This is then one of the major reasons why the author studies the freezing soil system experimentally.

One also observes that Penner's manner of treating the soil moisture transfer relates to the mechanism of soil moisture transfer in the film phase.

Moisture Transfer

The moisture transfer through a homogeneous, isothermal porous medium is commonly characterized by the coefficient of permeability, k. In a freezing soil system where temperature varies with depth below the ground surface, the soil moisture film is also at different points below the ground surface at a correspondingly different temperature. It is gratifying to observe that this idea has also found its way into Penner's work. The author realizes that "the unsaturated permeability coefficient is not a constant but is rather a function of the average suction . . ." It is felt appropriate to say at this point that the prime cause of the processes in the soil system under study is the freezing thermal gradient, or simply thermal potential, the suction being just a function of the temperature difference acting on the soil system. Because the temperature changes with depth, the soil moisture transfer characteristic is not a constant.

For this reason it would probably be better to speak of a coefficient of the system's transmissibility, k_s, which varies with depth rather than permeability. In the case of moisture migration in soil in the vapor phase, the coefficient of vapor diffusion applies.

The degree of concentration of electrolytes, keeping in view the relationship of film flow to the zeta-potential, which acts across the electric diffuse double layer, may also have its effect upon the amount of soil moisture transferred upon freezing. It is understood that electrolytes have a great influence upon the amount of soil moisture transferred to the frozen zone: the fewer electrolytes the more moisture transferred.

Ice Lensing

Relative to the topic of ice lensing in soil, the following can be added to the author's presentation: the thickness of the ice layers depends, among other things, upon the rapidity of cooling and the concentration of the soil moisture as an electrolyte, as well as upon pressure conditions. Also, the amount of banded ice layers in a soil system (number of layers per unit thickness of the frozen zone, thickness of the ice layers and distribution of visible ice layers) depends very much upon the rate of nucleation, which in its turn leads to the subject of undercooling. Generally, it has been observed by the discusser's soil freezing experiments, and it is also known from physics and geology, that when the soil system is frozen quickly the crystals, viz., ice layers, are very thin, or even invisible by the unaided eye, even if the whole soil sample is frozen solid throughout. Slow crystallization, viz., freezing of soil moisture, brings about large, clearly visible crystals, viz., ice layers.

According to Tammann, the degree of undercooling is a function of temperature and so is the rate of nucleation. In undercooled water only molecules with sufficiently low kinetic energy are able to form nuclei upon which ice crystals can form. With the decrease in temperature the rate of nucleation increases, but only up to a certain point, when the viscosity of the water (which increases exponentially with the decrease in temperature) slows down the molecular movement to such a degree that the rate of nucleation decreases.

Crystallization velocity of undercooled soil moisture is frequently facilitated by colloidal substances the particles of which are non-spherical. Spherical particles, as well as truly dissolved substances, lower the velocity of crystallization.

The condition of unfrozen water in freezing or frozen soil also depends, of course, upon pressure.

Density and Frost Susceptibility

The author's view on this topic is fully in accord with the discusser's view, namely, that one should consider the dry density-optimum moisture relationship of a soil according to which there is a maximum dry density at a certain optimum moisture content. With increase in moisture content beyond the optimum the dry density decreases. As to the heat transfer through a freezing soil, the thermal diffusivity, $\alpha = \frac{K}{c \cdot \rho}$, depends upon the coefficient of thermal conductivity, K, specific heat, c, and the unit weight of the soil, ρ. Usually c does not vary widely; therefore, in large-scale field operations, little can be done to improve this factor. If K is decreased, α decreases automatically, but again in large-scale compaction operations K can be decreased relatively little. The only factor here which seems to affect the decrease of the thermal diffusivity, α, is the unit weight of the soil, ρ. The greater ρ is, the less α is. This implies that the compacted soil would have a decreased diffusivity, but only up to the maximum compacted density, which is limited by the optimum moisture content. After the optimum moisture content is reached, the density of soil decreases and consequently the coefficient of thermal diffusivity increases, with the result of quick frost penetration into the soil. Of course, the increase in moisture content past the optimum has more total latent heat, which upon freezing is released and retards somewhat the frost penetration rate and total depth.

This aspect of the frost penetration problem in soil implies that soil compaction on roads should be emphasized and the work supervised and executed more rigorously than ever before if an improvement in road performance under load and freezing temperatures and their consequences is to be achieved. It can be said, thus, that what is good for compaction of soil has also practical value relative to improved performance against frost action in soil.

Conclusions

From the author's paper, and from this discussion, it can be concluded that:

1. Knowledge is a universal tool in research work, but research, in its turn, is essential for progress.
2. The various concepts put forward by scientists, and some of the knowledge which is already available in other brances of science, when satisfactorily interpreted and explained, are to some extent also applicable to matters which are not perfectly homogeneous in structure, such as the porous medium of soil, for example, when subjected to freezing temperatures.
3. The mystery with which the frost penetration problem was surrounded until recently is gradually and steadily being dispelled.
4. A systematic study over the past years of thoughtfully organized freezing soil systems has already shed some light on the nature of the processes and changes taking place in a freezing soil system.
5. It is now fairly well understood how a freezing soil system works in its entirety as an organic unit connected to ground-water via the soil moisture films and when subjected to freezing temperatures.
6. There is needed, however, more knowledge for the explanation of certain details, factors and processes within the freezing soil system. Particularly, more information is needed on water properties in the film phase, and a better explanation of the phenomenon of undercooling in soil, nucleation, and possibly other factors.
7. All processes occurring in the freezing soil system are in some way connected with the surface phenomenon of soil colloidal particles. Water in the form of soil moisture films is the medium where many changes in the soil system take place under the influence of temperature changes. The property of a colloidal soil particle of carrying on its surface an electrical charge and the functioning of the soil moisture as an electrolyte are of fundamental significance in the process of the translocation of soil moisture in the film phase when the soil system is subjected to an external, primary, freezing thermal gradient.
8. Evaluating the contents of Penner's contribution to this symposium, it can be said that he has made positive progress in his research activities pertaining to frost action research in soils, and this certainly adds to the store of knowledge on the important subject of frost action in highway soils.

The real understanding of these factors promises to explain better the freezing soil system and the consequences such a system brings about. It is hoped that in a not-too-distant future the studies of the freezing soil system, as knowledge increases, will be guided by more quantitative theories than by merely qualitative principles.

R. D. MILLER, Professor of Soil Physics, New York State College of Agriculture, Cornell University—The role of supercooling in frost heaving deserves careful attention, for there is some danger of confusing cause with effect. There is also danger of confusing supercooling with freezing point depression.

The Thompson equation (author's Eq. 1) is a freezing point depression equation for ice in porous media where the geometry of the voids imposes size restrictions on ice crystals formed in rigid pores. If an ice crystal in such a pore attempts to grow through a capillary neck into an adjacent pore, and if the interaction with the particle surfaces requires that the ice interface be parallel to the particle surface at its points of closest approach, the ice-water interface must be convex, and the ice and water can be at equilibrium at temperatures below the normal ice point. Under these conditions, the water is not supercooled with respect to the convex ice-water interface. During lens formation, when ice is forming at a finite rate, the water must be supercooled to a slight extent for the process to proceed, but this supercooling is related to the rate of ice formation rather than to the curvature of the ice-water interface. The temperature at which ice forms will be less than the ordinary ice point by an amount which represents the sum of the freezing point depression and the rate-dependent supercooling. Hence, calculations of energy available for heaving which relate freezing point depression to supercooling are misleading. Moreover, there is doubt that associating the energy required for heaving with supercooling is logical in the first place.

It is possible, and probable, that water in large, unfrozen pores will be supercooled in the sense that the water in these pores would freeze spontaneously if nucleated in an appropriate manner. However, during lens formation, water present in capillary necks which cannot freeze because of geometrical restrictions would not be supercooled more than the amount required to sustain freezing at a finite rate. If the system were brought to uniform temperature, equilibrium could be established between water in the necks and the curved ice-water interface. In this case, there would be no supercooling of neck water, but unfrozen water in large pores could persist in a metastable equilibrium (supercooled) state. This metastable condition would persist, if the Thompson equation applies, so long as ice already present was excluded from the supercooled pore by geometrical restrictions and the temperature was not low enough to initiate nucleation within the pore.

It follows that if water which is supercooled while in a large pore is transferred from the pore to the ice-water interface, it moves to a part of the system in which it can no longer be regarded as supercooled with respect to the ice present. If this is true, its free energy is the same as that of the ice phase, and the energy source proposed by Jackson and Chalmers vanishes.

The persistence of supercooled water in large pores below an ice lens may play an important (but passive) role in heaving, for it permits free conduction of water through the pore. If ice particles appeared in these pores, but were not connected to the main ice lens above, the latter might continue to grow by utilizing water conducted through unfrozen films surrounding the ice crystal.

The active part of the heaving system is not opposite the capillary necks, but opposite the particles, which actually provide the support for the ice lens and frozen soil above. Here the curvature of the ice-water interface may be zero, if the particles are flat, or concave if the particles are rounded. In this case the Thompson equation would predict elevation of the freezing point so that if curvature alone were considered, water at the ordinary ice point would be supercooled with respect to the ice at this interface. Thus, if the mechanism of frost heaving were dependent on energy derived from the freezing of supercooled water this mechanism would still exist as the temperature approached the normal ice point. The Thompson equation can be interpreted here to mean that a depression in an otherwise flat ice crystal would be unstable at the normal ice point and would fill with ice spontaneously at the expense of ice from the flat portions of the crystal.

Taber's conclusion that an unfrozen film of water persists between the ice lens and the soil particles is generally accepted. When a part of this film water freezes, there will be an uplift corresponding to the volume change of the water as it solidifies. This volume change is but a small fraction of the net uplift in the heaving process. The major uplift occurs when the film is reinflated to its original thickness. Hence, the major part of the energy required for heaving is derived from the forces which draw fresh water into the film to replace that lost to the ice phase. Recharge of the film does not involve a phase change and the freezing of supercooled water cannot be invoked as the source of energy for this process. The Thompson equation does not give any basis for supposing that film water can be supercooled with respect to adjacent ice, for as has already been shown, it would predict that the film water would freeze spontaneously, eliminating the film entirely.

The freezing point of film water must be depressed by interactions with the particle surface, as pointed out by Taber. These interactions may be expressed in terms of "adsorption forces" which serve two functions. The first is to depress the freezing point so that the film remains unfrozen at heaving temperatures, and the second is to draw fresh water from below to recharge the film when it is depleted by ice formation. Professor Low's contribution to this symposium reviews current ideas on the nature of these forces. Further studies of these forces and their nature are being made at Cornell.[3] It seems evident that the recharge function of these forces is identical with their function in producing swelling in clays, and that the heaving process is merely a special case of swelling. Water acquired by the surface film is constantly being borrowed and stored as ice and heaving continues indefinitely if heat is being extracted from the system and other necessary conditions are satisfied.

It is possible to construct a model which can simulate the function of the surface film and to produce heaving in the absence of soil and in the absence of geometrically induced supercooling. This model consists of a simple osmometer made in the form of a cylinder containing a salt solution. The lower end of the cylinder is a semipermeable membrane in contact with pure water in a reservoir. Resting on the solution is a loaded piston which simulates overburden. This system will spontaneously adjust to an equilibrium condition by transfer of water across the semipermeable membrane until the solution has an osmotic pressure which will just support the loaded piston. If some of the water from the solution is made to freeze on the underside of the piston, the equilibrium will be disturbed, and the solution will absorb fresh water, recharging the solution to approximately its original volume. Since the weight of the ice formed has been added to the overburden, the new equilibrium concentration will be slightly larger than before, but it can be shown that if the solution is present as a very thin layer, a great deal of ice must be formed to change the thickness of the solution appreciably. Hence, this model simulates the heaving process in all important respects. It can be elaborated to simulate other soil conditions, such as depth to the water table and soil permeability.[4]

With the proper geometry and temperature gradient, this model will produce heaving in the absence of any supercooling beyond that required to freeze ice at a finite rate. To make it operate, all that is needed is a heat sink to assure the conversion of water in the solution to ice. If the source of energy for most of the actual work done in lifting the overburden must be indicated, it might be said to be osmotic pressure (in the case of the model).

The role of supercooling in heaving, according to this discussion, is a passive one. The Thompson equation has not been questioned, and its consequences in preventing proliferation of ice through soil pores are presumed to be important to the efficiency of the heaving process. On the other hand, supercooling in large pores as a consequence of the Thompson equation is not accepted as the origin of the energy required for heaving.

E. PENNER, Closure—The author is grateful for the lengthy discussions and criticisms submitted by Jumikis, Martin and Miller. Unfortunately in the case of Martin and Miller, they were mostly related only to one aspect of the paper. An extensive rebuttal is obviously not warranted at this stage since substantiation or disagreement depends to a large extent on further experimentation. That limitations exist in the theory was recognized and stated by the author. The paper was, however, presented in the light that some useful discussion would develop. This, in the author's opinion, has been achieved.

With reference to Martin's discussion, his chief disagreement centers around the temperature and pressure relationships at the ice-water interface. The author can find no evidence to disagree with the model showing that ice and water are in contact

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[3] Contract DA-11-190-ENG-23, Phase II, Snow, Ice and Permafrost Research Establishment, Corps of Engineers, U.S. Army.

[4] This model and the Gouy-Chapman model of the electrical double layer have been examined in relation to the mechanism of frost heaving in an unpublished report prepared by L. A. Cass and R. D. Miller for the Snow, Ice and Permafrost Research Establishment, Corps of Engineers, U.S. Army, in fulfillment of contract DA-11-190-ENG-23, Phase I.

at the heaving front above the soil particle and that the "growing" ice phase rests on the adsorbed phase. Until more information becomes available on this point, the thermodynamic expression used in the paper appears to be consistent with the model. It may well be that the use of liquids other than water in a heaving system as suggested by Martin, may be helpful in unraveling the phenomenon.

Miller questions the suggested mechanism of supercooling as a source of energy for the work such systems can perform. The alternative offered that frost heaving results from osmotic pressures, as suggested in his unpublished report and in his discussion appears to have much merit. Undoubtedly, Miller recognizes that similar effects may result from different causes. The predicted heaving in his model osmometer in itself does not prove that this happens during frost heaving in soils.

Miller's suggestion seems more understandable in the case of clays where osmotic pressures arise from differential ion concentrations in the system to which swelling is attributed. In the case of coarser materials such as fine sands, these osmotic effects are more difficult to visualize since no adsorbed ions need necessarily exist. In fact, the author has measured heaving pressures of considerable magnitude in systems which have no possible exchange capacity and are devoid of any extraneous ions. In these systems classical osmotic pressures arising from ion concentrations do not exist. What is involved is a phenomena associated with the adsorbed water phase.

While reinflation of the film around the particle is brought about by differences in the free energy of the water in the unfrozen portion of the soil, one must also explain where the energy arises initially to remove adsorbed water for ice lens growth. This in fact initiates the process, and moisture flow from the unfrozen soil is an effect not a cause and is only necessary to sustain heaving.

In earlier work, the author showed experimentally that the maximum heaving pressure was related to the dry density of the porous medium. At high densities, the highest heaving pressures occurred; at low densities, much lower heaving pressures resulted. By changing the dry density the pore dimensions were obviously altered. Since the same material was used for all densities, it is difficult to ascribe these effects to other causes than those outlined by the author; perhaps these effects can also be explained in the light of the osmotic concept.

Finally, whatever its origin, if supercooling at the ice-water interface is necessary for ice lens growth and heaving, its magnitude would appear to be related to the pore restriction dimensions between adjacent particles. If this were not the case, unrestricted ice propagation between particles would prevent supercooling and only in situ freezing would result. This is the case of a non-frost susceptible soil even in the presence of an ample water supply.

The Factor of Moisture in Frost Action

P. F. LOW, Professor of Soils, Agronomy Department, and
C. W. LOVELL, Jr., Assistant Professor of Civil Engineering, Purdue University

Pertinent engineering and scientific literature on the nature and behavior of moisture as related to soil freezing are reviewed. Considered initially is the basic structural nature of water, of ice, and of ionic solutions. This is followed by summarization of the forces responsible for moisture adsorption in clay-water systems, the structure and properties of the adsorbed water, and the consequent effect upon supercooling and freezing of this water.

Having established a basic physical and chemical background, the paper proceeds through a brief review of what is known of in-service moisture conditions under pavements, and how these moisture conditions may change with time. Finally, consideration is given to the techniques of determination of service moisture quantities, and to the principles of control of such moisture quantities.

●THE AUTHORS have considered their function in preparing this paper to be one of review, summarization and systematizing. An effort has been made to meet the diverse demands of brevity, conciseness and completeness.

Discussion of the role of water in frost action proceeds from basic chemical and physical considerations into those applications of science generally considered basic by the engineer. Initially treated are the structures of water, ice and ionic solutions followed by the nature of water in clay-water systems, and the forces responsible for its adsorption.

The theory of supercooling is reviewed, as are certain aspects of the freezing behavior of soil water. Data on the quantities, as well as the sources and mechanisms of change in quantity, of moisture experienced under pavements in service are summarized. In conclusion, methods and principles of measuring, predicting and controlling these moisture quantities are outlined.

THE NATURE OF WATER, ICE AND IONIC SOLUTIONS

Studies of the isolated water molecule (82) have shown that is consists of a V-shaped arrangement of the atomic nuclei, the H-O-H angle being 105°, and the O-H internuclear distance being 0. 97 Å (Fig. 1(a)). The dipole moment of the water molecule is 1.83 x 10^{-18} esu, and has been regarded by Bernal and Fowler (11) as being due to the charge distribution depicted in Figure 1(b). This geometry and charge distribution gives rise to a tendency for water molecules to assume a tetrahedral arrangement as shown in Figure 2. Since the positively charged hydrogen ions of a given water molecule attract the negative charge centers of neighboring water molecules, the molecules are said to be held together by hydrogen bonds.

In ice, the water molecules exist in a tetrahedral arrangement with an O-O distance of 2.76 Å (98, 95). The hydrogen nucleus is not midway between the oxygen nuclei, but is 0.99 Å from one oxygen nucleus and 1.77 Å from the other. Most of the water molecules form the maximum of 4 hydrogen bonds and, for this reason, ice possesses rigidity. However, ice retains appreciable entropy (that is, disorganization or randomness), especially near the melting point (98). Accordingly, it is believed that the molecules can re-orient with considerable freedom, and that the hydrogen ions can re-locate by moving 0.78 Å from a position 0.99 Å from one oxygen to a similar position near the other bonded oxygen. If no hydrogen bonding existed in ice, each water molecule would have 12 nearest neighbors instead of 4, and its density would be 1. 840 instead of 0.917.

When ice melts, it is estimated that only about 15 percent of the hydrogen bonds are broken (98). Therefore, the resulting liquid water retains a loose tetrahedral configuration (11, 65, 90), and is said to have a "broken-down ice structure." There is still a tendency for each water molecule to bond itself tetrahedrally to 4 neighbors, but the bonds are continually breaking and reforming so that, on the average, each molecule has slightly more than 4 nearest neighbors but is bonded to fewer than 4 of them. As the hydrogen bonds are broken the resulting fragments tend to pack together as closely as possible so that some of the water molecules acquire more than 4 nearest neighbors. This tendency toward close-packing as bonds are broken explains the volume decrease of about 9 percent on melting, even though the intermolecular distance increases from 2.76 Å to 2.90 Å. As the temperature increases the increased thermal agitation results in the rupture of additional hydrogen bonds. But the increased agitation also results in an increase in intermolecular distances. The former effect of thermal agitation predominates below 4 C; whereas the latter effect predominates above 4 C. The result is that water has a maximum density at 4 C. By the time a temperature of 40 C is reached, somewhat more than one-half of the maximum number of hydrogen bonds are still present. Hydrogen bonding exists even at the boiling point. This bonding is responsible for the unusually high values for the melting point, boiling point, dielectric constant, specific heat and viscosity of water.

The solution of electrolytes in water has an effect like that of increasing the temperature in that the dissolved ions break hydrogen bonds and disrupt the water structure to cause closer packing. It appears, however, that the ions do not appreciably alter the intermolecular distances, because the net effect of electrolyte addition is to increase the density of the water. The disruptive effect of the ions depends on the ionic size; the larger the ion the greater the disruptive effect. These conclusions are based on the X-ray, partial molal volume, and compressibility work of Stewart (117, 118, 119, 120) and of Corey (25); the entropy work of Frank and Robinson (40) and of Frank and Evans (41); the dielectric constant work of Hasted, Ritson and Collie (50); and the viscosity work of Wang (126). The disruptive effect of the ions is probably due to the formation of ion-dipole bonds as diagramed in Figure 3. The spacial interference of the ions, however, also plays a part.

For more detailed discussions of water, ice and solutions, the reader is referred to the publications of Bernal and Fowler (11), Llewellyn (72), Pauling (98), Buswell and Rodebush (21), Robinson and Stokes (107) and Owston (95).

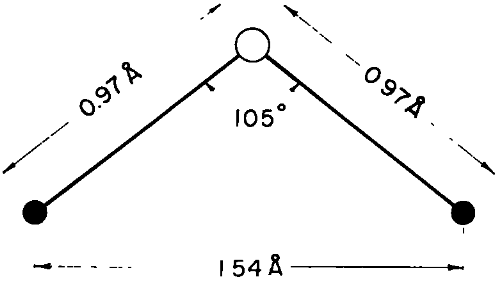

Figure 1(a). Internuclear distances and bond angle of the water molecule. (After Robinson and Stokes, 1955.)

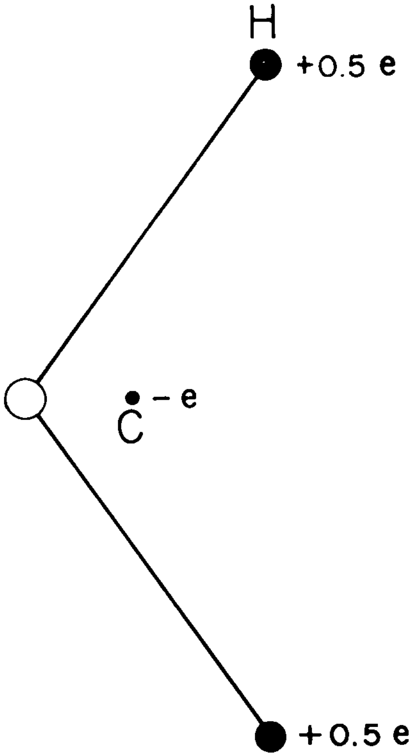

Figure 1(b). Model of the charge distribution in the water molecule. C is taken as the center of the molecule. Distance OC is not drawn to scale. (After Robinson and Stokes, 1955.)

NATURE OF WATER ADSORBED ON SOIL MINERALS

At the present time, all of the forces responsible for water adsorption by soils are not known. It is generally agreed, however, that the exhangeable ions are involved. In the earliest stages of water adsorption these ions form ion-dipole bonds with water molecules (Fig. 4(a)); that is, they hydrate and thereby hold water to the mineral surfaces (125, 93, 53, 104, 43, 89, 66, 83). With the addition of more water, the ions dissociate from these surfaces to form diffuse ion swarms which attract water by osmotic forces (114, 37, 14, 51, 127, 92). Attraction of this kind is depicted in Figure 4(a).

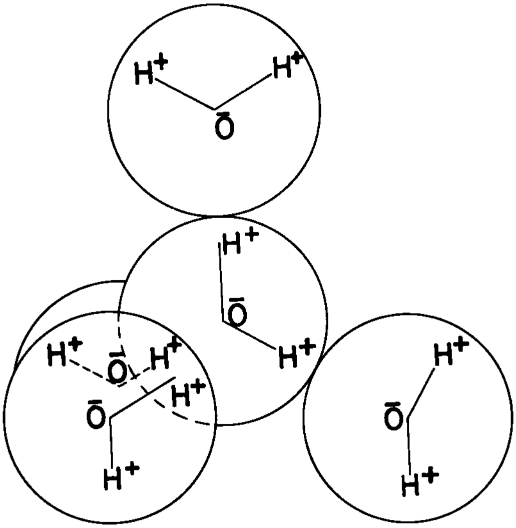

Figure 2. Tetrahedral arrangement of water molecules. (After Bernal and Fowler, 1933.)

The mineral surfaces also attract water. This attraction is probably due to hydrogen bonding between the water molecules and oxygen or hydroxyl ions in these surfaces (Fig. 4(b)). Hendricks and Jefferson (52) and Macey (79) have proposed possible water structures which might result from such bonding, but other kinds of bonding could be involved. For example, the negative charges in the mineral might attract the positive ends of the water dipoles. This attraction could be between individual charges and water dipoles (Fig. 4(c)) or it could be between the electric field produced by the cumulative effect of those charges and the water dipoles. Or the instantaneous fluctuations in charge distribution of the surface atoms could induce in the water molecules similar fluctuations in phase with themselves (Fig. 4(d)). Regardless of the nature of the bonds, the initial layer of water molecules would be strongly oriented. This oriented layer would, in turn, orient the next layer and so forth. Thus, by relayed action, thick oriented layers of water molecules could be built up.

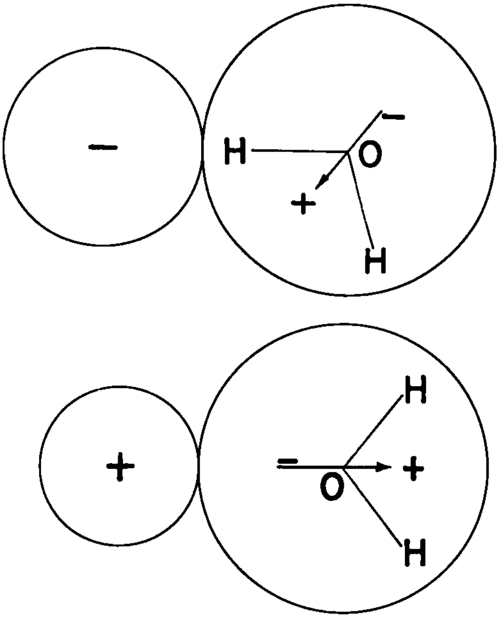

Figure 3. Anion hydration (above); cation hydration (below).

An oriented or ordered structure exists in the water adsorbed on at least a few soil minerals. Anderson and Low (4, 77) observed that the density of the water adsorbed on montmorillonite was less than the density of normal water up to distances of the order of 80 Å from the clay surface. The adsorbed water density decreased with the proximity to the clay surface and with a decrease in temperature. Figure 5 shows the data for potassium bentonite. Since exhangeable cations would disrupt this water structure and tend to increase its density, the clay surface must have been responsible for its development. Evidently, the regularity and extent of the adsorbed water structure increases, not only with a decrease in thermal agitation as the temperature is lowered, but also with an increase in cation dissociation from the clay. This fact is indicated by the following observations:

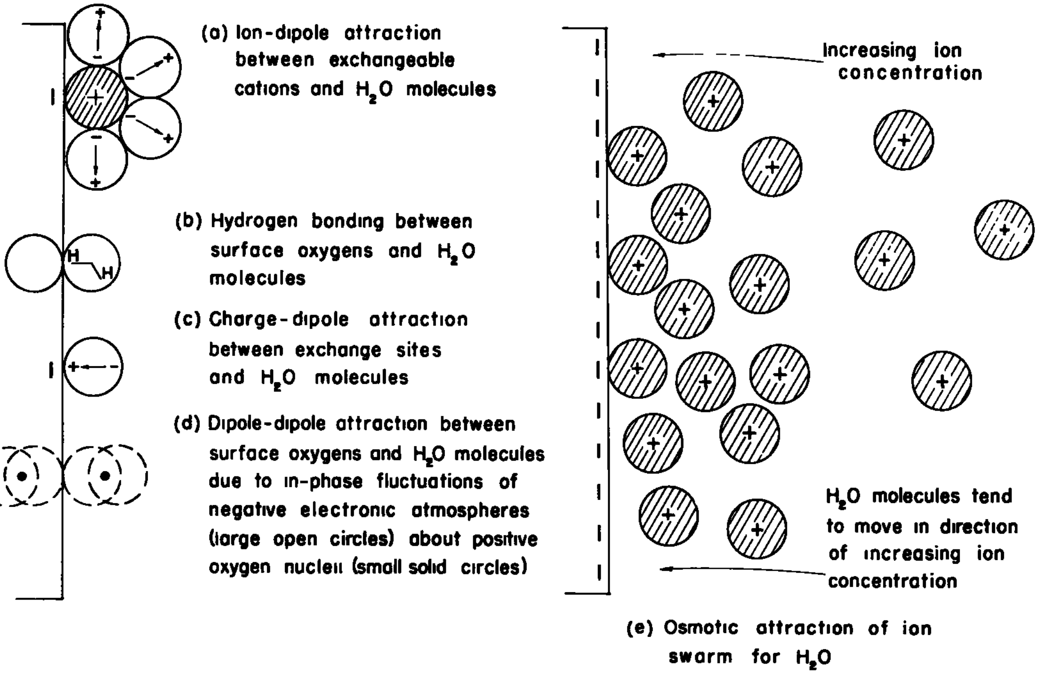

Figure 4. Ways in which water might be attracted to mineral surfaces.

1. The activation energy for ionic movement, which depends on the coherence of the adsorbed water structure, increases with increased ionic dissociation from the clay (78).
2. Supercooling of water in clay suspensions, which should be augmented by stuctural development in this water, increases with increased ionic dissociation from the clay as indicated by zeta potential measurements (33).
3. Unfrozen water in clay pastes at -5.0 C increases with increased ionic dissociation from the clay, even though the ions are not sufficiently concentrated to prevent freezing at this temperature (51).
4. Unfrozen water in clay pastes at -5.0 C increases with clay swelling, and is more extensive on external surfaces than on internal surfaces[1] (51).

It can be postulated that structural development in the adsorbed water is enhanced by increased ionic dissociation from the clay, because the disruptive effect of the ions is less when they are distributed through a relatively large volume than when they are concentrated at the surface where the structure is "anchored." Figure 6 illustrates this concept. The structure imparted to the water by the clay surface is not that of ice, because the adsorbed water supercools extensively; nor is it entirely rigid, because ion exchange occurs readily.

Several investigators (89, 92, 19, 133, 39) have used X-ray diffraction techniques to measure c-axis spacings of clay samples at various degrees of hydration, and have observed that expansion of the lattice layers occurs in definite increments. These increments approximate the diameter of the water molecule, or multiples thereof, up to spacings of 18 Å for montmorillonite. The general conclusion drawn from the results is that successive layers build up on the clay surface as it hydrates. Since it is not yet possible to locate individual water molecules by X-ray measurements on clay-water systems, no conclusions regarding the exact arrangement of the adsorbed water molecules are justified.

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[1] Note that the dissociation of cations from clay surfaces should depend partly on the proximity of adjacent surfaces; the nearer the surfaces, the less the dissociation.

Measurements of the dielectric properties of clay-water systems have indicated that the structure of the adsorbed water is different from that of normal water. Muir (91) examined the dielectric properties of hydrated samples of kaolinite, halloysite, metahalloysite and talc at different frequencies and at different degrees of hydration. He found that the frequency of maximum dielectric adsorption for the first layer of water was relatively low, and was nearly the same for all the minerals tested. Hence, he concluded that the first layer of water was strongly adsorbed with about the same intensity regardless of mineral type. As successive layers of water were added the frequency of maximum adsorption increased, suggesting reaction of the less organized outer layers with the first. Palmer, Cunliffe and Hough (96) observed that the dielectric constant of water on mica decreased with calculated film thickness, from more than 20 for films about 5 microns thick, to less than 10 for films about 2 microns thick. They also observed that, as in ice, the dielectric constant of the adsorbed water changed rapidly as the frequency was changed from 2 to 2. 5 megacycles per second. Since neither the dielectric properties of free water or mica are frequency sensitive over this range, they concluded that the adsorbed water approached the same degree of crystallinity found in ice. Cownie and Palmer (28) and Palmer (97), using an unspecified wet clay, found that the dielectric constant increased from a value of about 3 to a value of about 50 in moving from zero moisture to 80 percent moisture (Fig. 7). Thus, the evidence from measurements of the dielectric constant indicates that water

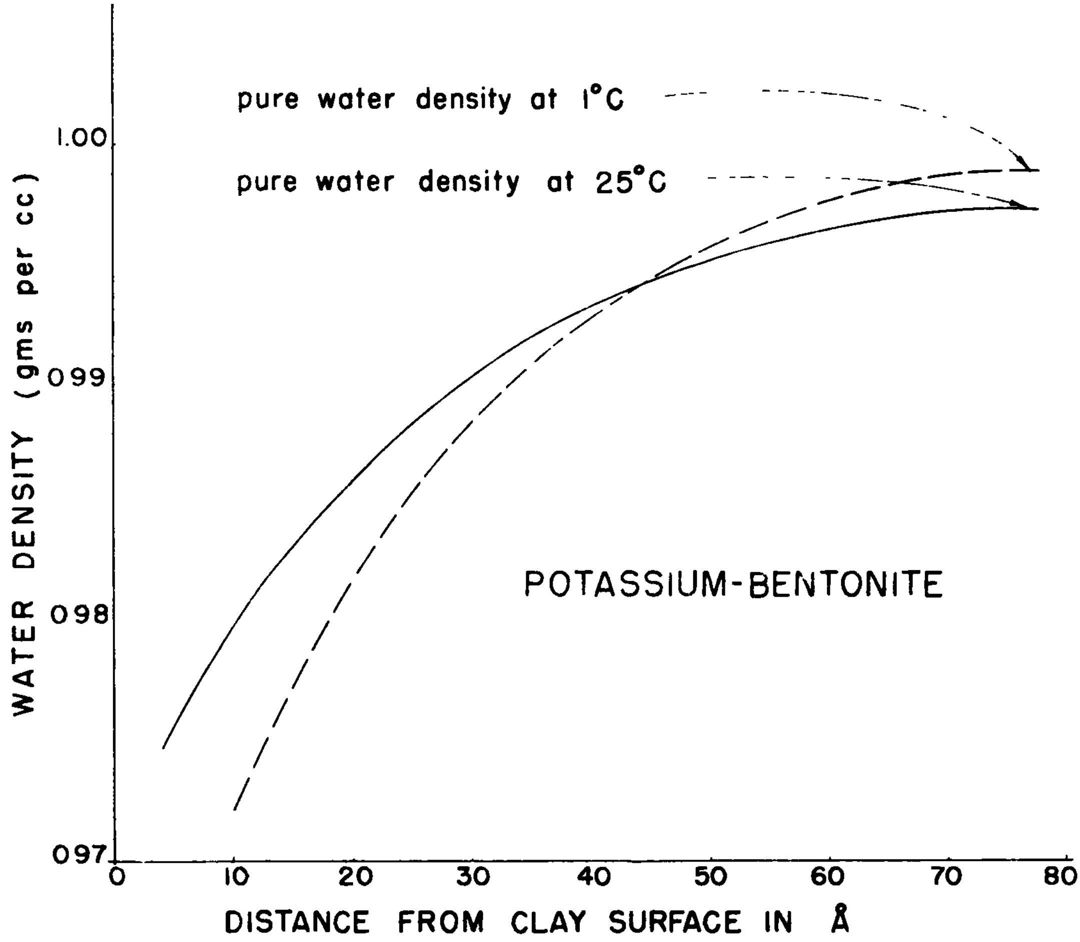

Figure 5. Change in water density with distance from the surface of potassium bentonite at two temperatures. (From data by Anderson and Low, 1958).

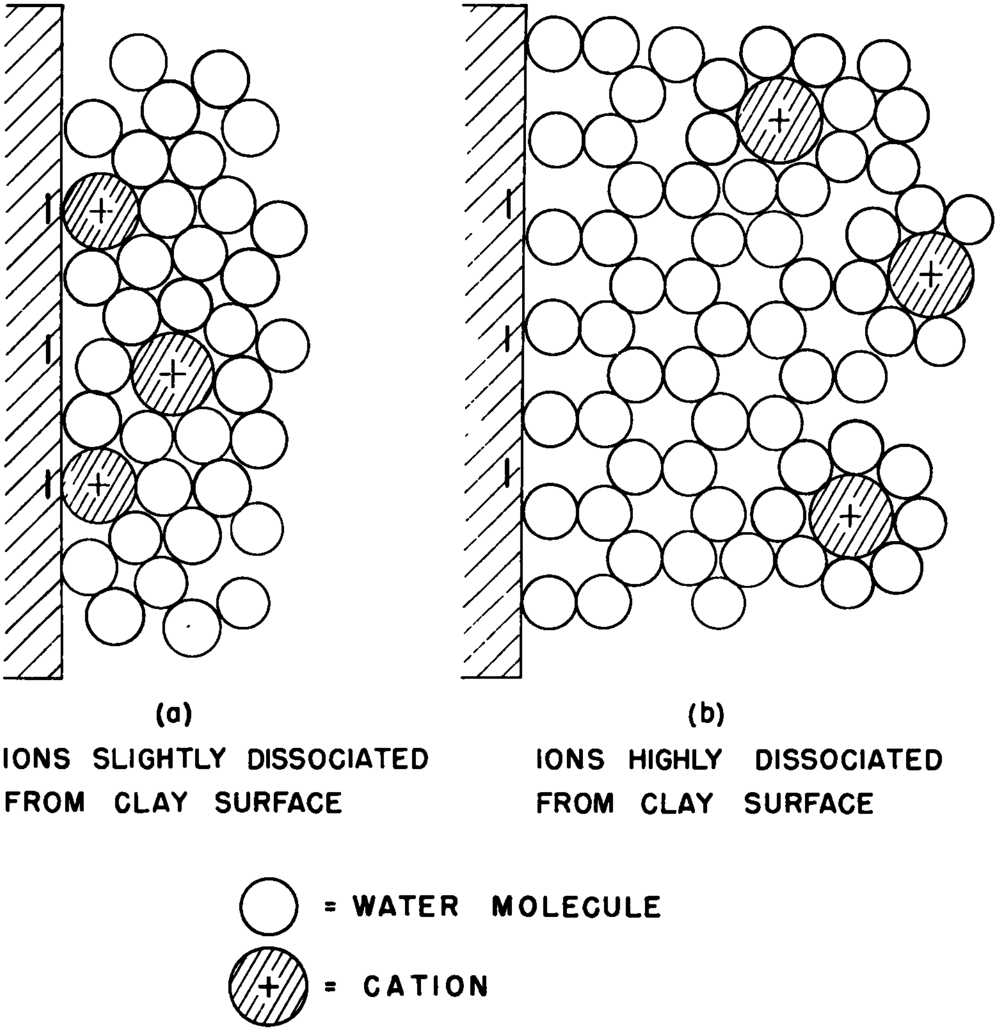

Figure 6. Effect of ion dissociation on the surface-induced water structure. (Illustrative only. Not intended to represent actual molecular arrangement.)

is strongly ordered at mineral surfaces, the degree of order decreasing with distance from these surfaces.

If the adsorbed water possesses a structure which is more ordered than that of normal water, its viscosity should be greater than the viscosity of normal water. Very little direct information is available in this regard. Macey (79), however, observed that none of the existing theories on water flow through porous media could be applied to clays without assuming that part of the water was immobile; that is, that its viscosity was infinitely high. Carman (23) and Von Engelhardt and Tunn (124) were obliged to make the same assumption to explain their data. Macey also found that the conductivity of clays for non-polar liquids was of the order of 10^4 to 10^6 times that for water, suggesting that, despite differences in clay packing, the viscosity of the water was unusually high. The work of Rosenqvist (109) supports these observations. By making certain assumptions relative to the geometry of the pores and using experimental data, Rosenqvist calculated a diffusion coefficient for deuterium oxide in the pores of a clay paste which was only about 5 percent that of pure water. Recently, Low (78) has shown that the activation energy for ion movement in the adsorbed water is higher than the activation energy for ion movement in pure water. The available evidence indicates that clay-adsorbed water has an unusually high viscosity. But it should be noted that electroviscous effects (36) or counterelectro-osmotic effects (87) might account for part of the retardation of water flow in porous media. It is unlikely that they account for all of it (54). A hypothetical viscosity vs distance curve is shown in Figure 8.

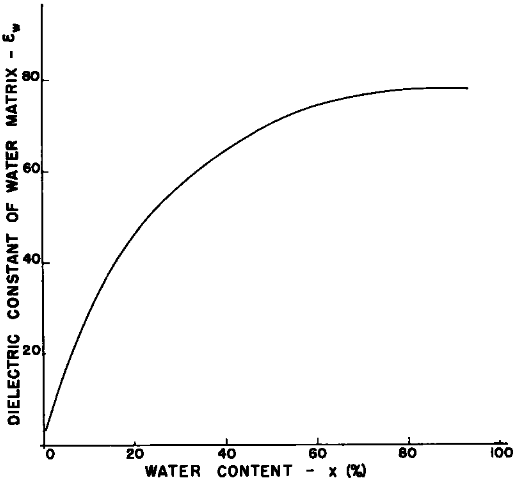

Figure 7. Variation of the dielectric constant of water in a wet clay with the water content. (After Palmer, 1952.)

The thermodynamic properties of water adsorbed on soil minerals are also different from those of normal water. For the equation,

$$\bar{F} - \bar{F}^0 = -\bar{v}\pi$$

where $\bar{F}$ and $\bar{F}^0$ are the partial molar free energy of the soil water and pure water, respectively, $\bar{v}$ is the partial molar volume of the soil water and π is the swelling pressure. It may be seen that the partial molar free energy of the soil water is less than that of pure water as long as the soil swells in pure water. Clay soils will swell in pure water until films as thick as 200 Å have developed on the particle surfaces (114, 37, 14, 51, 127, 92).

The heat content of this water is also less than that of normal water. There is considerable evidence (19, 133, 109, 116, 88, 47) which shows that heat is lost on the adsorption of water by clays until water films of appreciable thickness are formed. The initially adsorbed water has a heat content less than that of ice (109).

The data on the entropy of soil water are limited. However, they show that the soil water has a higher degree of order than normal water, up to water contents as high as the field capacity (106, 6). The water in the first monolayer on kaolinite is more ordered than ice (45).

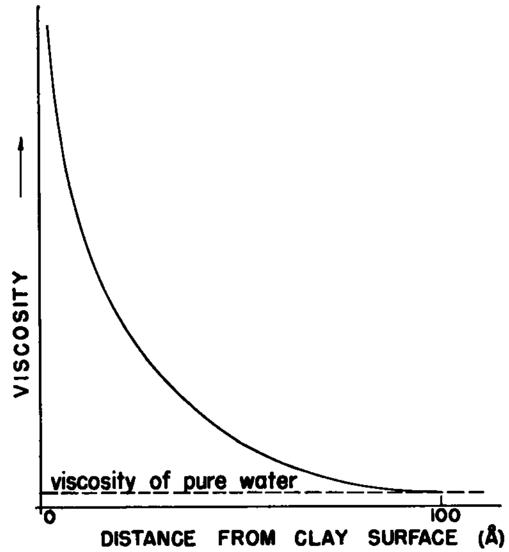

Figure 8. Hypothetical decrease of water viscosity with distance from the clay surface.

For additional information on the nature of adsorbed water, the reader is referred to the discussions of Grim (47), Williamson (128) and Mackenzie (80).

SUPERCOOLING AND FREEZING OF ADSORBED WATER

The evidence presented in the previous section shows that the structure and properties of water are altered when adsorbed on soil minerals. Now the consequences of this alteration on the supercooling and freezing of the water may be examined. The discussion will be brief because the subject of freezing will be treated in greater detail elsewhere in this symposium.

According to the nucleation theory of Turnbull and Fisher (122), as applied to water by Mason (85, 86),

$$\log J = 32.84 + \log T - \frac{U}{2.303kT} - \frac{760\sigma^3}{(T_0 - T)^2 T}$$

in which

J = rate of production of ice nuclei of critical size;
T = absolute temperature;
U = activation energy for the diffusion of water molecules across the water-ice interface;
σ = interfacial energy between water and ice; and
T_0 = thermodynamic freezing point.

A nucleus of critical size is one which is just large enough to grow to an ice crystal rather than evanesce. Now U is related to the viscosity η by the expression (5, 44),

$$\eta = Ae^{\frac{U}{kT}}$$

in which A is a constant; hence, the rate of production of ice nuclei of critical size is expected to be small; that is, there will be a tendency for the water to supercool if the viscosity of the water is high and if its interfacial tension against ice is large. There is evidence that the viscosity of the adsorbed water is unusually high. In addition, evidence exists that the adsorbed water has a different structure from normal water and, for this reason, should have a different interfacial tension against ice. If it is assumed that this interfacial tension is increased by the clay-induced modification in the water structure, the observed supercooling of water in clays and soils can be explained.

The freezing point of water can be lowered by increasing the ion concentration and pressure (110, 35) and by lowering the potential energy of the water relative to that of ice (6). Undoubtedly, the ion concentration and hydrostatic pressure are greater in the region of the charged mineral surfaces than in the bulk of the soil solution. If an attractive force exists between the water and mineral surfaces as indicated, the potential energy of the water should be lower in this region. It is not surprising, therefore, that all the water in a clay or soil system does not freeze at the same temperature; the adsorbed water can freeze only at a lower temperature (51, 15, 3, 20, 76).

In view of the ion concentrations and probable hydrostatic pressures in the systems studied thus far, it appears that these factors alone cannot account for the observed amounts of water remaining unfrozen. Consequently, the reduction in the potential energy of water near the mineral surfaces must also be a factor. This factor has not been generally recognized.

QUANTITY OF MOISTURE UNDER PAVEMENTS

Prediction of the moisture content or degree of saturation to be expected beneath a

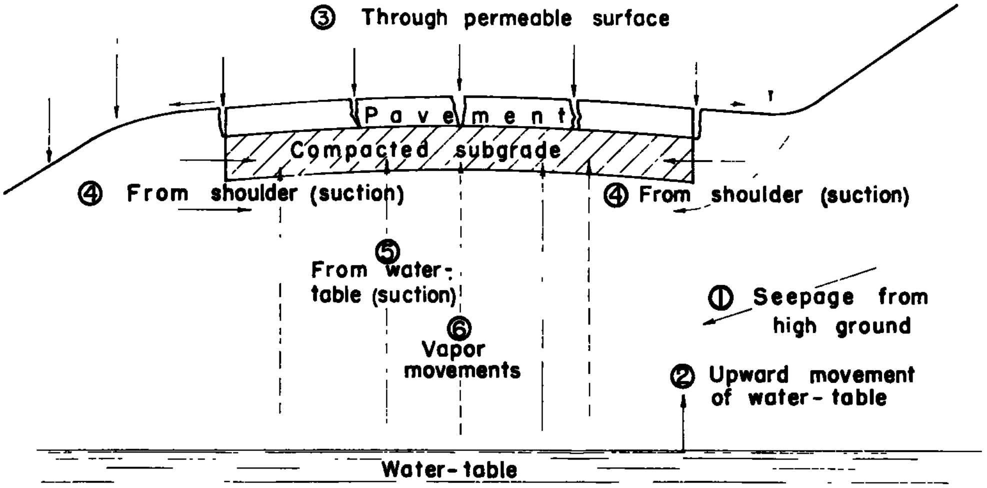

Figure 9. Ways in which moisture can enter road subgrades. (After Road Research Laboratory, 1952.)

pavement at a given time is in general a complicated matter. The multitude of variables and uncertain boundary conditions have limited the scope and conclusiveness of both the field measurement and rational or calculation type of approach.

In this regard, consider first the variable of initial or compaction moisture content, which is influenced by the soil texture, the type and magnitude of compactive effort, and the efforts of the engineer to specify and control it. As a result of a number of recent studies it is anticipated that progressively less emphasis will be placed on the simple achievement of high densities, and more on the specification of compacted moisture-density conditions capable of producing desired, predetermined properties in the service subgrade or embankment.

For example, Foster (38) and Turnbull and Foster (123) have shown that the strength of a compacted silty material can decrease with increase in density, unless the compaction moisture content is properly controlled. Wilson (129) demonstrates that for cohesive soils the properties of strength, resistance to deformation, permeability, and compressibility can be greatly influenced by variation of only the molding water content. Discussions of these papers point out the manner in which high densities and low molding water contents serve to increase swelling of clays.

Lambe (70a, 70b) has taken a fundamental approach to the matter of compaction moisture content, suggesting that the difference in soil properties wet and dry of optimum is logical in view of the differences in soil particle orientation for the two conditions. Seed (114a) in as yet unpublished research has successfully applied the flocculent vs dispersed structure concept in interpretation of laboratory data on compacted clays.

The observations of Hveem and Vallerga (59) and of Hveem (60)—with discussion, lend additional support to the belief that compaction specification must become increasing definitive of desired service properties. The trend to better control compaction moisture contents should, as a by-product, aid efforts in measurement and prediction of service moisture conditions.

Prominent among the studies of actual moisture conditions under pavements are those by Kersten (68, 69), Hicks (55), Corps of Engineers (26, 27), Redus and Foster (102) and Redus (103). This listing can be supplemented rather extensively if one includes work where, (a) the data reported are more limited, (b) the moisture measurements are much subordinated to another investigational endpoint, and (c) the observations are made under other than a pavement cover. The data reported serve to emphasize the relative importance of such factors as: type of pavement (including base and subbase layers); loading and its capacity to produce densification; age and condition of the pavement; texture and initial condition of subgrade or embankment; the environment—topographic position, ground water level, climate, season, severity of frost action; and depth, position and frequency of sampling.

These investigations show: (a) that the more clayey soils achieve higher degrees of saturation in service than do soils of low plasticity; (b) that climate, and more particularly precipitation has the anticipated effect at shallow depths; (c) that the moisture quantities show continuous, if small, variation with the seasons, but with an increase trend to some critical age; and (d) that moisture gradients exist laterally with respect to the pavement, as well as with depth under the pavement. Beyond this area of general agreement in data are important differences, assumed to be peculiar to the study sites and perhaps also to the investigational perspectives.

A generalized concept of the sources of sub-pavement moisture is presented in Figure 9 in which the following may be noted:

1. Moisture may permeate from the sides, particularly where coarse-grained layers are present or where surface drainage facilities in the immediate vicinity are inadequate.
2. The water table may rise, and indeed may be depended upon to do so in the winter and spring seasons.
3. Surface water may enter joints and/or cracks in the paving, penetrate at the edges of the surfacing, or percolate through the surfacing and shoulders.
4. Water may move laterally.

5. Water may move vertically in capillaries or interconnected water films.
6. Moisture may move in vapor form, depending upon the existence of adequate gradients and air void space.

Moisture can be removed from the soil by reversing the above actions and substituting evaporation for (3).

The study of mechanisms by which moisture moves in a porous medium is basic to a number of scientific and engineering disciplines. Certain quantities are "free" to move by gravity flow; other moisture is "held," and can move only in response to more complex energy gradients. Suction differences are capable of producing considerable liquid flow when the soil is saturated or nearly so. Temperature gradients provide prime motivation for vapor movement, particularly when soil texture and water table position combine to produce a relatively low degree of saturation.

The topic of moisture migration is one extensively studied with a primary reference to highway problems—Russell and Spangler (113), Winterkorn (131), MacLean and Gwatkin (81), Croney and Coleman (29), Road Research Laboratory (105), Wooltorton (132), Rollins et al. (108), Johnson (61); as well as the papers of the International Symposium on Moisture Conduction in Soils and Similar Systems (134).

The great capacity of the soil freezing process to "pull" moisture into the freezing zone has long been recognized and reported for both laboratory and field studies—Taber (121), Beskow (12), Shannon (115), Lund (74), Haley and Kaplar (48), and Lovell and Herrin (75). Within the last few years intensive investigations of the details of these moisture-moving potentials have appeared in engineering literature—Penner (100, 101), Gold (46), Jumikis (62, 63, 64), and Martin (84). It is found that very considerable suctions are operative for liquid flow to the area of crystallization.

DETERMINATION OF QUANTITY OF MOISTURE

The primary approach to determination of moisture quantities has been experimental, that is, measurement of in-service conditions. The oldest, and still dominant, measuring technique is the gravimetric method of sampling and oven drying. This technique has very pronounced and obvious deficiencies when applied to the problem at hand.

A variety of techniques of in-place moisture measurement have been subjected to experimental or to practical use. Perhaps the best known of these are the electrical resistance cells of Bouyoucos and Mick (16), Bouyoucos (17, 18), and Colman (24). The porous material of these units (plaster of paris, nylon or fiberglas) tends to remain in moisture equilibrium with the surrounding soil. The electrical resistance of the "block" changes with its quantity of moisture, and upon calibration becomes a measure of the moisture in the soil.

Another method, and one of considerable promise, is the neutron method of counting hydrogen nuclei—Belcher et al. (7), Belcher (8), Carlton (22), Horonjeff and Goldberg (57), Horonjeff and Javete (58), and Roy and Winterkorn (112).[2] In this method, neutrons are emitted, scattered, lose energy and become "slow" after collision with the hydrogen atoms in the soil-water system. As the quantity of moisture (in any form—solid, liquid or vapor) increases, the count of slowed neutrons increases. Upon calibration, the count becomes a measure of the average moisture content over a small sphere of influence.

Further possibilities are the heat diffusion technique, reported to have strong practical limitations by Aldous and Lawton (2), and the evaluation of moisture content by measurement of dielectric constant or capacitance—DePlater (34), Cownie and Palmer (28), and Palmer (97). The latter technique should be viewed as very much in the experimental stage. In addition, a recent modification of the electrical resistance method utilized an ionic moisture barrier to filter salts from the moisture being measured. Engineering development of this device has had primary reference to the moisture in hardened concrete—Blythe (13) and Klein (70).

A summary view of moisture measurement methods may be attained by review of

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[2] Contains a very extensive bibliography.

Penner et al. (99), Lull and Reinhart (73), and the references of the HRB Bibliography (56). The development and use of all the in-place measuring instruments pose, to varying degrees, similar questions and problems. These are concerned with: the range of moisture sensitivity, the need for length calibration periods, definition of exactly what the instrument measures, the effective zone of measurement, the effect of salts and of temperature, the intimacy of contact of the sensing element with the soil and the rapidity of response to moisture change, and others.

An interesting supplementary capacity of the electrical resistance method is that of determination of time or duration of soil freezing—Rowland et al. (111) and unpublished work at the AASHO Test Road in Illinois.

The approach of prediction through calculation for equilibrium of maximum moisture contents has been spearheaded by English investigators, using the suction concept—Croney et al. (30), Croney (31), and summarized by Croney et al. (32). With reasonable limitation on the boundary conditions, calculated moisture values have been found to check actual moisture conditions rather well. Wooltorton (132) has recommended as prediction alternates the use of density-moisture change curves or the field moisture equivalent.

CONTROL OF MOISTURE QUANTITIES

Reference is again made to Figure 9 and to the previous discussion of sources and mechanisms for moisture increase of subgrades and embankments.

Drainage is an obvious method of control for the gravitational water. Much of the water in the pores of the coarse-grained soils is in this category, and it is commonly possible to greatly reduce the degree of saturation of such soils by conventional subdrainage. For example, lateral seepage in granular layers can be intercepted, open-graded bases and subbases can be drained, and free water perched in a sandy stratum by a relatively thin layer of low permeability can usually be disposed of by subdrainage. The water table can be lowered by subdrainage in fine-grained materials also; but as the soil becomes more clayey, the time required to achieve significant lowering becomes progressively more impractical, and the reduction in degree of saturation effected by the removal of gravitational water becomes rather insignificant.

A number of investigators have addressed the problem of definition of a limiting initial moisture content or degree of saturation, below which ice segregation and frost damage are unlikely. These include Taber (121), Winn and Rutledge (130), Corps of Engineers (26), and Haley (49). This critical quantity of moisture varies with a number of factors, such as the availability of additional moisture and the rate of freezing.

Field observations have revealed that even though the water table often cannot be lowered sufficiently to eliminate frost damage, this damage can be very significantly reduced by lowering the order of several feet—Beskow (12), Keene (67), Road Research Laboratory (105), and Lawson (71). Experience also favors, as an alternate or supplement to ground water lowering, the use of an elevated grade line.

Certain profile situations need particular drainage attention, due to their tendency to "trap" free water—Aaron (1). The same is often true of situations where rock underlies the pavement at shallow depth—Bennett (10), Otis (94), and Fuller (42). Drains must, of course, be open and able to function during the critical thawing period.

Finally, it seems pertinent to mention the use of "barriers" to reduce capillary or vapor movement. The idea of interposing a granular layer which "cuts off" capillary flow is an old one—Beskow (12). Membranes capable of also sharply reducing vapor transmission have received increased recent attention. Particularly interesting, although beset with sizable practical difficulties, is the use of plastic films—Bell and Yoder (9).

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Discussion

A. R. JUMIKIS, Professor of Civil Engineering, Rutgers, the State University, New Brunswick, N. J. —Judging by their contributions to HRB activities in furthering the dissemination of basic knowledge for the purpose of good road and earthwork design in the past years, it can be observed that the efforts of engineers, scientists and researchers have stood the fundamental test of time and acceptance. Scientific ideas and methods of research and construction now seem to have penetrated through the once apparently impermeable barrier of ignorance and indifference, and basic knowledge and research personnel are now being appreciated at their true value. Hence one suddenly finds himself in the midst of a situation where it is recognized that there is not enough of basic knowledge available to explain one or another phenomenon. This is encountered not only in highway research in general, but also in frost action research in particular. In other words, it is realized that there exists a need for more basic knowledge in order that researchers can investigate and explain a new problem on phenomena met in highway engineering. The need for more basic knowledge is now also being accentuated by the new U. S. A. highway construction program.

The Freezing Soil System Not Fully Understood

One such phenomenon where much basic science can certainly be used is that of soil freezing with its associated moisture migration in soil.

While many processes and factors in a freezing soil system have been clarified during the past few years (moisture transfer in soils by various potentials, the classification of the existence and classification of various soil moisture transfer mechanisms, rhythmic ice banding in soil, the effect of additives to soil to reduce or increase the magnitude of frost heave, some properties of water and ice—to mention a few), there are still some important phenomena, processes, and factors occuring in a freezing soil system which are as yet neither understood nor explained. This is, probably, one of the reasons why up to now there is no satisfactory continuity and systematic treatment of the subject which this discussion terms the "Freezing Soil System" within the scope of thermal soil mechanics.

General Remarks

Realizing the importance of the problem of more basic knowledge, the HRB Committee on Frost Action in Soils organized this symposium to review the available knowledge as it may apply to frost action research in soils and to highway pavement design in frost areas.

The paper under discussion is one within the scope of this symposium which briefly reviews and summarizes in one place some of the knowledge now scattered in the many branches of the various sciences. The paper can be characterized as the exposition of the factor of moisture in frost action in soils. It makes the highway user conscious of the state and importance of the knowledge needed and/or available for good road design, and it should stimulate the work in frost action research in soils, the studies of the properties of soil moisture, and highway construction methods in frost areas. The organization and presentation of the material are clear enough to make the concepts of the authors and the discusser easily understood by a wide circle of highway, foundation and earthwork engineers, the young generation still in college, and the highway owner and user. The review also contains a rich list of reference sources, most of them from the last twenty years, and describes the essential features contained in these references. Hence this list may also serve in orienting one's self in pursuing a particular research topic. Obviously, to keep the paper down in volume, it has been necessary to make a severe selection of the material presented.

Nature of Paper

In view of the topic of the paper, the authors start out with describing the nature and some of the properties of water in bulk in general. After that, consideration is given to principles and methods of predicting, measuring and controlling the soil moisture regimen in connection with highway engineering.

Hence the nature of the paper can be characterized as presenting a two-fold discussion of:

1. The theoretical aspect of the nature of water, and
2. Soil moisture under a pavement which reflects a research phase with its practical aspects.

Theoretical Aspects of the Nature of Water

Hydrogen Bonding. Water is the only liquid with which there is any degree of familiarity. In much of its functioning water is commonplace. However, odd as it sounds commonplace things usually are the least appreciated and the most difficult to understand. It is known that the substance, water, is the most abundant liquid on the earth, and that it is used and exploited daily because it is an absolute necessity for sustaining life as well as well-being.

However, when it comes to the studies of freezing soil systems and their associated soil moisture migration, water, particularly in the film phase, turns out to be the least understood factor pertaining to the freezing process.

In describing the nature of water the authors are trying to explain some of the properties of water. They point out clearly that water is a polar liquid, and that hydrogen bonding (like a link) between the water molecules is the main reason for the high values of its melting point, boiling point, dielectric constant, specific heat, and viscosity. The bonding concept is illustrated by appropriate drawings. The explanations of these properties of water are buttressed by rich sources of reference, which reveal that the basic knowledge for the explanation of water properties was derived from recent research and by the application of modern research techniques and equipment.

In connection with the description of the nature of water and hydrogen bonding it is felt desirable to mention in this paper that much of this understanding is based on Debye's important work on polar molecules and on the structure of matter (1, 2, 3, 4).

This available knowledge on water helps one to understand the induced changes in density of water, viscosity, dielectric constant and other factors when a soil system is subjected to a thermal potential, that is, to freezing.

The structure of ice itself is reasonably well understood, although certain details are still in doubt, particularly when ice is under pressure.

Water Adsorbed on Soil Mineral Particles. The review on the nature of water adsorbed on soil particles reveals that at the present time not all of the forces partaking in the interaction between soil water and the surfaces of the soil particles are known. Thus, much work lies ahead to study this problem.

However, by now there is a good concept that water molecules forming moisture films are not the only factors that are adsorbed on the surfaces of solid particles. It is one of the conspicuous characteristics of a dispersed soil particle in a medium of water that under certain conditions it carries an electrical charge which, in contrast to heat, tends to reside on its surface. It is helpful, indeed, to consider soil as a disperse system. It should be understood that at the present time there is no satisfactory explanation available of the manner by which soil colloidal particles acquire their electric charges, a process which seems to be very complex indeed. There is also interest in how water adsorption at the interface affects such properties as phase boundary potentials. Unfortunately, in accord with the authors, one must regret that at the present time it is not yet possible to locate individual water molecules in the clay-water system, and therefore, no plausible conclusions as to the configuration of the adsorbed water molecules can be drawn.

The science, however, has presented an important fragment of knowledge, namely, that the amount of adsorbed moisture in a unit of given volume (or weight) of soil is proportional to the specific surface area of the soil particles. In other words, the finer the soil particles, the greater the possibility of having in a unit of volume more adsorbed moisture films.

Dielectric Constant. The factor, dielectric constant, was introduced in the Helmholtz electrical double layer theory in 1893 by Smoluchowski (5). This constant has since proved an important factor in studying the freezing soil system. The value of the dielectric constant, expressed in electrostatic units, is defined as the ratio of the mutual electrical capacity of a given pair of equipotential surfaces , fixed with reference to each other, when immersed in the dielectric to their capacity when immersed in a vacuum. The dielectric constant of water below 600 megacycles per second is about $D_w = 81.5$ electrostatic units at +17 C (6), and that of soil particles is $D_s = 5$ to 6 esu.

Therefore, in studying freezing soil systems it is necessary to know the values of the dielectric constants of soil, water and ice at different temperatures. As outlined by the authors, the appreciation of the importance of understanding the value of the factor of the dielectric constant has progressed in a fairly satisfactory manner.

Viscosity. The review under discussion also reveals that clay-adsorbed water has an unusually high viscosity. It is known that the viscosity of water varies inversely with temperature. Thus, upon freezing, the viscosity of the free soil water would change. It would be highly desirable to know what is the viscosity of film moisture, how the viscosity of film moisture varies upon freezing, whether such a moisture with such a viscosity facilitates the amount of soil moisture transferred from the groundwater to the cold front, and how to measure the viscosity of film water. The hydrodynamic process induced by the thermodynamic process in soil, and their mutual interaction, is complex and no effort should be spared in learning to understand these two flow processes and the change in properties of water and ice.

Another aspect relative to viscosity is the behavior of water under high pressure. It is known that Bridgeman found that the coefficient of viscosity increases rapidly with pressure. It is noteworthy that the effect of pressure on viscosity of water is greater than on any other physical property. Besides, viscosity varies exponentially with pressure. One sees that, as in other respects, in respect to viscosity water shows an exceptional behavior.

It is generally known that the effect of the increase in pressure from 1 to 2,000 kg/cm^2 upon the viscosity of water is considerable, namely, at 0 C the viscosity of water increases to about three times its normal value. However, it is of great importance to know what is the role of pressure upon water, and particularly film water, in a freezing soil system. If there is one, how is the pressure built up in a freezing soil system and why does it happen? And, how do the various phases of soil water and pressure under freezing temperatures in soil develop? These and other questions lead to the problem of undercooling of soil moisture in the voids of the soil and migration of soil moisture phenomena which are also still not satisfactorily understood.

Conclusion

The evaluation of the authors' review reveals to the engineering profession that:

1. There is already a rich store of knowledge available for the explanation of some of the properties of water and ice which is applicable in highway research, design and construction.
2. Still more basic knowledge about the properties of water and ice, and their behavior in soil under freezing conditions is needed.
3. More and better interpretation and explanation of the existing knowledge in these matters are needed in order to convey their meaning to larger circles engaged in highway research and design.
4. The application of this knowledge to soil technology must be clearly shown. This would be, among other things, the next immediate work to be done in frost action research.

To achieve this it is expected that the Highway Research Board will continue in the future its liberal policy of sponsoring highway research and encouraging and publishing researchers' contributions no matter how big or small they may be. It is at this early stage of development of scientific frost action research that such an appreciative understanding and tolerance for contributions should be cultivated; it facilitates the development of a field of science more rapidly, and it also encourages more people to engage in scientific work so badly needed. It is evident that nowadays science in engineering is being more and more greatly appreciated and it is hoped that this tendency will continue. Of course, science alone will not guarantee good roads. But knowledge will make it possible for engineers to do good work.

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W. L. DOLCH, Research Associate, Joint Highway Research Project, Purdue University, Lafayette, Indiana—The review of Low and Lovell and the great amount of work that it summarizes is further evidence of the growing importance of the application of physico-chemical principles to the nature and behavior of engineering materials. The nature of water in a soil system is a complicated matter and the authors are to be complimented for their concise and inclusive presentation.

They have particularly emphasized the importance of the water film adjacent to the clay particle in determining many of the properties of such systems. Leonards (1) has also pointed out that certain physical properties of clays can be interpreted by the assumption of rather extensive films of water that have properties different from bulk water. The authors have cited many different kinds of evidence. The conclusion seems to be, stated very qualitatively, that in clay-water systems there exists on the surface of the clay minerals a water layer that has some structural order greater than that in bulk water. This order is not that of ice but is energetically roughly equivalent to it. Such films extend for distances of many molecular dimensions and gradually become indistinguishable from bulk water as the distance from the solid surface increases. Many properties of this film are, furthermore, stated to be independent, to a certain degree, of its electrolyte content.

The purpose of this discussion is to reinforce this picture of the clay-water by pointing out that it is a specialized, although spectacular, case of a more general concept concerning the nature of surface zones and thin films of liquid.

Henniker (2) has given an excellent review of the subject that should be consulted for original references and details. He presents a large amount of evidence from the literature. Some of this evidence is "optical" in nature, such as the birefringence of films on solids, x-ray diffraction studies of clays and soap micelles, and contact angles of liquid drops on films of the same liquid. A case in point for this last is the observation of Terzaghi (3) of difficulty in wetting moist clay with additional water. Included also in this category are the results of experiments that show an orienting effect of a surface on crystals depositied thereon even though rather thick films of amorphous material intervene.

Other results are from what might be called "strength" measurements. These include determinations of adhesion of such films. Experiments on the strength of adhesive joints are examples. Also the very existence and stability of foams from solutions of surface active agents show the strength imparted to these fairly thick layers by the oriented solute molecules in the surfaces.

Dielectric measurements have been mentioned in the main paper. Other electrical measurements (for example, the large conductivity increases for thin films of oils that are insulating in the bulk phase) show structural changes to occur in thin films.

Of particular interest to persons concerned with freezing phenomena in soil systems are possible viscosity changes in the water films that would lead to a lowered permeability. Many measurements have been made showing anomalously decreased flow through finely-pored structures, especially in the case of water transmission. Viscosity measurements have been made with rotating plane surfaces between which is the liquid in question. All these fluid flow measurements are difficult to interpret because of the possibility of other effects influencing the results. Examples are the effect in porous media of gas bubbles that might be liberated into the system and block pores by meniscus effects, the influence of surface roughness or foreign matter in trapping stagnant volumes of fluid, and electrokinetic effects that cause an osmotic flow counter to that caused by the pressure gradient. Instances in the field of soils of the last two mechanisms are the papers by Schmid (4) and Michaels and Lin (5), respectively. However, the experiments that show viscosity increases in thin films where one bounding phase has been gaseous are more difficult to refute.

It should be emphasized that the work on the nature of thin films has involved a wide range of "liquids"—synthetic polymers, waxes, oils, polar and non-polar organic compounds, aqueous solutions, and water, among them—and a wide range of bounding phases such as gases, ionic crystals, metals, and liquids. The general conclusion that has been drawn can best be stated by quoting part of Henniker's summary.

> "The surface zone of a liquid is not merely a monomolecular layer with unaltered liquid immediately underneath it, but it is a region in which orientation extends effectively to many molecular lengths. The effective depth of the surface zone in tens or hundreds of angstroms in low molecular weight liquids, thousands of angstroms in long-chain molecules."

The forces responsible for such orientation over comparatively long distances are probably not all known, as is stated in the paper. The Van der Waals forces that decrease in magnitude with the seventh power of the intervening distance are too weak to be effective between isolated molecules separated by the distances in question here. The explanation may lie in a transfer or polarization process that proceeds from molecule to molecule in much the same manner, to use the analogy given by McBain (6), as a magnet's effects are transmitted by a chain of iron filings to a particle at a distance so great that without the intervening structure there would be a negligible interaction.

Such action in liquid layers is greatly influenced by the nature of both the liquid and the bounding phases. Polarization effects must be important as must special bonding processes, e.g. hydrogen-bonding. Illustrative of this is the point made by Rosenqvist (7) that clays form plastic mixtures with polar liquids but not with non-polar liquids unless there is the possibility of hydrogen-bonding (e.g. dioxane).

Other sources of information on the above topics are the texts by McBain (6) and Bikerman (8), the 1948 symposium of the Faraday Society (9), and the review by Williamson (10).

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Frost Penetration: Relationship to Air Temperatures and Other Factors

MILES S. KERSTEN, Professor of Civil Engineering, University of Minnesota

●THE FREEZING AND THAWING of soils and the detrimental effects on roads and pavements was one of the pertinent problems of highway engineers which led to the establishment of soil divisions in many of the state highway departments located in the frost zone of the United States. Early field investigations showed the important aspects of soil textures, available moisture, and temperature patterns and empirical procedures for coping with frost problems were developed. As this work continued, the need for fundamental studies in the mechanics of frost penetration was recognized and much work of this nature has been undertaken in recent years. Some of the studies were related to construction problems of the accelerated construction program in arctic and subarctic regions.

Publications during the past ten years, many in HRB reports, explain the information needed for frost depth calculations and the procedures to be used. This paper consists of two main divisions: first, a review of some of the basic considerations of frost penetration with reference to articles which explain methods of frost depth calculations; and second, the presentation of some field measurements which permit the study of one of the important assumptions used in such calculations.

The penetration of frost into a highway section is a heat-flow process; soil freezing occurs when the soil loses heat to the atmosphere above and the temperature of the soil drops below the freezing point. The temperature gradient which causes the upward flow of heat in the soil is produced by below freezing temperatures in the air above the soil; thus a good starting point for depth-of-freeze calculations is a record of air temperatures.

In order to see the relationship of some of the elements involved, one of the equations utilized for frost depth calculations may be considered. A very complete derivation and discussion of various equations for such calculations has been given by Jumikis (1). Methods of application of these to field situations have been given by Aldrich and Paynter (2), Aldrich (3) and Carlson (4). The equations which have been used in studies in Minnesota are the following:

$$h = \left(\frac{48 k F C_f}{L}\right)^{1/2} \qquad (1)$$

$$F_1 = \frac{L_1 h_1}{24}\,\frac{R_1}{2} \qquad (2)$$

$$F_2 = \frac{L_2 h_2}{24}\left(R_1 + \frac{R_2}{2}\right) \qquad (3)$$

$$F_n = \frac{L_n h_n}{24}\left(\Sigma R_{n-1} + \frac{R_n}{2}\right) \qquad (4)$$

in which

h = depth of freeze in a uniform soil;
k = thermal conductivity of soil in Btu/sq ft/deg F/ft/hr;
F = degree-days of freeze based on air temperatures, deg F;
C_f = air-surface correction factor;
L = volumetric latent heat of fusion in Btu/cu ft = 1.434 wd;
w = moisture content of soil in percent;
d = dry density of soil in lb/cu ft;

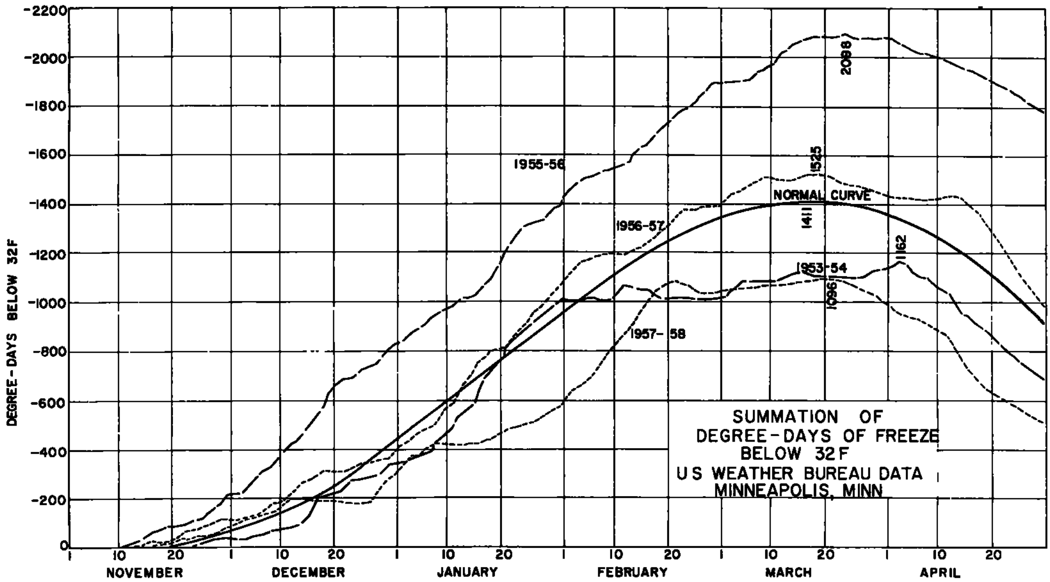


Figure 1.

F_1 = degree-days of freeze at surface required to freeze layer 1 in deg F;
L_1 = volumetric latent heat of fusion in Btu/cu ft for layer 1;
h_1 = thickness of layer 1 in ft; and
R_1 = thermal resistance of layer 1 = $\frac{h_1}{k_1}$.

Eq. 1 would be used for calculating the freeze in a soil profile with a uniform soil, that is, a one-layer system. The required data include that for the soil, k and L, and that from temperatures, F, plus the coefficient to change this to a surface temperature. This equation is one of the simplest which is in use; it is known as the Stefan Equation. Eqs. 2, 3, and 4 are adoptions of this to a layered system and are sometimes called the St. Paul Equations.

These equations are based on the simplifying assumptions that the heat represented by the latent heat of fusion of the soil mass constitutes the main heat quantity in the freezing process, and hence the only quantity which must be removed from the soil for it to freeze; that the average temperature below freezing during the freezing season can be used to establish the thermal gradient; and that the soil surface temperature is related to the air temperature by the coefficient C_f.

Values for the thermal conductivity of soils are usually obtained from published tables of charts. There have been various investigations on the determination of this coefficient. Van Rooyen and Winterkorn (5) have discussed many aspects of such determinations. Mickley (6), Makowski and Mochlinski (7), and Smith (8) have made different approaches to finding actual values, but the study covering the greatest variety of soils and soil conditions was that sponsored by the Corps of Engineers (9) and also reported by the Highway Research Board (10). This publication gives charts from which k-values can be selected for all moisture and density conditions apt to be encountered. Aldrich (3) has also presented this in convenient form.

The volumetric latent heat of fusion, L, is very simple to calculate. Since the latent heat of fusion of water is 143.4 Btu/lb, and the lb of water in a cubic foot of soil is $\frac{wd}{100}$, w being the moisture content expressed as a percentage of the dry weight and d the dry density in lb/cu ft, L = 1.434 wd.

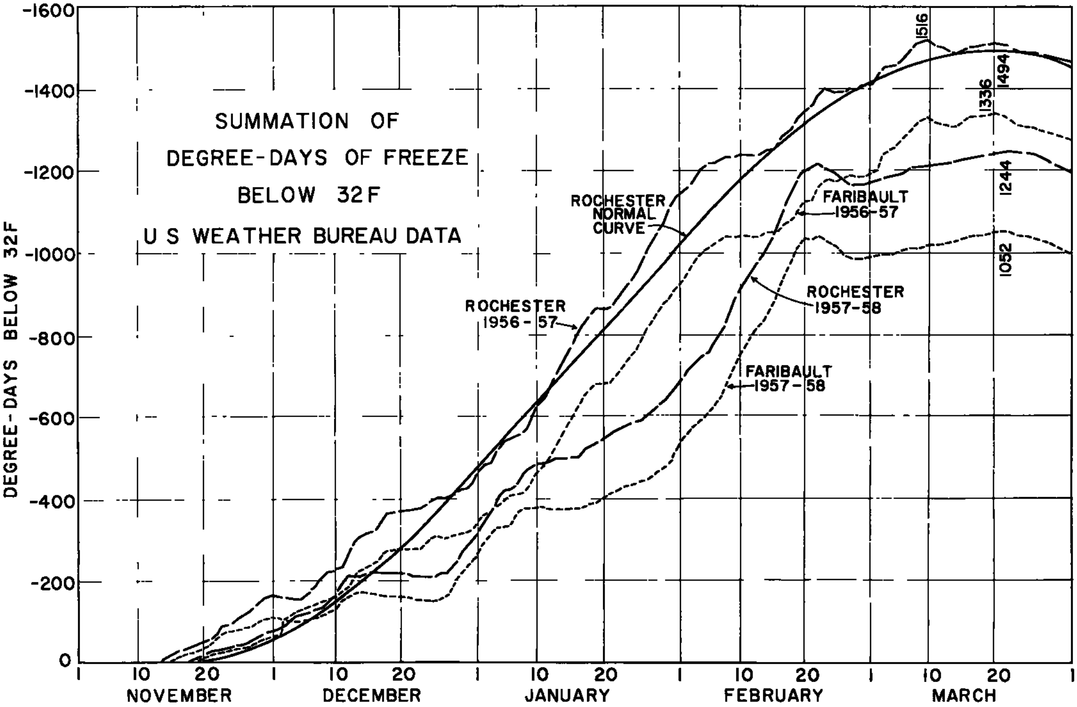


Figure 2.

Soils with high moisture contents will have high L values. This means that a large amount of heat must be extracted from them in order to change the water to ice. Although the soils with high moisture contents also have higher thermal conductivity co-

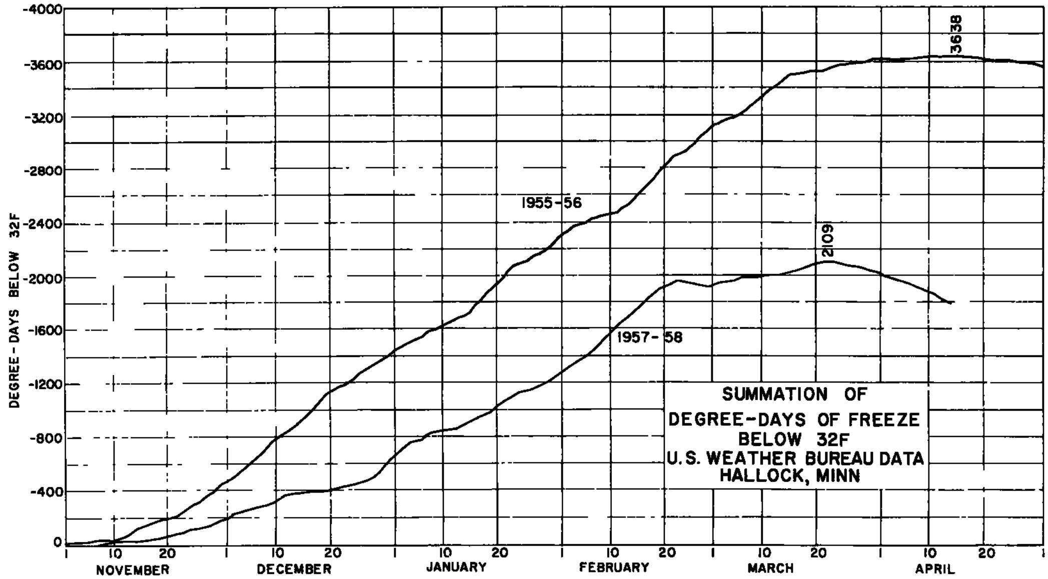


Figure 3.

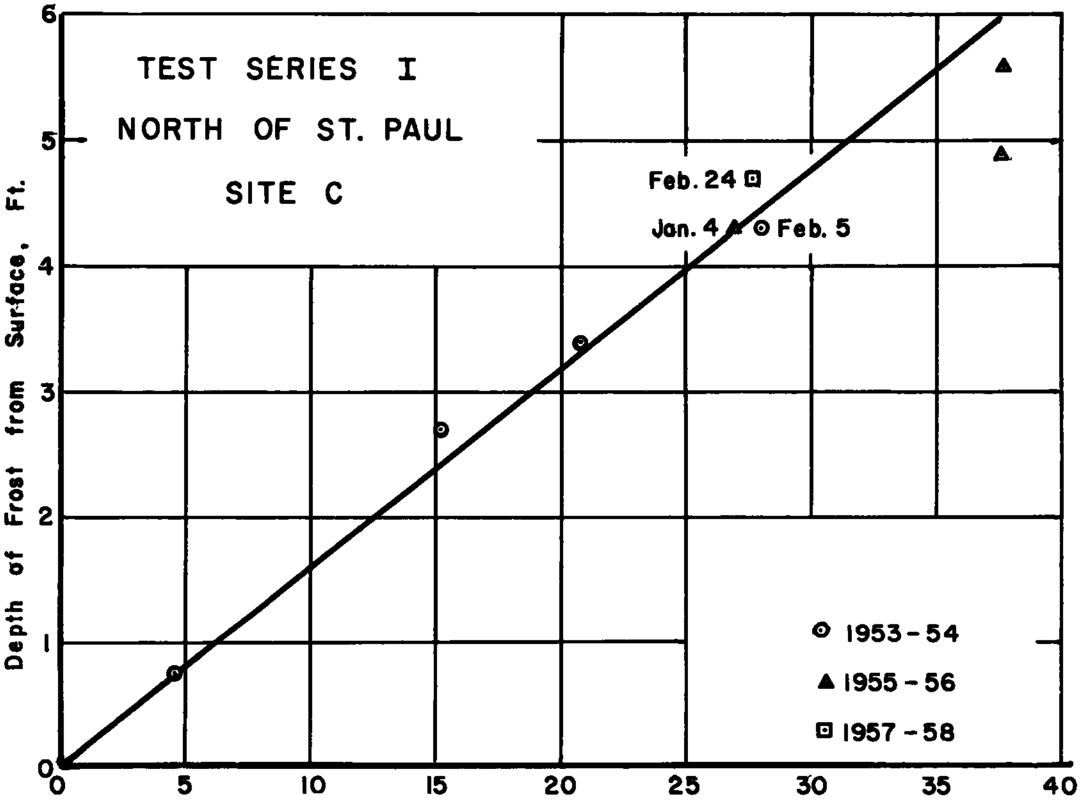


Figure 4.

efficients than drier soils, and hence would carry away the heat more readily, this effect is smaller than the effect of the high L value and thus frost will normally penetrate slower and to a lesser depth in wet soils than in dry ones.

Heat flows from the soil in the freezing process because there is a thermal gradient; that is, the ground surface is colder than the freezing front, or the level to which the frost has penetrated. Since air temperatures are usually available, these are utilized to approximate the gradient during the freezing period. The magnitude and duration of sub-freezing temperatures are measured in units of degree-days. For freezing calculations the degree-days, Fahrenheit, have usually been summed below 32 F. Thus a day with an average temperature of 19 F would give 32 - 19, or 13 degree-days. The magnitude of "cold" for any selected period is obtained by adding these values together for all days in that period. Examples of summations of degree-days of freeze for winter seasons are given in the latter part of this paper (see Figs. 1, 2, and 3).

It will be noted from Eq. 1 that the depth of freeze should vary with the square root of the degree-days of freeze. Also, one would obtain the same depth of freeze for a given number of degree-days (say 1,000) no matter whether this total was obtained in a long, slightly cold period, such as 100 days of 22 F temperatures, or for a short period of colder weather, such as 25 days of -8 F temperatures.

During freezing a pavement surface is usually warmer than the air above the pavement. Thus to transfer degree-days of cold based on air temperature readings to a pavement surface value the air values are multiplied by C_f, an air-surface correction factor, which has a value of less than unity. The Corps of Engineers (11) found that values of 0.6 or 0.7 were suitable for pavements in arctic or subarctic regions. John-

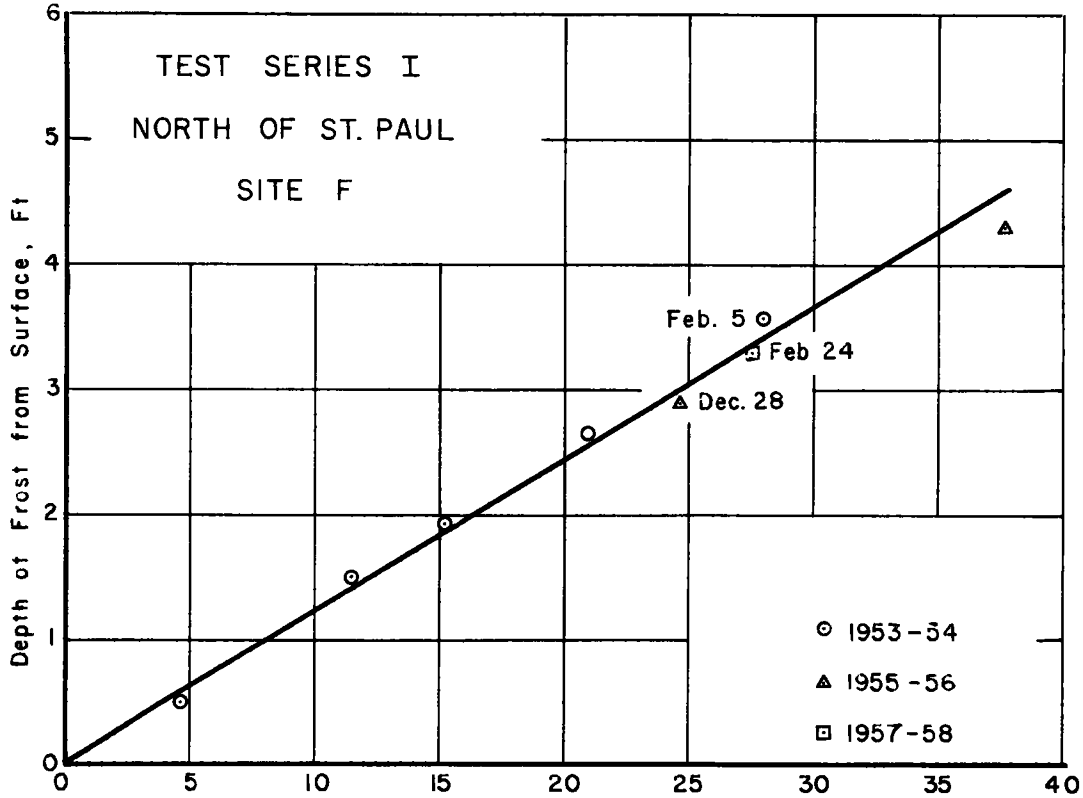


Figure 5.

son (12) found that 0.8 gave the best agreement between calculated and observed frost depths in a study in Minnesota and Braun (13) arrived at a value of 0.74 in another such study. Determination of reasonable values for this factor is one of the continuing needs in frost penetration studies.

Another way of handling this temperature difference between pavement surface and air would be to figure the degree-days of cold below a temperature other than 32 F and not use the C_f factor. Thus freezing below the pavement surface might be assumed to occur only when air temperatures are less than 29 F (or some other value less than 32 F). Degree-days of freeze would be represented by the summation below this temperature, again using the air temperature records.

Eqs. 2, 3, and 4 are merely an expansion of the reasoning followed in Eq. 1 to a layered system. Most highway sections would fall in this category, as they might have a pavement, a base course, and the underlying soil with possible variations in one or more of these parts.

All letters have the same meaning here as before; the subscripts refer to the layer number. In addition R is the thermal resistance of a layer and is equal to $\frac{h}{k}$, h being the thickness of the layer in ft, and k its thermal conductivity. ΣR_{n-1} is the resistance of all layers above layer n.

With the equations, one is able to calculate the degree-days of freeze at the surface to freeze each layer. The heat from any layer must flow through all layers above it, plus a part of the layer itself as it freezes. Since F_1, F_2, etc. are degree-days at the surface, they must be divided by C_f to obtain the equivalent number of degree-days of

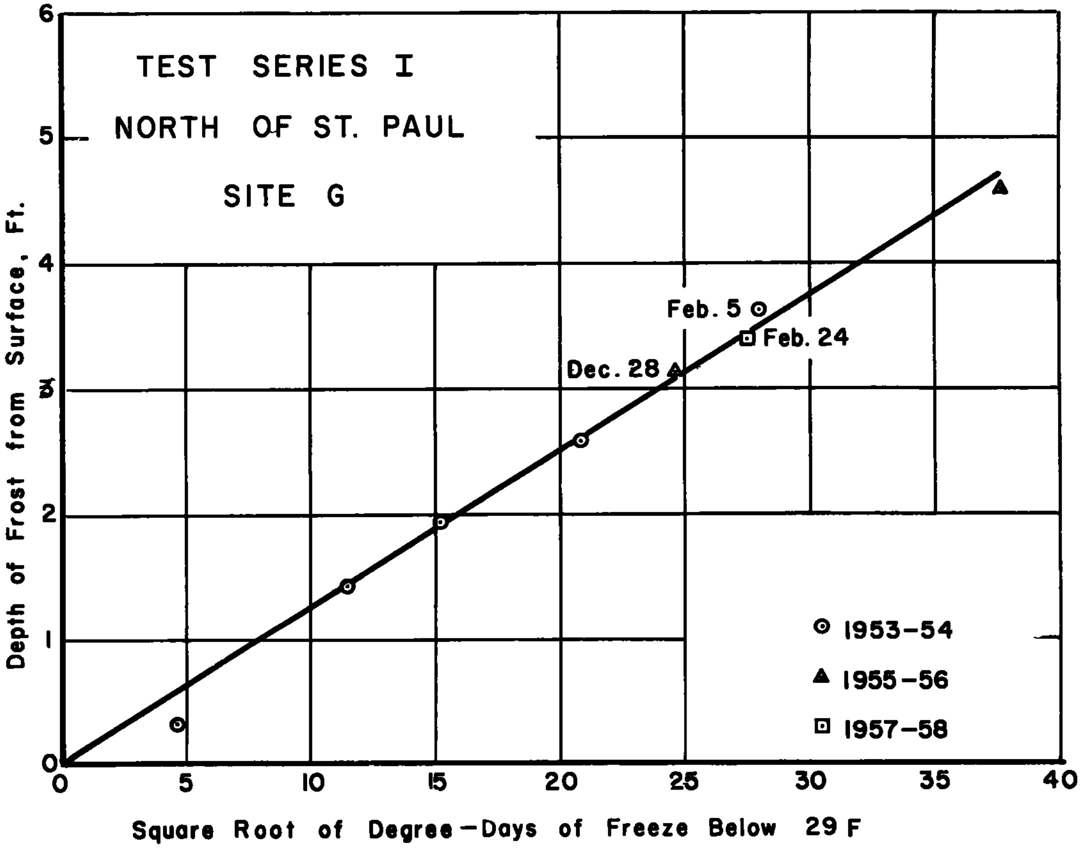


Figure 6.

freeze based on air temperatures. For a given winter season one may calculate the values of F_1 plus F_2 plus F_3, etc., change the total to degree-days air temperature, and find the depth for which this sum equals the total degree-days.

Further discussion of the layered system equations have been given by Carlsen and Kersten (14); Kersten and Johnson (12) have also given a detailed explanation and example.

The above equations have been found to be a useful tool for frost penetration studies in Minnesota. It is felt that they satisfy the important aspects of heat flow fundamentals and are simple enough to be applied without complications. One of the shortcomings in the approach is the neglect of those heat quantities not included in the latent heat of fusion, that is, that involved in cooling the soil mass to 32 F and also in dropping it to a lower temperature after freezing. Aldrich has studied this problem thoroughly and has presented a method of calculation which does take this factor into account (3). M. I. T. has made comparisons between results by this method and those by the St. Paul equations (15).

The remainder of this paper presents some actual field frost depth measurements and attempts to relate them to the air temperatures observed. As a somewhat new approach it has been attempted to ascertain if the summation of air temperatures below 29 F is a good measure of the effect of air temperature on frost penetration. If such is the case and if the soil conditions were reasonably uniform, it was reasoned that a plot of depth of freeze versus the square root of degree-days below the selected temperature would plot as a curve approximating a straight line, and that points for a given location should plot on the same curve for freezing seasons of different years, even though the winters were of different degrees of severity.

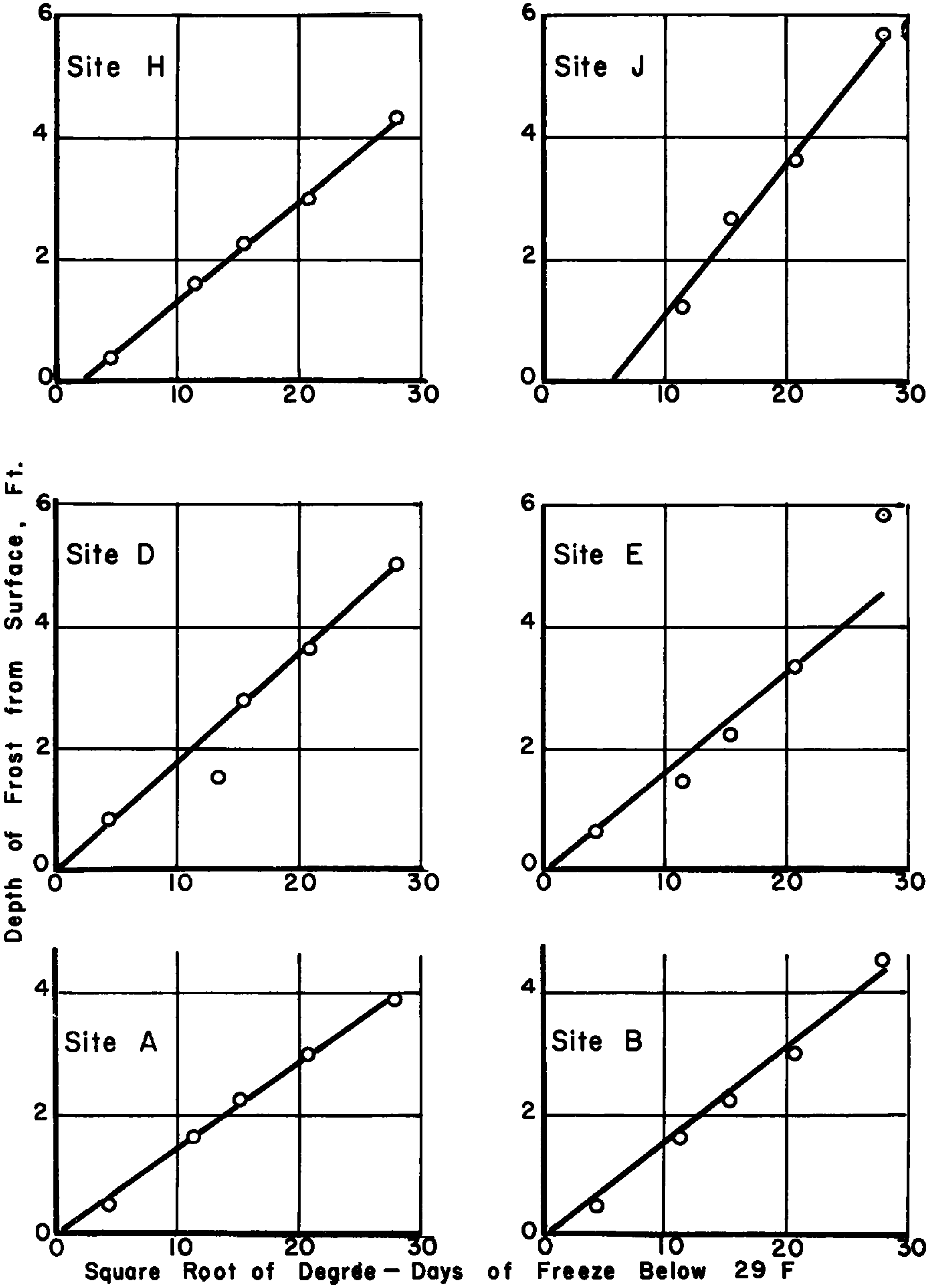


Figure 7. Test Series I, north of St. Paul, 1953-54.

There have been various programs of investigation at the University of Minnesota in which frost depths have been measured in different winters since 1953-54. On most of these the Minnesota Highway Department has cooperated; in one the Portland Cement Association has also rendered assistance. Most of these investigations have been parts of graduate studies of students of the University. By compiling the data from these various studies, some of which are current and continuing, the relationship

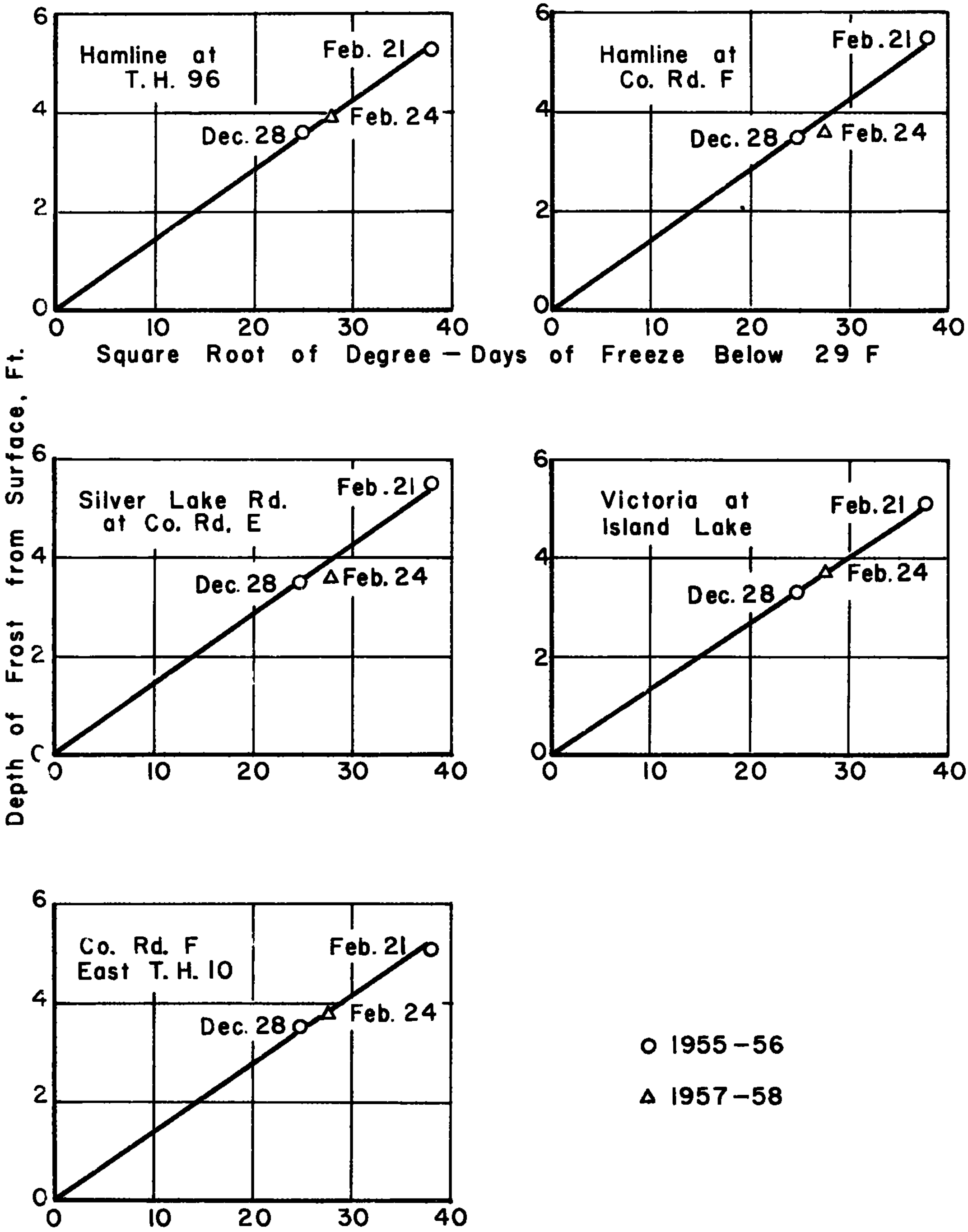


Figure 8. Test Series II, north of St. Paul.

between frost depth and air temperatures as represented by summation of degree-days can be observed.

Description of Test Locations

Five sets of data, each representing several test holes in one general location, were adaptable for this study. These will be described briefly.

Test Series I. In the winter of 1953-54 frost depths were measured at 9 locations in the area just north of St. Paul and northeast from Minneapolis. All points were in bituminous surfaced roads. The frost depths were determined by boring a hole and scraping the sides with a spoon, or "frost hook." Measurements were made five or six times.

Two sets of readings were taken at three of these points in 1955-56 and one set at the same three points in 1957-58.

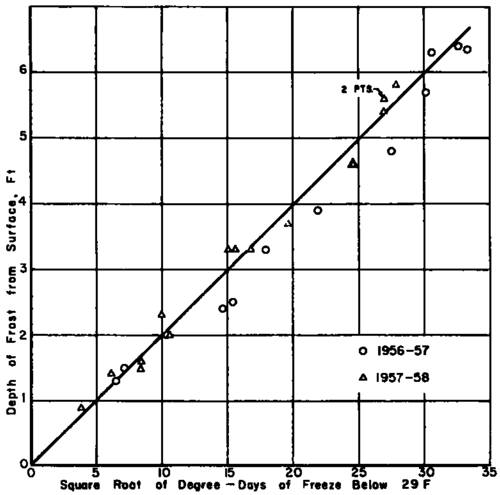


Figure 9. Test Series III; vicinity, Mpls. and St. Paul; Site 12A.

Test Series II. Five additional locations in the same general vicinity as Series I were selected and two measurements made in 1955-56 and another in 1957-58. These were also on bituminous surfaced roads and were made by auger.

Test Series III. As a part of a cooperative project by the Portland Cement Association, the Minnesota Highway Department, and the University of Minnesota, thermocouple assemblies were placed beneath concrete pavements in 6 locations near Minneapolis and St. Paul. These have been read at about weekly intervals during the winters of 1956-57 and 1957-58.

Test Series IV. In the winter of 1956-57; frost depth measurements were made at 10 locations in southeastern Minnesota (13). The frost depth was measured on four different dates during the freezing season. One set of measurements was made at 9 of these points in 1957-58. All points are on bituminous surfaced roads. The tests were made by auger.

Test Series V. To obtain information on frost depths in heavy clay soils in the coldest part of Minnesota, a single set of frost borings was made at 10 test points in the northwestern portion of the state in March 1956. These were repeated in late February 1958. All locations except one were on bituminous surfaced roads. They were located at various points between Ada and Hallock, Minnesota.

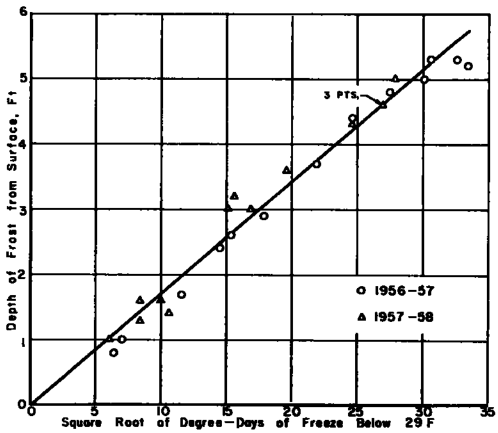


Figure 10. Test Series III; vicinity, Mpls. and St. Paul; Site 12B.

Temperature Data

Frost measurements at the various locations have been made during winters between 1953-54 and 1957-58. The manner used to portray the character of the air temperatures for these freezing seasons is a plot of the accumulation of degree-days below 32 F. Three such plots are shown.

Figure 1 is the curves for the Minneapolis area. These represent the climatic conditions for Test Series I, II, and III as described previously. The following items might be noted:

1. The year 1953-54 was about normal until February 1, but the month of

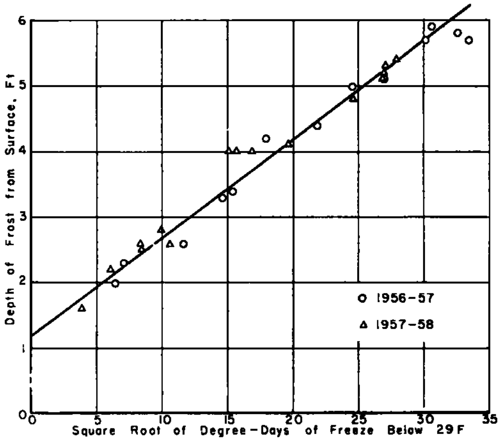


Figure 11. Test Series III; vicinity, Mpls. and St. Paul; Site 12C.

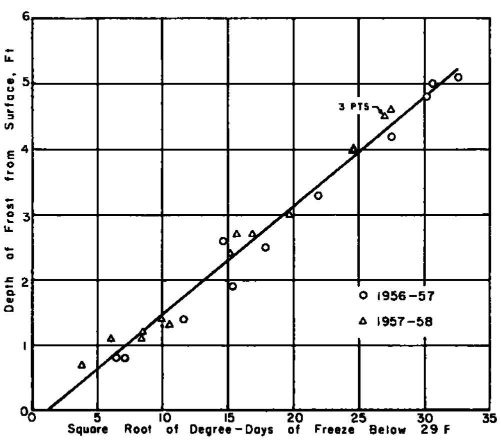


Figure 12. Test Series III; vicinity, Mpls. and St. Paul; Site 61A.

February was unseasonably warm, averaging about 32 F; March was only slightly colder. There was no measurable increase in frost depths after February 1.

2. The year 1955-56 was a steady, cold winter. Subfreezing temperatures started early and continued steadily with no midwinter thaws. Such cold winters have a frequency of perhaps once in ten years or more.

3. The year 1956-57 was very close to a normal year.

4. The year 1957-58 was distinctly a warm one. There were long mild periods in December and January. Some thawing occurred in the last week of February, although temperatures during the previous week had been sub-zero on several days. The freezing season was essentially ended at this time.

Figure 2 is a plot of the degree-days below 32 F at Rochester and Faribault, Minnesota. These data apply to the frost depths measured in southeastern Minnesota, Test Series IV. These two cities are only about 50 miles apart but it will be noted that Rochester had distinctly lower temperatures. Again 1956-57 was about a normal winter and 1957-58 was distinctly warmer than normal.

Figure 3 is a plot for one of the cities in the northwestern corner of Minnesota, Hallock. It may be noted that the degree-days of cold in this part of the state are about 50 percent greater than the other locations studied herein.

Discussion of Data

The various sets of data will be considered individually. Test Series I has been presented in part in a previous paper (12). The site descriptions and soil data will not be repeated here. The depth measurements made are not necessarily correct within 0.1 ft. There is a certain amount of judgment in selecting the depth at which resistance to the scraping changes; stony soils and light sandy soils with low moisture contents present difficult situations. Wet clay soils give the most definite indications. The points on the various graphs should therefore be considered to be the individual's best judgment of the frost line, and are probably correct within a quarter of a foot, but there may be a few points with more error than this.

Four or five depth measurements were made in 1953-54. The freezing season in that winter ended, for all practical purposes, at the beginning of February. At 3 of the test sites measurements have also been taken in 2 later winters. The data for these 3 points are shown in Figures 4, 5, and 6. The manner of plotting these curves as well as the others to be presented, is to express the temperature effect as the square root of the degree-days below 29 F. In previous studies with these and other data, there seemed to be some advantage to using such a scheme rather than using the degree-days below 32 F and multiplying by a coefficient, C_f, less than unity. However, these studies have not progressed to the point where one can definitely state that 29 F is the best base, although such an approach does have promise.

In the plots of depth of freeze versus the square root of degree-days below 29 F, it has been attempted to show the variation by a straight line.

Figure 4 is a plot of data for site C which had a fine sand soil with moisture contents between 4 and 7 percent. It is a soil condition for which it is somewhat difficult to recognize the exact frost depth by scraping. The plotted points give a fairly good straight-line relationship, with the exception of one of the Feb. 21, 1956 determinations. The data represent 3 distinctly different winters: 1953-54 was about normal until Feb. 1; 1955-56 was extremely cold; and 1957-58 was relatively mild (see Fig. 1). It is interesting to note that on Jan. 4, 1956, Feb. 5, 1954 and Feb. 24, 1958 at which time the degree-days of freeze were about the same, the depths of freeze were also approximately the same.

Figures 5 and 6 are for two locations which have very similar soils. The subgrade soils are silty clay loams with moisture contents in the middle 20's. The bituminous mat is relatively thin and the base course is somewhat mixed with the subgrade; the combined thickness is a half-foot or less. The frost line at these points was very sharp and easy to identify.

Both Figures 5 and 6 show very good straight-line plots, with the test points for all 3 years being essentially on a single line.

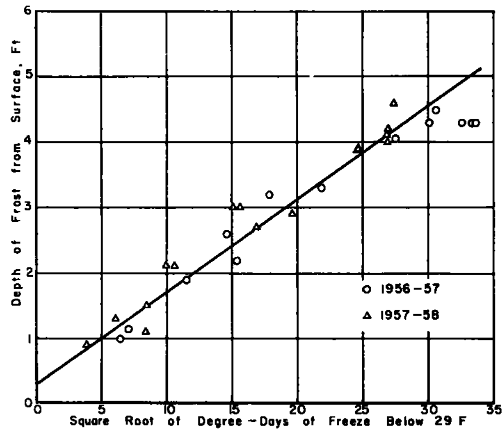


Figure 13. Test Series III; vicinity, Mpls. and St. Paul; Site 61B.

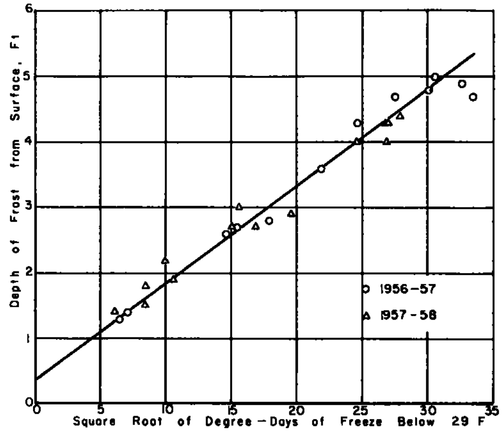


Figure 14. Test Series III; vicinity, Mpls. and St. Paul; Site 65A.

Tests were made at 6 other locations in 1953-54. No measurements have been made in subsequent years however. The plots for these 6 points are shown on a single plate, Figure 7. The frost depths vs square root of degree-days below 29 F are approximate straight-line relationships with the exception of Site E, where the final frost-depth measurement on February 5 seemed very high. At Sites H and J the straight line does not go through the origin, but is to the right on the plots. This would indicate that the freezing is effective only when the temperature is lower than some temperature colder than 29 F, or that a proportionately greater number of degree-days is required to freeze the upper layers of soil than the deeper layers, or perhaps some other unknown factor. Site J had a gravelly sand soil and it was difficult to identify the frost line because of the stones.

Considering all of the test points in this series, and particularly Sites F and G at which frost depth determinations are considered to be the most exact, it appears that the summation of air temperature degree-days below a value such as 29 F is a good guide to frost depth and that the relationship is represented by a straight-line graph between depth and the square root of degree-days. The frost depth would seem to be the same for a given number of degree-days regardless of whether this number was accumulated over a long period or over a shorter period of more intense cold.

The second group of tests, Test Series II, are from the same general area as Series

I, or just north of St. Paul. Frost-depth determinations were made on just 2 dates during 1955-56 which was the very cold winter and once near the end of the freezing season of 1957-58 which was quite mild. Although the number of measurements is small, they are considered valuable as comparisons of frost-depths for winters of a marked difference in magnitude of cold.

Tests were made at 5 points, all on secondary roads with bituminous surfacing and gravel bases usually about 0.7 ft thick. The soils in general were clay loam tills with moisture contents around 16 to 18 percent.

The plots of frost depth versus square root of degree-days below 29 F are shown in Figure 8. In all instances the points, though only three in number, indicate a straight line passing through or close to the origin. It is noted particularly that the frost depths on Feb. 24, 1958, at a time when the degree-days were only slightly more than on Dec. 28, 1955, check very closely the curves of the 1955-56 depths.

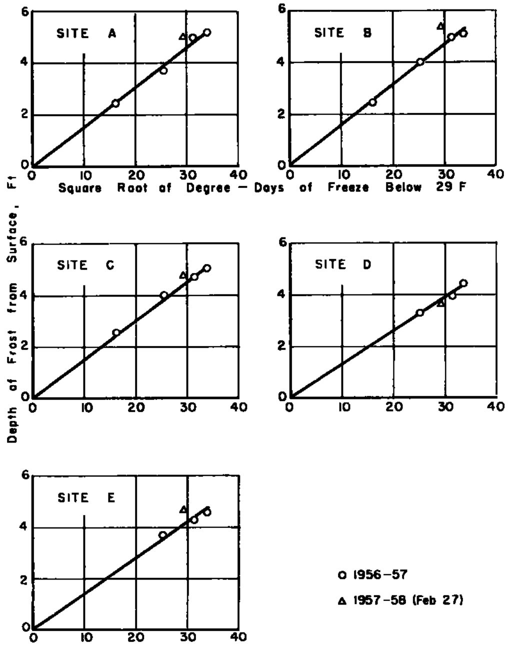


Figure 15. Test Series IV, Southeastern Minn. (near Rochester).

Test Series III differs from the other data being considered in two respects. First, they are measurements beneath portland cement concrete pavements; and second, the frost-depth determinations have been made by thermocouple readings. The soil profiles are also not as uniform as at most of the other locations. In this series the profiles consist of 0.75 ft of concrete pavement, a granular base course or lift of between 0.5 and 2.0 ft, and a fairly uniform subgrade soil. The subgrade soils vary in texture from clean sands to clay loam and silty clay loam. The 6 test locations are just outside of Minneapolis and St. Paul.

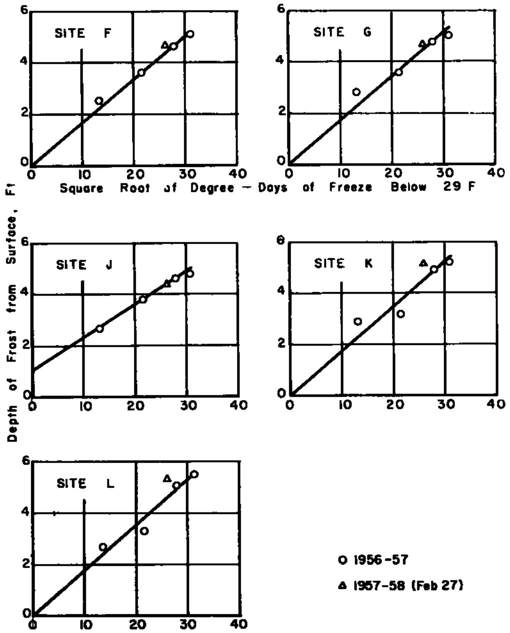


Figure 16. Test Series IV, Southeastern Minn. (near Faribault).

The details of the thermocouple test installation and the plotting of temperature profiles and determination of frost depth will not be presented here. In some instances the determination is judged to be quite exact—perhaps within 0.1 ft; in other temperature conditions, however, there is some personal judgment required, and possible variations of 0.3 or 0.4 ft may be encountered.

Readings have been taken for 2 winters, 1956-57 and 1957-58. The first of these 2 years was about a normal one; 1957-58 was warmer than normal, especially through January, with a cold February until Feb. 22, at which time the freezing season ended for all practical purposes (see Fig. 1).

Thermocouple readings were taken at about weekly intervals and hence there are a large number of points to show on the plots for the two winters. The results for the 6 locations are shown in Figures 9 to 14, inclusive.

Although there is some scattering of points on these plots, there still seems to be a straight-line relationship throughout the entire freezing season. At the end of the season when the degree-days are still showing some increase the depth of freeze does seem to remain about constant on most of the plots. In other words, at the end of the freezing period, factors other than air temperature must be having an influence, which was not the case in midseason. These might be variations in solar radiation effects, for example.

Again, the points for the 2 years seem to give the same general relationship. The specific dates for a given number of degree-days for the 2 years are as follows:

Degree-days below 29 F	Square Root of Degree-days	Date 1956-57	Date 1957-58
100	10	Dec. 9	Dec. 29
225	15	Dec. 30	Jan. 5
400	20	Jan. 10	Feb. 3
625	25	Jan. 22	Feb. 14
900	30	Feb. 3	Not reached

Thus, for example, a value of 20 on the square root scale of the figures represents Jan. 10 in 1957 and Feb. 3 in 1958; a reading of 25 represents Jan. 22 in 1957 and Feb. 14 in 1958. It will be noted that depths of freeze run about the same for the 2 years at these values.

Some of the curves in this series do not pass through the origin or close to it, particularly Location 12C (Fig. 11). This location has a clean sand subgrade which has a moisture content of only about 6 percent; this may or may not be significant, but it is the cleanest sand subgrade and the driest that has been worked with. Location 65A for which the curve is only about 0.4 ft from the origin is also a sand subgrade, but it is rather fine with around 8 to 20 percent passing the No. 200 sieve and a moisture content around 8 percent.

Test Series IV are tests made in the southeastern area of Minnesota near the cities of Rochester and Faribault. The locations are on state highways with bituminous surfaces. Tests were made on 4 different dates in 1956-57, which was a fairly normal winter, and on just one date at the end of the freezing season in 1957-58 which was very mild.

The results for 5 locations south of Rochester (most distant location about 25 miles southeast) are plotted on Figure 15. The subgrade soils at these locations were either clay loam tills or silty clay loams. It will be noted that the depth determinations made in 1956-57 plot reasonably close to a straight line passing through or close to the origin. The lines have been drawn on the basis of the 1956-57 data only. The single test in 1958 was made on Feb. 27. The degree-days of freeze on this date was 1164 below 32 F and 858 below 29 F. On Feb. 22 these values had been 1215 and 924, respectively, so there had been several days of warm weather just prior to the tests. In 1957 tests were made on Feb. 7 at which time the degree-days of freeze was 1225 below 32 F and 972 below 29 F. Thus there had been almost as much cold by that date (Feb. 7, 1957) as accumulated during the entire 1957-58 season (1244 degree-days below 32 F).

The frost depths for Feb. 27, 1958 plot above the curves of the 1956-57 data for all these locations except point D, and by an average of about 0.5 ft. This difference would be decreased a little if the points were plotted as having occurred on Feb. 22, or just at the end of the cold period and before the warm period.

The largest discrepancies are for Locations B and E where the 1958 depths are greater than any of those measured in 1956-57.

Tests in an area east and northeast of Faribault (most distant location about 22 miles) are shown in Figure 16. The subgrade soils represented are clay loam tills, silt loam, and clay. The plots of this figure are somewhat more irregular than those of Figure

15, but again it has been attempted to represent the trend of the 1956-57 points by a straight line. Locations K and L have similar clay soils (the locations are only 250 ft apart) and both seem to have a too-deep point for the first observation and a too-shallow point for the second one.

The single measurement made in the 1957-58 season (Feb. 27) again plots above the curve at all locations except one, and again by an average of almost 0.5 ft.

Test Series V is limited to just one frost-depth measurement near the end of the 1955-56 winter season (March 8) and one near the end of the 1957-58 season (Feb. 27) at 10 locations in northwestern Minnesota. The first of these seasons was an extremely cold one, the second an extremely mild one. The test locations were not referenced exactly at all points, and in some cases the frost-depth measurements may be a few hundred feet apart. The results should show general trends however.

The test points were all in bituminous surfaced roads. The extreme test locations in this series are about 110 miles apart. The temperature data are taken from the records of 3 towns or cities in this area, Ada, Crookston, and Hallock.

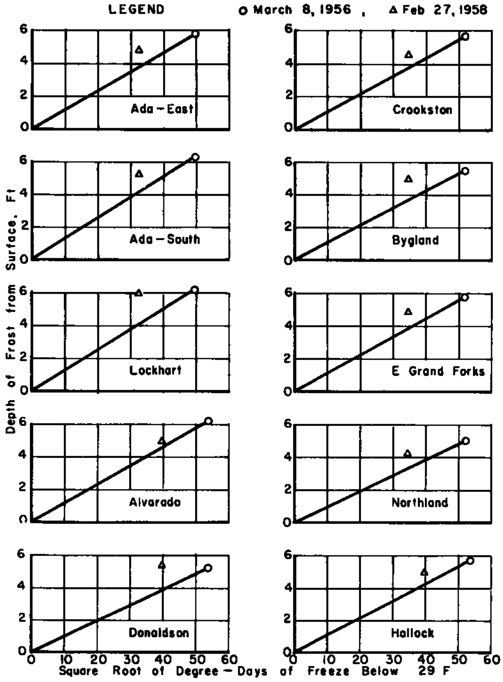


Figure 17. Test Series V, Northwestern Minnesota.

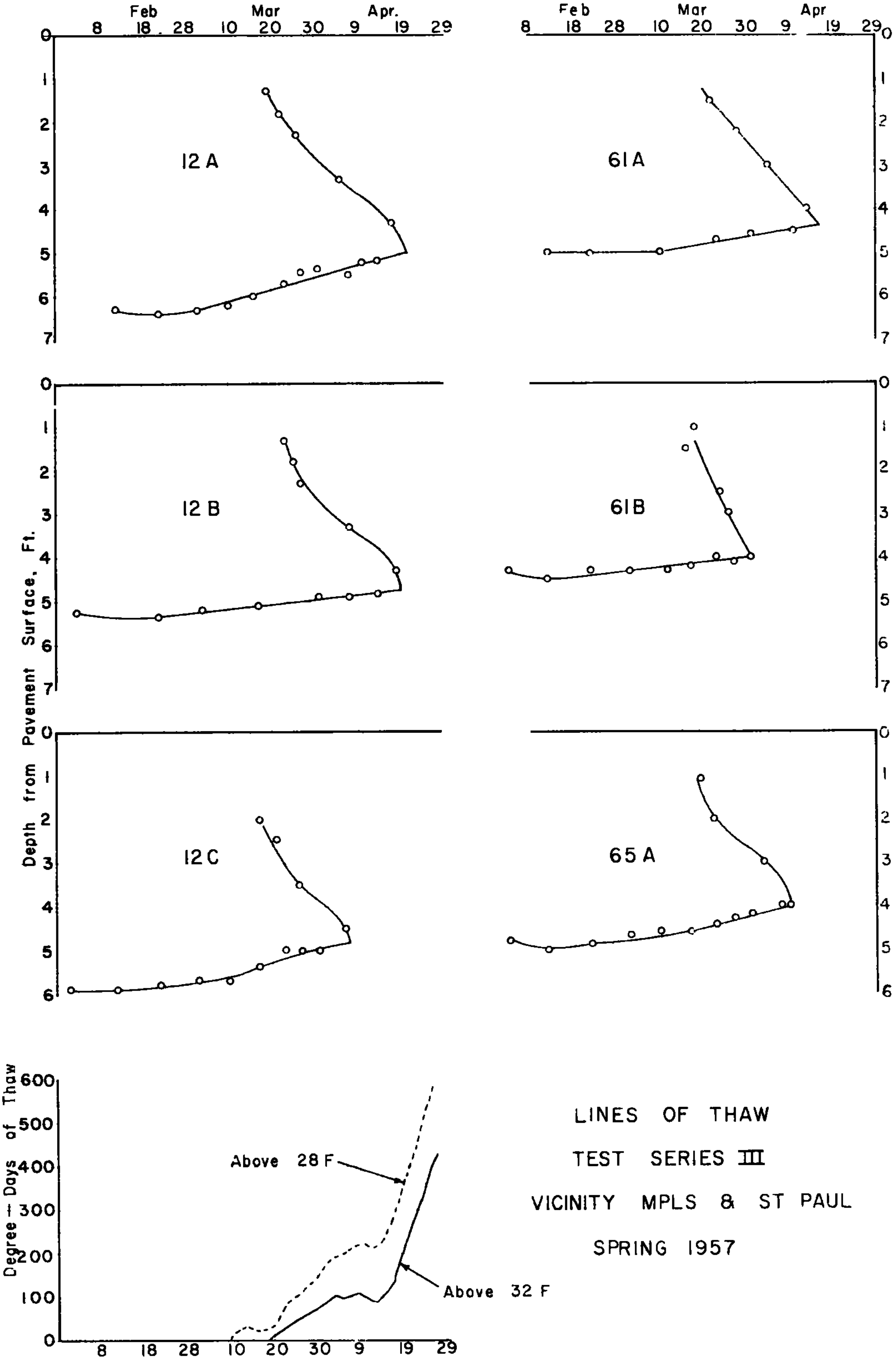
The test results are shown for all 10 points in Figure 17. The results seem to be quite different from those of the series previously presented.

The first obvious result is that the 1955-56 point, the 1957-58 point, and the origin are not on a common straight line. The 1955-56 tests (March 8, 1956) were taken by the author and Herbert Dale, District Soils Engineer of the Minnesota Highway Department. In Figure 17 straight lines have been drawn from the origin to these points. The 1957-58 depths (Feb. 27, 1958) were taken on the basis of mailed instructions by an Assistant District Soils Engineer who had not been on the previous year's measurements. This is not mentioned to question the accuracy of either set of data, but it is possible that a different judgment of what constituted the frost line may have been used. The author is prone to doubt this, however, since the frost line is usually quite definite in these soils. The 1958 readings were taken after 5 very warm days (average temperatures up to 49 F) and this may have caused some difficulties.

The Feb. 27, 1958 points all fall above the lines as drawn in Figure 17 and by an average amount of about 1 ft. This means that the frost line penetrated faster than one would anticipate from the 1955-56 experience. If straight lines were drawn through the 2 frost-depth determinations for each test location, the intercept at 0 degree-days would fall between 1 and 4 ft in a majority of the curves.

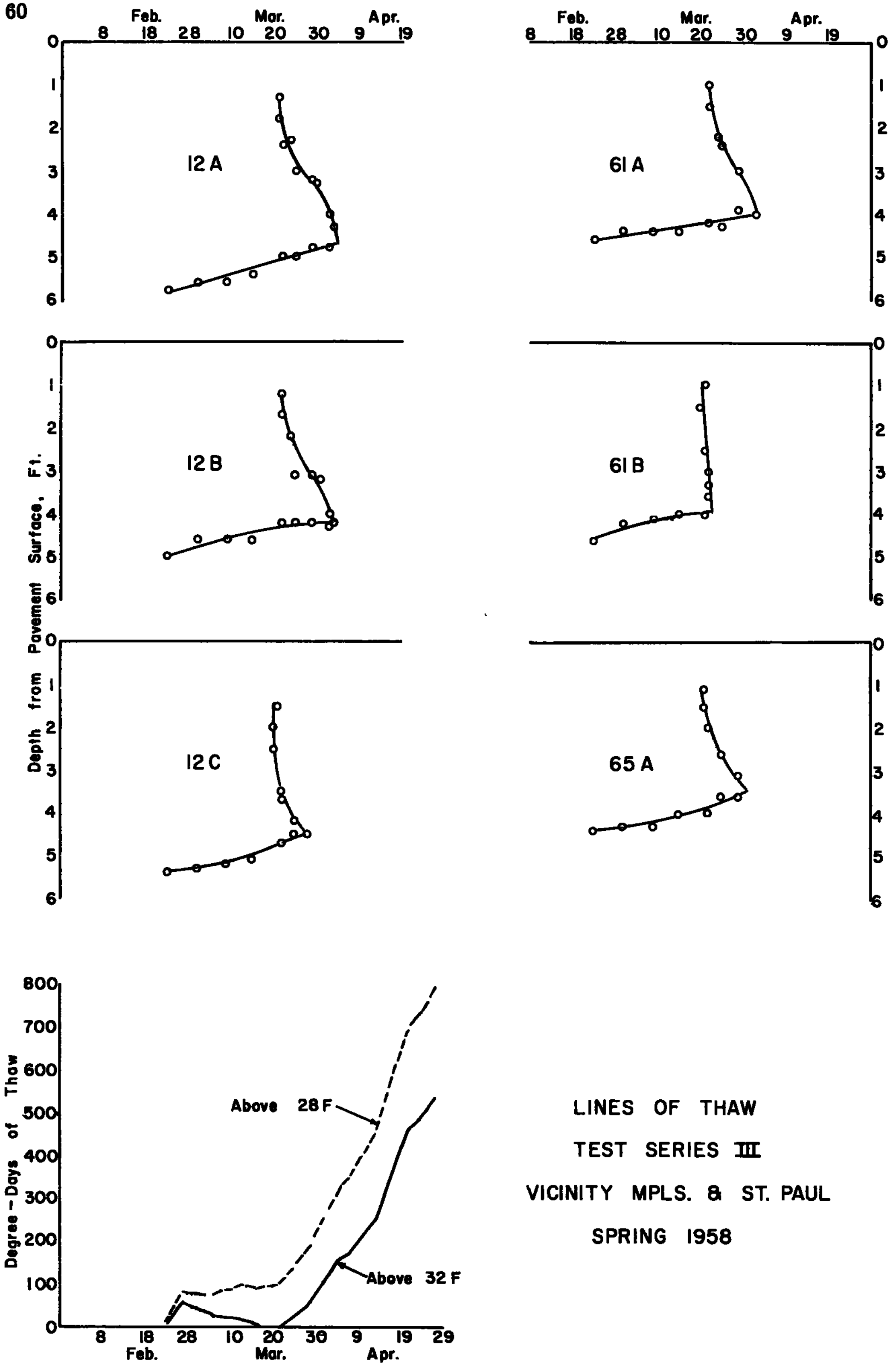
It is planned to make more calculations on these locations with the data on hand. Perhaps these will aid in explaining the seeming discrepancies. It would also be desirable to make more frost measurements in this region, with several depth determinations being made in one season.

To review the consideration of the 5 series of data, it would seem that 3 series, I, II and III, give good agreement between measured frost depths and an air temperature factor (degree-days below 29 F) for winters of different magnitudes of cold, and that a plot of depth versus the square root of this temperature factor approximates a straight line. On the basis of these data one would tend to accept the concept of the Stefan equa-



LINES OF THAW
TEST SERIES III
VICINITY MPLS & ST PAUL
SPRING 1957

Figure 18.



LINES OF THAW

TEST SERIES III

VICINITY MPLS. & ST. PAUL

SPRING 1958

Figure 19.

tion that depth does vary with the square root of a degree-day factor without mention of the time period required to accumulate this value.

Test series IV and V seem at some variance with this concept, however. In several measurements in these locations, frost depths at the end of a mild winter seemed to be about 0.5 to 1.0, plus or minus, deeper than would be estimated on a degree-day basis when compared with measured depths of a more normal winter.

It is entirely possible that other unmeasured factors caused these differences in Series IV and V. A rather important one is a possible variation in the moisture content of the subgrade. Complete moisture information was collected only in one year—1957-58 was a relatively dry winter and if this had a reflection in the subgrade moisture contents it could, and probably would, affect the frost depths. If this is true it would mean that one should take this factor into account along with the air temperature data in making an estimate of a frost depth on the basis of measurements during previous seasons. There is also the possibility that air temperatures at the field sites differed from those at the weather stations which were used.

Thawing of Subgrades

Nothing has been said thus far of the factors concerning and the calculation of the thaw of subgrade soils. The manner in which this thaw procedes would seem to have an important bearing on the loss of strength in the road structure and the possible "spring break-up." Since thawing is also a heat flow process, it would seem that it would be possible to write an equation for the process, substitute in it the necessary soils and air temperature data, and solve for the depths of thaw at selected times. Good checks were obtained by such procedures for some locations in Alaska (14). In climates such as that of Minnesota actual field measurements of thaw for making checks on such a procedure have been difficult to obtain, however. For one thing, the entire thawing is apt to occur in only a week or 10 days and it is easy to miss important measurements in many instances. Also, the temperatures in the frozen and thawed layers may be only a degree or two different, which means that accuracy is demanded in temperature readings.

There are only limited data in the studies in Minnesota to indicate how thaw does progress. The best of these are on the concrete pavement studies which were discussed in Test Series III. Figures 18 and 19 illustrate how these 6 sections thawed in the springs of 1957 and 1958. Although previous studies of thaw in the subarctic (14) had indicated that analytical calculations by a modified Stefan equation similar to freeze would give a good check for thaw, attempts to do the same for the Minnesota data have shown some complications.

While these studies are incomplete, some observations have been made which warrant further investigation. These include the following:

1. The amount of thaw from the bottom has varied from about 0.5 to 1.5 ft at the different locations. This thawing starts when the air temperatures start to average around 27 or 28 F. The thaw may be approximated by a calculation of upward heat flow using an average gradient during this period.
2. The thaw from the surface is quite rapid, exceeding that anticipated from previous observations. This thaw continues to deepen even on days with average air temperatures below 32 F once it has started.
3. Analytical calculations of thaw may have to utilize a large air-surface correction factor (such as 2.0) and also consider degree-days above some temperature less than 32 F, such as 28 or 29 F.

Conclusions

Studies of frost penetration including field observations, consideration of heat flow principles, and measurement of soil properties have led to the development of procedures by which calculations can be made for the depth and rate of ground freezing in pavement sections. References are available which explain such methods. It is felt that the methods and the required coefficients and other data are sufficiently correct so that reasonable answers can be obtained for most frost penetration problems of highway engineers. Continuing work will improve the knowledge of the coefficients and other items.

The calculation of rate of thaw is not nearly as advanced as the frost penetration procedures and further work is need on this phase of the problem.

The study of 5 series of frost measurements in Minnesota indicated in most instances that the freeze depths did vary in accordance with the concept of the Stefan equation in showing equal depths for a given magnitude of degree-days accumulated in varying periods of time for different winters. Since some measurements did not check this relationship, further study is desired.

The preliminary study of the Minnesota data also indicates that the summation of degree-days of freeze below some temperature less than 32 F, such as 29 F in this case, and the use of these values in the frost-depth equations, may have some merit.

ACKNOWLEDGMENTS

The author wishes to acknowledge the assistance in field work and analysis given by University of Minnesota graduate students, Rodney Johnson, Lawrence Stamstad and John Braun in Test Series I, III and IV, respectively.

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Discussion

FREDERICK J. SANGER, Special Assistant, Arctic Construction and Frost Effects Laboratory—The author does not say much about the modified Berggren equation beyond giving references to it (possibly to leave a topic for discussion). The experience of the Arctic Construction and Frost Effects Laboratory (Corps of Engineers, U. S. Army Engineer Division, New England) has been that this equation gives better results than others despite the limitations of any equation. All the variables in this equation are approximations; fortunately, errors usually cancel, but sometimes they do not.

ACFEL is attacking the frost penetration problem in two ways:

1. Taking the modified Berggren equation and trying to improve on its precision and make its use simpler; and
2. Approaching the problem de novo by the methods of micrometeorology, using analog computers to derive working tools with simplified techniques.

These remarks are decidedly of an interim nature but may be of general interest, and the work on the formula may have immediate value.

The modified Berggren formula, developed by Aldrich and Paynter (author's ref. 2) from the standard Neumann solution of the freezing problem is:

$$X = \lambda\sqrt{\frac{48knF}{L}}$$

in which

X = frost penetration in ft;
λ = a factor taking account of sensible heat;
n = surface correction factor = $\frac{\text{surface freezing index}}{\text{air freezing index}}$; and
k, F and L have already been defined.

From a statistical analysis of ACFEL field data, Aldrich and Paynter recommended a value of $n = 0.9$ for all bare paved surfaces; this value is being used, apparently with satisfactory results. The coefficient of thermal conductivity, k, has been studied extensively in the past year in an unsuccessful attempt to improve upon the author's curve of k, γ_d and w (author's ref. 9). Using Kersten's labor-

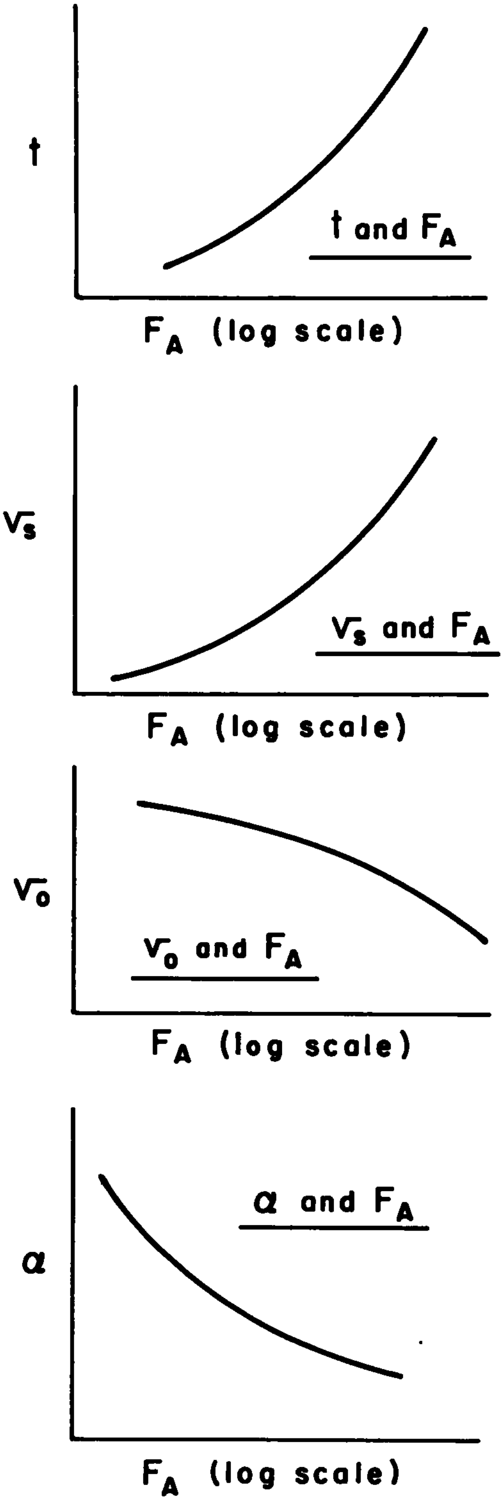

Figure 20.

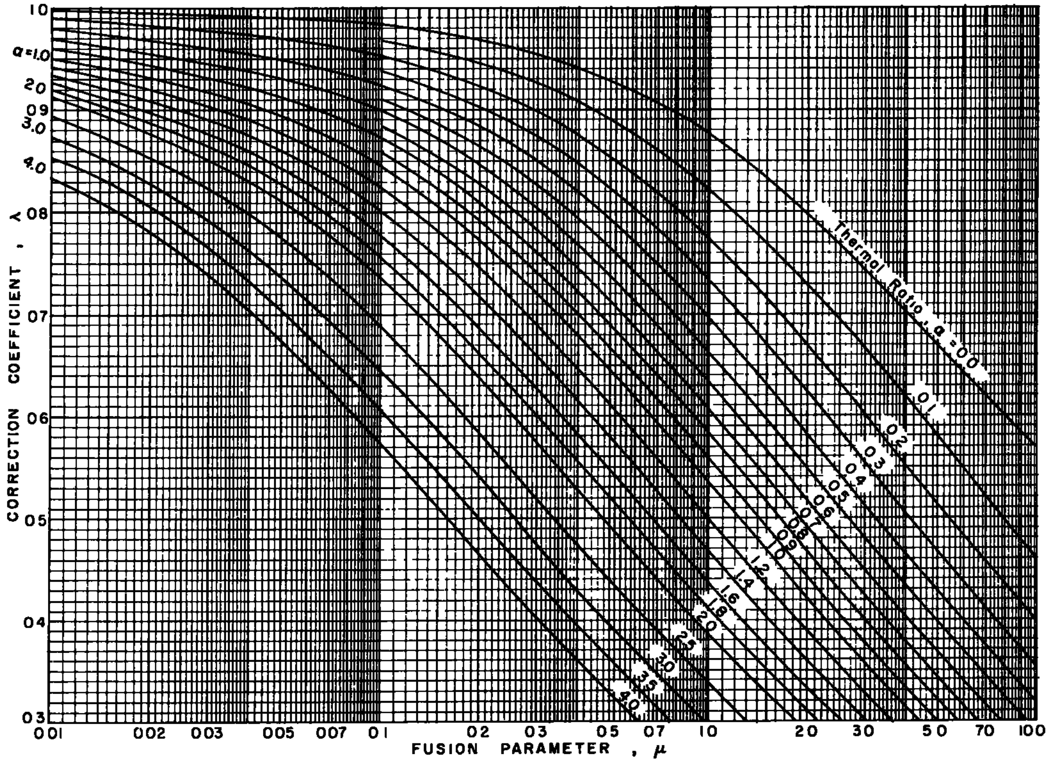

Figure 21. Correction coefficient λ and the modified Berggren formula.

atory data and soils descriptions, a theoretical formula suggested by Eucken (1) which assumes a non-continuous phase of solid particles in a continuous phase (air, water and ice were used in ACFEL studies) was used with mineralogical composition and k-values for individual minerals computed for the non-continuous phase. It soon became evident that quartz was the important mineral so that, finally, quartz content, dry unit weight, and moisture content were used for basic parameters. The results were no better than the existing curves, so ACFEL uses Kersten's values if the k-value of a particular soil has not been measured or cannot be estimated by comparison with other soils. For a job where soils are uniform and the profile is known for certain, laboratory tests are made, but that is a rare instance. The author's classification of soils into 2 groups—fine and coarse—is rather approximate but the mineralogical classification was no better; something else is needed to improve on the existing curves for k, possibly a classification based on the Unified Soil Classification System or on the Corps of Engineers Frost Effects Classification F1, F2, F3 and F4 soils (2).

The λ factor has been studied in ACFEL in some detail during the past year. As can be seen (author's ref. 2), λ is a function of μ and α; μ depends upon $\sqrt{s}$, the average surface temperature below 32 F, C, the volumetric sensible heat capacity of the soil and L, the volumetric latent heat of fusion; i. e., $\mu = \sqrt{s}\frac{C}{L}$ α is the ratio of $\sqrt{o}$, the mean annual temperature above 32 F, to $\sqrt{s}$ as just defined; $\alpha = \frac{\sqrt{o}}{\sqrt{s}}$. The original curves (author's ref. 2) did not cover a few soils encountered so ACFEL has recalculated the λ curves and has rearranged the parameters for convenience (Fig. 21). The λ factor was also studied statistically in an attempt at further simplification. A plot of air freezing index, F_A, against length of freezing season, t, for 16 locations in the northernmost states gave a good average curve showing the relationship between F_A and t.

(Actually Fairbanks, Alaska, and Thule, Greenland, fitted the curve excellently.)

The curve was very good above F_A = 200 degree-days approximately. Using F_A, t, and n = 0.9, the values of $\sqrt{s}$ were computed to give a curve of $\sqrt{s}$ and F_A. Values of $\sqrt{o}$ and F_A were then plotted to yield a curve of $\sqrt{o}$ and F_A. Then α was computed $\left(= \frac{\sqrt{o}}{\sqrt{s}}\right)$ for a curve of α and F_A. (C and L are functions of dry unit weight and moisture content w, and $\frac{C}{L}$ merely of w.)

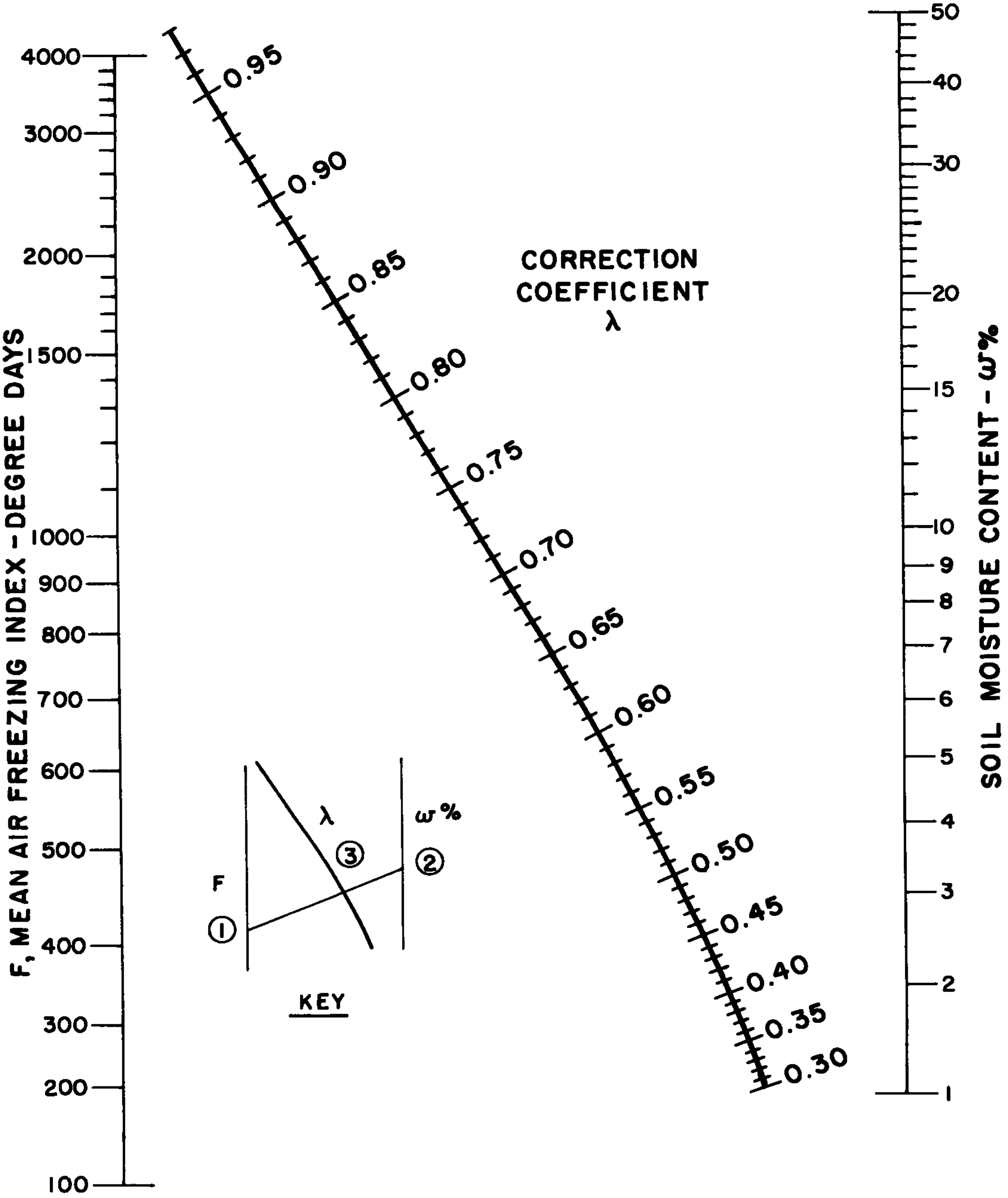

Figure 22. Modified Berggren Equation, F, w, λ.

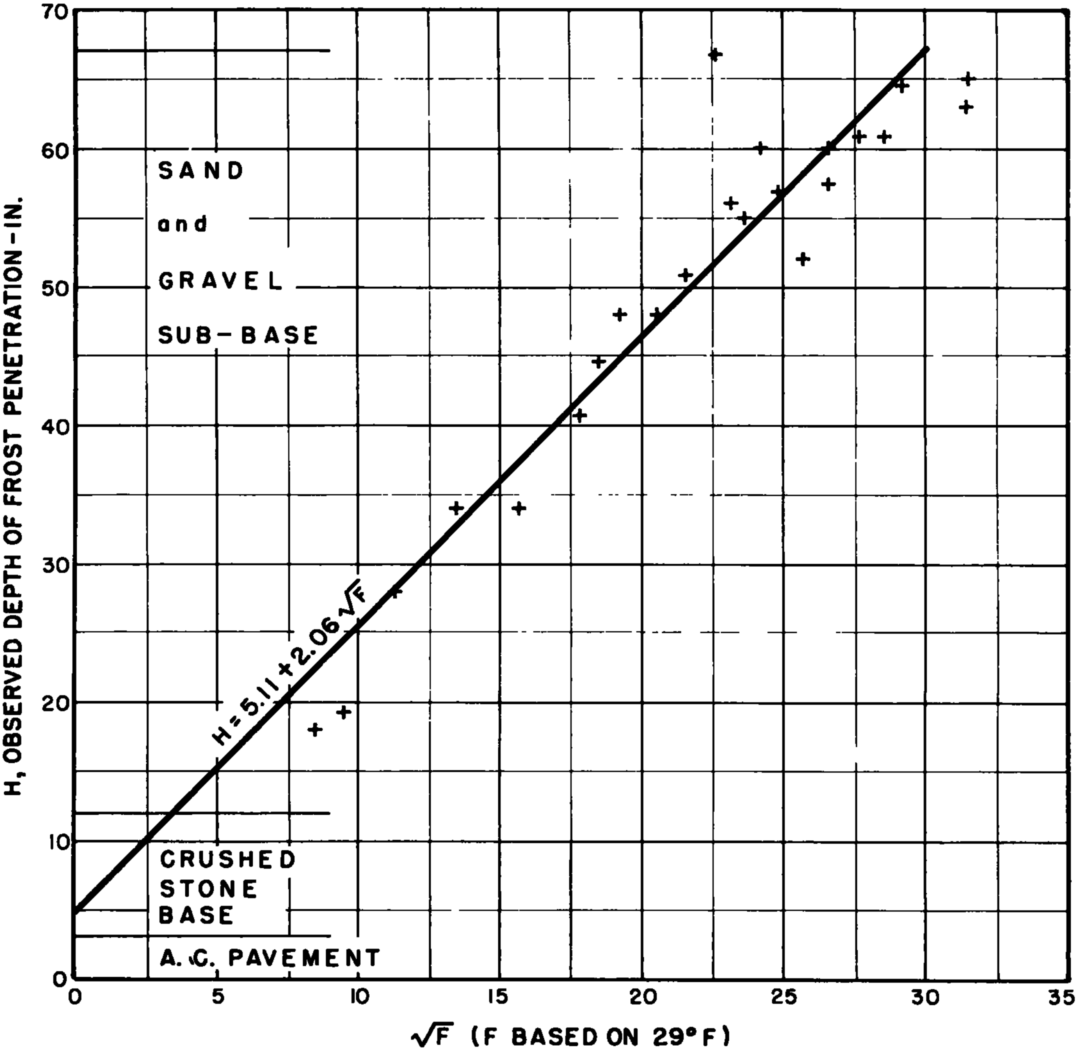

Figure 23. Observed depth of frost penetration and square root of freezing index based on 29 F.

Hence it was possible to compute $\mu = \sqrt{s}\frac{C}{L}$ on a basis of w, using values from the curve of $\sqrt{s}$ and F_A.

From the curves of Figure 21 values of λ were found and the result was the nomogram Figure 22 linking air freezing index, moisture content and λ. This diagram checks well despite its somewhat roundabout genesis. It is not recommended for use if λ can be computed more precisely, but quite often essential data are missing and then an approximate value is useful. The way that λ varies with freezing index and moisture content is very significant, even if the values of λ are not very precise. The diagram shows how large errors may arise from an assumption of a constant value of C_f and λ = 1, especially when w is small, then the sensible heat becomes as important as latent heat. Figure 22 is based on mean annual freezing and mean annual temperature; it becomes inaccurate for part freezing seasons.

The parameter, L, has been accepted for a long time as one of the easier to deal with. Actually, however, it may be responsible for many discrepancies between es-

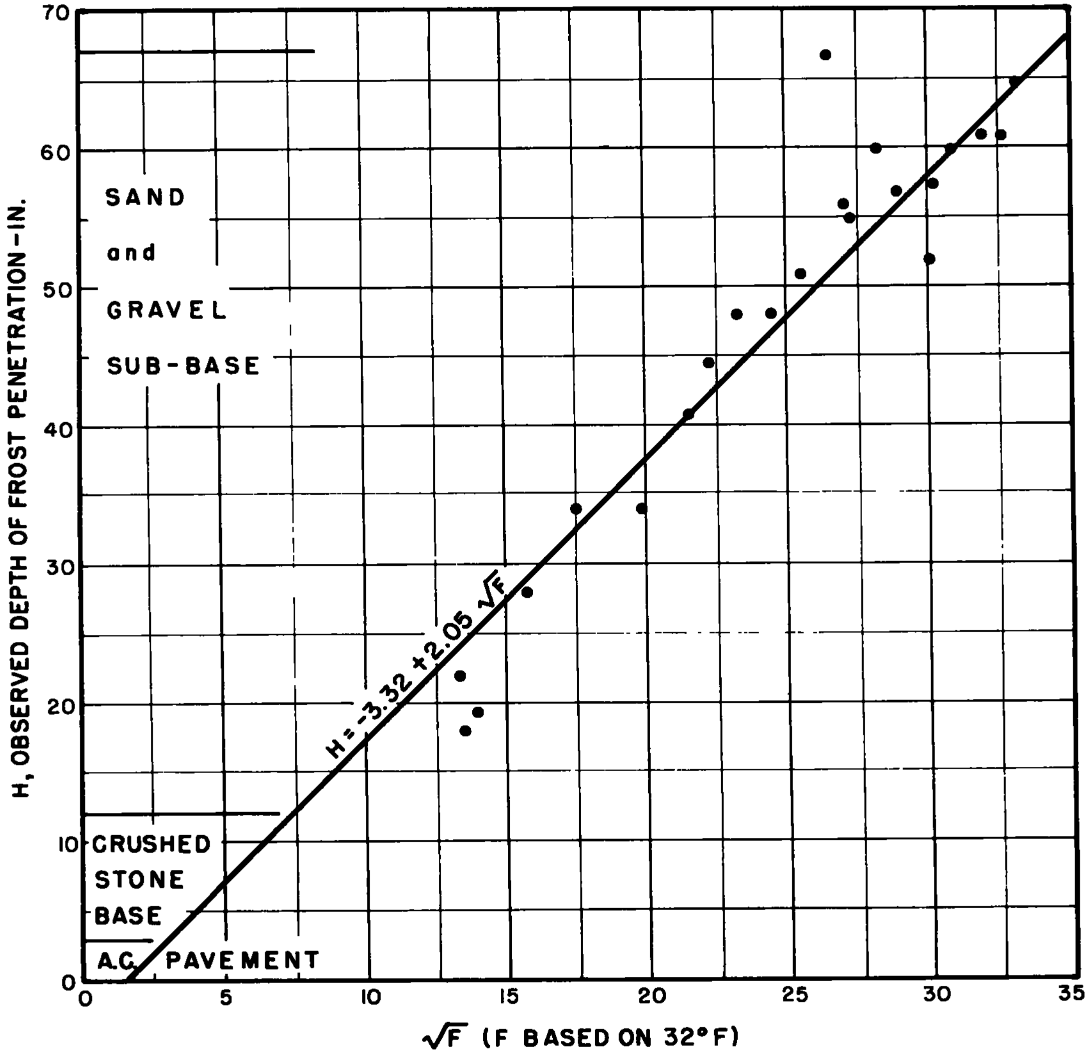

Figure 24. Observed depth of frost penetration and square root of freezing index based on 32 F.

timates and observations of frost penetration. It is computed on the assumption that all of the water in the soil freezes at ground temperatures, whereas it is known that this is far from the truth in fine-grained soils. The amount of unfrozen water varies with the soil, temperature, and time that the soil is exposed to freezing temperatures. Lovell (3) has recently written on the subject and Tsytovich (4), who gives further information on the phenomenon, shows that a clay may have about 25 percent of unfrozen water at 30 F, and about 16 percent at 20 F. Wintermeyer (5) summarizes the results obtained by many experimenters up to 1925. Taber, Bouyoucos, Winterkorn and Beskow (6) have all discussed this phenomenon.

The problem is still under study but the effect may explain why frost penetration in a clay is sometimes more than expected. It cannot explain discrepancies with gravels, however, because in clean sands and gravels essentially 100 percent of the water does freeze at ground temperatures. It looks as though the latent heat term should be studied seriously.

THE USE OF 29 F INSTEAD OF 32 F FOR THE DATUM IN COMPUTING DEGREE-DAYS OF FROST

The assumptions made in the development of frost penetration equations should be recalled when the various parameters in them are under discussion. The Stefan and modified Berggren formulas assume that the ground surface temperature suddenly drops below the freezing temperature of water and stays steady during the freezing season when the ground surface temperature suddenly rises again above the freezing temperature. The average temperature below freezing, $\sqrt{s}$, is multiplied by t, the duration of the freezing season in days, measures the energy abstracted from the soil. The Stefan equation assumes that all the energy goes into latent heat; the modified Berggren equation assumes that energy goes into sensible heat (in lowering ground temperatures) as well as into latent heat (in changing water to ice) and in that respect it is superior. The product of $\sqrt{s}\,t$ is given by the area under the temperature-time curve below the freezing temperature of water taken over the freezing season; this is called the surface freezing index F_s. Since surface temperatures are generally unknown air temperatures measured 4 to 6 ft above the surface which can be easily measured, or less reliably, estimated from observations taken at nearby places, are used with a correction factor C. In principle:

$$h = \sqrt{\frac{48kF_s}{L}} = C = \sqrt{\frac{48kF_A}{L}}$$

In the Stefan equation, C is usually associated with F_A, the air freezing index measured with 32 F as the freezing point of water:

$$h = \sqrt{\frac{48kF_A c_f}{L}} \qquad \text{(Stefan's equation)}$$

The c_f is found by equating observed frost penetration and values computed from the assumed formula.

It is clear that c_f has to cover many things, some quite unrelated to air ground temperatures, of which the sensible-heat effect is the most important.

In this paper the author takes several more steps to assume that "the soil surface temperature is related to the air temperature by the coefficient c_f" and applies it for part of a freezing season and apparently find discrepancies because he then starts to adjust F_A in a further assumption regarding the base temperature. In principle he changes his assumption of a constant ratio between air and surface temperatures to one of a constant difference between the temperatures. This may work well in a particular location; the more attractive way is to put the correction factor where it belongs—outside the root sign—and proceed to find it (if possible) rather than arbitrarily assuming a constant temperature difference. Actually the latter assumption may be a very good one if only freezing indexes are being considered, especially in the midwest where temperatures do drop quickly and stay low for the winter, then quickly rise again, but in general, temperatures do not fall and rise suddenly; at the end of the season there are fluctuations and the curve of temperature-time is far from rectangular, especially in New England.

Considering only freezing index again, the modified Berggren equation assumes that $\frac{\text{surface freezing index}}{\text{air freezing index}}$ is equal to 0.9 as a good statistical average based on a large quantity of data from ACFEL files. Recent analytical studies at M.I.T. under ACFEL contracts have shown that 0.9 is a good value to use north of latitude 45N but that it varies ±0.05 depending on solar radiation, wind and other factors. The writer thinks that the assumption of a constant temperature difference is at least as good as an assumption of constant temperature ratio but questions the temperature assumption as of general validity. By taking a whole freezing season the errors cancel to a considerable amount so that the assumption of a ratio between air and surface indexes for a whole season appeals to him as sound, whereas computations for a part season do not.

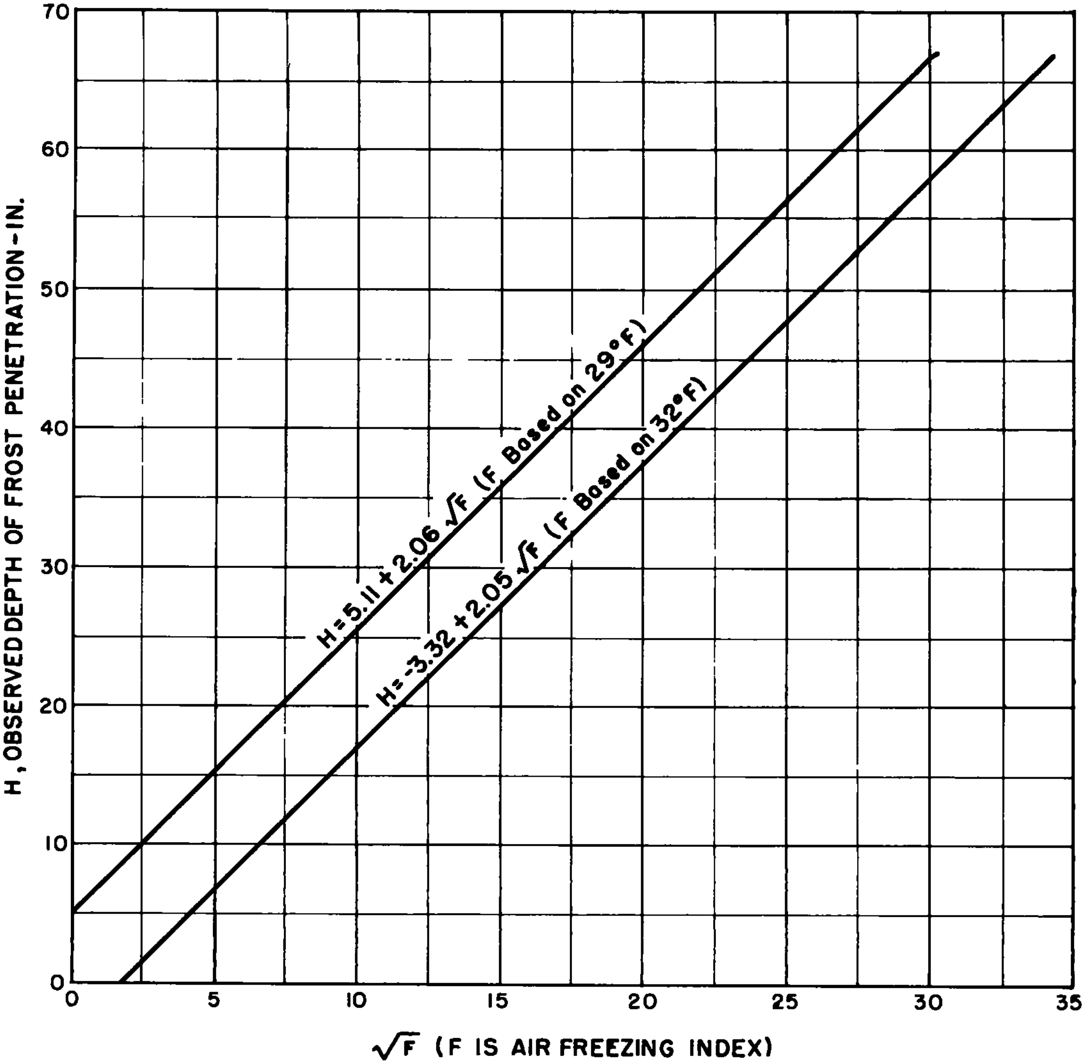

Figure 25. H, $\sqrt{F}$ curves from Figure 23 and 24 showing effect of freezing index based on 29 F and on 32 F.

In calculations for multi-layered systems there is no fallacy in computing degree-days for each layer but the result should not be taken to provide a plot of degree-days and time. The final penetration for the whole season is usually accurate enough using the modified Berggren equation and in a particular location, the simple Stefan equation (or an even simpler formula) might work well enough.

Author's Curves

A straight-line plot between H and $\sqrt{F}$ merely proves that within experimental limits H may be proportional to $\sqrt{F}$. Many straight lines (and curvilinear ones) can be drawn through experimental points; the "best" line is difficult to be sure of and the statistical analysis would be a big job. There are insufficient data available to use the author's curves and produce indexes based on 32 F but from ACFEL records of a location in northern Maine, plots have been made for a 29 F base and for a 32 F base. In each case a straight line has been drawn through the points using the method of least squares

(Figs. 23 and 24). Figure 25 shows both lines on a $\sqrt{F}$ base; which is better? If by means of the modified Berggren equation, X is plotted on a base of $\sqrt{F}$, the result is a curve of increasing slope (Fig. 26). It is probable that such a curve could be drawn through some of the author's points (again proving nothing).

The only real check on a new idea is computed depth versus measured depth at many locations, and under many conditions; but a formula of local application is still of value and should not be deprecated. The author has certainly covered a good range of soils in the Minneapolis area, and the use of 29 F with the Stefan formula may give results as good as, or better than, those obtainable using 32 F with that formula.

So much information on freezing indexes based on 32 F is now available that really strong evidence must be produced to justify a change from 32 F to 29 F for general usage.

The modified Berggren equation is not the final word in formulas; it shows discrepancies with granular soils of very low moisture content, giving results which are too big—on the safe side in design but uneconomical. The equation has other drawbacks also, especially in multi-layered systems. A constant value of surface temperature is assumed throughout a freezing season so that the formula should not be used for plotting frost penetrations against time throughout a freezing season although the result for a given full season is usually reliable. Nor at present can the equation be used in a system containing an interbedded insulating layer of zero moisture content.

No formula seems to work very well with granular soils of very low moisture content; perhaps the k values are the main reason for this.

At the present time (November 1958) methods based on micrometeorology are still not fully worked out although a promising start has been made at M. I. T. under contract with ACFEL and ACFEL is accumulating pertinent data for the evaluation of some quantities which so far have had to be estimated.

The writer considers that the best method of computing frost penetration is by a simple procedure and that the search for a very simple formula is on the wrong track. Numerical analysis with lumped elements, which is the basis of the analog solution (author's refs. 2, 15), is one possibility; the writing of Ingersoll (7) and Dusinberre (8) is recommended for the study of step-by-step procedures. All these approaches are fundamentally similar in using the first principles of heat flow. Structural designers use the moment distribution method without qualms—there is no reason why highway engineers should find the numerical treatment of heat transfer difficult; both techniques can give good results for specific problems where general solutions are very complicated or impossible. Accurate values of soil properties will always be a critical requirement whatever method is employed, and, of these, k is the most important.

In the meantime ACFEL is continuing the study of the modified Berggren equation to simplify its application still further.

THAWING OF SUBGRADES

A general formula for rate of thawing has not yet been found for seasonal frost areas but theoretical solutions to specific problems are obtainable by means of numerical procedures, either longhand or by analog computer (author's ref. 15). As the author points out, reliable measurements during the thaw period are extremely difficult to make; there is a considerable period of time when regions of the soil are at freezing temperature but part of the water is solid and part is liquid and the "depth of thaw" is meaningless. It is probable also that percolating water has an appreciable effect during the thaw period so that theoretical results may not be valid if this effect is ignored.

MICROMETEOROLOGICAL APPROACH

The direct method of studying the interaction between the air and the ground is a new approach which has shown promise but which still has a long way to go before it can be applied to engineering computations.

The weather data required are curves of air temperature and of windspeed observed at a standard height, cloud cover, sunshine duration, and vapor pressure (or relative

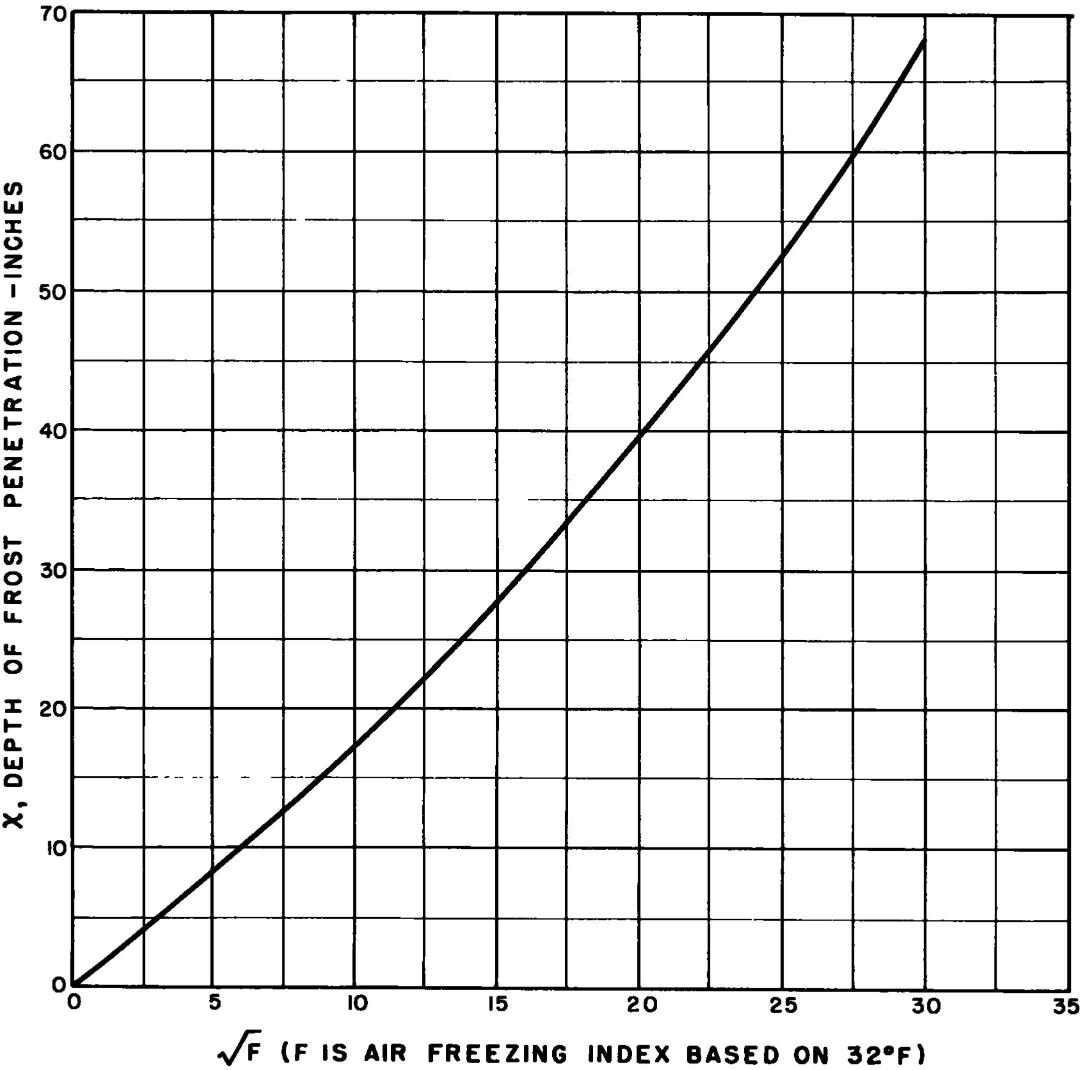

Figure 26. Modified Berggren formula, $X = 12\lambda\sqrt{\frac{48KnF}{L}}$. Typical curve of depth of frost penetration and square root of freezing index (γ_d = 140 pcf, w = 3.5%).

humidity) of the air. Ground data required are the nature of the srrounding surface and the soil profile with thermal properties of the soil. The latitude of the place must be known unless special measurements of heat radiation are made (not a usual procedure). If some of these requirements are not met, estimated values may cause serious errors.

The princple used, which is attractive, is to balance out the heat entering and leaving the surface of the ground; this enables the curve of air temperature to be modified to a curve of surface temperature from which the frost penetration can be computed either by a computer or by a numerical process from the known soil conditions. While attractive in principle, the method is quite difficult, combining the complexity of the weather with soil variability and the problem of freezing well known to "frost men."

The heat quantities are:

1. Solar Radiation. The sun radiates a known amount of energy received at the outside of the earth's atmosphere. This depends upon latitude and can be found in the

Smithsonian Tables. On its way through the atmosphere the flow is reduced by air, dust and clouds and at the surface some energy is reflected back, leaving a net amount of shortwave radiation, the main heat supply.

2. Longwave Radiation. If the earth's surface is at a different temperature from that of the air or of the clouds, longwave heat will be radiated between the "surfaces," the amount depending upon temperatures, surface emissivities and cloud cover. Estimation of this heat flow is somewhat uncertain at present. The surface temperature curve must be known for this heat computation and has to be assumed to start with. Its importance is evident from the low temperatures of calm, cloudless nights in winter when a lot of heat is being radiated away from the earth's surface.

3. Convective Heat Transfer at the Ground Surface. Air flowing over the surface leads to a heat exchange by forced convection at the surface. Windspeed over the surface is important and can be computed quite well from weather observations but surface roughness is not easy to evaluate because the wind is affected by a large area around the site.

4. Evaporation, Condensation, Sublimation, and Transpiration. Heat quantities involved in these phase changes of water substance and in plant metabolism are safely ignored in highway and airport computations, though very important in the micrometeorology of horticulture.

5. Conduction in the Soil. The net amount of heat left for conduction in the soil depends upon the balance of the other heat quantities and hence upon differences between large amounts—an unfortunate situation since small errors become enormously increased thereby.

The result of the heat balance computations is a curve of surface temperature and time from which the frost penetration can be found, preferably by means of a computer (the writer prefers the hydraulic analog type despite its drawbacks) but also by simple numerical procedures, or even, somewhat crudely, by formulas. In any event a computer is really necessary in the trial solutions for surface temperature; a complete curve has to be assumed and then checked, an extremely tedious process without a computer.

At present ACFEL has a theory and the computers. Field observations have been coming in but only for a year or two of complete micrometeorological data so it will be some time before the method will be satisfactory for engineering purposes. Most published material is for grassland, etc., during fair weather and that leaves a big gap. The analysis of a tremendous mass of weather data is a formidable task, but it is hoped that ultimately there will be simplified techniques for the direct solution of frost penetration problems from weather stations and soils data.

ACKNOWLEDGMENTS

Much of this discussion is based on data from the files of the Arctic Construction and Frost Effects Laboratory under the direction of Kenneth A. Linell. Peter A. Martus of the laboratory has been a valuable assistant to the writer in working up the data and making computations for the figures.

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HARL P. ALDRICH, Jr., Haley and Aldrich, Cambridge, Massachusetts—Situations arise where refined procedures for computing the depth of frost penetration are desired. The Stefan equation described by Kersten and even the modified Berggren formula discussed by Sanger may not fulfill requirements of a thorough study where an exact solution is required. The writer wishes to add, therefore, a few comments regarding analog, digital and hand numerical solutions, all of which have been used in recent years to solve specific problems or to verify approximate formulas.

These solution techniques are all based on a finite difference approximation of the differential equations governing the heat diffusion process. In simpler language the process involves dividing the soil profile in small "lumps" or layers of finite thickness and writing a series of simple mathematical equations for heat flow between midpoints of the lumps. The accuracy of the solution increases as the size of the lumps decreases.

Analogs

Two useful analogs have been used in recent years to solve a wide variety of complex practical problems, especially problems involving multi-layered soil profiles with surface temperatures varying with time. Both hydraulic and electronic analogs are in operation at the Arctic Construction and Frost Effects Laboratory of the New England Division, Corps of Engineers in Waltham, Mass.

Analogs follow from the formal correspondence between terms and equations in 3 important braches of physics, namely heat conduction, current conduction and laminar fluid flow, as given by Aldrich (1). These analogous relationships make it possible, for example, to model the heat flow frost problem with a simple fluid flow model containing a series of vertical standpipes connected by means of capillary tubes. Each standpipe represents a lump of soil while capillary tubes are scaled according to thermal conductivity and distance between lumps.

Design and operation of a hydraulic analog for one-dimensional frost problems is reported by M. I. T. (2). Scott (3) also describes the "computer" which was constructed at M. I. T. under a research contract with the New England Division, Corps of Engineers. Principal advantages of the hydraulic analog are initial cost, simplicity of programing and operation, and provision for a continual visual check on the solution. Principal disadvantage is the difficulty of maintaining a constant resistance in laminar flow capillaries.

An electronic analog computer for the frost problem was conceived in 1952 by Paynter of M. I. T. (4). During the following two years a computer containing 100 elements and capable of solving two-dimensional frost problems, was constructed and placed in operation at the ACFEL. The cost of the electronic analog is approximately ten times that of the hydraulic analog. Its principal advantage is the speed at which solutions can be obtained.

Numerical Solutions

Derivation of the simple mathematical equations which can be solved by hand using a desk calculator or slide rule or which may be solved by the IBM card programed computer, begin with the continuous Fourier one-dimensional conduction equation:

$$q = -k\frac{\delta v}{\delta x} \qquad (1)$$

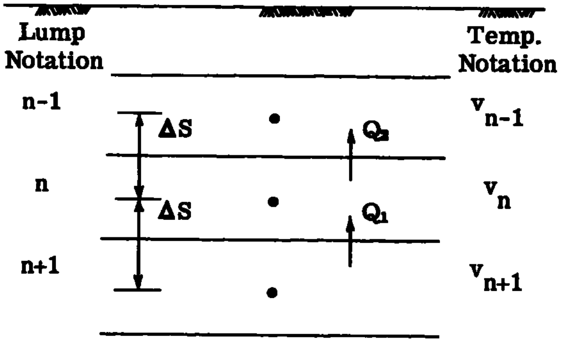
which is more familiar as:

$$Q = kiA \qquad (2)$$

in which

v = temperature in deg F;
Q = rate of heat flow in Btu/hr;
k = thermal conductivity in Btu per (hr)(ft)(deg F);
i = thermal gradient in deg F/ft; and
A = area in sq ft, assumed 1.

The finite difference equation for one-dimensional heat flow in the absence of freezing and thawing is derived with the following notation:



where the following approximate equations may be written:

$$Q_1 = k\frac{v_{n+1} - v_n}{\Delta S}1$$

$$Q_2 = k\frac{v_n - v_{n-1}}{\Delta S}1$$

The net rate of heat flow into lump n is now:

$$Q_1 - Q_2 = k\frac{v_{n+1} + v_{n-1} - 2v_n}{\Delta S} \qquad (3)$$

The net rate of heat flow will be equal to the time rate of change of thermal energy u (Btu) of the layer:

$$Q_1 - Q_2 = \frac{\Delta u}{\Delta t}, \quad \text{where } \Delta u = C\Delta v_n(\Delta S \cdot 1 \cdot 1) \qquad (4)$$

$$= \frac{C\Delta v_n \Delta S}{\Delta t}$$

in which

t = time in hrs; and
C = volumetric heat in Btu per (cu ft)(deg F).

Equating Eqs. 3 and 4:

$$\Delta v_n = \frac{k}{C}\frac{\Delta t}{\Delta S^2}\left[v_{n+1} + v_{n-1} - 2v_n\right]$$

or

$$v_{n,k+1} - v_{n,k} = \beta \left[v_{n+1,k} + v_{n-1,k} - 2v_{n,k} \right] \quad (5)$$

in which

n-1, n, n+1 . . . = space notation;
k-1, k, k+1 . . . = time notation; and

$$\beta = \frac{k}{C} \frac{\Delta t}{\Delta S^2} \text{ (dimensionless)} \quad (6)$$

The developments presented above are extensively outline in the available literature. The introduction of latent heat from freezing or thawing complicates the basic solution somewhat. To the writer's knowledge, the numerical solution involving diffusion when latent heat effects are present was published first by Aldrich and Paynter (4).

For this development the heat storage relationship is considered for a cubic foot of soil containing water within at least a portion of its voids. A graph representing the idealized thermal energy versus temperature characteristics of the soil is shown in Figure 27.

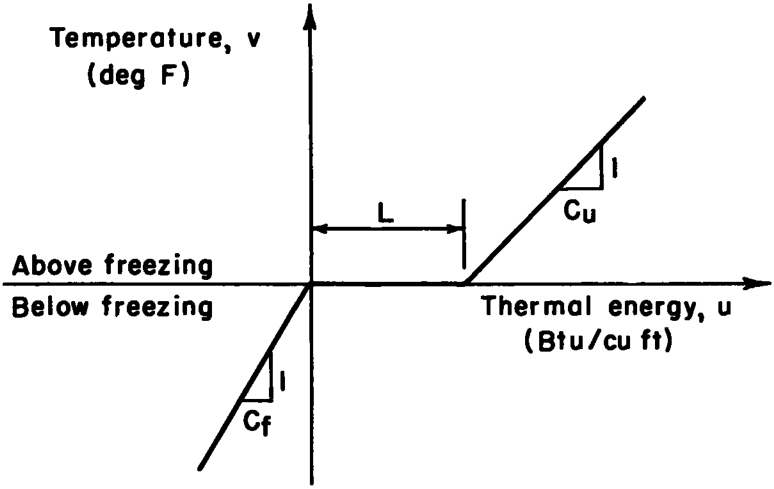


Figure 27.

in which

C_u, C_f = volumetric heat of unfrozen and frozen soil, respectively, expressed in Btu per (cu ft)(deg F); and
L = latent heat of soil moisture in Btu/cu ft.

Define a dimensionless quantity, e , which is a measure of the temperature, v, and is given by:

$$e = v\frac{C}{L} \quad (7)$$

Furthermore, define a dimensionless quantity, S, which is a measure of the thermal energy, u, and is related to e by the curve in Figure 28.

Since e is a function of v, Eq. 5 may be written:

$$e_{n,k+1} - e_{n,k} = \beta \left[e_{n+1,k} + e_{n-1,k} - 2e_{n,k} \right] \quad (8)$$

Finally, the following equations and conditions may be written:

$$S_{n,k+1} - S_{n,k} = \beta \left[e_{n+1,k} + e_{n-1,k} - 2e_{n,k} \right] \quad (9)$$

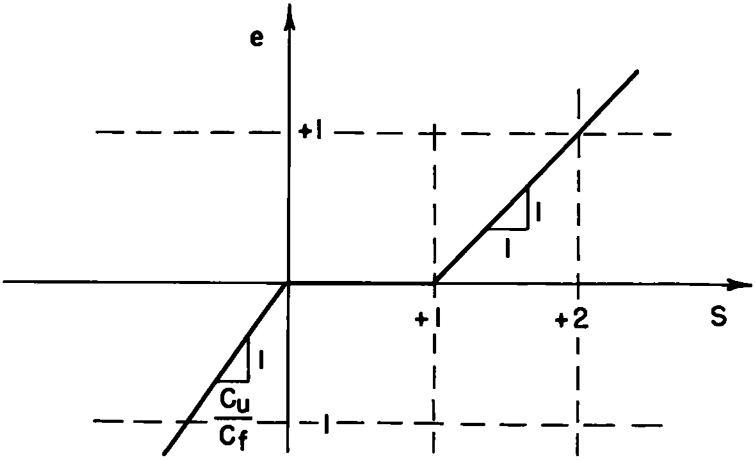


Figure 28.

where,

$$e = S - 1 \qquad \text{for } S > 1$$

$$e = 0 \qquad \text{for } 0 \leq S \leq 1$$

$$e = S\frac{C_f}{C_u} \qquad \text{for } S < 0$$

and where,

$$\beta = a_u \frac{\Delta t}{\Delta S^2} \qquad \text{for } S > 0.5$$

$$\beta = a_f \frac{\Delta t}{\Delta S^2} \qquad \text{for } S \leq 0.5$$

Numerical solutions based on the above set of normalized conditions have been made by Goldberg (5) for multi-layered soil profiles. As an illustration of the procedure and suggested form for tabulating computations, the following example is offered.

Consider a homogeneous stratum of soil semi-infinite in extent and initially at a uniform temperature of 62 F (30 F above the freezing point of soil moisture of v_o = 32 F). The temperature at the surface of the stratum is suddenly lowered to 22 F (10 F below freezing or v_s = 10 F). Assume thermal properties of soil as follows:

k = 1.0 Btu per (hr)(ft)(deg F);
C = 30 Btu per (cu ft)(deg F); and
L = 600 Btu/cu ft.

It is assumed here that k and C are the average for the frozen and unfrozen condition.

In terms of temperature then, the initial conditions and boundary conditions are:

depth	n \ k (Time →)	0	1	2	3	
	0	v_o 30 F	v_s 10 F	v_s 10 F	v_s 10 F	ΔS
	1	v_o 30 F				ΔS
	2	v_o 30 F				ΔS
	3	v_o				
		Δt	Δt			

In terms of the dimensionless parameters e and S,

$$e = v\frac{C}{L}$$

Initially, then, throughout the depth,

$$e_o = v_o\frac{C}{L} = 30\frac{30}{600} = 1.50 \tag{a}$$

and at the surface when the temperature has been lowered to v_s:

$$e_s = -v_s\frac{C}{L} = -10\frac{30}{600} = -0.50 \tag{b}$$

Corresponding to condition (a), $S > 1$, therefore,

$$S_o = e_o + 1 = 2.50 \tag{c}$$

and corresponding to condition (b), from the thermal energy diagram it follows that $S < 0$, therefore,

$$S_s = e_s = -0.50 \tag{d}$$

since $C_f = C_u$ is assumed.

In terms of the dimensionless parameters the initial conditions and boundary conditions are:

k / n	0		1		2	
Surface 0	1.50	2.50	-0.50	-0.50	-0.50	-0.50
1	1.50	2.50				
2	1.50	2.50				
3	1.50	2.50				

Notation:

k / n	0	
0	$e_{n,k}$	$S_{n,k}$

For the numerical solution, select,

$$\beta = \tfrac{1}{4} = \frac{a\Delta t}{\Delta S^2} \tag{10}$$

Then from Eq. 9,

$$S_{n,k+1} = S_{n,k} + \tfrac{1}{4}(e_{n-1,k} - e_{n,k}) - \tfrac{1}{4}(e_{n,k} - e_{n+1,k}) \tag{11}$$

Finally, the numerical solution and a suggested form for recording computations is given on the following page.

n \ k	0		1		2		3		4		5
0	1.50	2.50	-0.50	-0.50	-0.50	-0.50	-0.50	-0.50	-0.50	-0.50	-0.50
	0	0	-2.00	-0.50	-1.50	-0.375	-1.25	-0.312			
1	1.50	2.50	1.50	2.50	1.00	2.00	0.75	1.75	0.594	1.594	
	0	0	0	0	-0.50	-0.125	-0.625	-0.156			
2	1.50	2.50	1.50	2.50	1.50	2.50	1.375	2.375	1.250	2.250	
	0	0	0	0	0	0	-0.125	-0.031			
	1.50	2.50	1.50	2.50	1.50	2.50	1.50	2.50	1.469	2.469	
							0	0			
							1.50	2.50	1.50	2.50	

ETC.

In the tabulation given above, the following notation is used:

	k		k+1	
n-1	$e_{n-1,k}$			
	$e_{n-1,k} - e_{n,k}$	$\frac{1}{4}(e_{n-1,k} - e_{n,k})$		
n	$e_{n,k}$	$S_{n,k}$	$e_{n,k+1}$	$S_{n,k+1}$
	$e_{n,k} - e_{n+1,k}$	$\frac{1}{4}(e_{n,k} - e_{n+1,k})$		
n+1	$e_{n+1,k}$			

The terms encircled are those appearing in Eq. 11. The real time and space relationship at any point in the solution is obtained from Eq. 10.

Numerical solutions have been programed on the IBM Card Programed Calculator or the M. I. T. Statistical Services Division and on the IBM—701 computer in New York City.

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R. W. J. PRYER, Soil Engineer, Quebec North Shore and Labrador Railway—Procedures which allow climatic data to be used more effectively for the prediction of ground freezing and thawing are of great practical value. The field measurements reported in this paper will be of general interest since they cover an extended period of time and are accompanied by adequate site descriptions.

A study of frost penetration records for a number of successive Canadian winters was reported by Legget and Crawford (1) in 1952. The results of this study prompted the authors to suggest that the freezing index concept might be modified to take into account the slope of the freezing index curve. The correlations obtained by Kersten are particularly interesting since his use of a cumulative degree-day total based upon 29 F tends to make such an allowance.

The author's review of the five series of data presented in the paper includes the statement, "On the basis of these data one would tend to accept the concept of the Stefan equation that depth does vary with the square root of a degree-day factor without mention of the time required to accumulate this value." However, since the term F in the Stefan equation is usually understood to be the summation of degree-days below 32 F, it should be noted that the substitution of 29 F as the base for the summation and the elimination of the surface correction factor C_f is equivalent to the use of F and a new correction factor, X. Thus:

$$h = C\sqrt{F_{29}} = C\sqrt{FX}$$

in which

F = summation of degree-days below 32 F; and
F_{29} = summation of degree-days below 29 F.

The value of X will be given by:

$$1 - \frac{3t}{F} + \frac{3t_1 - F_x}{F} \qquad \text{for values of } F > F_x$$

in which

F = summation of degree-days below 32 F;
F_x = summation of degree-days below 32 F when $F_{29} = 0$;
t = duration of the freezing perod from $F = 0$ (days); and
t_1 = interval between $F = 0$ and $F_{29} = 0$ (days).

The magnitude of the correction factor X depends, therefore, upon the ratio F/t or the average rate at which degree-days are accumulated during the freezing period. If t_1 is assumed to be small—a condition which is likely to exist when mean daily air temperatures drop rapidly at the start of the freezing season—the normal freezing index curve for Minneapolis (Fig. 1) indicates that X should increase from about 0.6 when F = 200 to about 0.8 when F = 1,200.

Experience in the Labrador Peninsula region of eastern Canada supports the author's observation that a given number of degree-days of cold can result in relatively deep frost penetration during a mild winter. In a locality where the normal freezing index is in the order of 5,000, importance is attached to the average mean daily air temperature during the 15-day period which precedes the onset of the freezing season. High temperatures during this period are usually associated with moderate rainfall, the melting of early snow cover and a marked increase in the moisture content of the soil. Measurements have been made in railroad subgrade sections in soils which are not susceptible to serious ice segregation and where snow plow operations produce fairly uniform snow cover conditions. The results suggest that when a mild winter is preceded by a two-week period during which the average mean daily air temperature is low (33 F), frost penetration may be more rapid than is the case when a severe winter follows a period of mild temperatures (44 F). This effect is most pronounced during the early part of the freezing season when estimates of frost penetration based upon degree-day totals and the measurements of previous years may be in error by as much as two or three feet.

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CLOSURE, Miles S. Kersten--The discussers have made valuable contributions to the subject of methods of calculating frost penetrations. The explanation of the use of of the modified Berggren equation by Sanger, and particularly the presentation of the chart for λ correlated with air freezing indexes, gives a promising procedure which can be strengthened by further correlation studies. The solution techniques described by Aldrich may likewise be useful where a "more exact" procedure is required. In all frost calculations, one must initially decide what degree of completeness is desired and then adopt either a simple, though approximate, method, or a more advanced one taking into account more of the influencing factors; in the latter case some knowledge of these factors is obviously required, and the accuracy of the results is dependent upon the correctness of these values as well as on the completeness of the method. Continued study of all of these methods, including the micrometeorological approach described by Sanger will lead to more dependable values and better results.

The experience of ACFEL has apparently indicated the poorest correlations between calculated and measured depths for sand soils. This corresponds to the observations in Minnesota.

The data presented in the paper were not intended to prove superiority of the use of degree-days below 29 F rather than 32 F. It merely suggested that such a system might have some merit, particularly for calculations in the initial parts of a freezing season, and that further studies might be profitable.

Pryer's discussion suggests another factor which merits consideration. This is the temperature and precipitation conditions in the 15-day period preceding the onset of the freezing season.

The Factor of Soil and Material Type in Frost Action

KENNETH A. LINELL, Chief, Arctic Construction and Frost Effects Laboratory; and
CHESTER W. KAPLAR, Engineer, Chief, Cold Room Studes Section, ACFEL

I. INTRODUCTION

The earliest known published observations of frost action in soils date back to more than a hundred years. Since then a voluminous literature on the subject has been built up. The door to this amazing and significant phenomenon was opened in this country about 40 years ago in the early published works on growth of crystals by Taber, University of South Carolina (47, 48). Taber became intensely interested in the subject of soil freezing and spent many years studying and analyzing many aspects of this interesting phenomenon. He demonstrated conclusively that ground heaving during the winter was the result of growth of ice lenses in the soil, the excess water being supplied from free ground water available from below the plane of freezing. Taber published a number of articles on crystal growth and force of crystallization, and offered explanations of the mechanics of moisture migration and ice lens growth in soils which remain unchallenged to this day. Although some of his earlier studies were reported as early as 1916, his best known articles were published in the Journal of Geology in 1929 and 1930 (51, 52).

Another outstanding contributor to knowledge of frost action in soils in Gunnar Beskow of Sweden whose well-known work "Soil Freezing and Frost Heaving with Special Application to Roads and Railroads," was published in Swedish in 1935. An English translation by Osterberg was published in the United States in 1947 (9). The works of Taber and Beskow are classics on this subject, and subsequent investigations in this field have, for the most part, verified their findings.

A notable contribution on frost action in natural soils under natural freezing conditions was made by Casagrande (12), who performed field experiments at M. I. T. and in New Hampshire. From these studies came the widely known and used Casagrande criteria for frost-susceptible soils based on the percentage of material finer than 0.02 mm.

Further interesting contributions have been made by another European, Ducker (14, 15, 16, 17) of Germany who has published several articles on frost behavior in cohesive soils and on the effects of soil colloids on frost action.

While the present paper does not attempt to cover these special factors of frost action in soils which pertain only under permafrost conditions, a substantial part of the present knowledge of frost action has been contributed by the considerable number of investigators who have made studies in permafrost regions. One of the best known of these was Leffingwell (32) who made substantial original geological studies of permafrost phenomena in the Arctic more than 40 years ago.

Any review of frost action knowledge would be incomplete without acknowledgment of the invaluable aid which recent research workers in this field have received from the excellent survey of literature on frost action prepared by Johnson (24a).

II. DEFINITIONS

Definitions of the following terms used in this paper have been taken principally from a list prepared and approved by the HRB Committee on Frost Heave and Frost Action in Soil (22).

Frost Action. A general term for freezing and thawing of moisture in materials and the resultant effects on these materials and on structures of which they are part or with which they are in contact.

Frost Heave. The raising of a surface due to the formation of ice in the underlying soil.

Percent Heave. The ratio, expressed as a percentage, of the amount of heave to the depth of frozen soil before freezing.

Frost-Susceptible Soil. Soil in which significant, detrimental ice segregation will occur when the requisite moisture and freezing conditions are present.

Non-Frost-Susceptible Materials. Cohesionless materials, such as crushed rock, gravel, sand, slag and cinders in which significant, detrimental ice segregation does not occur under normal freezing conditions.

Ice Segregation. The growth of ice as distinct lenses, layers, veins and masses in soils, commonly, but not always, oriented normal to the direction of heat loss.

Ice Lenses. Ice formations in soil occurring essentially parallel to each other, generally normal to direction of heat loss, and commonly in repeated layers.

Open System. A condition in which free water in excess of that contained originally in the voids of the soil is available to be moved to the surface of freezing to form segregated ice in frost-susceptible soil.

Closed System. A condition in which no source of free water is available during the freezing process beyond that contained originally in the voids of soil.

Frost-Melting Period. An interval of the year during which the ice in the foundation materials is returning to a liquid state. It ends when all the ice in the ground has melted or when freezing is resumed. Although in the generalized case there is visualized only one frost-melting period, beginning during the general rise of air temperatures in the spring, one or more significant frost-melting intervals may occur during a winter season.

Rate of Heave.[1] The average rate of heave in millimeters per day, determined from a representative portion of a plot of heave versus time, in which the slope is relatively constant, and during which the penetration of the 32 F isotherm is at a relatively uniform rate and between ¼ in. and ¾ in. per day. Rate of heave is averaged over as much of the heave versus time plot as practicable, but the minimum number of days used for a determination is five. This measure of frost susceptibility is used in open system tests only and pertains to data presented and discussed in this paper.

III. SOIL FACTORS WHICH INFLUENCE THE EFFECTS OF FREEZING AND THAWING

A. Soil Type—General

Frost action can be controlled or eliminated by controlling water availability, penetration of freezing temperatures, or the frost-susceptibility characteristics of the soil. Of these three factors the latter has proven, in the past, to be the most feasible element of control in road design. It is common knowledge to road designers and construction engineers, through experience, that clean, free-draining sands and gravels are suitable pavement foundation materials provided that the fines are kept to a minimum. Engineers have found through local experience that certain soils are more likely to give trouble than others and that certain soil profile combinations are more likely than others to cause difficulty. Since the factor of soil and material type is the most feasible element of control in the present state of knowledge, it is of outstanding practical importance in highway pavement design in frost regions.

B. Geological, Stratigraphic and Pedological Considerations

It will be apparent to every observant engineer in frost regions that the intensity of frost action is influenced by local geologic factors.

The nature of the parent bedrock in a given frost area affects frost action by determining the nature of the soil formed by weathering action. These characteristics are, in turn, reflected in frost susceptibility of the materials. Residual soils take their characteristics from the rock at the immediate location from which they were formed. In glaciated areas, glacial drift materials inherit their characteristics from the source rocks, which may be either quite local or at some distance. A till derived from a gneiss or granite tends to be much less clayey in nature than one derived from a schist;

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[1] Not on list of definitions prepared by HRB Committee on Frost Heave and Frost Action in Soil.

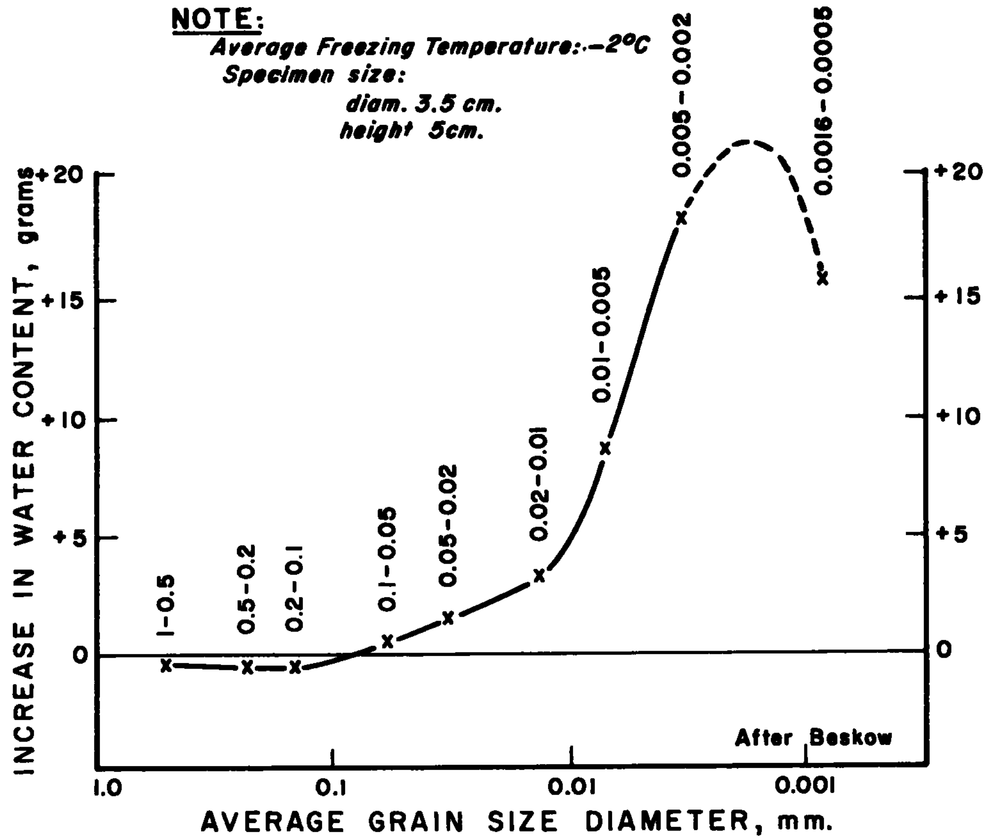


Figure 1. Relation between moisture increase and average grain size diameter of pure soil fractions.

there may also be more and larger cobbles and boulders in the former. Alluvial soils, of course, show little relation to the bedrock at the point of deposition, having usually been transported substantial distances; however, on a regional basis a relationship may exist. Wind-deposited soil formations and strata of volcanic ash may have distinctive frost characteristics and be identifiable with specific geologic situations or over specific areas. Thus, a knowledge of the local bedrock and surficial geology, when correlated with field performance, will frequently provide valuable estimates of frost action potential at given locations.

The soil profile has a profound influence on frost action, as is apparent to all soils engineers in frost regions and as has been widely reported in the literature. The most obvious influence of the soil profile upon frost action is the control exerted by stratification and by the effective permeability on moisture-availability at the plane of freezing.

In some cases stratification results from the manner of deposition; in other cases strata near the ground surface may be the result of modification by weathering and percolation. The strata may have slightly different to widely different (as in varved clay) physical properties, depending upon the mineral and particle characteristics and the physical structure. An impervious stratum in or under more pervious frost-susceptible material may result in a perched water table capable of providing sufficient moisture for ice segregation during the freezing period and may slow the escape of thaw water during and following the frost-melting period. A water-bearing pervious layer in or under a more impervious frost-susceptible material may carry moisture to

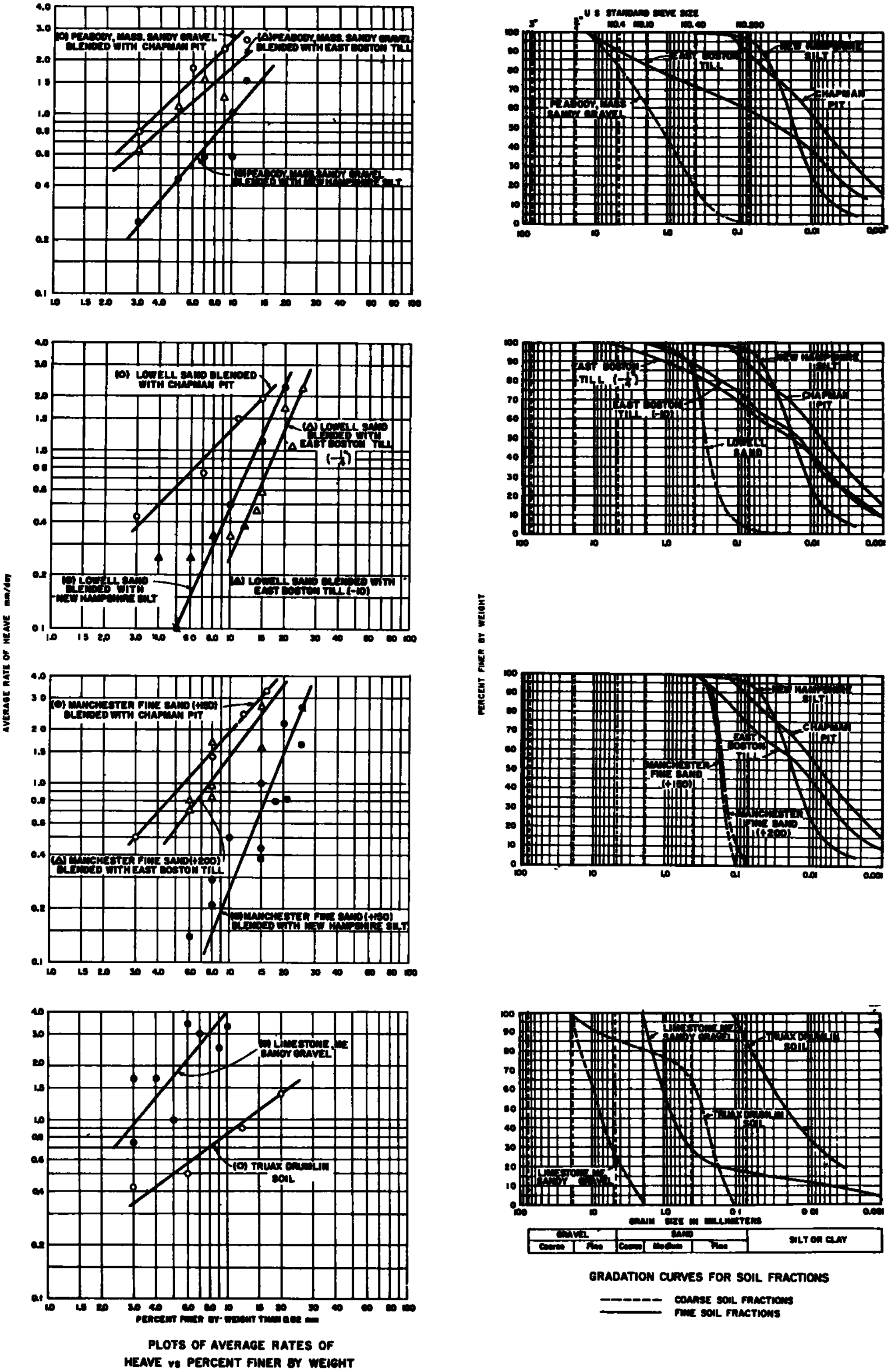


Figure 2. Effect of percent finer than 0.02 mm.

feed growing ice lenses laterally from a source outside the paved area. Isolated silt pockets and layers in otherwise free-draining, non-frost-susceptible soils may cause serious differential heaving of pavement surfaces because of their tendencies to absorb and hold, and to perch above them, infiltrating surface water, either from shoulder areas or from pavement cracks and joints.

Varved clays may be encountered in glaciated areas. The varves consist of alternating layers of inorganic silts and clays and in some instances fine sands. The thickness of the layers rarely exceeds ½ in., but occasionally very much thicker varves are encountered. They are likely to combine the undesirable properties of both silts and soft clays. Varved clays are likely to soften more readily than homogeneous clays with equal average water content. However, under favorable conditions, as when insufficient moisture is available for migration, there may be little or no detrimental frost action. Some pavements in the seasonal frost zone constructed on varved clay subgrades, where the deposit and depth to ground water are relatively uniform, are reported to have performed very satisfactorily (55).

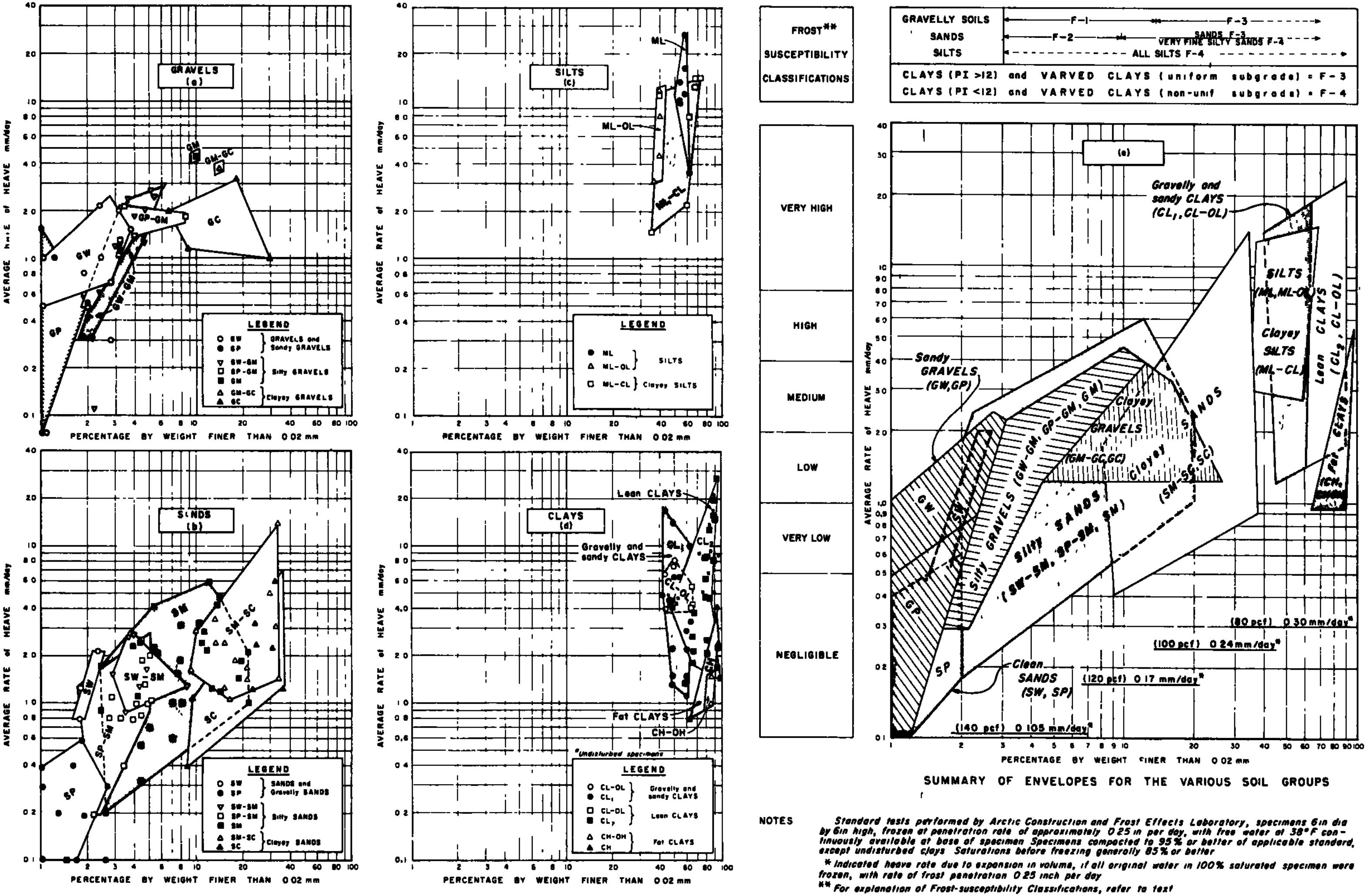
Effective over-all permeability in fine-grained soils may be substantially greater than the permeability of individual soil samples because of fissures caused by freezing and/or dessication, by holes left by decayed roots, worms, etc. This effective permeability is difficult to measure and little is qualitatively known about it.

When bedrock occurs within the zone reached by winter freezing, it introduces a special factor into the soil profile. Paradis (37), Lang (31), Bennett (8), and Otis (36) and others have observed that detrimental frost heaves frequently occur over ledge rock. This may result from several conditions. First, the presence of the bedrock may affect the availability of ground water for frost heaving. The irregular surface of bedrock may trap ground water in underground "pools," making ground water available at such points. Also, if the rock is low-lying relative to the surrounding ground, fissures in the bedrock may carry water to the plane of freezing more readily than through the overburden. Second, the relatively high thermal conductivity of bedrock may result in a slow to negligible rate of advance of the freezing plane near bedrock, so that a condition conducive to thick ice lens growth may persist for some time, with water being supplied in relatively unlimited amount from the bedrock. Third, bedrock frequently contains seams of material which have weathered into a highly frost-susceptible soil; under these conditions the placing of clean non-frost-susceptible material on the bedrock surface cannot prevent differential frost heave at the mud seams. All these bedrock conditions are conducive to quite irregular frost heave, and the occurrence of ledge rock within the seasonal frost zone may therefore actually result in a more detrimental frost heave condition than in areas where rock is deep.

Conditions of climate and topography indirectly affect frost action in soils by their effect on soil properties and characteristics. For example, certain soils in the western United States located on low or flat areas have a high content of salt which serves to prevent freezing of frost-susceptible soils down to as low as 10 F. Below this depressed freezing temperature, normal frost heave characteristics are experienced. It may be presumed that soils in elevated well-drained locations in this same western region would have a different salt content and would perform distinctly differently when subjected to freezing temperatures. The differences in leaching action between semi-arid and relatively humid regions, and between soils of natural high and low pH values, may also possible result in differences in frost susceptibility. Pedologists have done much in relating soil types to climate, and, as brought out by Johnson (24), numerous investigators and agencies have done much to relate pedological soil types to frost experience. However, little appears to have been done to relate the fundamental differences in the mineral, chemical and physical characteristics of these soils to these differences in performance.

C. Soil Properties Affecting Frost Behavior

1. Grain Size and Soil Gradation. Investigators of frost action in soils early discovered that certain types of soils were more susceptible to frost action than others. It was observed that greater heave and more numerous and larger ice lenses appeared



NOTES Standard tests performed by Arctic Construction and Frost Effects Laboratory, specimens 6in dia by 6in high, frozen at penetration rate of approximately 0.25 in per day, with free water at 38°F continuously available at base of specimen. Specimens compacted to 95% or better of applicable standard, except undisturbed clays. Saturations before freezing generally 85% or better.

* Indicated heave rate due to expansion in volume, if all original water in 100% saturated specimen were frozen, with rate of frost penetration 0.25 inch per day

** For explanation of Frost-susceptibility Classifications, refer to text

1959

Figure 3. Average rate of heave vs percentage finer than 0.02 mm for natural soil gradations.

in the silts and lean clays. Taber (51) made many experiments with various fine-grained and coarse-grained soils and soil mixtures. He demonstrated effectively the influence of fine particle size on ice segregation.

Beskow (9) conducted laboratory experiments with soil fractions of selected size ranges. He demonstrated that observable heaving, i. e., ice segregation, was first noticeable in the soil fraction containing particles ranging from 0.05 to 0.1 mm. Heaving became greater as the average particle diameter decreased. The maximum heaving was observed to occur in the soil fraction containing soil grains with diameters ranging from 0.005 to 0.002 mm. The results of Beskow's experiments are plotted in Figure 1.

Casagrande (12) drew the following conclusion from his studies in 1927-29 at M. I. T. and in New Hampshire on natural soils under natural freezing conditions:

> "Under natural freezing conditions and with sufficient water supply one should expect considerable ice segregation in non-uniform soil containing more than 3 percent of grains smaller than 0.02 mm, and in very uniform soils containing more than 10 percent smaller than 0.02 mm. No ice segregation was observed in soils containing less than 1 percent of grains smaller than 0.02 mm, even if the ground water level was as high as the frost line."

Casagrande's frost criteria as proposed in 1931 for natural soil gradations still afford the most expedient rule-of-thumb means of identifying, without benefit of laboratory freezing procedure, soils in which damaging frost action may occur. It should be carefully noted that the values of 3 percent and 10 percent finer than 0.02 mm are not intended to represent points at which ice segregation is entirely absent. There is no sharp line of demarcation at the 3 or 10 percent points. As used in pavement engineering, the Casagrande criteria of 3 and 10 percent finer than 0.02 mm are intended to represent levels below which frost heave will not usually exceed tolerable limits in ordinary applications.

A series of freezing tests was performed at ACFEL to check the validity of the Casagrande criteria for frost-susceptible soils and to determine the relationship between the 0.02 mm size and the ice segregation produced for soils of various gradations ranging from well-graded sandy gravel to very uniform fine sand. Three cohesionless soils were combined with the fines (minus 200 mesh material) from a silt, a till and a clay, respectively, to observe the effect of different soil fines on frost behavior. Also, two soils, limestone, Maine, sandy gravel and truax, Wisconsin, drumlin soil, were recombined with their own fines to produce the desired percentages finer than 0.02 mm. The test results are summarized in Figure 2 in plots showing the rate of heave versus percent finer than 0.02 mm size.

Examination of Figure 2 reveals that for equal percentages of material finer than 0.02 mm, relatively large variations in the average rate of heave were recorded. Based only on the grain size distribution, it appears that the finer the grains or the more of colloidal sizes contained in the finer soil fraction, the more effective the finer soil fraction is in producing ice segregation. From these results it can be concluded that the intensity of ice segregation in soils is dependent not only on the percent of grains finer than 0.02 mm, but also on the grain size distribution and/or physicochemical properties of these fines. Fine soil fractions with a high percentage of clay sizes were found in these tests to be more potent than silt sizes in producing ice segregation in soils of borderline frost susceptibility.

Tests were also performed at the Arctic Construction and Frost Effects Laboratory by a standardized test procedure to determine the relative frost susceptibility of base course and subgrade soils from various airfields and highways in the northern United States, Alaska, Canada, Iceland and Greenland (5). The materials were generally tested in the remolded condition, at a density between 90 and 100 percent of maximum density as determined by applicable laboratory compaction procedures. Some of the specimens of silt and clay were prepared from undisturbed samples of these soils. Tests were made on the unmodified, natural gradations, so far as possible, with maximum stone sizes varying from ¾ in. up to 2 in. for specific soils. When larger size stones were present they were replaced with an equivalent percentage by weight of smaller stones graded from ¼ in. to the maximum size utilized in preparing the specimens.

Figure 3 shows results of all of these tests conducted at ACFEL to date. They are grouped into four general categories, that is, soils which are predominantly gravels, sands, silts, and clays (Figure 3a, b, c, and d). Figure 3e shows a composite summary of the various envelopes. The soil classifications are in accordance with the Unified Soil Classification System (56). In the figures the average rate of heave of 6-in. diameter specimens frozen in the open system at a rate of freezing of about ¼ to ½ in. per day is plotted against the percent finer than 0.02 mm.

The data on Figure 3 do not represent a selection of all the possible gradations that might be found in nature but represent instead all soils which have chanced to be submitted for testing to ACFEL by U. S. Army Engineer Districts and other government agencies. It is possible, therefore, that the envelopes shown on Figure 3 may be revised as additional soils are received and tested.

Examining Figure 3a it may be noted that as the silt and clay content of the gravelly soils increases as denoted by an increasing percentage of material finer than 0.02 mm, and by the alphabetical classification assigned, the average rate of heave also increases. With one exception, all of the poorly-graded sandy gravels (GP) fall into the negligible or very low frost-susceptibility classification. It can be observed that some of the well-graded gravels exhibit somewhat undesirable heave rates (above 1.0 mm/day) even though containing low percentages of minus 0.02 mm material. The data on Figure 3a show that some extremely well-graded materials containing from 1 to 3 percent of material finer than 0.02 mm may heave significantly under the severe conditions of the laboratory freezing tests. On the other hand, some of the silty, sandy gravels classified as GW-GM and GP-GM, and containing up to 4 percent of minus 0.02 mm material may be of very low frost susceptibility (heave rate less than 1.0 mm/day) and thus may be suitable for use in well-drained base and subbase courses in frost areas. According to the results to date, all materials classified as GM, GM-GC or GC and all gravelly soils containing more than 4 percent of minus 0.02 mm material should be considered undesirable for base and subbase use from the standpoint of frost susceptibility. Very well-graded gravelly soils, GW, containing more than 2 percent finer than 0.02 mm size should be evaluated by laboratory freezing tests. In exceptional cases and in special applications, extremely well-graded gravels containing even lower percentages of minus 0.02 mm material may need to be so tested.

In Figure 3b sands classified as SP are indicated to be of negligible frost susceptibility. Well-graded sands, SW, should be further examined if the amount finer than 0.02 mm is above 2 percent. Silty gravelly sands (SW-SM, SP-SM) and silty sands (SM) are, as a group, variable in their behavior, with objectionable heaving indicated in some soil gradations containing as little as 2 percent finer than 0.02 mm size. In other gradations of these types materials, the percent of minus 0.02 mm material may be as great as 10 percent or even higher without the occurrence of objectionable heaving. According to the results to date, however, the great majority of sands containing more than 10 percent of minus 0.02 mm material appear undesirable from the standpoint of potential frost action. It is true that in the case of clayey sands and gravelly, clayey sands (SM-SC) a few instances occur (see Fig. 3b) where heave rate is near or slightly below 1.0 mm per day, with the amount smaller than 0.02 mm as high as 20 percent. However, the authors are hesitant to place too much significance on the test results in the lowest part of the envelopes, that is, those showing the lowest rates of heaving in their respective groups, since there is always the possibility that the few lowest test results may be in error due to possible undetected restriction of water supply, possible excessive side friction against the walls of the specimen container or other causes arising during testing, all of which would tend to lower heave values.

As shown in Figures 3c, 3d, and 3e, the silts and lean clays generally exhibit the highest heave rates. The fat clays (CH) and organic fat clays (CH-OH) have shown markedly smaller rates of heaving than most of the silts and lean clays in standard freezing tests. This is believed due to the increased imperviousness of these soil types and to the greater particle surface forces associated with these types of soils.

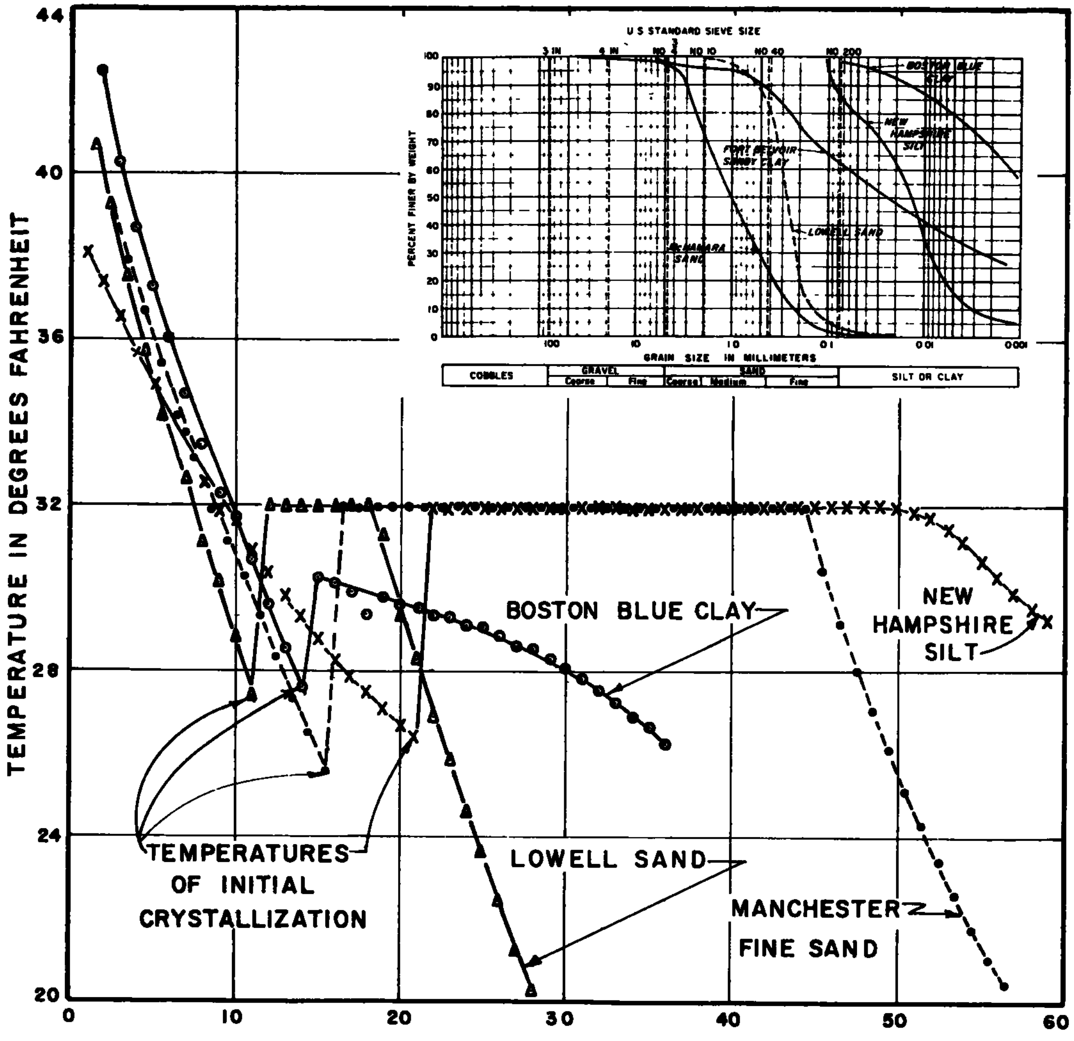
As is apparent from Figure 3, accurate prediction of relative heave rate cannot be made simply from general soil type and percent finer than 0.02 mm. Soils of even similar gradations may vary significantly in frost behavior. Factors not apparent from a gradation analysis affect the behavior. Some of the more important factors are density or degree of compaction of the soil, initial water content or initial degree of saturation, permeability, and mineral composition of the fines. These factors are discussed elsewhere in the paper.

It is considered that the ACFEL results shown on Figure 3 reasonably confirm Casagrande's criteria for average "non-uniform" and "very uniform" soils and that for these two material categories and average situations his criteria represent reasonable engineering approximations for limits of allowable potential frost heave. However, because of their extreme simplification, the criteria cannot be expected to cover all soils and materials or be applicable for all situations. Therefore, it is inevitable that soils should be encountered which deviate significantly in performance from the criteria, in both safe and unsafe directions, and engineering problems should arise in which the maximum heave possible under the Casagrande criteria may be excessive. The problem then arises as to further identification steps for recognition of potentially troublesome materials. In many cases, undoubtedly, the Casagrande criteria are adequate for the type construction involved. In others, as where a crack-free rigid pavement must be constructed to the highest standards of smoothness, it may be essential to freeze test any potentially borderline materials to aid in determining suitability and possible necessity for treatment or rejection.

In trying to make use of laboratory data it must be borne in mind that the standard laboratory freezing tests used by ACFEL are performed under severe conditions with respect to proximity and availability of unlimited free water. Such conditions are not normally encountered in a well-drained and well-designed base course. The full intensity of heaving experienced in the laboratory tests does not generally occur in the field except where conditions are quite extreme. The laboratory test as performed does, however, give a quantitative measure of the potential of the material for frost heaving, which may be converted to a relative measure on an arbitrary scale as is done by ACFEL. It also permits the frost susceptibilities of new materials to be compared directly with those of materials previously tested and gives a value which may be used for correlation with field performance.

In the studies being conducted at ACFEL, question has often arisen as what maximum particle size should be used in the specimens being tested. In highway and airfield construction in the United States it is common practice to use suitable borrow material with maximum sizes up to 4 in. in the base course. To provide data on potential frost susceptibility of natural soil gradations to Corps of Engineers offices and other government agencies submitting base course type materials to ACFEL for frost tests, ACFEL has deemed it desirable to test these materials with the largest size stone feasible in a 6-in. diameter container, that is, 2-in. maximum size. Study is currently being given to possible adoption of a relatively small maximum particle size to permit relative evaluation to be made between the finer soils fractions of different gradations. Toward this end the data on Figure 3 are being completely restudied and replotted on basis of the characteristics of the fine fractions of the soils. For the present it is felt that the current techniques used have considerable merit by providing pertinent and useful data for direct application to field problems without recourse to dubious extrapolation or correction factors until such time as more is known of the significance of all the factors involved.

2. Void Characteristics and Specific Surface Area. According to Jackson and Chalmers (23) the energy needed for drawing water to an ice lens and for lifting the overlying soil is made available as a result of supercooling of the pore water below its normal freezing temperature. The greater the supercooling the more energy is made available when the pore water eventually freezes. The magnitude of supercooling is dependent upon the mean radius of curvature of the ice-water interface. The effective radii are determined by the channel sizes present in the soil. The channel sizes in turn are controlled by the shapes, sizes and distribution of sizes of particles in the soil. If the particles are of different sizes and shaped such that they pack well between each



MATERIAL	TEST CONDITIONS			
	DRY UNIT WEIGHT, pcf	WATER CONTENT, %	DEGREE OF SATURATION, %	AVERAGE FREEZING CABINET TEMP., °F
LOWELL SAND	99.2	6.0	23.4	+ 3.3
MANCHESTER FINE SAND	98.4	15.6	59.4	+ 4.6
NEW HAMPSHIRE SILT	92.4	10.9	34.6	+ 18.5
BOSTON BLUE CLAY	76.3	17.0	34.9	+ 3.6

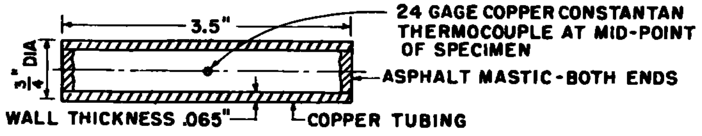


Figure 4. Typical plots of temperature change during freezing.

other, the channels will be smaller than for uniformly sized particles of the same average linear dimension. If the range of particle sizes present is very large and the smaller particles fill the spaces between the larger ones, the channel sizes formed will be more characteristic of the smaller particles present. This is obviously the case in well-graded, gravelly soils. This accounts for the fact that these soils may be frost-susceptible with only a relatively small percentage of fines.

Attempts have been made by ACFEL to correlate the specific surface area (as determined by the glycol retention method) of the fines portion of a number of natural soils with the heave rates exhibited by both the parent soil and its minus 200 mesh fraction in laboratory freezing tests. To date the results of these studies have been negative. No discernible relationship has been found between the specific surface of a soil and its frost-heaving characteristics. Other factors, some of which have already been mentioned and discussed, are involved in a complex relationship which needs clarification for a complete understanding of the mechanics involved. Considerable research is needed in this area.

3. Freezing Point and Freezing Characteristics. When a soil first freezes or first appears to be frozen, as it is progressively cooled not all of the water present in the voids is at once changed into ice. The percentage of the total volume of water initially frozen in a soil at or slightly below the freezing temperature of water depends upon the type of soil and its water content. It has been demonstrated that the water in large pores freezes at temperatures close to 32 F once crystallization has started. Water in the smaller pores and in the moisture films close to the surfaces of the soil grains requires lower temperatures. This is illustrated for several soils in Figure 4 which shows temperature changes measured at the center of a small cylindrical soil specimen enclosed in a copper tube after being suddenly moved from a region of high temperature to one of a very low temperature. It will be noted that some supercooling occurred each time before initial crystallization took place, whereupon the temperature abruptly rose or "kicked-back" to the apparent freezing temperature of the soil moisture. For the cohesionless soils such as the Lowell sand, Manchester fine sand, and the New Hampshire silt, this latter temperature remained fairly constant for a considerable time until all the latent heat of fusion available at this temperature was removed. The length of time for the latent heat of fusion to be removed is an indication of the amount of water being frozen at those temperatures. The apparent freezing point of pore water in the sands and the silt is shown to have been at or close to 32 F; that of the clay was somewhat lower (30.2 F). Furthermore, the apparent freezing temperature of the clay did not remain constant, even for a short time, thus indicating that very little moisture was frozen at 30.2 F. The much flatter slope of the cooling curve of the clay immediately after initiation of freezing, as compared with the slope before freezing, is attributed mainly to progressive release of latent heat as more and more water became frozen. The fairly steep slopes of the cooling curves of the sands after initial freezing probably indicate that most of the moisture froze at 32 F and little latent heat remained to be released at lower temperatures. However, the slopes of the cooling curves after the initial freezing undoubtedly were also influenced by the changed thermal properties of the soil following the change of state, as well as by some tendency toward asymptotic flattening as the specimen temperature dropped toward the limiting lower temperature. The flatter slopes of the cooling curve for the New Hampshire silt both before and after the initial freezing are attributed to the fact that the lower temperature limit used for the silt was 14 to 15 deg. higher than that applied to the other soils shown.

Soil moisture freezing is covered in detail in two other papers in this symposium. The freezing temperature of soil moisture will be further discussed.

4. Soluble Salts. The presence of soluble salts in the pore water produces a lowering of the freezing point depending upon the quantity of solute and its valence. In clay type soils the introduction of a salt solution may also change the thickness of the adsorbed water film on the particle surfaces due to cation exchange and thus produce changes in the physical properties of the soil. Many investigators (2, 3, 9, 11, 41, 45, 57, 58) have studied the effect on frost susceptibility of addition of soluble salts. Salts used have been principally chlorides. These have proved effective in various degrees but have suffered from the failing that they are not permanent and in time will

leach out by lateral and vertical diffusion. Pyne (40), for example, found that in central Massachusetts the effectiveness of a calcium chloride treatment in the sandy silt subgrade soil under a sealed, but not completely water-tight, penetration-macadam pavement was about 3 yr.

Recently, in connection with design of proposed new pavements at Wendover AFB, Utah, a problem arose as to the extent of required frost protection because of naturally present salts. The soil water in the upper foot of the natural subgrade contained as much as 8 percent dissolved salts, mostly sodium chloride. The salt content decreased rapidly with depth. Freezing tests showed that the average initial freezing temperature was approximately 10 F in the top foot of subgrade, increasing with depth. Theoretically, this would allow a smaller thickness of pavement and base to be used since the upper portion of the subgrade could be allowed to cool to substantially lower temperatures than 32 F without freezing. However, no information was available as to how long the differential of salt content with depth would remain after a pavement was placed over it. The laboratory freezing tests showed that when the temperature was reduced sufficiently to cause freezing, the rate of heaving and intensity of ice segregation in the salt laden soil was comparable to that observed in other soils of similar gradation. Thus the effect of the salt was simply to lower the temperature level at which frost heaving started and if the salt content of the upper foot of the subgrade should decrease after the pavement was placed over it, frost heaving might be absent at the start but appear later and become more intense with time.

The depression of freezing point caused by soluble salts is important not only in soils containing high percentages of salt but undoubtedly also in soils containing even trace levels of soluble materials, as a result of the tendency for soluble substances to become concentrated immediately ahead of and at the boundaries of growing ice crystals. The manner in which this effect combines with the effects of pore size on freezing point is a complex phenomenon which is little understood and on which research is much needed.

5. Mineral Type. In a paper presented at the HRB 1951 Annual Meeting, Grim (19) analyzed the possible effects of clay mineral composition on frost action in soils, although substantiating field or laboratory data of frost heaving characteristics were not included. Two considerations were used by Grim in evaluating the potential of various clay mineral types in developing ice segregation in soils. The first consideration was that a movement of water through the soil is necessary to supply the growing ice crystal. The second consideration was that soils consisting of "very fine colloid-sized clay materials show very little or no segregation of ice on freezing." Grim reasoned that those clay minerals which absorb a quantity of water in a definite molecular pattern immobilize the water adjacent to the adsorbing surface, thus reducing the permeability and the ability of the soil to supply water for ice segregation.

A somewhat similar concept is held by Winterkorn (59) who has stated:

> "Directly adjacent to the adsorbing soil, solidly adsorbed water is found; the center of the pore space is occupied by ordinary water freezing at about 0 C, and between the ordinary water and the solidly adsorbed water there is a zone of liquid water possessing a melting point down to -22 C which serves as a passageway for the conduction of water to freezing centers."

The adsorption characteristics of the various types of clay minerals toward water and various ions and organic molecules were discussed by Grim (19) together with possible effects on frost action as follows:

> a. "Montmorillonite Soils. In montmorillonite, adsorption water penetrates between indivisual molecular layers, and as a consequence has tremendous adsorptive surface and enormous water adsorption capacity. There seems to be little doubt that the water adsorbed on the surface of montmorillonite particles would consist of water molecules in a definite pattern, and, therefore, the water would not be fluid or mobile. Grim[1] has presented an analysis of certain

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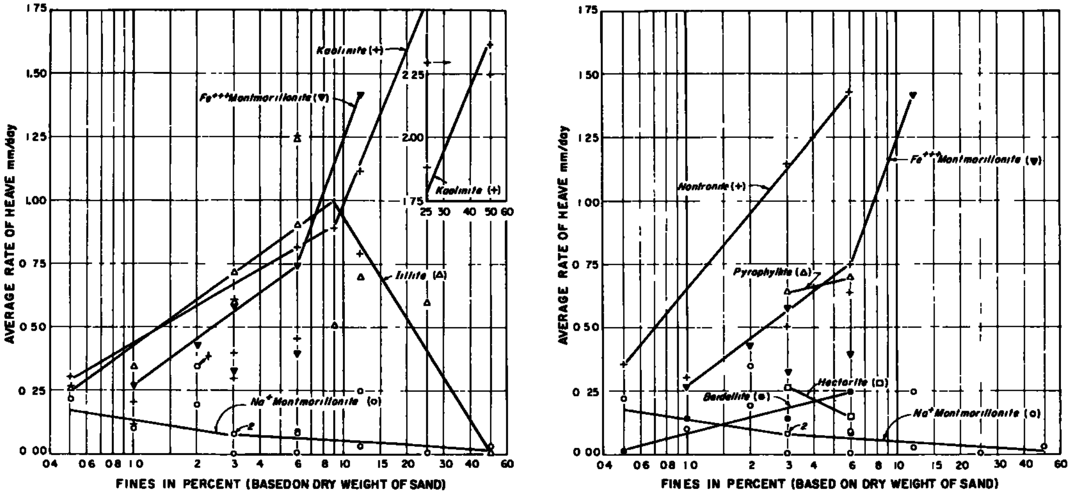
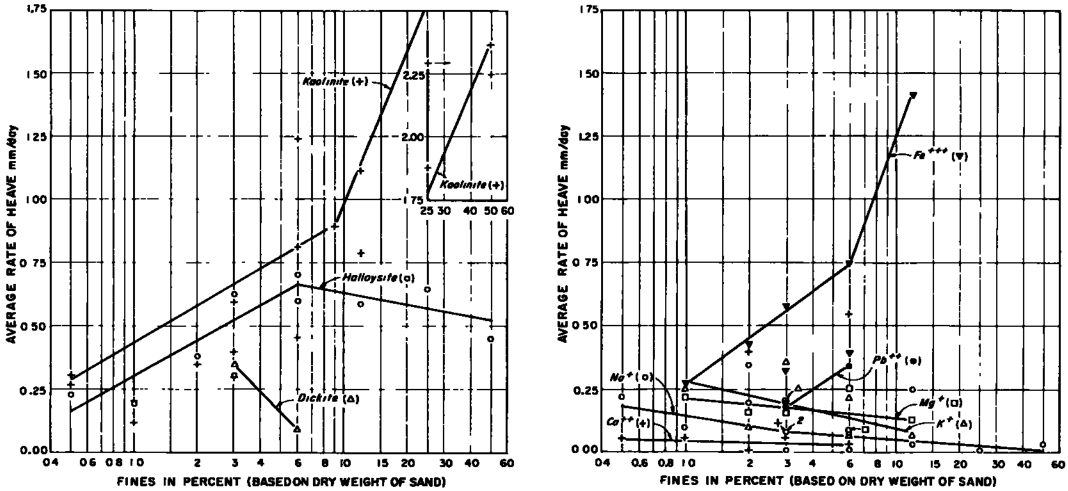
[1] Grim, R. E., "Some Fundamental Factors Influencing the Properties of Soil Materials," Second International Conf. Soil Mechanics Proc., Vol. III, pp. 8-12, 1948.



(a) COMMON CLAY MINERALS

(c) MONTMORILLONOID GROUP



(b) KAOLIN GROUP

(d) MONTMORILLONITE

NOTE

In drawing the curves where scatter of data present, the high points were favored as representing the most probable frost behavior of these sand-clay mixtures. Any obstruction to free water supply such as entrapped air, would reduce heaving, high points indicate optimum test conditions

Figure 5. Effect of clay minerals with McNamara sand.

properties of clay-water mixtures which provided convincing evidence that the water initially adsorbed is rigid rather than mobile or fluid and that at varying distances from the adsorbed surface the rigid water changes to liquid water.

"Montmorillonite has high adsorption capacity for certain cations, anions, and organic molecules. The tremendously significant fact is that the character of the adsorbed ion to a very considerable extent controls the perfection of orientation of the water molecules and the thickness of the water layers, showing a definite configuration, and as a consequence exerts an enormous influence on the properties of clay-water systems.

"In montmorillonite carrying sodium as the adsorbed ion, water can enter easily between all the unit layers, and in the presence of an abundance of water, adsorbed water layers with a definite configuration of water molecules can build up to great thicknesses (probably with thicknesses of the order of at least 100 Angstrom units). Thus even in the presence of large amount of water in which the water content would be in excess of the clay-mineral content, there would be no fluid water. Such clays, are, therefore, substantially impervious, and on freezing there is little or no concentration of ice in layers.

"In montmorillonite carrying calcium, magnesium, or hydrogen as the exchangeable ion, the situation would be quite different than for a sodium montmorillonite. When the alkaline earths or hydrogen are present as adsorbed ions, water enters between the unit layers with some difficulty and forms relatively thin layers of rigidly adsorbed water. In such clays water present beyond a certain relatively small amount (about 40 percent of the dry clay), in comparison with Na+ montmorillonite clay, is fluid. In such clays, therefore, concentration of ice in layers may develop on freezing only if the moisture content is fairly high.

"In montmorillonite clays containing potassium, there is very little adsorption of water with a definite configuration. Therefore, in the presence of even small amounts of water, some fluid water would be present.

b. "Kaolinite Soils. In soil materials composed of kaolinite, the kaolinite particles occur in relatively large units, 100 to 1,000 times the size of the montmorillonite units in a montmorillonite soil, and consequently the surface area is relatively small. Because of the nature of the crystalline structure of kaolinite, only about half the total surface seems particularly likely to develop adsorbed water with a definite configuration, that is, rigid water. It may therefore be concluded that at even relatively small water contents kaolinite soils would contain some fluid water. Kaolinite soils therefore are not particularly impervious, and should readily show a concentration of water in ice layers on freezing.

c. "Illite Soils. Many soil materials are primarily composed of the mica type of clay minerals like illite and chlorite. The characteristics of such soils range between those of kaolinite soils and montmorillonite soils but usually are closer to the former than the latter . . . . Somewhat more adsorbed water would be immobilized in illite clays than in kaolinite clays, but the total quantity would still be relatively small, and at relatively low water content illite clays would be expected to contain fluid water. Illite clays are not impervious and should show readily the concentration of water in ice layers on freezing.

"Many illite soils contain small amounts of montmorillonite interlaminated with the illite layers. It has been pointed out previously[a] that small amounts of such montmorillonite can have an effect on physical properties out of all proportion to the amount actually present. This conclusion should also apply to frost action. A small amount of montmorillonite would greatly increase the amount of water immobilized, particularly if adsorbed sodium ions were present and as a consequence increase the imperviousness and decrease the tendency for water to concentrate in ice layers on freezing."

In the series of ACFEL tests discussed in Part III C under "Grain Size and Soil Gradation," the fines from limestone sandy gravel (Chapman Pit) were found to be more potent in producing ice segregation than the fines from East Boston till and New Hampshire silt. The fines of the limestone sandy gravel had 40 percent kaolinite and 20 percent illite, those of East Boston till 20 percent kaolinite and 40 percent illite, and those of New Hampshire silt, no kaolinite, montmorillonite or illite. This might appear to

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[a] Ibid.

indicate that the presence of kaolinite had somewhat greater effect on frost susceptibility. However, as shown in Figure 2, the fines from these soils differed in particle size distribution, which also may account for the differences in ice segregation in the specimens into which they were blended.

ACFEL also performed freezing tests on the minus 200 mesh fractions of several soils as shown below:

Source of Minus 200 Mesh Fraction	Average Rate of Heave mm/day	Principal Minerals	
		Mineral	Percent
Chapman Pit sandy gravel (Limestone, Maine)	15.5	Kaolinite	40
		Illite	20
		Limonite	5
		Magnesite	5
East Boston till (East Boston, Massacusetts)	15.0	Kaolinite	20
		Illite	20
		Quartz	30
		Feldspar Mica and Limonite	Several Percent or less
Truax Drumlin soil (Truax, Wisconsin)	17.5	Illite	65
		Quartz	15
		Dolomite	20
Peabody sandy gravel (Peabody, Massachusetts)	17.0	Quartz	40
		Garnet Topaz Amphibole	-

As shown, the average rates of heave were not substantially different from one another and were very high. If there were any differences in the potential effects of the different mineral compositions upon the tendency to ice segregation at the plane of freezing, they were countered by other factors such as differences in permeability in such a way as to result in rates of heave all of about the same magnitude.

Freezing tests made at ACFEL in cooperation with Lambe of M.I.T. (6), using a clean cohesionless sand (McNamara sand, gradation shown in Figure 4) to which various mineral fines were added have demonstrated the significant influence of the composition of the soil fines on frost behavior. The pronounced effect of the nature of the exchangeable ions on the frost-heave-producing ability of montmorillonoid fines has also been demonstrated. The clay mineral fines used in these experiments were kaolin (kaolinite, dickite, halloysite), montmorillonoids (montmorillonite, beidellite, nontronite, hectorite, pyrophyllite), illite, chlorite and attapulgite. The non-clay minerals used were quartz, labradorite, muscovite, calcite, magnesite, dolomite and limonite. The test results are shown plotted in Figures 5 and 6.

The following conclusions were drawn by Lambe (6) from this series of experiments:

a. At low concentrations of fines, the clay minerals are higher frost-heave producers than the non-clay minerals; at higher concentrations, the heave producing ability of the clay minerals varies over a very wide range which brackets the effects produced by the non-clay minerals. There are exceptions to this general statement.

b. If montmorillonite is the soil fine, the rate of heave can range considerably over a hundred-fold depending on the nature of the exchangeable ion.

c. Sodium as an exchangeable ion gives the lowest heave, while ferric iron gives the highest heave.

d. Iron montmorillonite, nontronite, attapulgite and possibly kaolinite are minerals of high frost heave producing ability.

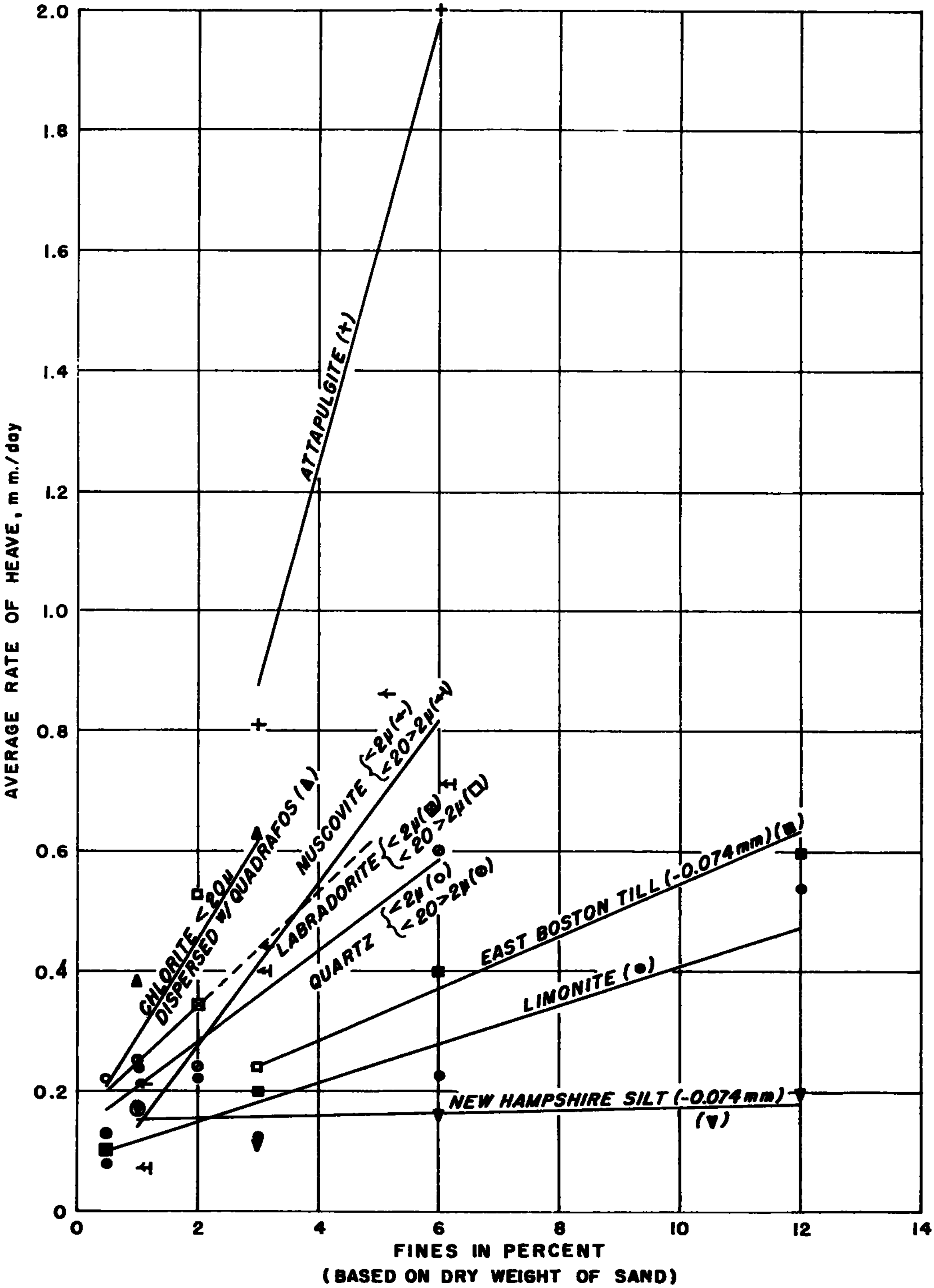

Figure 6. Effect of non-clay minerals and miscellaneous clay minerals with McNamara sand.

e. The increase of fines concentration above a certain minimum can result in a decrease of frost heave rate for the more plastic clays such as montmorillonite (exceptions are iron and lead montmorillonite), illite and hectorite.

The above conclusions indicate that when a clay mineral is present in a soil in a minor amount, its effect may be quite different than when the percentage of that mineral is high enough so that its properties are predominant. For example, a clay mineral which forms such highly impervious soil that frost heave is negligible if that mineral is predominant, may intensify frost heave or may make significant ice segregation possible in otherwise non-frost-susceptible material, when present in small amounts insufficient to make the basic soil impermeable.

In a further series of tests made at ACFEL, various percentages of relatively pure sodium montmorillonite, ranging from 0.01 to 12 percent of dry weight of soil, were added to natural gradations of a highly frost-susceptible silt (New Hampshire), a sandy clay (Ft. Belvoir, Virginia) and a lean marine clay (Boston, Massachusetts). The results of the freezing tests are shown in Figure 7. Low level treatments (less than 0.05 percent) increased the frost heave in the silt and lean clay; additions of 1.0 and 2.0 percent and greater reduced the heaving of these soils. Heave of the sandy clay was reduced at all levels of treatment above 0.01 percent.

The possibility that soil moisture in certain clays might be sufficiently bound at

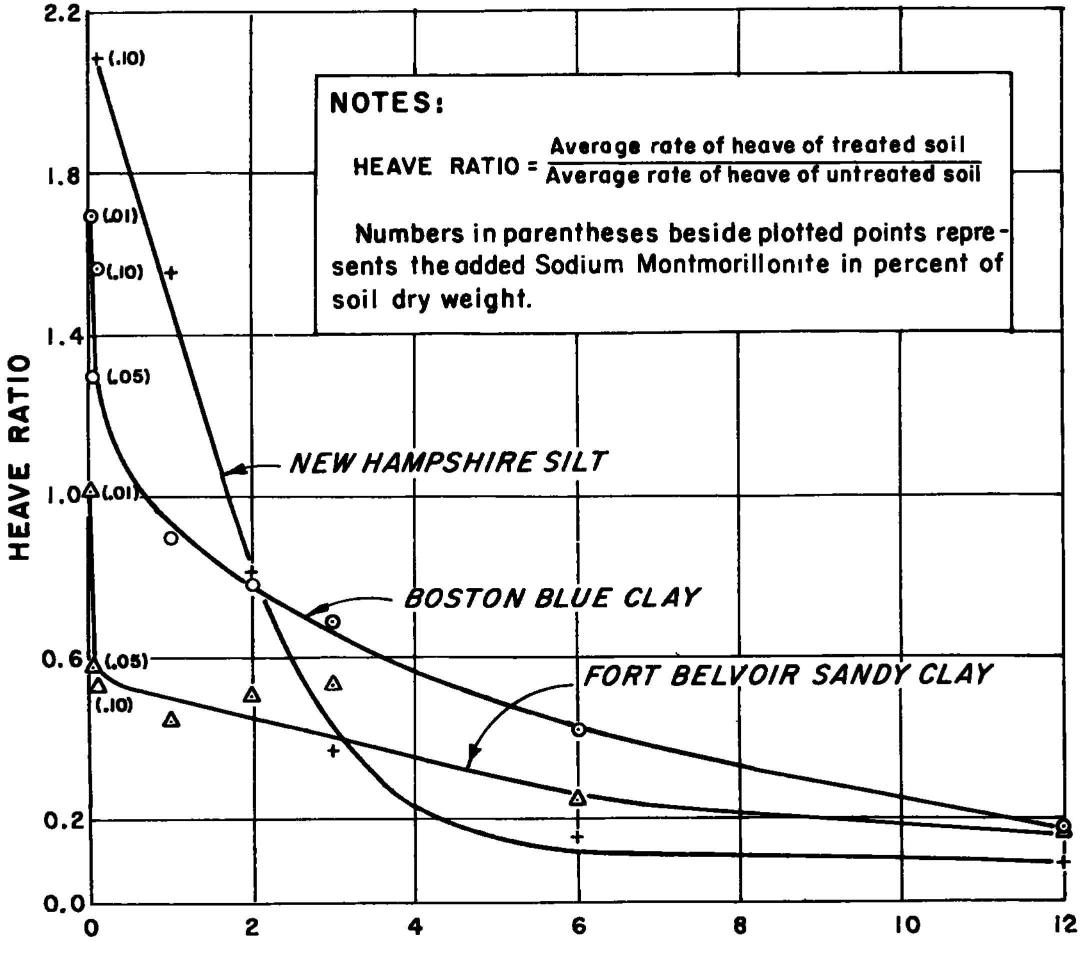

Figure 7. Effect of sodium montmorillonite on frost heave.

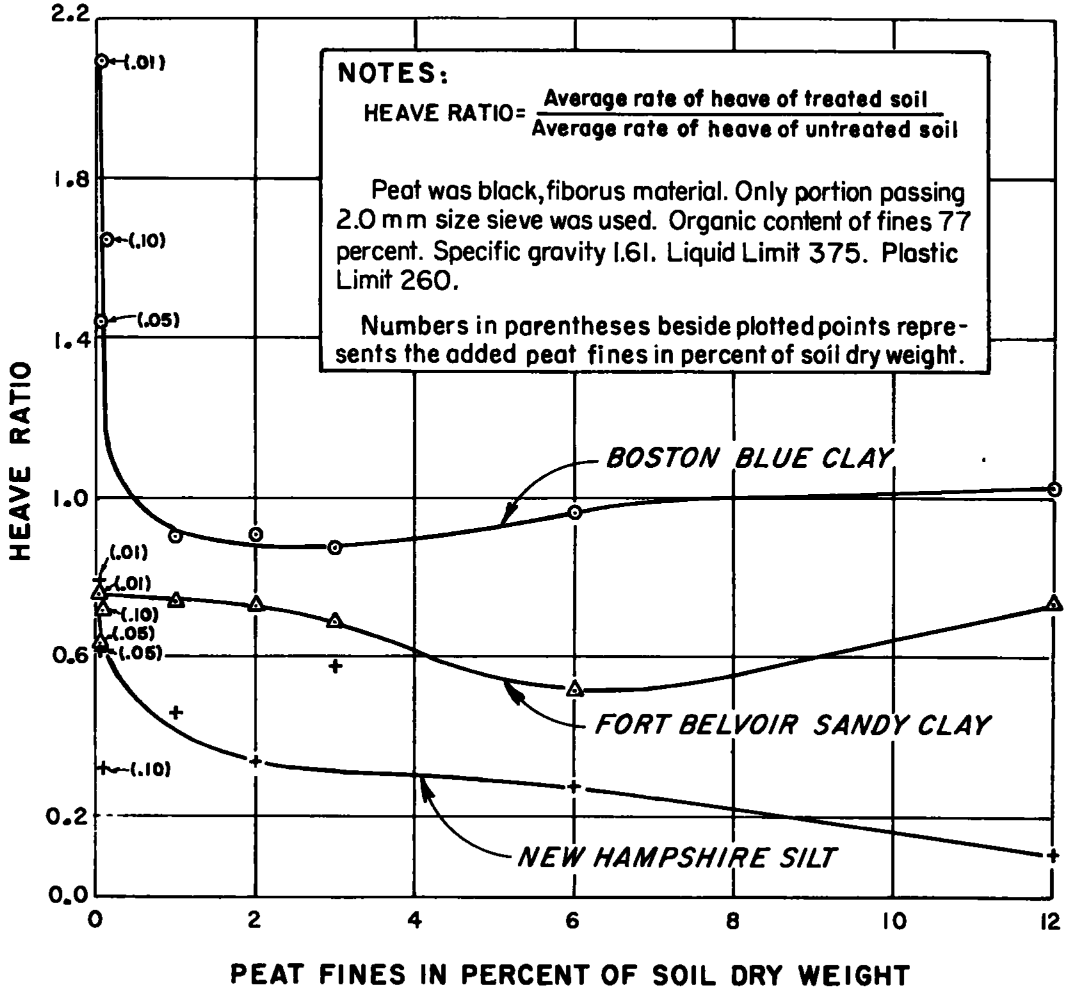

Figure 8. Effect of peat fines on frost heave.

water contents below certain values so that the clays could be considered non-frost-susceptible is an interesting one. So long as ice lenses can form by extracting water from the soil immediately below the plane of freezing, it is possible that a weakened condition can occur during the frost melting period. Therefore, there would be obvious advantage in being able to identify certain types of soils as not being subject to ice segregation below certain moisture levels, or in being able to modify the soils by chemical treatment so as to raise the minimum moisture content level at which ice segregation can occur and in turn to minimize ice segregation at water content levels above this minimum.

6. Organic Content. The organic content of a soil, particularly in the fines portion, may exert considerable influence on frost behavior. Freezing tests were made at ACFEL (6) with processed peat[3] added in various percentages to a sandy clay, a

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[3] The peat was obtained at a depth of 4 ft below the surface. It was black fibrous material with some sand and gravel mineral particles. The portion finer than 2 mm was used in freezing tests. The peat fines had a specific gravity of 1.61, liquid limit of 375 and plastic limit of 260. The organic content was found to be 77 percent, by the H_2SO_4 - K_2CrO_7 digestion method (adapted from Peech (38)).

silt, and a marine clay (see Fig. 4 for soil gradations). The test results plotted in Figure 8 show that the peat fines caused a reduction in rate of frost heave at all concentrations in the sandy clay and in the silt. In the clay, the peat caused an increase in the rate of heaving at very low concentrations (0.1 percent and less); tests at 1 through 6 percent resulted in decrease. The reduction in heaving is attributed to a reduction in the permeability of the soil.

The effect on frost action of the presence of colloidal organic materials in a soil is not known, although it is thought that such colloidal material in fine-grained soils may tend to increase its frost susceptibility and therefore, for this and other obvious reasons, subgrade soils of high organic content should be considered undesirable construction materials.

According to Grim (19) some clay minerals have rather high adsorption capacity for certain cations, anions, and organic molecules. Montmorillonite will adsorb certain organic molecules, particularly those that have high polarity (34) and such organic molecules are held on the water adsorbing surface. The presence of such organic molecules destroys the water adsorbing power of the montmorillonite so that water with a definite configuration does not develop on the clay mineral, thus increasing the frost potential of the material by decreasing the amount of immobilized water. The effect of adsorbed organic molecules is believed to be the same for kaolinite but to a considerably smaller extent.

7. Effect of Degree of Compaction. Since the effective pore or channel size appears to be one of the major factors governing frost action in soils, anything that alters this parameter will cause changes in frost behavior. Taber (53) observed that a denser soil packing reduced the amount of heaving in a remolded Cretaceous clay. Winn and Rutledge (58) observed a relation between density and frost heave on a natural sandy clay. They found that heaving increased with density up to a critical value, beyond which heaving decreased with further increase in density.

Subsequent studies made at ACFEL on many different soil types, ranging from clay to sandy gravels obtained from various parts of the North American continent, have shown the rate of heave to be quite responsive in most soils to changes in density or unit weight (5). The test results from these studies are summarized in Figure 9. The effect of variations in dry unit weight on rate of heave is seen to vary with the soil type.

While it seems obvious that the rate of heave in a given soil should be governed in some degree by the size and shape of the voids, as controlled by the grain size distribution and degree of densification, it is not necessarily obvious whether an increase in degree of compaction in a given soil should result in an increase, or in a decrease, in the rate of frost heave in absence of experimental test results such as shown in Figure 9 or that soils of similar gradation characteristics will show similar trends of rate of heave versus dry unit weight. A basic study of the frost action phenomenon in soils could probably interrelate quantitatively the effects of such variables as void ratio, void size, physico-chemical properties and permeability, so as to provide a fuller explanation of the observed trends.

Since frost penetration was kept advancing into the specimens during these tests, the rate of heave was not limited by rate of removal of heat, but by rate at which water was made available at the freezing plane. In turn, the rate at which water could be made available must have depended on (1) the pressure differential which could be generated within the soil water to draw moisture to the plane of freezing, (2) the effective permeability and the compressibility of the soil mass below the plane of freezing, and (3) the facility with which water could be made available to the ice through moisture films at the soil-ice plane (according to Beskow's concept). Since the surcharge pressure (0.5 psi) was not varied in these tests, the vertical pressure on the plane of freezing at the start of test was identical in all specimens. Pressures at end of test did vary somewhat because of different amounts of ice segregation and different unit dry weights of specimens.

In considering the performance of the silt samples, it is obvious that the effect of lower permeability at the higher unit weights is greatly outweighed in these materials by other influences acting to produce an opposite trend. One of the factors thus acting might be an increase in the force of moisture attraction to the growing ice lenses with

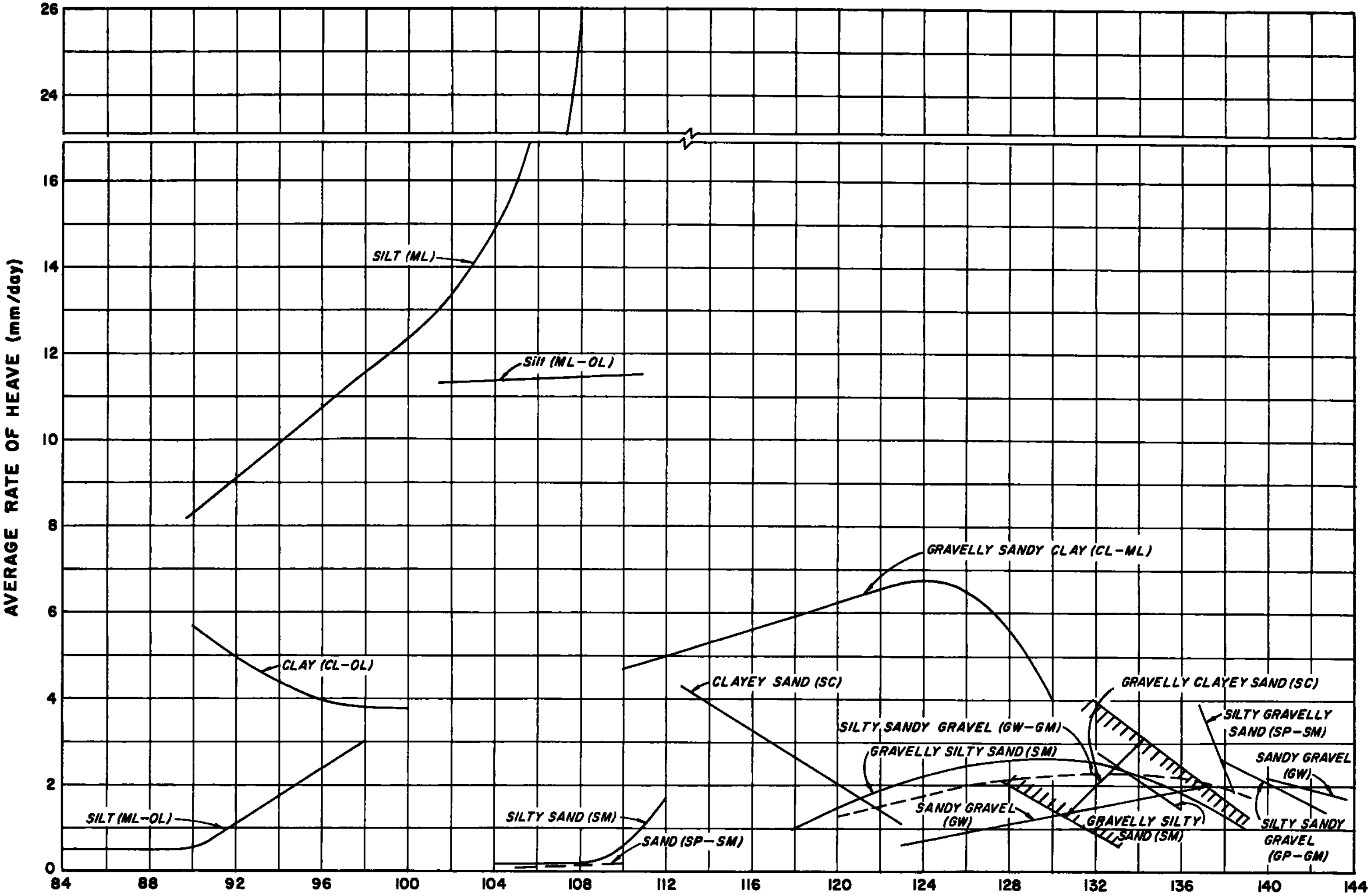

Figure 9. Effect of dry unit weight on average rate of heave.

increase in density. Such an increase might be the result of more effective supercooling in the soil immediately below the plane of freezing, which in turn might result, in part, from the reduced cross-sections of the moisture threads filling the voids. In addition, it is possible that closer packing of the soil grains provides better continuity of the adsorbed moisture films and more soil-ice contacts of individual grains per unit area at the freezing plane (and consequently less pressure from the surcharge load on the moisture film surrounding each individual grain), with the result that greater volume of moisture can flow to the freezing surface, in spite of the lowered permeability of the densified soil.

In the clay soils and the well-graded soils, which show a reduction of rate of heave with increasing density, it is presumed that permeability reduction with increase in dry unit weight outweighs the other factors, which probably already have achieved maximum or near-maximum effectiveness at the lowest degrees of densification of these materials.

More thought should be given to simple experiments to measure and evaluate the individual factors discussed above.

Due consideration must be given to the practical aspects of pavement design in the application of such findings as indicated by these tests. It is probable that frost-susceptible soils compacted to initially very high densities would lose at least a portion of this compaction in the first winter as a result of loosening by frost action. The most obvious present solution for guaranteeing the built-in stability of high density base course and subgrades in modern highways and pavements is to use only free-draining non-frost-susceptible materials within the freezing zone. The treatment of borderline frost-susceptible soils with trace quantities of inexpensive chemicals may, however, offer a long-range possibility for the achievement of both permanent high density and resistance to frost action.

8. Effect of Initial Water Content (Initial Degree of Saturation) in Closed System Freezing. When freezing occurs under conditions in which no source of free water is available for growth of ice lenses beyond that initially present in the voids of the soil, it is called "closed system" freezing. Since no water has been added into the soil cross-section, the over-all water content of the frozen strata thus is the same after freezing as before. A closed system is easily obtained in the laboratory by freezing the soil specimen without any access to an outside source of water. In the field a condition which is approximately equivalent to this results if the soil is so impervious that only a negligible supply of water can move to the freezing plane from underlying strata during the period of freezing. This would occur, for example, if the soil is a relatively impervious clay in which movement of soil moisture as a result of freezing is effective only to a depth of a few inches below the freezing plane under natural rates of freezing. A typical sequence in a fat clay under these conditions is as follows: (1) initiation of an ice lens at the plane of freezing; (2) growth of the ice lens by extraction of moisture from the soil immediately below the plane of freezing; (3) simultaneous consolidation and partial drying out of the latter soil, accompanying the withdrawal of moisture; and (4) initiation of a new ice lens deeper in the soil as a result of progressive advance of the freezing temperatures. The result, then, in a relatively impervious fine-grained soil may be a sequence of alternating ice lenses and partially desicated soil layers, the over-all moisture content of the whole being the same as the original material. In a more pervious frost-susceptible soil frozen without access to outside water at the base, most of the available free water may be drawn to the upper part of the soil column early in the freezing process and the lower levels may then freeze without ice segregation. Also, there may, in such soil, be little or no dessication of the soil between ice lenses in the upper part of the soil column frozen with free water still available.

Results of closed system laboratory freezing tests performed by ACFEL on 6-in. high by 6-in. diameter specimens of a silt, a glacial till, and 2 lean clays are shown in Table 1 and on Figure 10. The data include Atterberg limit and shrinkage limit values. It may be seen that the water content of the upper frozen portion of each test specimen was increased considerably above its original value and that in the cases of the till and silt, the water content thus reached bore a direct relationship to the initial

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Specimen No.	Name and Source of Soil	Corps of Engineers Unified Soil Classification		Grain Size Percentage Finer Than			
		Description	Letter Symbol	No. 4 Sieve	No. 40 Sieve	No. 200 Sieve	0.02 mm
NH-5	New Hampshire silt Goff's Falls, New Hampshire	Silt-C (remolded)	ML	100	99	96	58
NH-6							
NH-7							
NH-8							
NH-48		Silt-A (remolded)	ML	100	100	85	61
NH-49							
EBT-40	East Boston till-C Revere, Massachusetts	-¾-in. gravelly, sandy clay (remolded)	CL	82	65	46	32
EBT-41							
EBT-5	East Boston till-A Revere, Massachusetts	-¾-in. gravelly sandy clay (remolded)	CL	84	72	56	43
EBT-6							
EBT-7							
EBT-8							
SC-4	Searsport clay Searsport, Maine	Clay (undisturbed)	CL	100	100	99	80
SC-5							
SC-3							
SC-8		Clay (remolded)	CL	100	100	99	80
BC-19	Boston blue clay North Cambridge, Massachusetts	Clay (undisturbed)	CL	100	100	100	94
BC-18							
BC-22							
BC-21		Clay (remolded)	CL	100	100	100	94

[1] Lw = Liquid Limit, Iw = Plasticity Index, Sw = Shrinkage Limit (ASTM method), Pw = Plastic Limit

[2] Degree of saturation in percent.

[3] Measured from top of specimen in inches.

[4] Undisturbed shrinkage limit.

[5] Location not recorded.

degree of saturation. Fat clays may perform differently. Spontaneous freezing after supercooling resulted in quick freezing in at least the upper part of some of the closed system test specimens,[4] with probable lowered water gain there. As a result, water contents in the top inch of some of the specimens, as plotted in Figure 10, are somewhat lower than if spontaneous quick freezing has not occurred.

The water contents in the lowest portions of the specimens decreased to relatively low values which were relatively constant for a given soil and which in the case of the East Boston till and the New Hampshire silt were essentially independent of the initial degree of saturation. Of the four soils shown on Figure 10, the greatest decrease in moisture content was observed in the silt, in which the moisture content of the bottom inch of the specimens ranged from 2.2 to 6.1 percent, as compared with an average initial water content of the 6 silt specimens of 21.9 percent.

The differences in performance between the silt and clay samples are attributed to differences in such factors as amount and proportion of mobile moisture present in the soils, differences in mineral nature and physico-chemical properties, and differences in effective permeability.

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[4] This difficulty is now avoided in ACFEL tests by either seeding the tops of specimens with snow or granulated ice, or by quick surface cooling of the tops of the specimens sufficiently to initiate crystallization.

ABLE 1

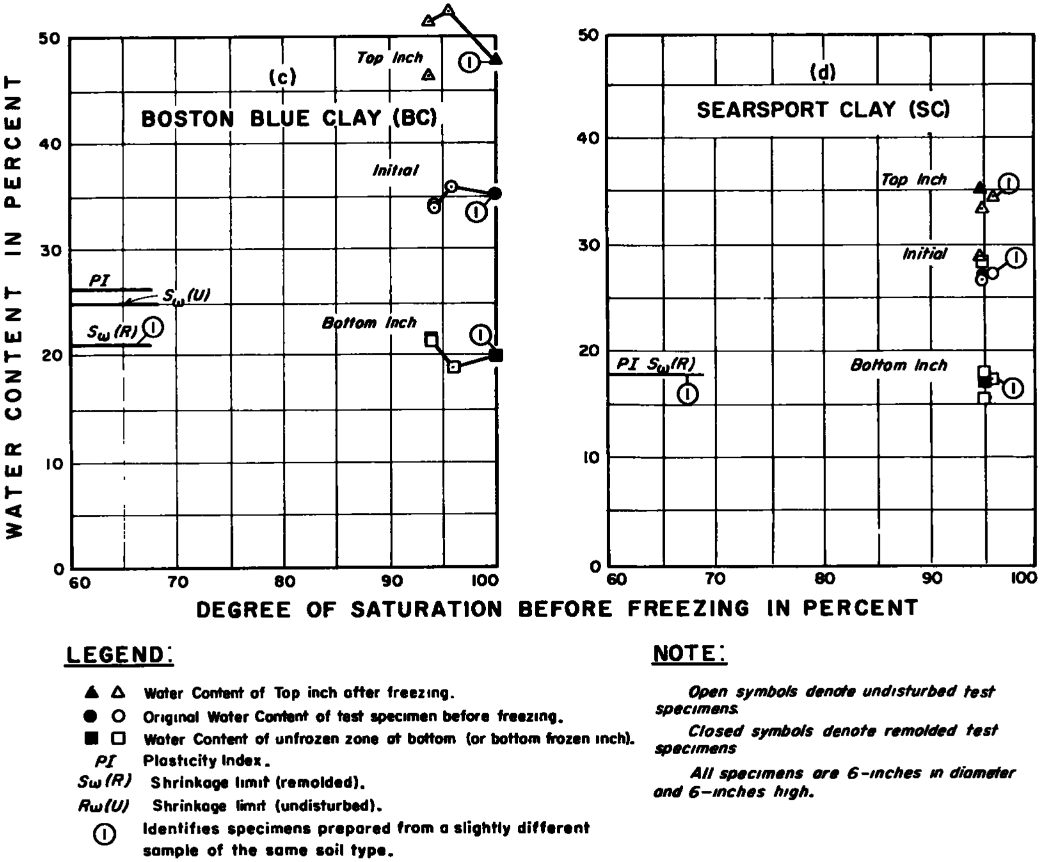
SYSTEM TESTS

	Atterburg Limits[1]				Dry Unit Weight	Water Content Determinations in Percent						Percent Heave
						Total Specimen Before Freezing		After Freezing				
								Frozen Zone			Unfrozen Zone or Bottom Frozen Inch	
								Top Inch	Soil Between Ice Lenses			
0. 005 mm	Lw	Pw	Iw	Sw	pcf	Water Content	G[2]		Percent	Location[3]		
10	27	27	0	-	99	17. 5	68	24. 9			6. 1	1. 3
					100	20. 0	79	27. 1			6. 1	4. 8
					100	22. 5	88	28. 0			4. 8	5. 5
					100	25. 0	100	36. 0			5. 5	9. 5
16	24	18	6	22	102	22. 8	91	38. 2	33. 7	0-1	2. 2	7. 8
					103	23. 4	96	43. 5	34. 3	0-¾	2. 7	9. 1
32	23	15	8	12	128	11. 9	96	20. 2	15. 9	0-1	7. 6	8. 6
									13. 2	1-2		
									12. 7	2-3		
					128	12. 2	98	20. 6	22. 1	0-1	10. 0	7. 3
									19. 6	1-2		
									15. 1	2-3		
									15. 4	3-4		
26	23	16	7	17	125	9. 5	70	10. 6			6. 8	0. 3
					126	10. 9	81	13. 7			7. 1	1. 8
					125	12. 2	90	13. 7			8. 3	2. 3
					127	12. 9	100	20. 9			7. 1	4. 7
12	36	18	18	-	95	28. 0	95	33. 8			18. 1	5. 8
					97	27. 0	95	28. 8			15. 8	7. 3
					97	27. 3	96	34. 6			17. 5	4. 5
12	36	18	18	18	97	27. 0	95	35. 6			17. 5	9. 7
81	53	27	26	25[4]	86	34. 3	94	51. 1			21. 8	11. 1
					86	34. 0	94	46. 5			21. 5	8. 9
					85	35. 8	96	52. 3	29. 1-33. 4	[5]	18. 9	10. 7
81	53	27	26	21	88	35. 2	100	48. 0	20. 1-21. 2	[5]	19. 9	11. 0

The water content of the soil between segregated ice lenses in the frozen zone was also determined in three of the four test materials as shown in Table 1. It may be noted that the most impervious specimen of the group tested for moisture contents between the ice lenses, the remolded Boston blue clay (BC-21), showed a reduction of moisture content to the shrinkage limit, whereas the coarsest material, the New Hampshire silt (NH-48 and NH-49) actually showed considerable increase over the initial moisture content. Other materials showed intermediate results. In the silt ice segregation evidently occurred even within the soil between the ice lenses and moisture was readily withdrawn from the underlying soil from some distance so long as it remained available within the sample. On the other hand, it was apparently very difficult in the remolded clay to replace extracted moisture by movement from below. The undisturbed Boston blue clay, (BC-22) seemingly was able to do this somewhat more readily, or else moisture extraction was cut off before achieving full effect by formation of an ice lens at a lower level, since the results show moisture content between ice lenses about 10 percent higher than in the remolded Boston blue clay. This may be due to the flocculent structure and lower compressibility of the natural clay (13).

Some of the scatter of the closed system test results reported above is probably caused by variations in initial dry densities. Variations in ice segregation would be expected with differences in density.

In general, these data indicate that a reduction of percent saturation to the order of 70 percent does not eliminate ice segregation and heave but does reduce it substantially,



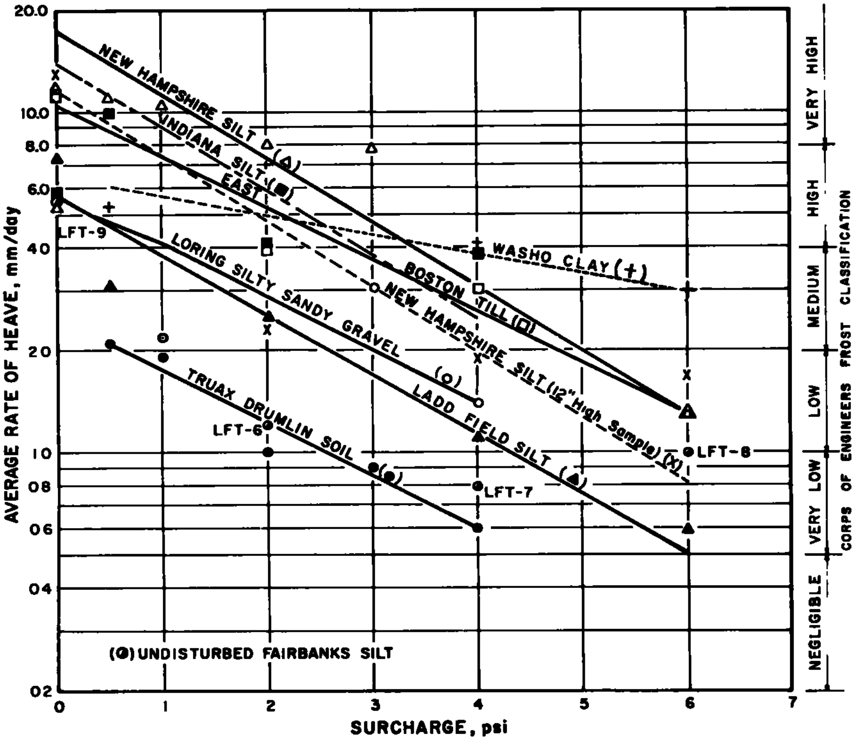
NOTE:

Open symbols denote undisturbed test specimens.

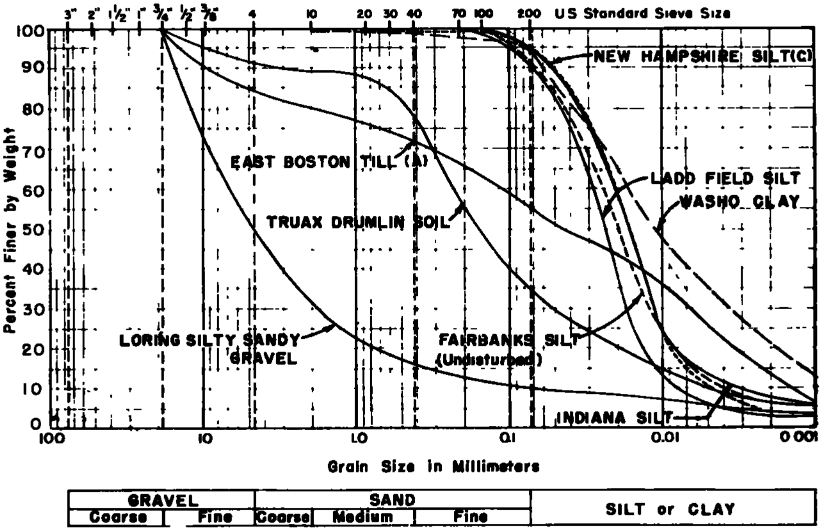
Closed symbols denote remolded test specimens.

All specimens are 6-inches in diameter and 6-inches high.

Figure 10. Summary of closed system freezing tests.



(a) AVERAGE RATE OF HEAVE vs SURCHARGE

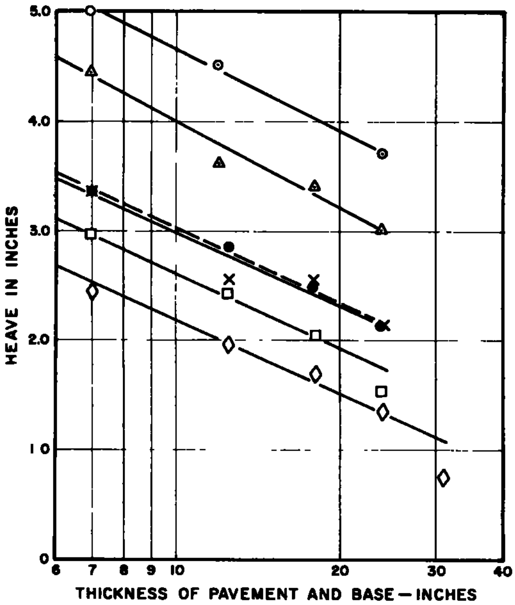


(b) GRADATION CURVES

Figure 11. Effect of pressure on rate of heave.

as well as reducing moisture gain in the top inch of the sample.

9. Capillarity. Beskow (9) has stated that "of the direct physical properties which migh possibly be used to determine the frost heave characteristics of a soil, capillarity has been found to be most useful. There are several reasons for this, principally that capillarity is an approximate measure of the grading of a soil, and is also important in the upward flow in the soil. Also, it is a very easy property to determine and requires only a very small sample." Beskow made determinations of capillarity on a large number of frost heaving and non-frost heaving soils using material passing the 2.0 mm sieve, and reported good correlation between capillarity and frost heaving characteristics for relatively uniformly graded sedimentary type soils and for unsorted variably graded soils in which the fine materials fill the pores of the coarser particles when compacted. For unsorted soils such as moraine deposits and base course mixtures in which the fines fail to fill the pores he concluded that it is useless to try to obtain definite values of capillarity. Beskow concluded that soils with a capillarity of less than 1 meter at standard loose degree of compaction are under no circumstances frost heaving; soils with capillarities immediately above this value may be dangerous for small loads with high ground water.



SYMBOL	YEAR	FREEZING INDEX	GROUND* WATER
⊙	1950 – 1951	1529	3 FT.
△	1951 – 1952	1927	5 FT
X	1952 – 1953	1647	13 FT.
◇	1953 – 1954	1737	16 FT
□	1954 – 1955	1854	16 FT
●	1955 – 1956	1987	16 FT.

* DEPTH FROM SUBGRADE SURFACE

Figure 12. Heave vs pavement and base thickness of frost test area at Loring Air Force Base, Limestone, Maine.

On the basis of Beskow's study it would appear that capillarity measured on natural gradations at appropriate degrees of compaction may offer a useful means for estimating the frost susceptibility of uniformly graded soils, but that the capillarity of a fine fraction (such as the minus 2.0 mm size material) of a coarse-grained soil containing appreciable gravel size particles does not necessarily provide a measure of the behavior of the whole gradation as used under a pavement, because the whole material may be markedly different in void and thermal characteristics. In addition, it should be noted that Beskow measured capillarity by determining the tension at which air was drawn through the soil specimens. This method measures the capillarity of the larger voids. However, the larger voids, particularly if they are a minor portion of the total voids, may not be the controlling element in determining the frost heaving characteristics of the soil.

10. Effect of Pressure on Plane of Freezing. It has been noted by various investigators, including Taber (51) and Beskow (9), that a load placed on a specimen during freezing reduces the rate of heaving. This is not surprising since the amount of energy made available in a specific time interval during freezing can only perform a certain amount of work. Some of the energy is used up in moving water from below to the freezing zone and some in lifting the weight of overlying material. If the load is increased then the amount of energy available for raising the load is expended on lifting it a somewhat shorter distance than if the load had not been present.

In addition, the fundamental ability of the system to support ice segregation may be reduced or eliminated through the effect of the load. As theorized by Gold (18), and also by Penner (39) in light of his experimental results, this may function through the

TABLE 2

FREEZING TESTS ON "DIRTY" GRAVELS

Lab No	Source	Untreated Gravels				Gravels Plus 0 3 Percent Tetrasodium Pyrophosphate			Heave[1] Ratio
		Molding Water (%)	Dry Unit Weight (pcf)	Finer Than 0 02 mm Size (%)	Average Rate of Heave (mm/day)	Molding Water (%)	Dry Unit Weight (pcf)	Average Rate of Heave (mm/day)	
	Greenland, TP-250	5 0	140 1	2 0	3.5	3.0	143 0	0 2	0 06
	Dow AFB, Bangor, Maine, B-11	5 0	131 4	2 4	1.0	5 0	131 4	0.4	0 40
	Dow AFB, Bangor, Maine, B-18	5 0	132 2	3 2	1.2	5.0	133 0	0.6	0.50
49-11	Ellsworth AFB, Weaver, South Dakota	6 0	137 0	8	1.3	5 0	137 0	0.0	0
49-8A	Clinton County AFB, Wilmington, Ohio	9 0	129.0	9	3.8	5 0	129 4	0.5	0.13
49-21	Spokane AFB, Spokane, Washington	6 0	128.0	4 0	0 9	5 0	128 2	0.4	0.44
49-102	Lincoln AFB, Lincoln, Nebraska	7 0	132.2	4 7	1 1	4 8	134 4	0 2	0.18
49-60	Fairchild AFB, Spokane, Washington	4 5	131.3	10	2 9	6 3	131 3	1.1	0.38
49-54	Portsmouth AFB, Portsmouth, New Hampshire	8 5	127 0	14	4 7	5 0	129 8	1 3	0.27
49-17	Sioux Falls Airfield, Sioux Falls, South Dakota	4.0	131.0	8.9	1 6	11 1	128 5	0.2	0.12
49-9	Patterson AFB, Fairfield, Ohio	5 0	134.9	15	2 5	4.7	137.3	0 2	0 09

[1] Heave Ratio = $\frac{\text{Average rate of heave of treated soil}}{\text{Average rate of heave of untreated soil}}$

effect of the load in reducing the freezing point differential between the pore water just below the plane of freezing and the ice-water interfaces immediately above the soil particles. According to this theory there should be a critical pressure value for a given pore size at which frost heaving will stop.

A number of freezing tests on various soils were made at ACFEL to observe the effect of loadings up to 6 psi (equivalent to approximately 6 ft of pavement and high-density base) on the rate of ice segregation. It was hoped that this relationship of reduced heave with increasing pressure could be taken into account in formulating engineering design criteria for construction on frost-susceptible soils. In Figure 11 are shown the observed relationships between the rate of heave and pressure for various soils. The gradations of the soils used in the tests are also shown.

All the test results show the tendency for decrease in rate of heave with increase in pressure surcharge. The two samples containing the highest percentages of clay sizes, namely the East Boston till and the WASHO clay, show a tendency toward smaller decrease in rate of heave with pressure than the other soils which have more or less parallel curves. This result appears to be in agreement with Beskow's observations; he found, similarly, that the finer-grained soils were less affected by pressure (9). According to Beskow's reasoning, in clay soils the film of water at the critical plane between the already-formed ice crystal and an underlying soil particle may be less readily cut off by pressure on the soil structure than it is in the coarser-grained soils such as silts. This may be not only because of relatively thicker films on the clay particles, but may also relate to the vastly greater number of key particle contact points and moisture-feeding pores at the freezing surface in the clay as compared with the silt. Gold's (18) hypothesis also indicates that the effect of load on frost heaving should be less with decreasing pore size. Another consideration is that if supercooling of soil pore water is greater in the clayey soils, then a greater amount of energy is available to do work.

In evaluating the laboratory surcharge pressure tests in terms of field conditions, it must be remembered that the laboratory test condition represents freezing of a surface which extends indefinitely in a horizontal plane and over which heave is at all points uniform, so that there is no shear or bending action in the frozen layer. Actually, however, if heave is restrained by a load locally, as where a freezing layer passes under a road embankment, the resulting shear and bending developed in the layer of frozen material at the edges of the embankment results in mobilizing lifting force over an area which extends well outside the immediate area over which the embankment loading is actually applied. Again, however, the latter condition is for one of assumed uniform frost penetration in the frost-susceptible layer, both under and beyond the roadway pavement. The comparison becomes somewhat complicated if one considers such facts as (1) that snow and organic cover will normally reduce (or even eliminate)

TA

CHARACTERISTICS PERTIN

Major Divisions		Symbol				Name	Value as Subgrade When Not Subject to Frost Action	Value as Subbase When Not Subject to Frost Action	Value a When N to Fros
(1)	(2)	Letter (3)		Hatching (4)	Color (5)	(6)	(7)	(8)	(
Coarse-Grained Soils	Gravel and Gravelly Soils	GW		⁖	Red	Well-graded gravels or gravel-sand mixtures, little or no fines	Excellent	Excellent	Good
		GP		⁖		Poorly graded gravels or gravel-sand mixtures, little or no fines	Good to excellent	Good	Fair to
		GM	d	▥	Yellow	Silty gravels, gravel-sand-silt mixtures	Good to excellent	Good	Fair to
			u				Good	Fair	Poor to able
		GC		▨		Clayey gravels, gravel-sand-clay mixtures	Good	Fair	Poor to able
	Sand and Sandy Soils	SW		⁖	Red	Well-graded sands or gravelly sands, little or no fines	Good	Fair to good	Poor
		SP		⁖		Poorly graded snads or gravelly sands, little or no fines	Fair to good	Fair	Poor to able
		SM	d	▥	Yellow	Silty sands, sand-silt mixtures	Fair to good	Fair to good	Poor
			u				Fair	Poor to fair	Not suita
		SC		▨		Clayey sands, sand-clay mixtures	Poor to fair	Poor	Not suita
Fine-Grained Soils	Silts and Clays LL is less Than 50	ML		▥	Green	Inorganic silts and very fine sands, rock flour, silty or clayey fine sands or clayey silts with slight plasticity	Poor to fair	Not suitable	Not suita
		CL		▨		Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays	Poor to fair	Not suitable	Not suita
		OL		▥		Organic silts and organic silt-clays of low plasticity	Poor	Not suitable	Not suita
	Silts and Clays LL is Greater Than 50	MH		▥	Blue	Inorganic silts, micaceous or diatomaceous fine sand or silty soils, elastic silts	Poor	Not suitable	Not suita
		CH		▨		Inorganic clays of high plasticity, fat clays	Poor to fair	Not suitable	Not suital
		OH		▨		Organic clays of medium to high plasticity, organic silts	Poor to very poor	Not suitable	Not suital
Highly Organic Soils		Pt		≋	Orange	Peat and other highly organic soils	Not suitable	Not suitable	Not suital

Note:

1. Col. 3, division of GM and SM groups into subdivisions of d and u are for roads and airfields only Subdivision is on basis of Atterberg limits; suffix (e.g., GMd) will be used when the liquid limit is 25 or less and the plasticity index is 5 or less; the suffix u will be used otherwise

2. In Col. 13, the equipment listed will usually produce the required densities with a reasonable number of passes when moisture conditions and thickne lift are properly controlled. In some instances, several types of equipment are listed because variable soil characteristics within a given soil group ma quire different equipment In some instances, a combination of two types may be necessary

   a. Processed base materials and other angular materials. Steel-wheeled and rubber-tired rollers are recommended for hard angular materials with limited fines or screenings Rubber-tired equipment is recommended for softer materials subject to degradation

   b. Finishing. Rubber-tired equipment is recommended for rolling during final shaping operations for most soils and processed materials.

   c. Equipment size. The following sizes of equipment are necessary to assure the high densities required for airfield construction:

      Crawler type tractor—total weight in excess of 30,000 lb.

      Rubber-tired equipment—wheel load in excess of 15,00 lb, wheel loads as high as 40,000 lb may be necessary to obtain the required densities for materials (based on contact pressure of approximately 65 to 150 psi).

      Sheepsfoot roller—unit pressure (on 6- to 12-sq in. foot) to be in excess of 250 psi and unit pressures as high as 650 psi may be necessary to obt the required densities for some materials. The area of the feet should be at least 5 percent of the total peripheral area of the using the diameter measured to the faces of the feet.

3. Col. 14, unit dry weights are for compacted soil at optimum moisture content for modified AASHO compaction effort.

the extent of frost penetration beyond the edges of a pavement, thus tending to balance the reduction in heave under the pavement due to pressure against a reduction in heave at the edges because of less severe freezing; and (2) that under a no-snow cover condition the pavement and non-frost-susceptible base course over the frost-susceptible layer may delay and reduce frost heave as compared to adjacent areas.

It is believed that the relationship between frost heave and pressure which has been shown in these tests can be taken advantage of in actual cases if a reasonable assumption of the effect or equivalent area over which heave forces act under a highway can be made. In order to obtain field data on this point and to confirm the validity of the laboratory tests, field tests of effect of pressure are needed. The method of test should be carefully considered in order that the effect of pressure will not be obscured by var-

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T TO ROADS AND AIRFIELDS

ase ubject ction	Potential Frost Action (10)	Compressibility and Expansion (11)	Drainage Characteristics (12)	Compaction Equipment (13)	Unit Dry Weight lb per cu ft (14)	Typical Design Values	
						CBR (15)	Subgrade Modulus k lb per cu in. (16)
	None to very slight	Almost none	Excellent	Crawler-type tractor rubber-tired roller, steel-wheeled roller	125-140	40-80	200-300
d	None to very slight	Almost none	Excellent	Crawler-type tractor, rubber-tired roller, steel-wheeled roller	110-140	30-60	200-300
d	Slight to medium	Very slight	Fair to poor	Rubber-tired roller, sheepsfoot roller, close control of moisture	125-145	40-60	200-300
suit-	Slight to medium	Slight	Poor to practically impervious	Rubber-tired roller, sheepsfoot roller	115-135	20-30	100-200
suit-	Slight to medium	Slight	Poor to practically impervious	Rubber-tired roller, sheepsfoot roller	130-145	20-40	100-300
	None to very slight	Almost none	Excellent	Crawler-type tractor, rubber-tired roller	110-130	20-40	200-300
suit-	None to very slight	Almost none	Excellent	Crawler-type tractor, rubber-tired roller	105-135	10-40	200-300
	Slight to high	Very slight	Fair to poor	Rubber-tired roller, sheepsfoot roller, close control of moisture	120-135	15-40	200-300
	Slight to high	Slight to medium	Poor to practically impervious	Rubber-tired roller, sheepsfoot roller	100-130	10-20	100-200
	Slight to high	Slight to medium	Poor to practically impervious	Rubber-tired roller, sheepsfoot roller	100-135	5-20	100-300
	Medium to very high	Slight to medium	Fair to poor	Rubber-tired roller, sheepsfoot roller, close control of moisture	90-130	15 or less	100-200
	Medium to high	Medium	Practically impervious	Rubber-tired roller, sheepsfoot roller	90-130	15 or less	50-200
	Medium to high	Medium to high	Poor	Rubber-tired roller, sheepsfoot roller	90-105	5 or less	50-100
	Medium to very high	High	Fair to poor	Sheepsfoot roller, rubber-tired roller	80-105	10 or less	50-100
	Medium	High	Practically impervious	Sheepsfoot roller, rubber-tired roller	90-115	15 or less	50-200
	Medium	High	Practically impervious	Sheepsfoot roller, rubber-tired roller	80-110	5 or less	25-100
	Slight	Very high	Fair to poor	Compaction not practical	-	-	-

iations in freezing conditions or other factors. For example, use of gravel layers of different thicknesses to apply different pressure intensities will result in differences in frost penetration in the frost-susceptible layer.

Figure 12 shows the results of field observations over a period of 4 yr at a small test area constructed at Loring Air Force Base, Limestone, Maine. The test section was constructed primarily to obtain information relative to the magnitude and duration of reduction in pavement supporting capacity resulting from frost action as measured by plate bearing tests (final report now in preparation by ACFEL). However, other data on soil frost behavior obtained at this site during the study have also proved to be quite interesting. The test section consisted of 4 adjacent test segments, 14 by 18 ft, paved with 1-in. thick asphaltic concrete, with base course thicknesses of 7, 12, 18, and 24 in., respectively, over a natural glacial till subgrade. In Figure 12 it is apparent that heave was reduced as base course thickness increased. However, the quantitative effect of pressure alone in reducing pavement heave is obscured by differences in depth of frost penetration into the subgrade which occurred because of the varying base course thicknesses.

Figure 12 also provides interesting information on the effects of freezing index and depth of water table on magnitude of heaving. It will be seen that the maximum heave occurred in the first winter after construction, with a high water table, even though that winter had the lowest freezing index.

Lowering the water table should reduce heaving since more of the available energy for a given set of conditions is required to lift water through the intervening soil to the plane of freezing and less will be available to do work in raising the frozen soil above. Penner (39) theorizes that increased tension in the pore can act in the same manner as pressure on the soil structure to decrease the freezing point of the ice-water interfaces above the soil particles and, at the same time, increase the freezing temperature of the pore water below the plane of freezing to establish temperature equilibrium between the two so that there is no further tendency for an ice lens to grow. The data in Figure 12 indicate a combination of low water table and heave pressure on the freezing plane may be very effective in reducing heaving from frost action.

11. Thermal Properties. The thermal properties of soils are controlled by such factors as water content, dry unit weight, shape and mineral nature of particles, grain size distribution, stratification and whether or not the soil is frozen. The most comprehensive measurements of actual thermal properties of a variety of soils in the frozen state are those which were performed by Kersten under sponsorship of the U.S. Army Corps of Engineers (27). This work was reported in detail in the HRB Proceedings (26). Shannon and Wells have also reported valuable data on the thermal properties of frozen soils (43). Aldrich (1) has pointed out that "our ability to predict the actual depth of frost penetration below a given pavement depends primarily on the reliability of thermal properties and surface temperature used in the computation." Johnson and Lovell have summarized in some detail needed further research on thermal properties of soils (25). Their recommendations for further studies include the following:

1. Study of the proportions of water frozen in soils at different temperatures below 32 F.
2. Extension of thermal property measurements to conditions of low density and high degree of saturation.
3. Study of effect of ice stratification in soils on thermal properties.
4. Study of the problem of moisture migration in laboratory thermal determinations.
5. Continued development of in situ thermal instruments to permit field measurements of thermal values.
6. As a corollary investigation, study of the forces operating in depressing the freezing point of soil moisture.

E. Relation of Soil Classification Groups to Frost Action

For pavement design purposes, frost action can be evaluated on the basis of either (1) frost heave, or (2) weakening during the frost-melting period. A soil with high heave will not necessarily show maximum thaw weakening. A relatively pervious frost-susceptible soil may develop substantial ice segregation because of the ease with which water may be drawn to the plane of freezing, but because of its relatively good drainage properties may allow thaw water to escape nearly as rapidly as it is released by melting and thus show relatively little weakening during thaw. A clay soil on the other hand may develop less ice segregation and heave but because of its poorer drainage characteristics may exhibit greater and more prolonged weakening under traffic during the thaw-melting period.

In the Unified Soil Classification System (56) a general evaluation of potential frost action is included as shown in Col. 9 of Table 3. The evaluation of potential frost action shown therein is a very general one. It may be assumed to be a measure primarily of potential frost heave, not a measure of weakening during the thawing period.

Using the Unified Soil Classification System as a basis, the Arctic Construction and Frost Effects Laboratory has proposed an adaptation specifically for use with frozen soils. The essence of this system is outline in Table 4. Basically, the frozen ground classification system (1) identifies the soil phase, (2) describes the soil characteristics resulting from the frozen state of the soil, and (3) describes the ice condition in the soil. This system is intended to be used in the same manner as the Unified Soil Classification System for classification and description of foundation materials as they may be recovered from borings, without involving geologic origin or history.

For specific frost design, the Corps of Engineers uses the following design classification system, which is keyed to special frost design charts for flexible and rigid pavements:

Group	Description
F1	Gravelly soils containing between 3 and 20 percent finer than 0.02 mm by weight.
F2	Sands containing between 3 and 15 percent finer than 0.02 mm by weight.
F3	(a) Gravelly soils containing more than 20 percent finer than 0.02 mm by weight, (b) sands, except very fine silty sands, containing more than 15 percent finer than 0.02 mm by weight, (c) clays with plasticity indexes of more than 12, and (d) varved clays existing with uniform subgrade conditions.
F4	(a) All silts including sandy silts, (b) very fine silty sands containing more than 15 percent finer than 0.02 mm by weight, (c) clays with plasticity indexes of less than 12, (d) varved clays existing with non-uniform subgrade conditions.

The above classification groupings are also based largely on frost heave potential of the soils, although thaw weakening characteristics have also been taken into account in a general way in assignment of the specific soils into their respective groups. In order to improve the frost classification groupings to take their weakening more adequately into account, some work has been done by Taucher (54) to obtain quantitative data on thaw weakening of soils, using a miniature vane borer to measure the shear strength during thaw, immediately above the point of thawing. However, these tests have been only of an exploratory nature to date and much more work is needed to provide a quantitative basis for a classification grouping based on thaw weakening characteristics. The ultimate classification system, or systems, must take into account not only heave and simple strength characteristics during thaw, but also the consolidation and/or remolding effects of traffic loading on the strength properties of the soil under pavements.

Various local or regional correlations of frost action characteristics of soils with the Bureau of Public Roads classification system have been published, as by Morton (35), Livingston (33) and Rogers and Nikola (42). These correlations have apparently been based on the heave rather than the thaw weakening characteristics of the soils, except in the case of Rogers and Nikola who used weighted plungers, the penetrations of which were measured under cycles of freeze and thaw during the winter period. These correlations with the Bureau of Public Roads classification system have generally shown that clean soils in the A-1 and A-3 soil groups experience little or no heaving or loss of strength, but that throughout the other major groupings frost-susceptible materials are encountered.

In the CAA system of classification of soils for airport construction, an allowance is made in design for frost penetration into the subgrade, depending on the type of subgrade material, but no separate frost classification grouping of soils is established.

Various state highway departments in the United States also make allowances for frost action based on local experience with the types of materials encountered in their

TAB

FROZEN SOILS

A PRELIMINARY NON-GENETIC CLASSIFICATIO

PART I DESCRIPTION OF SOIL PHASE (Independent of frozen state)	Classify Soil Phase by the D			
	Condition of Material (2)	Major Groupings (3)	Key Descriptive Terms Relating to Ice Phase (4)	
PART II DESCRIPTION OF FROZEN SOIL	Frozen or Unfrozen	Homogeneously Frozen Soils: Soils in which water is frozen within the material voids without macroscopic segregation of ice. N	No Ice Segregation	Well-Bonded W
				Poorly Bonded to Friable P
		Heterogeneously Frozen Soils: Soils in which part of the water is frozen in the form of macroscopic ice occupying space in excess of the original voids in the soil. I	Stratified Ice Lenses or Layers S	
			Irregularly Oriented Lenses, Veins, and Masses I	
			Coatings on Particles C	
			Crystals X	
PART III DESCRIPTION OF ICE STRATA IN SOIL	–	Ice or Ground Ice: Soil phase is negligible or absent	Designate material as ICE (1) and use descriptive terms as follows, usually one item from each group as applicable:	

Hardness	Structure	Color	Admixtures
hard soft (of mass, not individual crystals)	clear cloudy porous candled granular stratified	colorless gray blue (examples)	contains few thin silt inclusions (examples)

Definitions:

Coatings on particles are discernible layers of ice found on or below the larger soil particles in a frozen soil mass. They are sometimes associated with hoarfrost crystals, which have grown into voids produced by the freezing action.

Clear Ice is ice which appears to be internally transparent and contains only a moderate number of air bubbles. (2)

Cloudy Ice is ice which appears internally relatively opaque due to entrained air bubbles or other reasons, but which is essentially sound and non-pervious. (2)

Porous Ice is ice which contains numerous voids, usually interconnected and usually resulting from melting at air bubbles or along crystal interfaces from presence of salt or other materials in the water, or from the freezing of saturated snow. Though porous, the mass retains its structural unity.

Candled Ice is ice which has rotted or otherwise formed into long columnar crystals, very loosely bonded together.

Granular Ice is ice which is composed of coarse, more or less equidimensional ice crystals, weakly bonded together.

Well-bonded signifies that the soil particles are strongly held together by the ice phase and that the frozen soil possesses relatively high resistance to chipping or breaking.

Poorly-bonded signifies that the soil particl the ice phase and that the frozen soil conseq ping or breaking.

Friable denotes extremely weak bond betwee easily fractured or crushed.

Ice Lenses are lenticular ice formations in to each other, generally normal to the direc repeated layers.

Ice Segregation is the growth of ice as distir masses in soils, commonly but not always o loss.

Crystal as designated by letter symbol X in dividual ice particle visible in the face of a ent alone or in combination with other ice ph

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(1) Where special forms of ice can be disting explicit identification can be given.

(2) Observer should be careful to avoid bein frost coating on the ice.

4

VESTIGATION

ND DESCRIPTION SYSTEM FOR FROZEN SOILS

rtment of the Army Unified Soil Classification System

Letter (5)	Field Identification (6)	Pertinent Properties of Frozen Materials Which May be Measured by Physical Tests to Supplement Field Identification (7)	Guide Criteria for Airfield Pavement and Highway Construction on Soils Subject to Freezing and Thawing. (From Chapter 4, Part XII, E.M.) (8)
NW	Identify by visual examination State degree of ice saturation	In-Place Temperature Density and Void Ratio a. In frozen state b. After thawing in place Water Content (total H_2O, including ice) a Average b. Distribution Strength a. Compressive b. Tensile c. Shear d. Adfreezing Elastic Properties Plastic Properties Thermal Properties Ice Crystal Structure (using optical instruments) a. Orientation of axes b. Crystal size c. Crystal shape d. Pattern of arrangement	Generally all gravelly and sandy soils which contain less than 3 percent of grains by weight finer than 0.02 mm in diameter are not susceptible to significant ice segregation within the soil mass during freezing. They, therefore, usually occur as Homogeneously Frozen Soils. In permafrost areas ice wedges or other ice bodies may be found within such soils, but it is considered their mode of origin may be different. Finer-grained-soils may also be homogeneously frozen if insufficient moisture is available to permit ice segregation.
NP	Identify by visual examination State degree of ice saturation		
IS	Identify by visual examination For ice formation, record following as applicable: Location Orientation Thickness Length Spacing Hardness Structure Color } per Part III, below		Generally all silt and clay soils and gravelly and sandy soils which contain more than 3 percent of grains finer than 0.02 mm in diameter, by weight are susceptible to occurrence of ice segregation within the soil mass and, therefore, occur as Heterogeneously Frozen Soils if frozen at normal rates with water readily available.
II			
IC	Identify by visual examination For ice formations, record following as applicable: Location Type and size of particles Thickness		
IX	Identify by visual examination For ice formations, record following as applicable: Location Size Shape Pattern of arrangement		
ICE	Identify by visual examination	Same as Part II above, as far as applicable, with special emphasis on Ice Crystal Structure.	

are not strongly held together by
ently has poor resistance to chip-

soil particles. Material is

il occuring essentially parallel
on of heat loss and commonly in

t lenses, layers, veins, and
ented normal to direction of heat

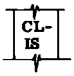
art II above, is a very small in-
il mass. Crystals may be pres-
se forms.

ished, such as hoarfrost, more

misled by surface scratches or

Notes:

The letter symbols shown are to be affixed to the Unified Soil Classification letter designations, or may be used in conjunction with graphic symbols, in exploration logs or geological profiles. Example—a lean clay with essentially horizontal ice lenses:



or

The descriptive name of the frozen soil type and a complete description of the frozen materials are the fundamental elements of this classification scheme. Additional descriptive data should be added where necessary. The letter symbols are entirely secondary and are intended only for convenience in preparing graphical presentations. Since it is frequently impractical to describe ice formation in frozen soils by means of words alone, sketches and photographs should be used where appropriate, to supplement descriptions.

particular areas, but again do not attempt to assign separate frost classification groupings.

The only laboratory frost evaluation system for frost-susceptible soils established to date appears to be that of the Arctic Construction and Frost Effects Laboratory, which is based upon the measurement of the rate of heave in a standard laboratory freezing test. These tests are further described in Part IV of this paper. Based upon a large number of freezing tests on frost-susceptible soils from many locations in North America, Iceland and Greenland, the following tentative scale of average rate of heave has been adopted for rates of freezing in the laboratory tests between $\frac{1}{4}$ and $\frac{3}{4}$ in. per day:

Average Rate of Heave mm/day	Frost Susceptibility Classification
0.0 - 0.5	Negligible
0.5 - 1.0	Very low
1.0 - 2.0	Low
2.0 - 4.0	Medium
4.0 - 8.0	High
Greater than 8.0	Very high

The above measure of susceptibility to frost heave was originally suggested by Casagrande in his capacity as a consultant to the Arctic Construction and Frost Effects Laboratory. In laboratory tests consisting of only one freezing cycle, this measure may not always give the true potential of frost susceptibility of some soils, particularly the clays. In virgin clays, for example, the rate of heaving initially may be low but as the clay becomes fissured and weathered, the rate of heaving may become much greater. This frost classification has proven very useful to the Corps of Engineers and has been used by the Arctic Construction and Frost Effects Laboratory to obtain frost susceptibility evaluations of soils of borderline or questionable frost characteristics submitted to the laboratory from Corps of Engineers construction projects throughout the seasonal frost and permafrost regions. However, the Corp of Engineers recognizes that the test as presently developed measures mainly the relative frost heave potential of the soils and does not indicate quantitatively the thaw weakening characteristics or evaluate the possible remolding susceptibility of the soil. There clearly is substantial need for further research to develop an improved frost classification grouping system for soils.

F. Effects of Mechanical Manipulation in Relation to Soil Type.

1. Effect of Remolding on Ice Segregation. As is well known to soils engineers, the remolding of fine-grained undistrubed soils may produce marked changes in their properties, including their compressibility and permeability. Experiments made at ACFEL indicate that manipulation and remolding of fine-grained soils may also alter (reduce) frost susceptibility. However, in coarse-grained soils frost susceptibility may be increased in construction handling and working because of degradation and manufacture of additional fines.

A series of freezing tests was made at ACFEL on 4 clays and a silt soil to observe the effect of remolding on ice segregation. Tests were made in both the closed and open system for comparison. The test results obtained are summarized in the table on the following page.

With the exception of Portsmouth stratified clay, the test results indicate that when these soils are remolded, the precentage heave is generally greatly reduced in an open system and slightly increased in a closed system as compared to the corresponding percentage heaves for undisturbed specimens. This frost behavior change is attributed to the structure alteration produced by the rearrangement of the soil particles during remolding. Fine alluvial material in nature is likely to have a loose and random flocculated structure. Even though consolidated under overburden pressure, the original porous structure remains, exhibiting considerable strength. Upon remolding, the particles are oriented into new positions. The permeability is decreased. For example, others have observed that the permeability of a remolded Boston blue clay

		Undisturbed		Remolded	
Material	System	Original Height of Portion Frozen (in.)	Heave (%)	Original Height of Portion Frozen (in.)	Heave (%)
Boston blue clay	Open	4.00	111.8	3.94	58.9
	Closed	5.12	10.7	5.43	11.0
Searsport clay	Open	3.25	240.3	4.28	47.2
	Closed	6.00	7.3	6.00	9.7
	Open	3.75	155.2	5.36	38.6
	Closed	6.00	4.8	6.00	6.8
Fargo clay	Open	-	-	5.80-5.75	18.4-24.0
	Closed	6.00-5.50	2.0-2.2	5.60-6.00	8.6-9.7
Fairbanks silt	Open	4.42	124.0	4.80	81.8
	Open	-	-	5.30	102.1
Portsmouth stratified clay	Open	2.99	95.3	3.07	114.9
	Closed	5.00	6.8	5.00	5.0

may be 1/200th of that in the undisturbed state (28). A decrease in permeability would affect the rate at which water could be supplied to a growing ice lens. The large decrease in heave observed in open system tests after remolding is attributed to this decrease in permeability.

In the closed system, water is made available for ice segregation only from within the soil specimen, and, if all portions of the specimen were to remain saturated, the total increase in sample volume would not exceed the volume increase of the portion of the water in the sample which actually freezes. In reality, the increase tends to be larger in frost-susceptible soil because of the tendency for free water to be removed from soil voids and be concentrated in the ice lenses, leaving some voids partially filled. Water is supplied for ice lens growth from the material directly below the plane of freezing, resulting in a tendency to consolidate this material under the resultant pore water tension. If ice forms within the soil voids as well as in ice lenses as the freezing plane advances, the voids may then tend to be distended again as crystallization occurs. As the plane of freezing advances the material next below goes through the same cycle and the process continues until no more mobile water is anywhere available. In the open system the process is the same except that water is drawn up from the source at the bottom of the specimens as well as from the soil voids.

Since the soil in the remolded state is also more compressible than the same soil in the natural state (13), it is visualized that during the freezing process a slightly greater volume of pore water is made available for ice lens growth in the remolded cohesive soil than in the undistrubed. The slightly greater closed system heave may, in part, be attributed to the expansion of this additional amount of water in freezing. However, other effects of the changed structure brought about by remolding may also be involved.

Although the Fairbanks silt material exhibited the same trend as the clays, this frost behavior change cannot be entirely attributed to a structure alteration similar to that effected by remolding clay soils. Vertical seepage fissures and paths developed by past freezing and the presence of old root holes undoubtedly resulted in a more ready source of moisture for ice segregation in the undisturbed Fairbanks silt sample.

In the one exception in this series of freezing tests and the percentage heave of remolded Portsmouth stratified clay increased in an open system and slightly decreased in the closed system type of tests as compared to the natural material. This reversal in frost behavior is attributed to the stratification in the natural material. Remolding probably in this case increased the over-all vertical permeability, and by producing a relatively well-graded mixture possibly also slightly increased the capacity of the thickness equivalent of the sand and silt layers to retain moisture against the suction created by the growing ice lenses. This reasoning points up the fact that differences in frost action of varved clays is strongly dependent upon the permeability of the finest layers, when water is available only by flow in the vertical direction.

From the standpoint of decreasing the effects of frost action, however, the possible advantage of remolding lean clays and silt has not been proved, since rearrangement and fissuring of the structure of these silts might result after a few freezing cycles which might restore the availability of water for ice segregation.

2. Mechanical Breakdown. The construction of a first-class modern pavement for use under extremely heavy wheel loads, particularly airfields, requires rigid adherence to specifications calling for a frost-free granular base course of sufficient thickness. Obtaining an approved and apparently satisfactorily graded material from a borrow pit does not necessarily guarantee its conformity, after compaction, to the specifications with respect to its grain size distribution. Gravel deposits may contain decomposed, soft and friable particles which fracture very readily or may even completely disintegrate during loading, trucking, dumping, grading and rolling operations. In this way, the fines content of an apparently suitable base course material may be increased sufficiently to make it a potentially frost-susceptible soil. Disintegration of weak particles of the sand and gravel from these causes was recently adjudged a contributing factor in the extensive cracking of pavement slabs in a new heavy duty parking apron in a northern airfield as a result of frost action in the base course. Petrographic analysis of the coarser particles (3/8 to 1 in.) showed the mineral composition of this material to be as follows: 39 percent quartzite, 14 percent schist, 13 percent shale, 11 percent limestone, 7 percent sandstone, 10 percent miscellaneous and 6 percent decomposed rock. A special test embankment of the same base course material was later constructed to study the effect of rolling technique on the manufacture of additional fines. The embankment was compacted in 4 lifts, each 12 in. in loose thickness. Each lift was compacted in compliance with the existing specifications to a dry unit weight ranging between 95 and 100 percent of the Providence Vibrated Density Test method (30). An average of 12 gradation tests on the material in the embankment following compaction showed increases of minus 0.02 mm material amounting to 1.6 percent in the upper half of the lifts and 0.7 percent in the lower half of the lifts. Somewhat greater increases were observed in the minus No. 200 mesh portions, 2.4 percent and 1.4 percent, respectively. While these percentages may appear small, the gravel was a very well-graded material with an extremely low percentage of void space, and the effect of small changes in percent of fines was marked.

These observations indicate that careful advance scrutiny must be given to possibly questionable materials. An effective laboratory test procedure for estimating the degradation that will probably occur during field placing and compaction of a granular material is needed.

IV. LABORATORY FACILITIES AND PROCEDURES FOR STUDY AND EVALUATION OF FROST ACTION IN SOILS

The Division of Building Research, National Research Council of Canada at Ottawa, the U. S. Army Snow, Ice and Permafrost Research Establishment (SIPRE) at Wilmette, Illinois, and the U. S. Army Arctic Construction and Frost Effects Laboratory at Waltham, Massachusetts, are all intensively developing and improving laboratory facilities, techniques and procedures for study of frost action in soils. The Division of Building Research has developed for purposes of basic research on the phenomenon of frost action in soils a frost cell wherein the upper and lower portions of a small soil specimen can be subjected to precisely controlled temperatures by means of circulating liquids around the soil specimen (39). SIPRE (57) has developed single-specimen, thermally insulated, portable freeze cabinets which are placed inside a low temperature cold room for freezing of soil specimens. ACFEL has developed equipment for the dual aims of (1) direct support testing for military construction and (2) investigations to develop design criteria for frost action in soils. In the current ACFEL procedure the soil freezing equipment is operated in a cold room held at about 35 F, which provides a fixed temperature at one end of the specimen. Freezing is obtained by decremental lowering of the air temperature at the other end of the specimen. A procedure was also used for about 2 yr in which the air temperatures at the ends of the sample were controlled by separate individual cooling units without use of a cold room; however, this proved more troublesome than the cold room technique.

The various types of equipment used by the organizations referred to above are all capable of research type use within the physical limitations of their respective designs. However, it is believed that only the ACFEL equipment has been used also for a major program in direct support of engineering design and construction.

The laboratory technique used by ACFEL since 1950 as a standard test procedure for evaluating frost susceptibility of soils for the Corps of Engineers is based on the techniques used earlier by Taber, Beskow, Casagrande, Winn and Rutledge and others. It consists of freezing a cylindrical specimen of soil approximately 6 in. in diameter and 6 in. high in a slightly tapered (wider at top) lucite container. De-aired water is supplied at the bottom while the specimen is frozen from the top down at a rate of approximately ¼ in. per day.[5] During freezing specimens are insulated on the sides to insure uni-directional freezing. A minimum surcharge pressure of 0.5 psi is applied to each specimen to simulate the pressure of a minimum thickness of 6 in. of pavement and base. The surcharge weight is separated from the specimen by an air space. Its load is transmitted by 3 lugs to a thin metal plate which rests directly on the top of the specimen and helps prevent sublimation of moisture during the test. The specimens are usually tested in groups of 4 in specially-designed freezing cabinets. Details of the most recent cabinet design are shown in Figure 13. Details of test procedures and sample preparation can be found in a report by ACFEL (5) and in a paper by Haley and Kaplar (20).

The freezing tests briefly described above have been designed to subject the soil to a very severe combination of the conditions conducive to frost action. The soils are generally compacted to densities in the range of field densities normally encountered, and the rate of penetration of freezing temperature into the specimens of about ¼ in. per day is considered to be representative of field conditions during the latter half of the freezing period when rate of penetration is slower and ice lensing per unit depth is frequently greatest. However, except for special tests an unlimited supply of water is provided at the base of the specimens. In the field this would correspond to an extremely pervious aquifer only a short distance below the plane of freezing. This is a severe condition and it results in virtually the maximum possible rate of ice segregation and heave which the soil can exhibit under natural field conditions. The heave results are, therefore, not considered quantitatively representative of the actual heave to be expected in the field. The results are considered, however, to give a satisfactory relative measure of frost susceptibility of soils, with the possible exception of unweathered clays which may show unduly low heave in at least the first cycle of freezing.

The evaluation given by the standard freezing test is empirical in nature. Average rate of heave as measured in the test does not represent a simple and fundamental physical value, since such factors as surcharge and moisture availability at the plane of freezing vary continuously during the test. Thus, the test is undoubtedly only a first step toward an ultimate rational evaluation test procedure which will evolve from research now in progress.

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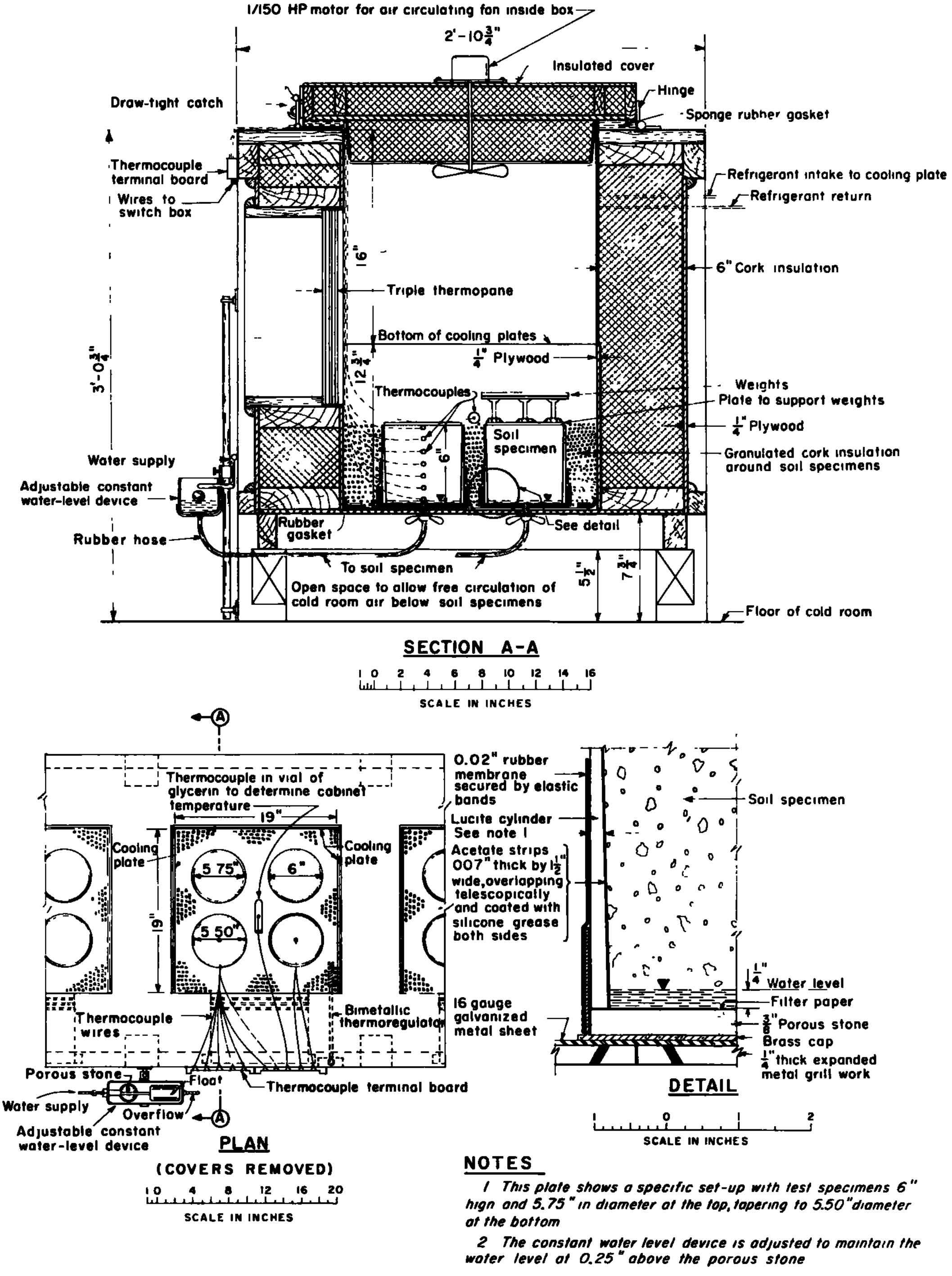
[5] Tests are currently under way to investigate the possibility of speeding up the rate of freeze to hasten the test procedure. The rate of heave results thus far obtained, using ½ inch per day rate of freeze on sands and predominantly coarse-grained soils have checked closely with those obtained with the slower procedure.



NOTES

1 This plate shows a specific set-up with test specimens 6" high and 5.75" in diameter at the top, tapering to 5.50" diameter at the bottom

2 The constant water level device is adjusted to maintain the water level at 0.25" above the porous stone

Figure 13. Details of test cabinet and specimens.

V. BASIC CONSIDERATIONS FOR REMEDIAL MEASURES IN RELATION TO SOIL AND MATERIAL CHARACTERISTICS

A. Limitations of Conventional Design Measures

Current frost design measures for pavements are limited to use of sufficient thickness of pavement and non-frost-susceptible base and subbase so that heave, thaw-weakening, or both, are held within tolerable limits. This requires that sources of suitable, non-frost-susceptible base and subbase materials be available. In many areas sufficiently clean materials are scarce or are available only at substantial cost by hauling from a distant source. Frequently materials are available near the construction site which are slightly on the "dirty" side with respect to amount of fines, and the engineer may try to find some way of using these materials in their natural state or of modifying them by some economical means to make them usable. Since the current widely-used frost susceptibility criteria based upon percentage finer than 0.02 mm are not precise, it is possible, especially if the material is very uniformly graded, that it may actually be usable even though failing to meet the 0.02 mm criteria. In other cases the reverse may be true. It is therefore advisable in borderline cases involving substantial quantities of material to perform laboratory freezing tests to evaluate the actual relative frost heave susceptibility of the material, as described in Part IV. Sometimes, if the deficiency is slight and the road embankment not too wide, local experience may show it is possible to achieve adequate results by using 6 to 12 inches greater thickness of the borderline material than would be used if the material were clean and met the 0.02 mm requirements, the greater thickness tending to compensate for the poorer drainability of the "dirty" material. However, any encroachment on the 0.02 mm criteria is risky unless supported by the above-described laboratory frost susceptibility evaluation test. Use, for convenience in control, of other size values than 0.02 mm—such as the 200 mesh size—is also not warranted unless the soils are from a source of consistent gradation and a correlation between the 0.02 mm size and the 200 mesh or other size is specifically established for the job. Uniformly graded soil has been tested by ACFEL which was of negligible frost susceptibility even though having 54 percent passing the 200 mesh sieve (6 percent finer than 0.02 mm).

B. Additives and Admixtures

Since the time when the cause of frost heaving was first explained by Taber many attempts have been made by numerous investigators to reduce or eliminate ice lens growth in soils by the use of additives and chemicals. Some of the possible approaches by which additives can perform these functions are the following:

1. Plug Soil Voids. If the voids can be effectively plugged or sealed so that water cannot migrate, then ice lenses cannot grow.
2. Cement Soil Particles. This approach is closely related to the plugging of soil voids. Portland cements and bitumens, of course, are very effective.
3. Alter Characteristics of Pore Fluid. Salts may be added to lower the freezing point of the pore fluid. Lowering the freezing point reduces the depth of frost penetration under a given set of temperature conditions but does not affect the heave characteristics of the soil. The main disadvantage to use of soluble salts for pore fluid treatment is their non-permanency.
4. Alter Soil Properties by Aggregation of Fines. It has been clearly established that soil fines are principally responsible for the frost susceptibility of a soil. A frost-susceptible soil can be made non-frost-susceptible by removing the troublesome fines. In case of a "dirty" gravel intended for use as a base course under a pavement this can be done by washing out the fines. However, the effective quantity of fines can also be reduced by additives that cause small particles to aggregate into larger units, thus effecting a "cleaner" soil.
5. Alter Soil Properties by Dispersion of Fines. Treatments which can increase the interparticle repulsion in the soil fines tend to disperse the soil aggregates. Particles which do not stick together can be manipulated into a more orderly and denser

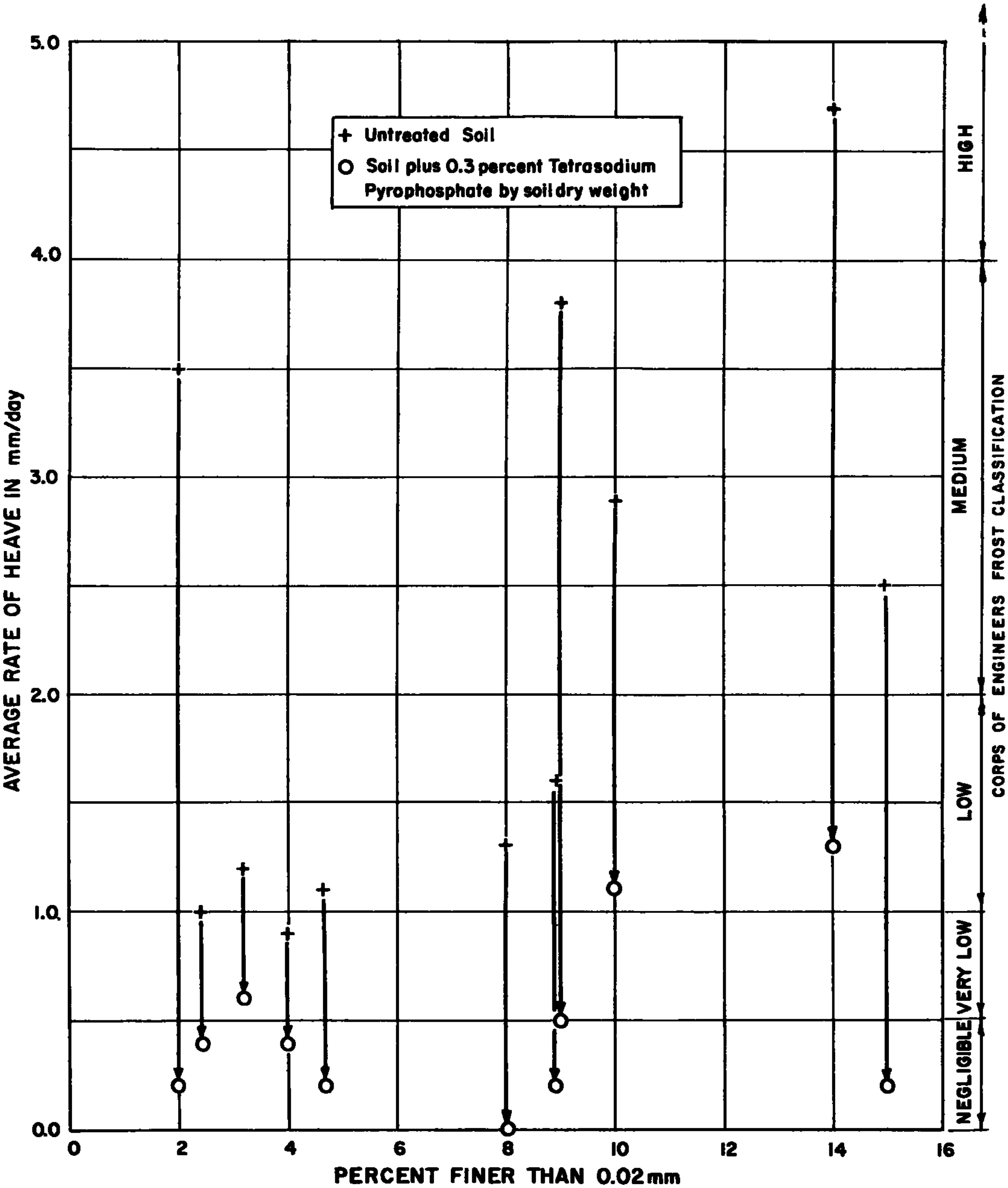


Figure 14. Freezing tests on "dirty" gravels.

structure. Concomitant to improved structure are higher density and lower permeability. The effects of trace quantities of chemical dispersants in altering soil properties have been described by Lambe (29).

6. Alter Characteristics of the Surfaces of Soil Particles. With proper additives mineral surfaces can be made hydrophobic. A soil so water-proofed cannot be "wetted" and should have little or no adsorbed moisture. Conversely, coating soils with additives that have highly polar groups exposed to the soil moisture can increase the amounts of moisture adsorbed and thus, perhaps, reduce the permeability of fine-grained soils enough to make them non-frost-susceptible.

The void pluggers are among the more effective additives. The Corps of Engineers (2, 3) has experimented successfully with Bunker "C" oil, Tar RT-2 and combinations of Bunker "C" oil and Tar. A drawback of these methods is that the percentage of the additives needed approaches that used in pavement surfaces, and thus becomes economically impracticable, particularly in northern areas where frost penetration reaches many feet. Further, the fact that the treated soils contain little or no moisture tends to result in increased total frost penetration because of the absence of latent heat. Also many of the bituminous additives require special mixing and curing for best results, making field treatment slow and expensive.

Hardy (21) reports moderately successful results from use of waste sulphite liquor in reducing frost heaving in both laboratory and field experiments on silty soils. He attributes the effectiveness of the sulphite liquor to its high viscosity which reduces the permeability of the treated soil. Leaching tests, however, indicate that effectiveness is not permanent.

Freezing tests have recently been carried out at the Arctic Construction and Frost Effects Laboratory in cooperation with Lambe of M. I. T. (6, 29) in an effort to discover a chemical additive which when added to a soil in trace quantities (less than 0.5 percent by weight) will inhibit ice segregation. These experiments have involved basically aggregants, dispersants and waterproofers.

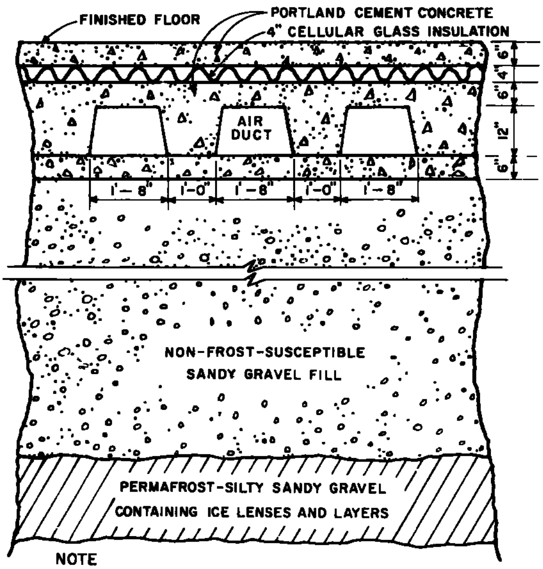
A number of cations were investigated in this test program for their effect on frost heaving. These included iron, lead and mercury salts, not so much as aggregants but as waterproofers since they have non-hydratable ions. Enough of each salt was added to various frost-susceptible soils to saturate the exchange capacity of the soil with the salts' cations. The required treatment level was low, always below 0.5 percent. The results of these tests showed that some benefit was experienced in a number of the soils used in the experiments, particularly where ferric chloride was used as an additive. Until much more is known about the reactions which actually occur on the particle surface and on the effects produced in the pore water, it will be necessary to consider such studies as preliminary.

Most of the chemical dispersants are made of a polyanionic group, e. g. phosphate sulfonate, and a monovalent cation, usually sodium. The anions act in a soil by forming insoluble products with the removed cations or by becoming attached to the soil mineral surface. The monovalent cation in the dispersant becomes linked to the soil, replacing the removed polyvalent exchangeable cations. The dispersants act to expand the diffuse double layer around the soil colloids and thus increase interparticle repulsion. The dispersants appear to offer the best hope for the treatment of borderline frost-susceptible soils. The laboratory test results on 11 "dirty" gravelly soils which were treated with 0.3 percent of tetrasodium pyrophosphate are shown in Figure 14. The reduction in observed rate of heave is significant. The pertinent soil data for this series are presented in Table 2. Three cycles of freeze and thaw on the Portsmouth, Loring, Dow and Lincoln soils showed no loss of effectiveness of treatment. A laboratory program is currently underway to study the permanency of treatment and resistance to leaching.

The following conclusions can be presently drawn from results of these chemical additives studies:

1. Polymeric aggregants are generally not very effective.
2. The use of cations such as ferric chloride has the disadvantage of requiring the drying of the treated soil for fixation of ions.
3. Dispersants are quite effective but the question of permanence and durability needs to be determined.
4. Waterproofers are unpredictable and also undesirable because of drying and curing requirements.
5. The best area for the possible application of chemical treatment and additives lies in the borderline and so-called "dirty" frost-susceptible materials.

Comparative cost studies made at ACFEL reveal that where ample quantities of "dirty" materials are involved and the hauling distance is not too great, washing out of the fines is less costly than chemical treatment. However, situations are visualized



NOTE
Winter air flow through air ducts refreezes sandy gravel fill annually. Mean annual air temperature = 12.5°F.

Figure 15. Insulated floor slab design for hangar.

where relatively small quantities of materials are involved and/or suitable "clean" materials are not locally available, in which it would economically or expediently advantageous to resort to chemical treatment.

C. Insulating Courses and Modification of Thermal Properties

Beskow (9, 10) and Skaven Haug (44) have described the use of insulating courses of organic materials such as moss, straw, and peat under secondary roads and railroads in Sweden and Norway to limit damaging frost heave. The U. S. Army Corps of Engineers Permafrost Division also constructed test pavements in 1947 on insulating courses composed of cellular glass block, cell concrete, and expanded aggregate type concrete, compacted moss, and compacted spruce logs and branches (4). The principal advantage of courses of wet organic materials is derived not from their thermal conductivity characteristics but from their high volumetric heat capacities, which limit the depth of frost penetration. The organic materials suffer from compressibility. In Scandinavia this is overcome by compressing peat in machines to sufficient extent to support the anticipated railway and highway loads. Cell concrete and expanded aggregate type concrete were found by the Corps of Engineers to offer no advantage as insulating materials when placed between the subbase and the subgrade, as they became saturated throughout and lost their initial lower thermal conductivity. The cellular glass insulation, however, similarly installed, has remained effective in a non-trafficked section for at least 10 yr. It appears that any insulation placed in the ground must consist of completely sealed individual cells impervious to moisture, in order to have more than temporary insulating effectiveness.

However, if the problem is approached from the point of view not of providing insulation but of providing as much volumetric heat capacity as possible, as in the case of peat described above, then a cheap cellular-type material in which the cells are filled with water, which is capable of carrying high loads and which will not be disrupted by freezing, would theoretically be a desirable material for use under pavements in frost areas.

Cellular glass block insulation has been used effectively in concrete pavements of hangars at Thule Air Force Base, Greenland. Floor slab design is shown in Figure 15. Although the number of load repetitions has naturally been low in this hangar installation, heavy aircraft wheel loadings have been carried for a period in excess of five years without report of any distress.

Recent design studies have also shown that in the case of a light load airfield pavement in a northern frost region, the use of a cellular glass insulation course at the base of a rigid pavement slab was nearly economically competitive with washing of the available gravel (3-mile haul) to reduce the percent of fines to an acceptable level, the cost of furnishing and placing the insulation course being nearly balanced by the reduction in required thickness of subbase (of the order of 4 ft) which would have been made possible. This suggests that in areas where suitable non-frost-susceptible base and subbase materials are very expensive the use of insulating materials in or under heavy airfield pavements may be economical. However, no experience (except that at Thule) nor any engineering criteria covering structural requirements for rigid insulating courses in or under highway or substantial airfield traffic are presently available. These are needed before any extensive installation could be made. Cellular plastic insulation, granular forms of cellular glass insulation and compressed peat offer possibilities worthy of investigation.

VI. IMPORTANT NEEDED RESEARCH CONCERNING THE FACTOR OF SOIL AND MATERIAL TYPE

1. Study is needed concerning the actual effective permeability of in-place soils within the zone of frost action as distinguished from the permeability of unfissured laboratory specimens.
2. Further study is needed of the role of bedrock in causing detrimental frost heave.
3. Research is needed to explore chemical and mineralogical differences between the various strata in the pedological soil profile in relation to frost susceptibility differences.
4. The currently used Casagrande frost susceptibility criterion based upon the percent of grains finer than 0.02 mm by weight is admittedly a rough engineering rule-of-thumb but is the best criterion presently available. Study is needed to develop a more refined or new criterion.
5. Further research is needed to investigate the individual and combined effects on frost action of the various fundamental influencing factors, including especially the following: void size, soluble materials in pore water, physico-chemical properties of soil fines, and degree of saturation. Simple experiments should be devised to measure and evaluate the effects of these factors.
6. Further research is needed on thermal properties of soils.
7. Present frost classification grouping systems for frost-susceptible soils need to be further developed to provide for evaluation of all the following factors: frost heave, thaw weakening characteristics, and loss of strength by remolding.
8. Study is needed to improve and simplify present laboratory freezing tests for frost evaluation of soils for engineering applications.
9. Research is needed on possible methods of using insulating materials and high volumetric heat courses in and under pavements as a means of controlling frost action by limiting the depth of frost penetration and of using admixtures in trace quantities to modify frost characteristics of soils.

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Discussion

K. B. WOODS, Director, Joint Highway Research Project and Head, School of Civil Engineering, Purdue University, Lafayette, Indiana—The paper under consideration has been carefully done and the subject has been covered with thoroughness. There is little to be said in discussion of the paper other than to compliment the authors for the excellence of their endeavors.

However, on the subject of soil characteristics, it has been this writer's observation that increased emphasis should be given to the pedological and geological aspects of frost-action areas. From this standpoint a few comments to supplement the material presented by the authors are in order.

Pedological Considerations

All of the factors of soil formation, that is, parent material, topography, age, climate and vegetation, must be considered in highway location, design, and construction. To illustrate this, there are many similarities between the engineering properties of glacial soils of Wisconsin age and those of Illinoian age. However, from the frost action standpoint the differences in the properties of these soils are of greater significance than the similarities. In very slightly undulating till plains of North Central Indiana where the Crosby and Brookston soils predominate, any highway or airport location which requires slight cuts and slight fills (even 4 or 5 in. of either) builds into the design a serious frost problem because of the significant variations of the various horizons in the soil profile. Thus, a "fill section" is always indicated in this region. In contrast, in the Illinoian drift area immediately to the south in Indiana, an almost completely level terrain generally occurs. The surface horizon is generally 20 in. deep and is made up of frost-susceptible silts. Yet differential frost heaving is unknown except in those situations where cuts are made into the B horizon. In this latter instance all of the prerequisites are present for a potential frost problem including a frost-susceptible silt, a high ground-water table and, at least during normal winters, prolonged periods of cold weather.

This is only one example of literally hundreds which can be drawn upon to illustrate the extreme importance of the conditions of the soil profile and the importance of the over-all environment in designing to protect against frost action.

Geological Considerations

Here, too, a great many cases can be cited to illustrate the need for a basic understanding of the geology of a given situation with respect to the frost-action problem.

The authors have mentioned the transition between cut and fill sections. This point must be given added emphasis. Frost problems are encountered under appropriate climatic conditions in the transition between cut and fill in most rock regions. However, there is one added situation which is especially vulnerable, namely, transition between rock of the Laurentian shield in Canada and the adjacent granular drift. Some of the most severe frost heaves on the continent may be seen in this type of geological situation.

Another series of "geologic area" from the standpoint of frost phenomena may be found in sourthern Ontario and portions of sourthern Michigan and northern Indiana. Here may be found considerable areas of shallow sands on till. If adequate explorations have not been made prior to the location of the highway or airport and protective measures have not been taken in the design, then 6 in. to a foot of sand very frequently will feed water into a shallow sand cut which results in some winters in very severe frost heaves in materials which laboratory-wise would be considered non-frost susceptible.

A third case is that of the Yukon silts which occur so extensively along the Yukon River and other streams in Yukon territory. These silty soils are very frost-susceptible according to laboratory evaluations. Then, too, the periods of extreme cold are certainly adequate to cause a frost problem. However, these silts occur in elevated, terrace-like positions and because of the low rainfall, the frost problem as such is really quite insignificant.

In conclusion, this discussion has been directed at pedological and geological aspects of the frost action problem to strongly emphasize some of the points already mentioned by the authors. This is indeed a fine presentation.

A. E. MATTHEWS, Engineer of Soils, Michigan State Highway Department—The writer wishes to congratulate the authors of this paper. It is an excellent summary of the available information. The conclusions are supported by tables and charts. An extensive review of the literature is apparent. The amount of information known on some of the phases is very limited and these are shown in Section V as "Needed Research."

Of the three main factors affecting frost action, namely temperature, water, and soils, this paper is devoted to the effect of soil and material type. This factor can be controlled within limits and an understanding of the conditions is very important in highway pavement design in frost regions. The early investigators, according to the authors, discovered that certain types of soil were more susceptible to frost action than others. It is gratifying to note that more recent research has borne out Casagrande's conclusion that under natural freezing conditions and with sufficient water supply one should expect considerable ice segregation in non-uniform soil containing more than three percent of grains smaller than 0.02 mm, and in very uniform soils containing more than ten percent smaller than 0.02 mm. From further research, the authors point out that the intensity of ice segregation in soils is dependent not only on the percent of grains finer than 0.02 mm, but also on the grain size distribution, the properties of the fines, the physical state of the material, the degree of density, etc. They conclude that the size to which ice lenses can grow in a soil or the rate at which they grow depends on a number of interrelated factors, among them soil type, soil void sizes, permeability, freezing temperatures, the initial water content of the soil and on the availability of free water.

It logically follows that the next section of the paper be devoted to the relation of soil classification groups to frost action. They show the application to the Unified Soil Classification System and its modification, also the adaptation to the Bureau of Public Roads classification system, and state that the clean soils in the A-1 and A-3 soil groups show little or no heaving or loss of strength while in the other groups frost-susceptible materials are encountered. In the CAA classification system of soils for airport construction, allowance is made in design for frost penetration according to the authors. The frost evaluation system can be readily adapted to the pedological system. Engineering design charts in Michigan, however, do not carry a column as such but allowances are made in design for frost action based on experience.

The authors believe that the only laboratory frost evaluation system for frost-susceptible soils is that of the Arctic Construction and Frost Effects Laboratory of the New England Division, Corps of Engineers. It is based upon the measurement of the rate of heave in a standard laboratory freezing test and is a measure of the frost heave potential of the soils and does not necessarily indicate the thaw weakening characteristic. The authors emphasize the need for further research to develop an improved frost classification.

The last section of the paper deals with the corrective measures in relation to soil and materials for control of frost action. Current corrective measures for highway and air field pavements are limited mainly to the use of sufficient thickness of pavement and non-frost-susceptible base and subbase so that heave, thaw-weakening, or both are held within tolerable limits. In Michigan, 14 in. of subbase under concrete pavements is used with an allowable 5 percent passing the No. 200 sieve to control heave, thaw-weakening. For the correction of differential heaving, subbases of 3 to 4 ft are used.

Since the current widely-used criterion of 3 percent finer than 0.02 mm as the limit between frost-susceptible and non-frost-susceptible is not precise, the authors revise the laboratory freezing tests to evaluate the actual relative frost heave susceptibility of the borderline materials. In case of slight deficiency, they suggest consideration of an increase of 6 to 12-in. in thickness of borderline material. It occurs to the writer that a questionnaire covering the corrective measures of the state highway departments in the frost zone might shed some interesting light on this problem.

The subject of additives and admixtures for control are discussed briefly. They conclude that the best area for the possible application of chemical treatment and additive lies in the borderline and so-called dirty frost-susceptible materials. Very little research of this type has been done in Michigan due mainly to the wide distribution of granular materials throughout the state.

The authors are to be complimented on the handling of a difficult subject. The needed research as pointed out in this article will furnish all with important information relative to these problems.

Frost Action in Soils—A Symposium Analysis

CARL B. CRAWFORD, Head, Soil Mechanics Section, Division of Building Research, National Research Council, Ottawa, Canada

● THE PURPOSE of this symposium is to make an up-to-date assessment of knowledge of the basic considerations pertaining to frost action in soils. The scope of the symposium was divided into four parts and four authors were invited to prepare papers on each part. Draft versions of the papers were presented at the summer meeting of the committee in August 1958, the contents were discussed and a number of persons were invited to submit formal discussions to the papers.

The papers are arranged in such an order that the reader is first acquainted with the mechanism of frost action, a fundamental phenomenon that escaped the comprehension of scientists and engineers for many decades. Then the important contribution of moisture in frost action is discussed. Next the extent to which temperatures in the ground can be related to weather conditions is reported, and finally the influence of soil type on frost action is completely reviewed. In reality it is impossible to separate the influences of soil type, water, and temperature conditions on the mechanism of frost action and there is therefore a certain amount of overlapping in the four papers.

The application of fundamental principles to the mechanism of frost heaving has reached an interesting and useful stage. This development has occurred almost entirely in the last thirty years. The classical work of Taber and Beskow postulating the migration of water under freezing conditions in certain soils to form ice lenses is now universally accepted. An explanation of the exact mechanism requires a knowledge of the forces which act to move the water and a satisfactory concept of channels of unfrozen water up to the growing ice lens.

In order to explain his experimental results, Penner invokes thermodynamic principles which relate soil pore size to freezing point depression in the pore water and to pressure changes in the liquid water. A qualitative appraisal of these two relationships in harmony with film adjustment in the adsorbed water phase around the particle is suggested as an explanation of the mechanism of ice lensing.

In discussion, Martin, also using a qualitative approach, suggests that maximum crystal growth rate plus preferential growth of the larger crystals accounts for lensing quite independent of pore size. Miller argues that osmotic pressure is the energy source for frost heaving. Jumikis emphasizes the profound influence on ice lensing of the mutual interaction of the heat exchange between a freezing soil system with its surroundings and thermally activated moisture migration.

Low and Lovell consider the supercooling and freezing of adsorbed water. They suggest that in addition to the thermodynamic limit to the rate of crystallization and a consequent supercooling of the water, the reduction in the potential energy of water near the mineral surfaces due to attractive forces is a factor in the freezing point depression in the water and hence in the ice lensing mechanism.

Although there may be doubt about the mechanism of frost lensing, carefully controlled laboratory experiments have provided some important concepts. These include a better understanding of the influence of pore size, and indirectly the grain size, on ice lensing; the secondary effects of density, homogeneity and water supply; the dependence of frost heave on overburden pressure; the probable relationship between rate of heave and rate of heat extraction; the dependence of number and thickness of ice lenses on rate of crystallization and soil water proerties; the necessity of considering unsaturated permeability factors in frost heaving considerations; and the probable effect of chemical stabilizers on the mechanism of ice lensing in soils. This is certainly a welcome addition to the engineering literature.

Engineers in general have been forced by their rather practical training to neglect the fundamental influence of water on the properties and performance of materials. It is particularly appropriate therefore to record in this symposium the admirable interpretation of the scientific literature on the properties of water in the paper by Low and Lovell.

While supplementing and encouraging the authors Jumikis reminds the reader that under transient temperature conditions several properties of the water in a clay-water system are changing continuously. For this reason much work is yet to be done to extend basic knowledge and to apply it in practice. Dolch supplements the paper with numerous examples of the unusual behavior of solid-liquid interfaces.

Due probably to problems of instrumentation, the changing soil water conditions under pavements are not well documented. However, Low and Lovell found sufficient material to make several useful generalizations which indicate that a substantial change may occur, particularly during the early life of the pavement. Much less is known of the effects these changes may have on the performance of the pavement. The authors noted an increasing interest in the magnitude of the equilibrium water content under the pavement and less emphasis on the obtaining of maximum densities which may in fact be temporary. The implications of ice lensing in these considerations are obvious.

The development of a satisfactory method of predicting frost penetration in soils is the subject of Kersten's contribution to this symposium. In this prediction water again plays an important and complicating role by introducing discontinuities in the heat flow process due to changes in state and movement through the soil media. In order to allow for these difficulties in thermal computations corrections are applied and thermal constants are used which neglect moisture transfer in their determination and in their application.

In a limited study in Minnesota, Kersten found a satisfactory correlation between frost depth and the square root of degree-days below an arbitrary temperature of 29 F. Sanger questions whether this method would have as general an application as the air-surface correction factor.

The two most popular heat flow formulas applied to frost penetration computations (the Stefan equation and the modified Berggren equation) are discussed and the assumptions and possible errors are given a thorough treatment. Significantly, it is pointed out that a considerable error may result from assuming that all water freezes in a fine-grained soil and that there is usually a rather large discrepancy when dealing with fairly dry granular soils. Because of such difficulties, attention is being directed to a micrometeorological approach in which an attempt is made to balance heat flow inward and outward at the earth's surface. While this unique approach shows much promise it is in its infancy. Of more immediate interest are the numerical solutions and the use of computers described by Aldrich.

There is a limit to the possible accuracy of computed temperature conditions under pavement due to the difficulty of selecting appropriate thermal constants and of handling the complex transient heat flow conditions. This is further complicated by changing soil moisture conditions with time after construction and seasonally. In his discussion, Pryer quotes experience in the Labrador peninsula to illustrate the marked effect on frost penetration of the weather just before freeze-up. There is, however, ample justification for employing methods outlined in this symposium for the prediction of frost penetration in most circumstances.

In their paper, Linell and Kaplar point out that the control of soil characteristics is the most feasible method with which to control detrimental frost action. It is of particular value to the engineering profession to have the stated opinion of these authors that the original Casagrande frost criteria is "the most expedient rule-of-thumb means of identifying without benefit of laboratory freezing procedure soils in which damaging frost action may occur." Based on evidence from a long-term investigation by the Arctic Construction and Frost Effects Laboratories of the U. S. Corps of Engineers, certain qualifications to the simple Casagrande criteria are introduced and the recognition of the most difficult soil groups are discussed. Other criteria such as the capillarity of the fine-fraction in the soil did not impress the authors.

The authors recognize the potential loss of strength and density due to frost action and indicate how this is taken into account in the Corps of Engineers design procedure. Laboratory test methods for rating the frost susceptibility of a soil are described in detail.

It is suggested by Woods in discussion that pedological and geological aspects in frost-action areas should be given more emphasis and several practical observations are given in support of this suggestion. Matthews points out that the "frost evaluation system can be readily adapted to the pedological system" and notes that this is done in Michigan on the basis of experience.

This symposium has attempted to provide for the practicing engineer a background of information to assist in assessing the possibility and severity of detrimental frost action in a particular region. A second symposium will consider the problems of design in frost areas.

On the basis of meteorological information and certain test results or assumptions it has been show that, in most cases, a satisfactory assessment of frost penetration can be made. Although it is not discussed, it is clear that a statistical treatment of weather probabilities may be necessary for design.

Too little is known of the availability and treatment of water under pavements. It is a problem, however, that is receiving increased attention—much of a fundamental nature. In an engineering assessment it is usually assumed that an unlimited supply of water is available unless there is reliable evidence to the contrary.

The assessment of soil material with regard to its frost susceptibility is a complicated matter. There is little argument against the qualitative use of the Corps of Engineers criteria. Much effort is being devoted to an improvement of the criteria.

These considerations only assess the potential heaving of a soil due to frost action. One is impressed by the lack of technical information on the loss of bearing capacity resulting from thawing. Again it is noted that attention is being directed to this aspect of the problem. In the meantime the susceptibility of a soil to ice lensing must be taken as an indication of its frost action potential.

Concerning the mechanism of frost lensing in a soil it is apparent that much progress has been made in recent years. The fact that the matter has not been completely resolved is illustrated by the difference in interpretation of basic physical laws by the several contributors. There is reason to believe that essential agreement on the mechanism is not far off.

A most important conclusion is that if engineers are to be able to treat properly frost action problems in the field, they must understand the mechanism in order to determine which factor can be treated most economically. For instance, should a subgrade be insulated against the penetration of frost or should the frost be encouraged to penetrate rapidly? Should attempts be made to remove soil moisture or should the properties of the moisture be changed? Should the natural soil be replaced or treated mechanically or physically? What is the most effective treatment? These are questions that are being answered slowly by carefully controlled basic studies.

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The HIGHWAY RESEARCH BOARD was organized November 11, 1920, as an agency of the Division of Engineering and Industrial Research, one of the eight functional divisions of the NATIONAL RESEARCH COUNCIL. The BOARD is a cooperative organization of the highway technologists of America operating under the auspices of the ACADEMY–COUNCIL and with the support of the several highway departments, the Bureau of Public Roads, and many other organizations interested in the development of highway transportation. The purposes of the BOARD are to encourage research and to provide a national clearinghouse and correlation service for research activities and information on highway administration and technology.