The Factor of Soil and Material Type in Frost Action

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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;

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

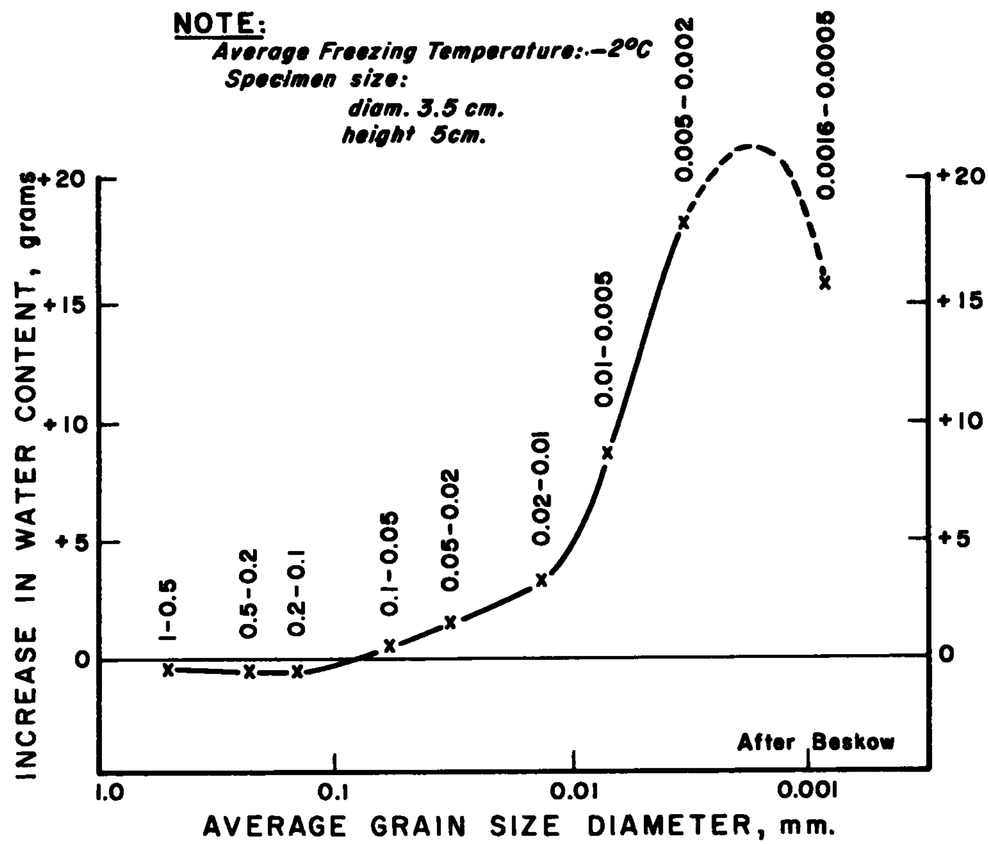


Figure 1. Relation between moisture increase and average grain size diameter of pure soil fractions.

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

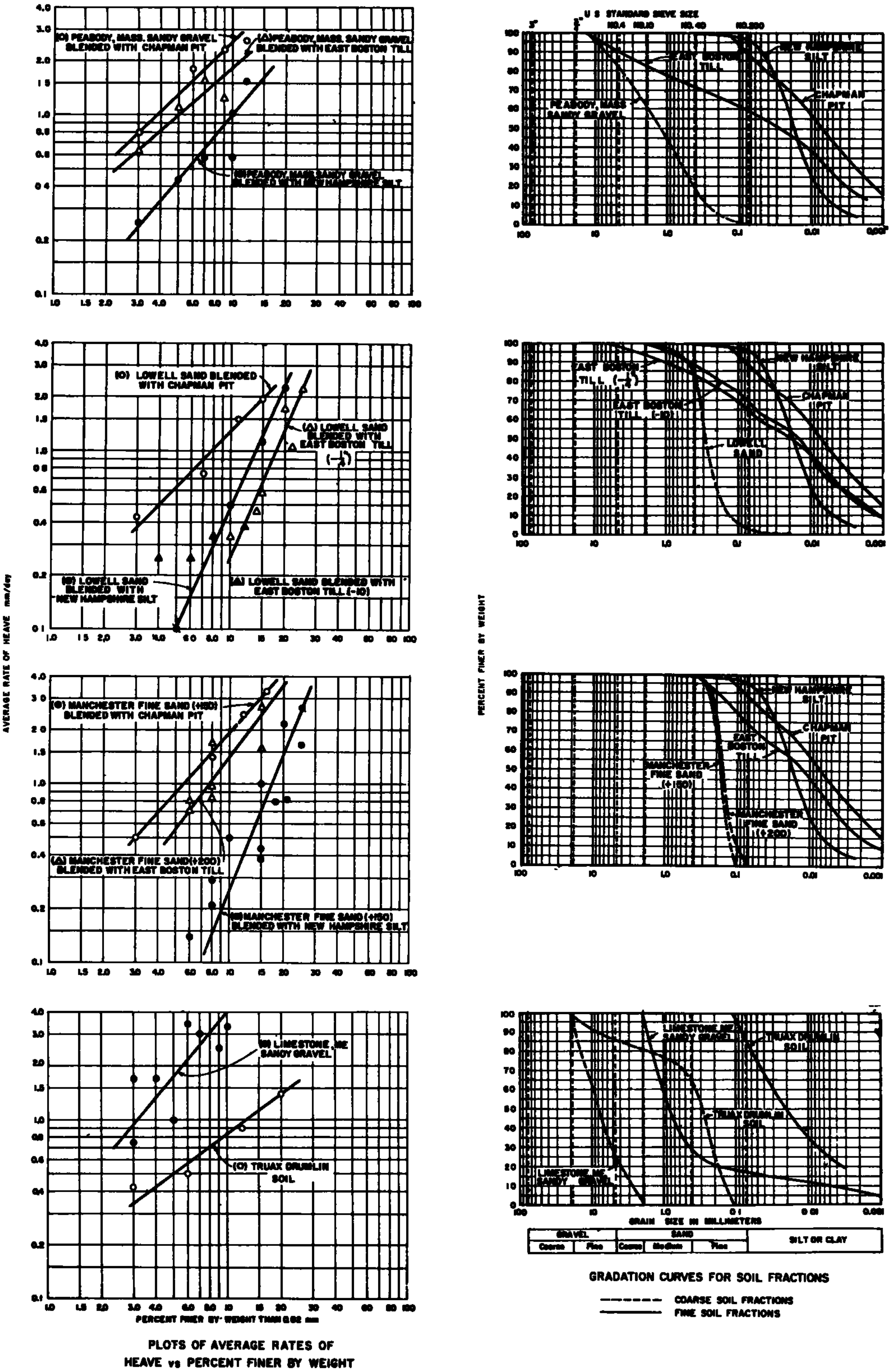


Figure 2. Effect of percent finer than 0.02 mm.

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

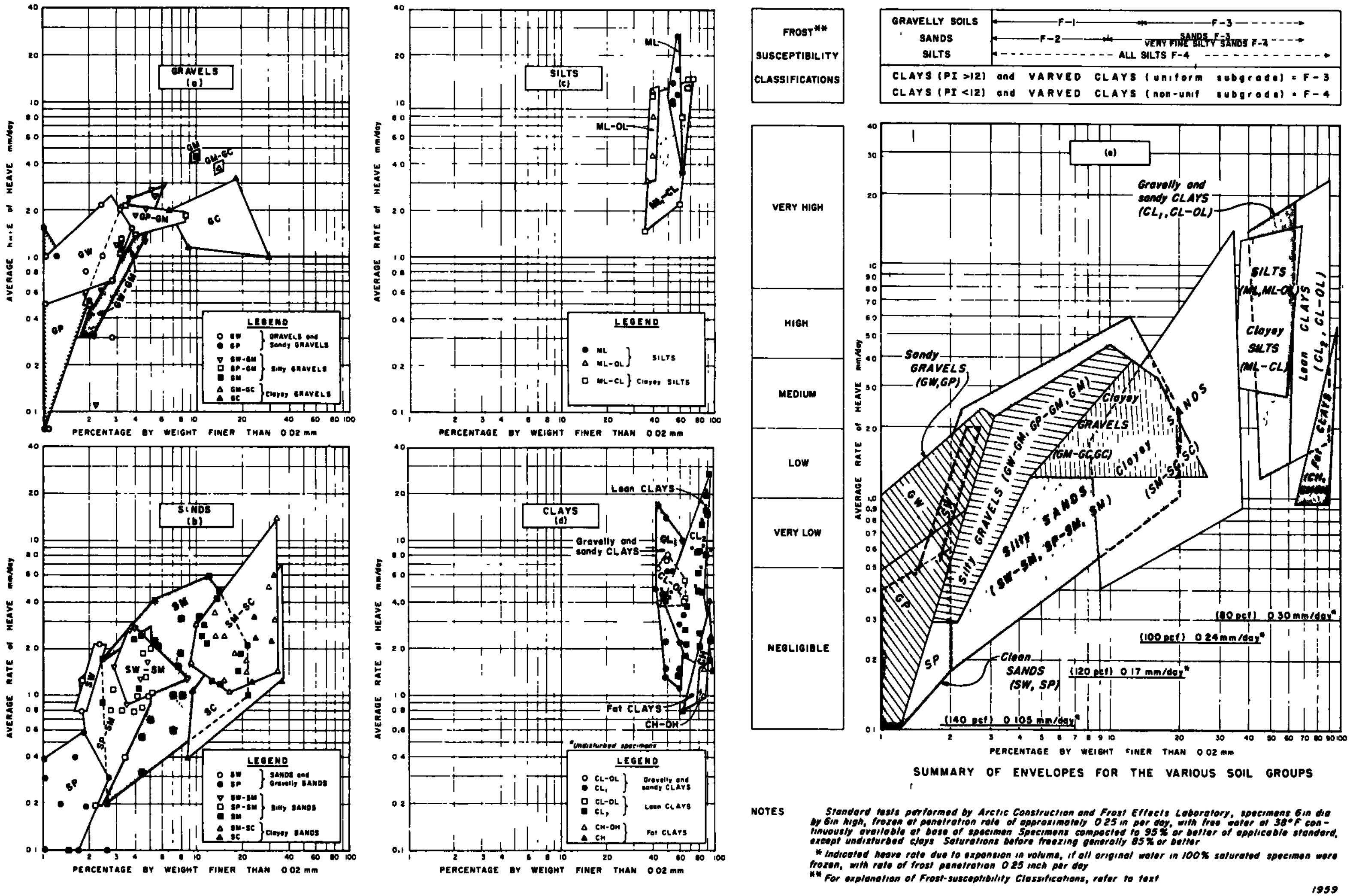


Figure 3. Average rate of heave vs percentage finer than 0.02 mm for natural soil gradations.

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 physico-chemical 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 1/4 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 1/4 to 1/2 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.

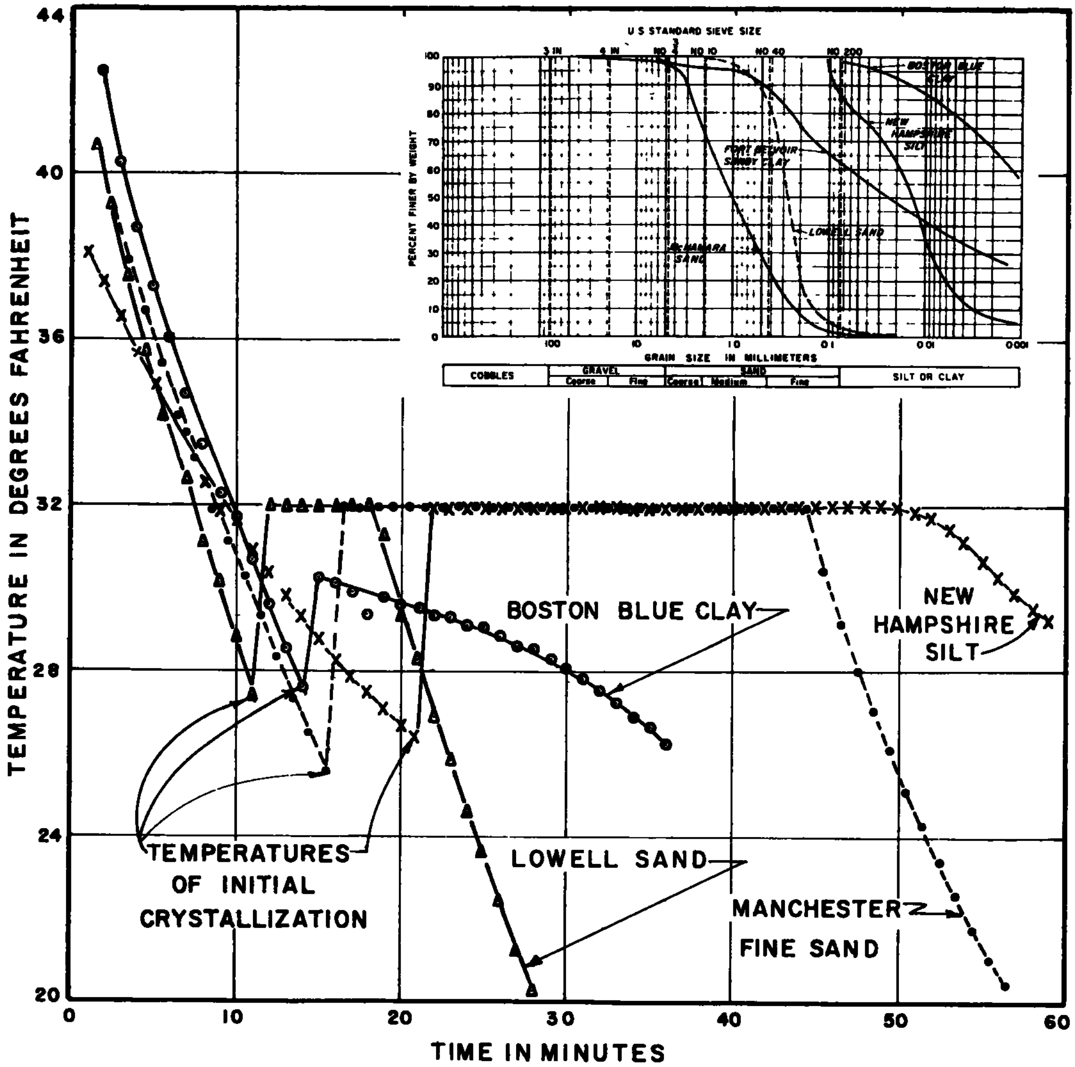
As is apparent from Figure 3, accurate prediction of relative heave rate cannot be made simply from general soil type and percent finer than 0.02 mm. Soils of even similar gradations may vary significantly in frost behavior. Factors not apparent from a gradation analysis affect the behavior. Some of 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

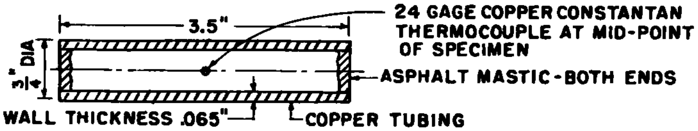


Figure 4. Typical plots of temperature change during freezing.

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.

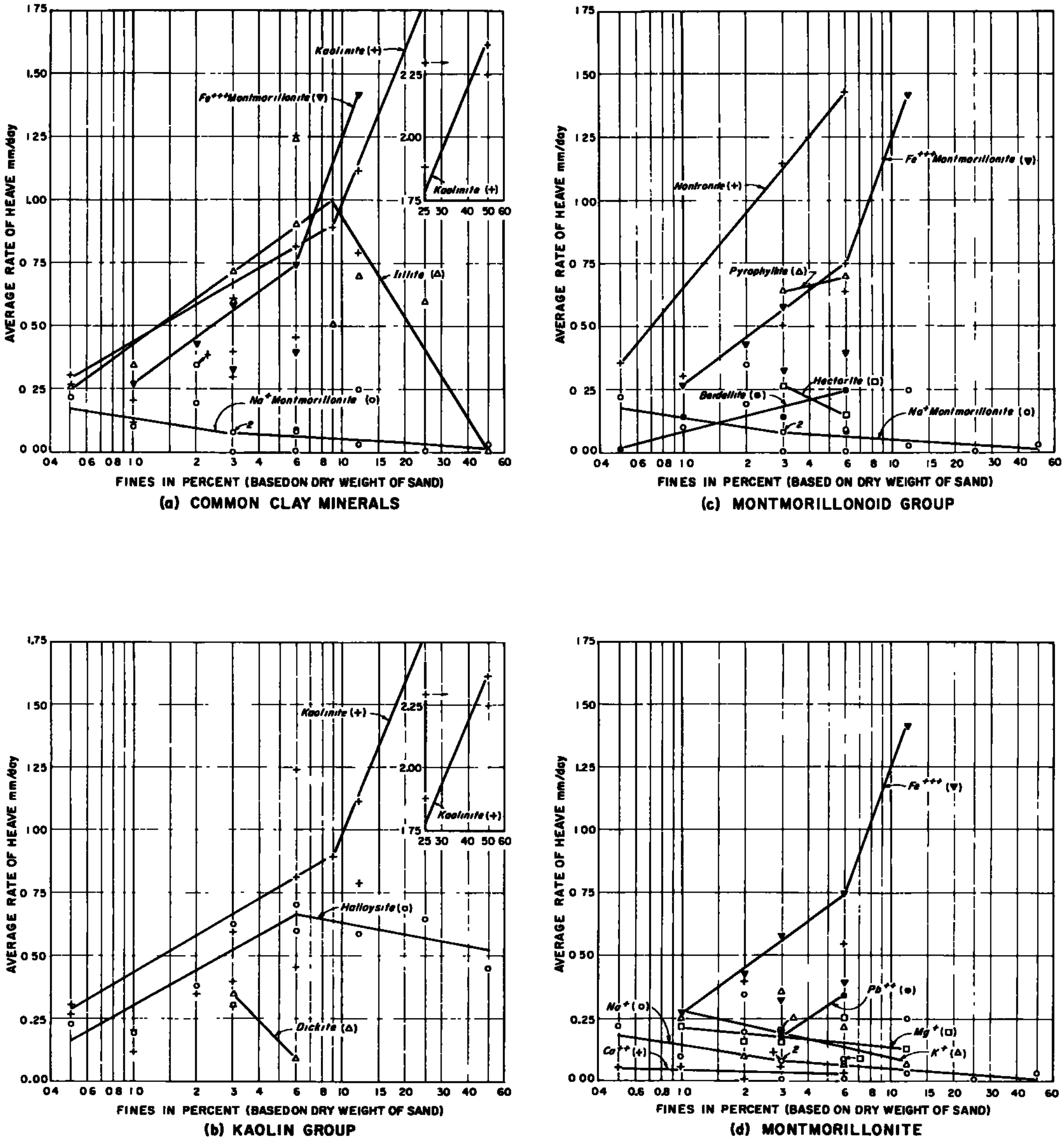
A somewhat similar concept is held by Winterkorn (59) who has stated:

> "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

[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.



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

[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	Principal Minerals: 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.

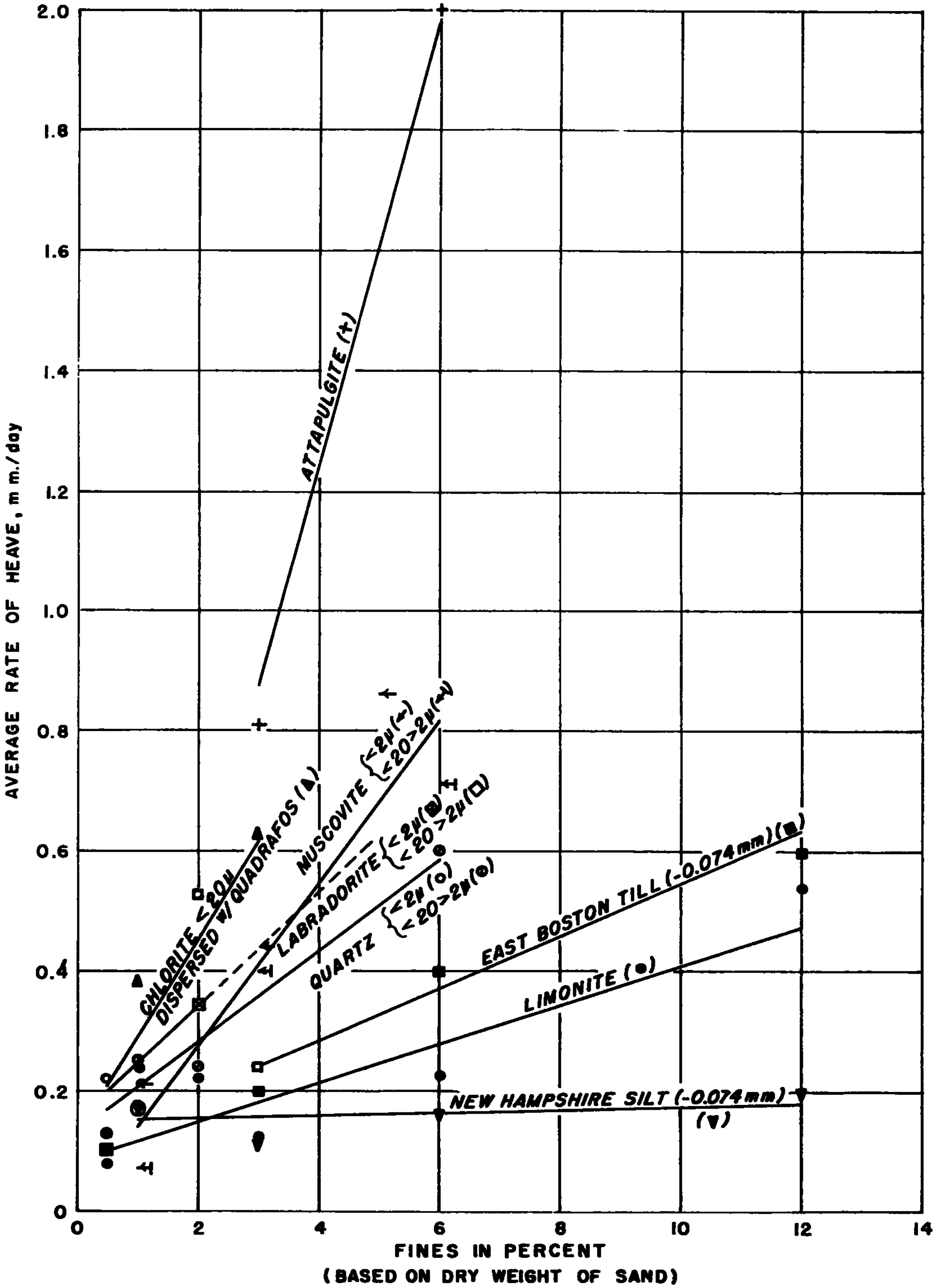


Figure 6. Effect of non-clay minerals and miscellaneous clay minerals with McNamara sand.

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

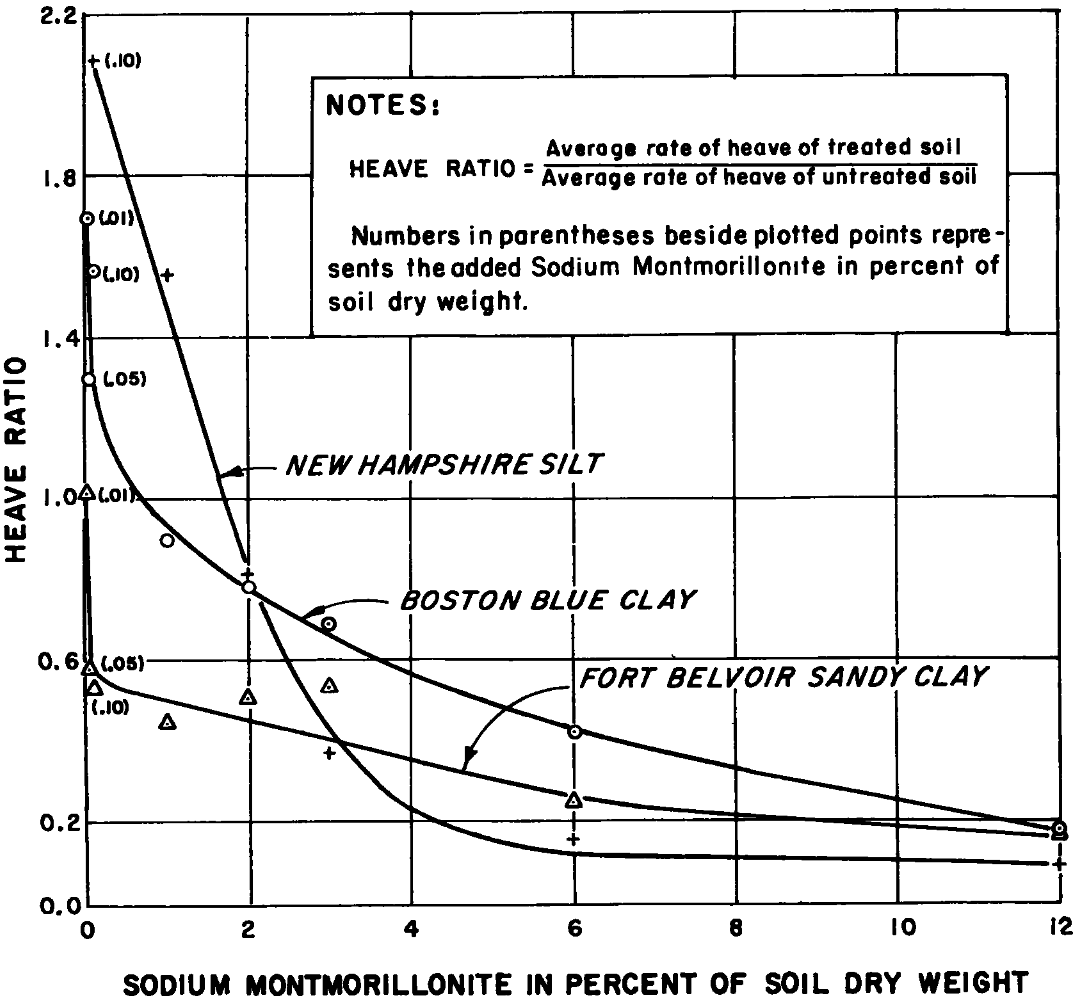


Figure 7. Effect of sodium montmorillonite on frost heave.

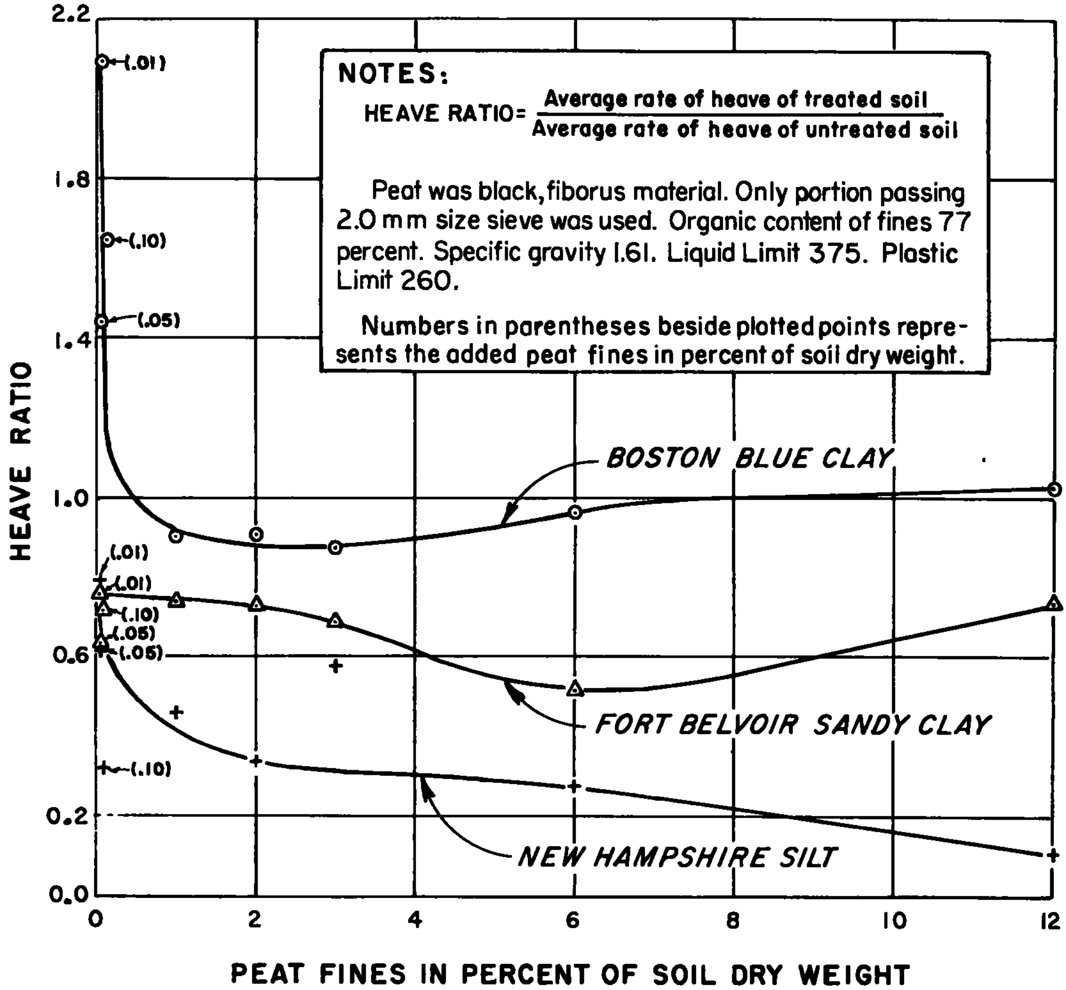


Figure 8. Effect of peat fines on frost heave.

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

[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

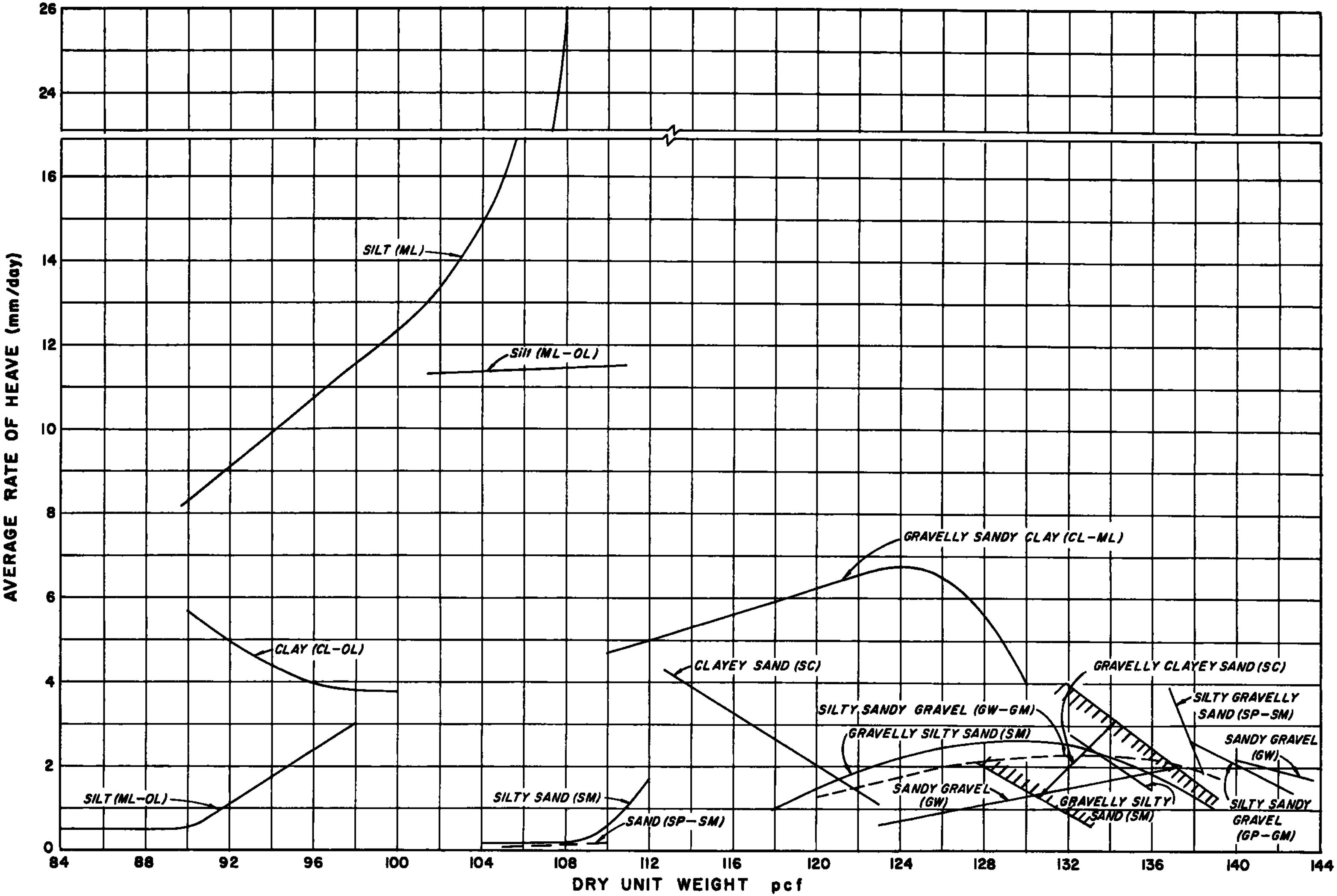


Figure 9. Effect of dry unit weight on average rate of heave.

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

T

CLOSED

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 NH-6 NH-7 NH-8	New Hampshire silt Goff's Falls, New Hampshire	Silt-C (remolded)	ML	100	99	96	58
NH-48 NH-49		Silt-A (remolded)	ML	100	100	85	61
EBT-40 EBT-41	East Boston till-C Revere, Massachusetts	-¾-in. gravelly, sandy clay (remolded)	CL	82	65	46	32
EBT-5 EBT-6 EBT-7 EBT-8	East Boston till-A Revere, Massachusetts	-¾-in. gravelly sandy clay (remolded)	CL	84	72	56	43
SC-4 SC-5	Searsport clay Searsport, Maine	Clay (undisturbed)	CL	100	100	99	80
SC-3 SC-8		Clay (remolded)	CL	100	100	99	80
BC-19 BC-18	Boston blue clay North Cambridge, Massachusetts	Clay (undisturbed)	CL	100	100	100	94
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.

[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

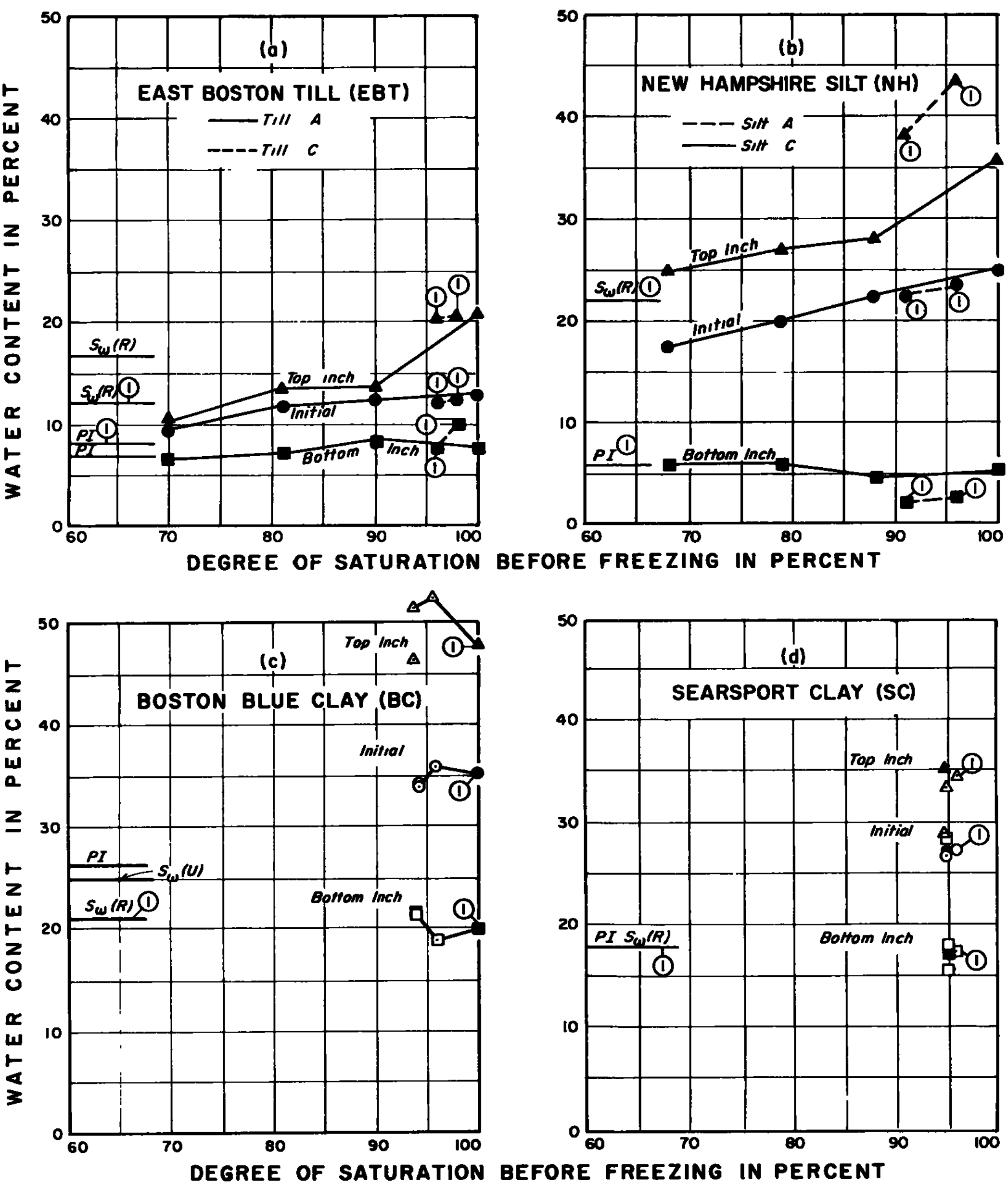
SYSTEM TESTS

0.005 mm	Atterburg Limits[1] Lw	Pw	Iw	Sw	Dry Unit Weight pcf	Water Content Determinations in Percent: Total Specimen Before Freezing: Water Content	G[2]	After Freezing: Frozen Zone: Top Inch	Soil Between Ice Lenses: Percent	Location[3]	Unfrozen Zone or Bottom Frozen Inch	Percent Heave
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,



LEGEND:

- ▲ △ Water Content of Top inch after freezing.
- ● ○ Original Water Content of test specimen before freezing.
- ■ □ Water Content of unfrozen zone at bottom (or bottom frozen inch).
- *PI* Plasticity Index.
- *Sω(R)* Shrinkage limit (remolded).
- *Rω(U)* Shrinkage limit (undisturbed).
- (I) Identifies specimens prepared from a slightly different sample of the same soil type.

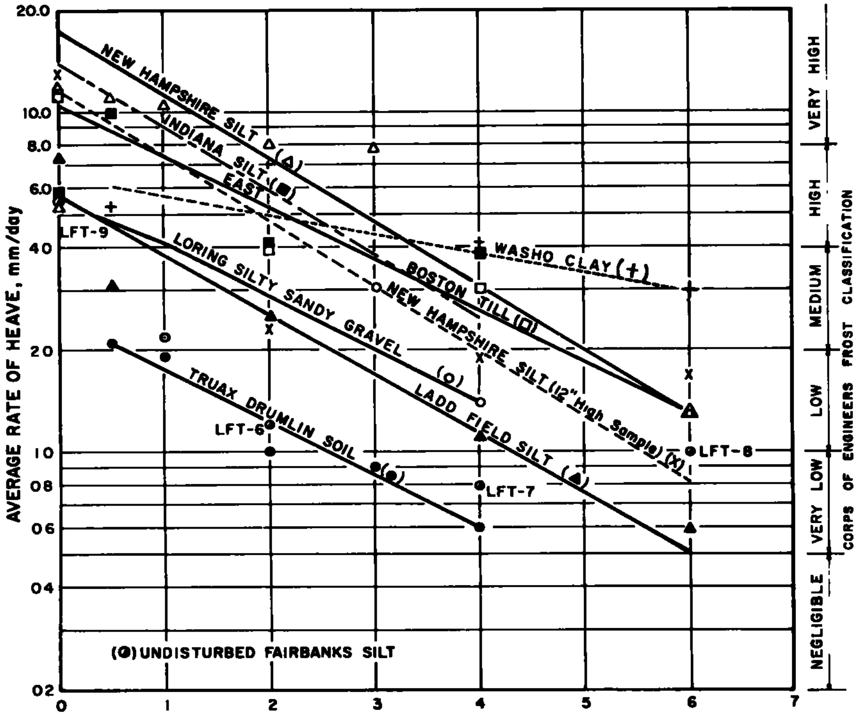
NOTE:

Open symbols denote undisturbed test specimens.

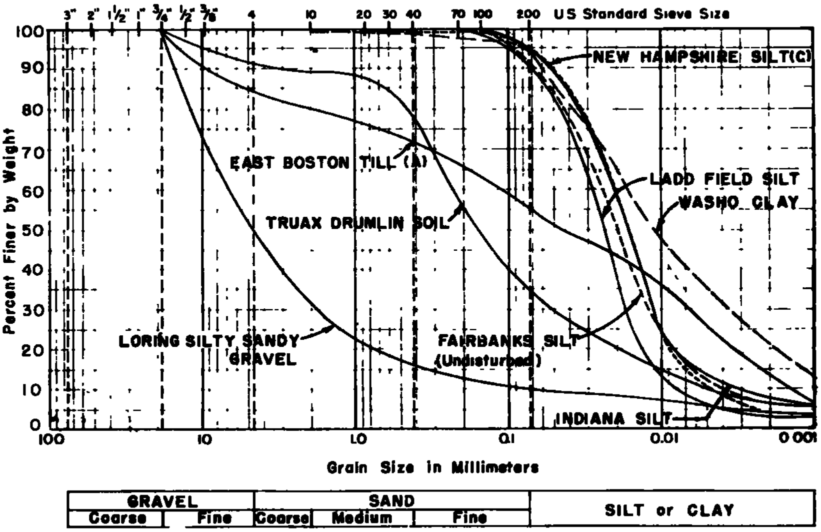
Closed symbols denote remolded test specimens.

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

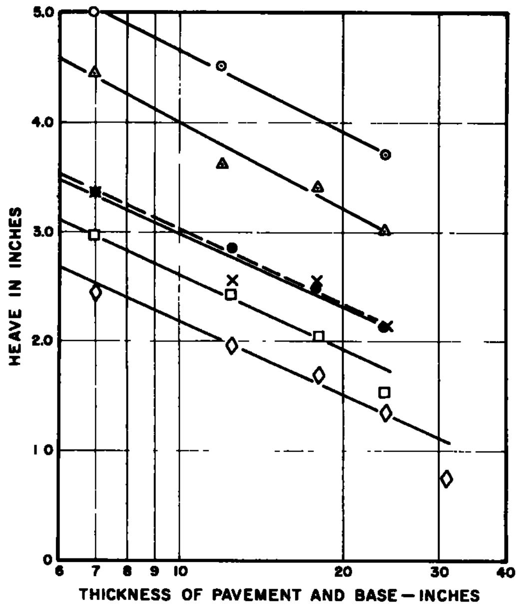


(b) GRADATION CURVES

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
×	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: Molding Water (%)	Untreated Gravels: Dry Unit Weight (pcf)	Untreated Gravels: Finer Than 0 02 mm Size (%)	Untreated Gravels: Average Rate of Heave (mm/day)	Gravels Plus 0 3 Percent Tetrasodium Pyrophosphate: Molding Water (%)	Gravels Plus 0 3 Percent Tetrasodium Pyrophosphate: Dry Unit Weight (pcf)	Gravels Plus 0 3 Percent Tetrasodium Pyrophosphate: Average Rate of Heave (mm/day)	Heave[1] Ratio
	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 (1)	(2)	Symbol Letter (3)	Hatching (4)	Color (5)	Name (6)	Value as Subgrade When Not Subject to Frost Action (7)	Value as Subbase When Not Subject to Frost Action (8)	Value a When N to Fros (!
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 excel-lent	Good	Fair to
		GM d		Yellow	Silty gravels, gravel-sand-silt mixtures	Good to excellent	Good	Fair to
		GM 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
		SM u				Fair	Poor to fair	Not suita
		SC			Clayey sands, sand-clay mix-tures	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 clay-ey 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 dia-tomaceous 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-

E 3

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: hard; soft (of mass, not individual crystals) Structure: clear; cloudy; porous; candled; granular; stratified Color: colorless; gray; blue (examples) Admixtures: 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 columar 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 betwe 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 disti 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 p

(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 } per Part Structure } III, below Color		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

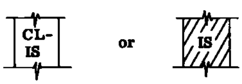
art II above, is a very small in-
il mass. Crystals may be pres-
se forms.

ushed, 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:



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 1/4 and 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

Material	System	Undisturbed: Original Height of Portion Frozen (in.)	Undisturbed: Heave (%)	Remolded: Original Height of Portion Frozen (in.)	Remolded: 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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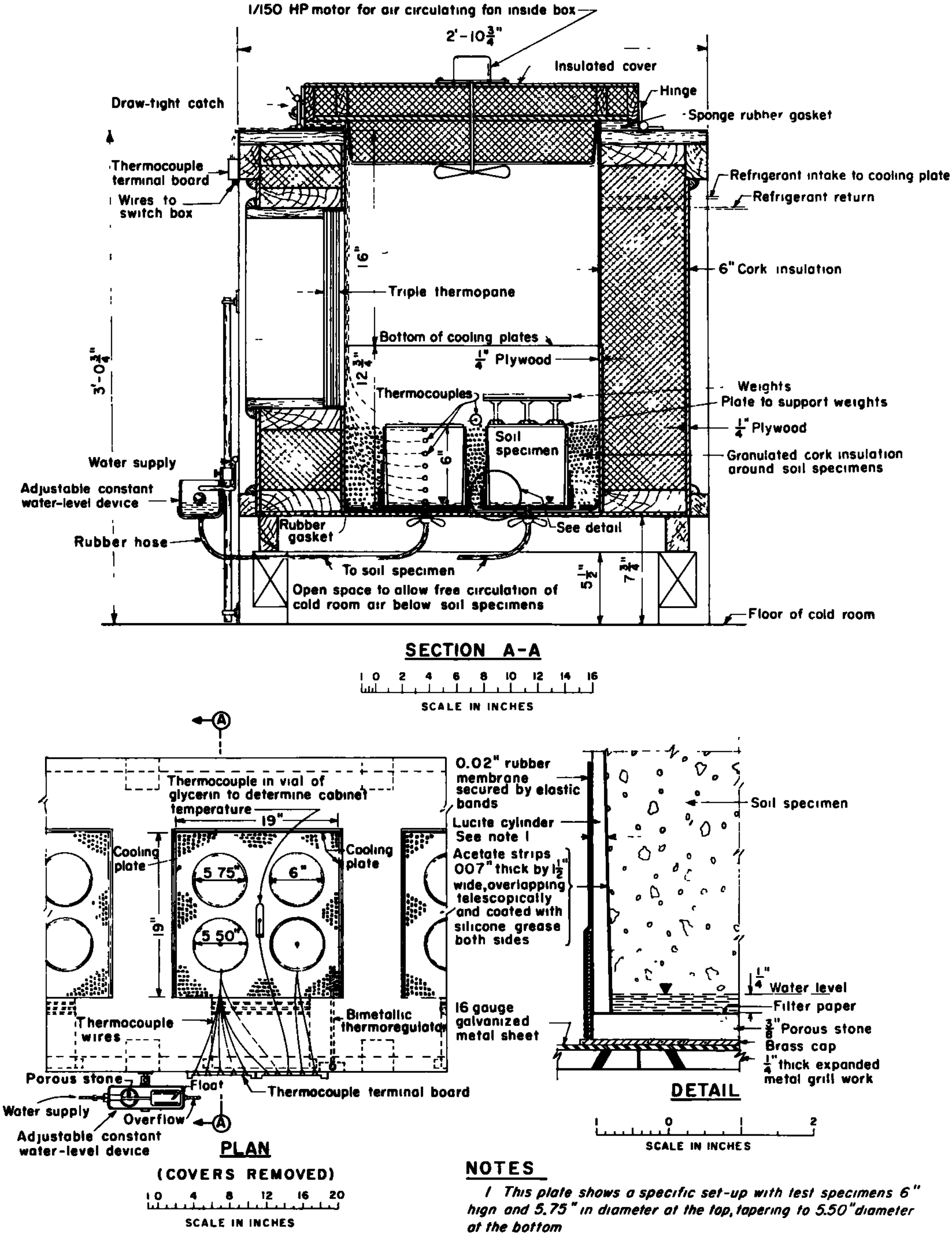
[5]Tests are currently under way to investigate the possibility of speeding up the rate of freeze to hasten the test procedure. The rate of heave results thus far obtained, using ½ inch per day rate of freeze on sands and predominantly coarse-grained soils have checked closely with those obtained with 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

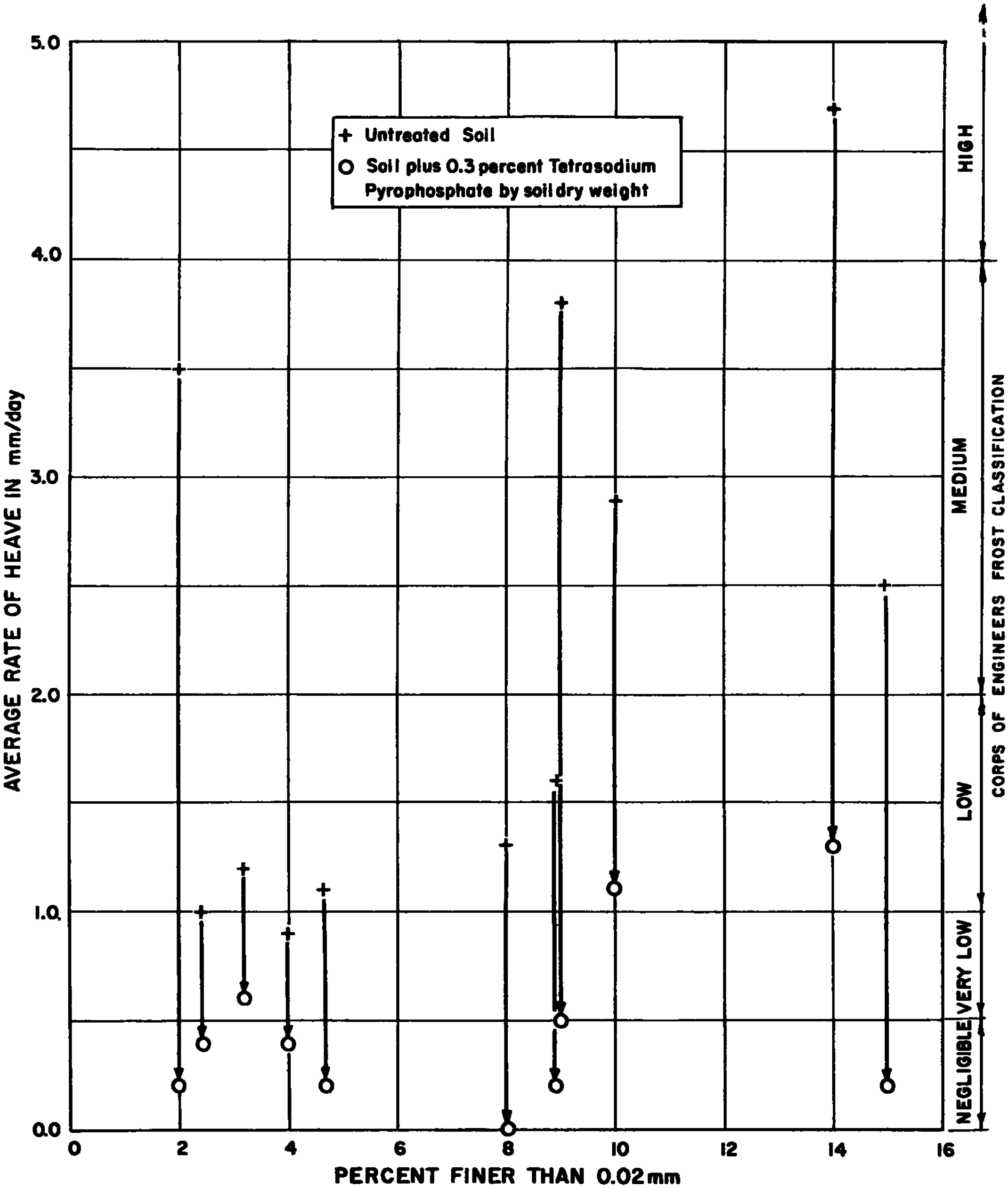


Figure 14. Freezing tests on "dirty" gravels.

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

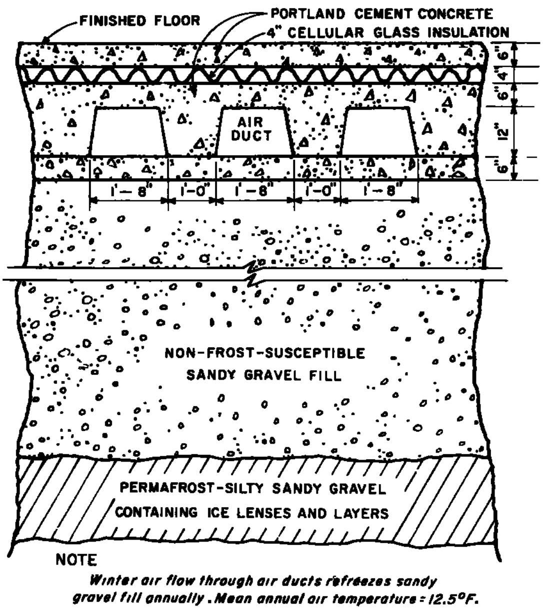


Figure 15. Insulated floor slab design for hangar.

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.