Frost-Action Research Needs

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● SINCE the earliest of pavements, it has been known that ground freezing has produced rough-riding surfaces and often cracked pavements as a result of heaving. In some instances of intense heaving, subsequent thawing has produced such marked softening of the subgrade material that traffic has forced the soil to the surface in the form of mud, resulting in frost boils. Associated with the increase in the numbers and weights of vehicles, there occurred a more widespread and general structural failure of pavements during the spring thawing season, which became known as spring breakup. Only in recent years have many engineers become aware of a general reduction in the load-carrying capacity of roads during and following the thawing of roadbeds. The overall effect of ground freezing and thawing, as it is now understood, is referred to as the effect of frost action. Soils are spoken of as having a high or low frost susceptibility depending on the degree in which heaving, reduction in load-carrying capacity, and other physical properties are influenced by the freezing and thawing processes. Figure 1 indicates the possible effects of freezing and thawing processes on highway and airfield paving.

Many factors influence the intensity of frost action. Climate, location, degree of exposure, and the nature of the ground cover (including the pavement) influence the depth and rate of both freezing and thawing. The nature of the soil its chemical and physical composition and the state of the soil its moisture content and distribution, its porosity and structure govern its thermal properties and influence the nature of freezing and thawing. Further, the composition and state of the soil govern the physical properties of the soil and thus influence the degree in which frost action affects the load-carrying capacity of the soil. Any further improvement of our knowledge of frost action requires detailed investigation of the effect of a number of influencing factors and their relation to each other.

If the fundamentals of frost action were well understood, and means for applying that basic knowledge to design of pavements for given loads were better developed, it should be possible to construct pavements whose behavior with respect to frost action could be closely predicted. There would remain the economic phase of determining which pavements should be built to insure adequate strength for all seasons, and which pavements should be built to a given design with legal provision to restrict loadings during periods of low strength. The problem of frost action in roads and airfields is not one which presents a simple solution.

The majority of problems faced are of such magnitude as to preclude their complete solution within a short period of time. Extensive research efforts both large and small, are required of many engineering organizations. The total of this experimentation is capable of gradually reducing the complexity of frost-action problems.

The purpose of this paper is to present, in generalized statement, some of the research needs relative to the frost-action problem. Formulation of these needs was achieved through extended review and analysis effort. The writers have read several-hundred references, studied the current research programs of a number of important organizations, and discussed frost-action problems with many qualified individuals. Some portions of this review procedure dealt primarily with seasonally frozen ground, others with permafrost. These efforts, added to personal experience, have constituted the background for and shaped the perspective of this presentation.

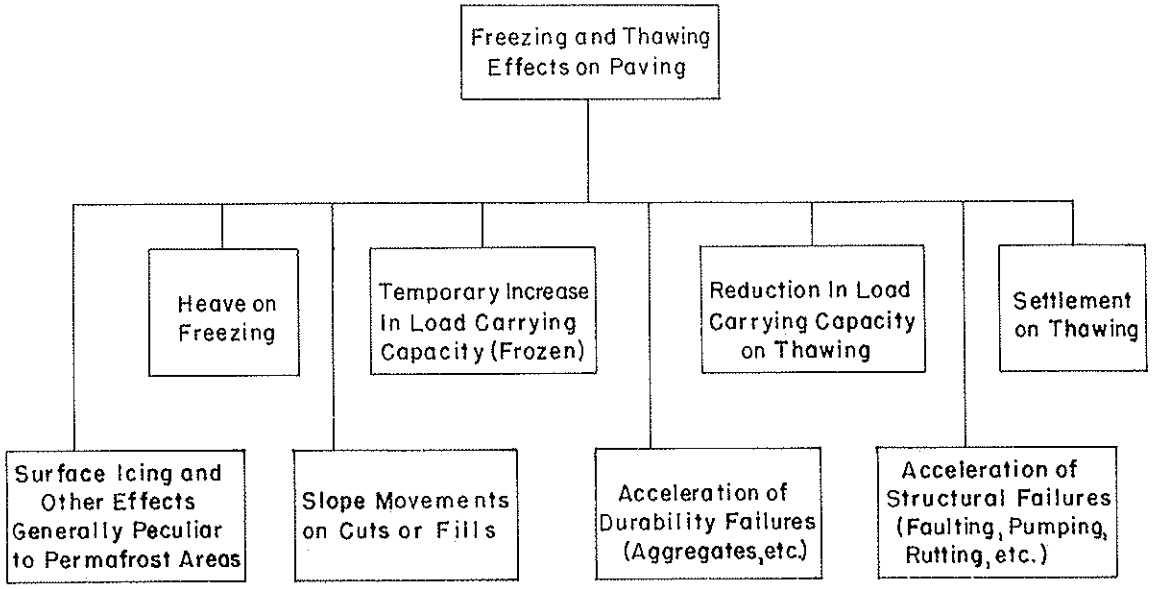


Figure 1.

FACTORS WHICH INFLUENCE FROST ACTION

Because the nature of frost action is complex and involves many variables, no systematic approach to increasing knowledge of the subject can be made without first separating the major variables and then determining the relative influence of them. The factors which influence frost action can be divided into extrinsic and intrinsic, that is, those which are outside but which act directly on the soil and those which belong to or are properties of the soil.

Extrinsic factors are those which determine the nature of the climate and those which modify the effect of climate insofar as climate may influence the depth and rate of frost penetration and the rate and depth of thawing. The intensity of frost action in a base course or subgrade soil is dependent in some degree on the weight of the overlying pavement. Some engineers believe that moving loads also influence frost action, although the writers have found no factual data to support such belief. The extrinsic factors which influence the nature of frost action are summarized in the block diagram of Figure 2.

Intrinsic factors are those inherent to the soil mass which have an influence on frost action. They include the composition of the soil, both chemical and physical, and the state of the soil mass with regard to soil moisture content, density, and structure. They determine not only the thermal properties but also the physical properties. More specifically they determine (1) latent heat of soil moisture, (2) volumetric heat capacity of water and soil, (3) thermal conductivity, (4) specific heat, and (5) thermal diffusivity. They also determine the load-carrying capacity, the ability of the soil to move water to the freezing zone, and thus influence the amount of heave or shrink. The major intrinsic factors are indicated in outline form in the block diagram in Figure 3.

AVAILABILITY AND USEFULNESS OF INFORMATION ON FROST ACTION

Most differences of opinion on engineering matters stem from differences in experiences and in knowledge gained from the experiences of others. First need for any engineering endeavor is for all engineers to have available to them, in usable form, a summary of knowledge gained to date. Some of the knowledge is not readily passed from the more to the less experienced. However, much of the knowledge gained is recorded in published literature. There are now two publications (1, 2) which present in summary form much of the available knowledge on soil freezing and related subject matter. However more work needs to be done with the information which is available and with new information as it becomes available.

Some of the needs briefly stated are:

1. Develop and standardize terminology relative to ground freezing and thawing processes and effects. The Corps of Engineers has recently (3) worked toward this end for their own particular purposes.

2. Make a critical study of presently available information, state fundamental principles where data are adequate to insure their validity, and give such limiting values as can be set from current experience. This has been done within the limits of different engineering organizations, but has not been adequately attempted by a group of highway and airfield engineers whose experiences cross all important limiting boundaries of organizational perspective and geography.

3. Expand present means for collecting, systematizing, and disseminating information as it becomes available. The delay between time of experimental findings and application of these findings to practice is all too familiar. Certainly this difficulty can be reduced by organizations and committees dedicated to the functions of making new knowledge quickly available in usable form. The efforts of the Snow, Ice and Permafrost Research Establishment, Corps of Engineers (4, 5), the Highway Research Board Committee on Frost Heave and Frost Action in Soil (6, 2), and others are recognized. Much valuable reviewing, abstracting, translating, surveying of research facilities and personnel, and sponsoring of meetings and conferences has been accomplished; but many areas of activity remain undeveloped.

STATE OF THE SOIL MASS

The state of the soil mass, that is, its moisture content and uniformity of distribution, porosity and volume weight, temperature, and structure (including not only the arrangement of soil particles in the soil aggregate but also the profile of the ground as determined by mode of deposition and intensity of weathering) all strongly influence the nature of frost action. Of these factors, soil moisture is of dominating influence in determining the magnitude of freezing and thawing effects.

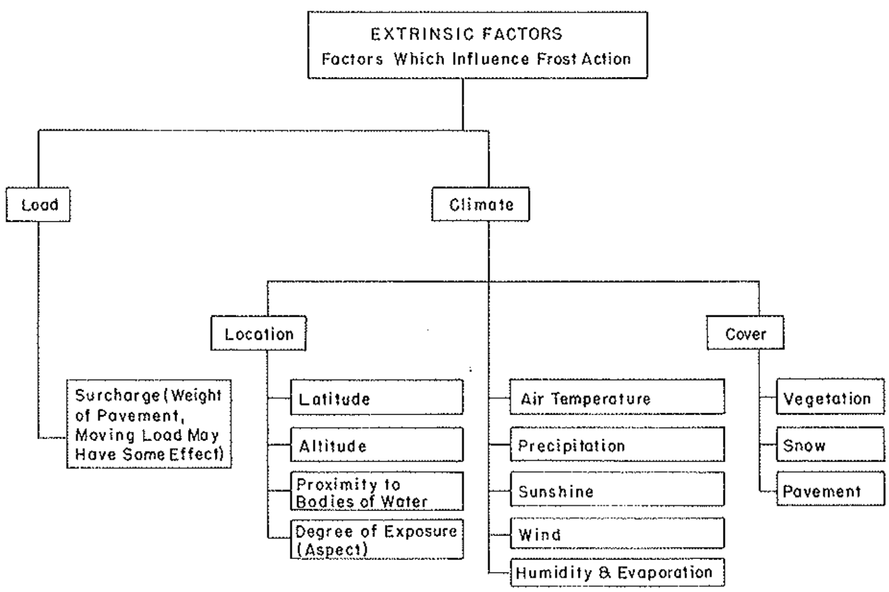


Figure 2.

Effect of Moisture Content and Distribution

The moisture content of soil at the beginning of freezing largely determines the amount of segregated ice and the heaving of the soil on freezing. The increase in amount of soil moisture and change in its distribution through the soil plus the changes in soil density and soil structure which result from ice segregation determine the magnitude of the reduction in load-carrying capacity on thawing. Substantial heaving and very marked reduction in load-carrying capacity can result from freezing of water contained within the soil. That is true for most frost susceptible soils. Thus, an outside source of free ground water is not a requisite for frost action in soils. However, the availability of free ground water near the zone of freezing greatly intensifies all phases of frost action.

The increase in moisture content in the material during freezing is dependent among other things on the initial moisture content. The higher the initial degree of saturation the greater the heave and the greater the reduction in load-carrying capacity on thawing. When free ground water is not available, the moisture content of the soil beneath the frozen layer decreases to a relatively constant value, independent of the initial degree of saturation but dependent on the nature of the soil. Thus, soil water has a double effect. Freezing may increase the available water, so a second freeze may be more detrimental than the first if the water content was low during the first freeze.

The magnitude of the initial degree of saturation necessary to cause ice segregation and subsequent reduction in load-carrying capacity differs for different types of soil, conditions of water availability, and climatic influences. Meager data show no detrimental frost action if the initial moisture content is less than 65 percent of saturation (7, 8). Normal moisture contents of soils in service in subgrades and base courses may range from less than 50 percent for coarsely grained sandy and gravelly soils to almost 100 percent of saturation for the finer-grained silty and clayey soils (9, 59).

The problem here is one of determining: (1) the limits of moisture content at which detrimental frost action begins, (2) the in-service moisture contents of different common base and subgrade gradations, and (3) whether practicable means can be devised to control frost action in various materials by controlling the moisture content of these materials. The following studies are suggested:

1. Expand determinations of the degree of susceptibility of more soils to detrimental frost action. Include soils of different textures and study the effect of different degrees of saturation at the beginning of freezing. This should provide data on the minimum degree of saturation at which ice segregation is possible in various types of soils, without the availability of an adjacent supply of ground water. Such studies should also indicate the relative intensity of ice segregation (and reduction in strength) which occurs in soils of various textural groups at different initial degrees of saturation.

2. Carry on field studies to check field behavior under maximum, minimum, and normal conditions indicated for the above laboratory investigation.

3. Corollary Studies: (a) Develop for practical field use, automatic devices to record changes of in-place moisture contents of subgrades and granular bases. There are at present no entirely adequate instruments for achieving this purpose (6, 10, 11). (b) determine seasonal and long time period ranges of moisture contents of subgrades and bases of different textures. The practical capacity to achieve this is largely dependent upon success in Corollary a. (c) Determine practical techniques of more effectively draining pavement-subgrade combinations or of stabilizing the subgrade materials so that their water-holding capacity and thus their susceptibility to frost action is reduced, or develop some admixture which will prevent the soil from attracting and retaining water in detrimental amounts.

Effect of Porosity and Volume Weight

The intensity of all phases of frost action depends on the amount of water available, and the rate at which it can be drawn to the freezing zone. Both the amount of water contained by the soil and the rate of water movement to the freezing zone are controlled by the nature (size and total volume) of the soil pores. Thus, frost action in a given soil depends on the degree of densification. Some laboratory tests have been made to evaluate the influence of initial soil porosity on the magnitude of heaving and water gain (12, 8). These tests were made with the soil in

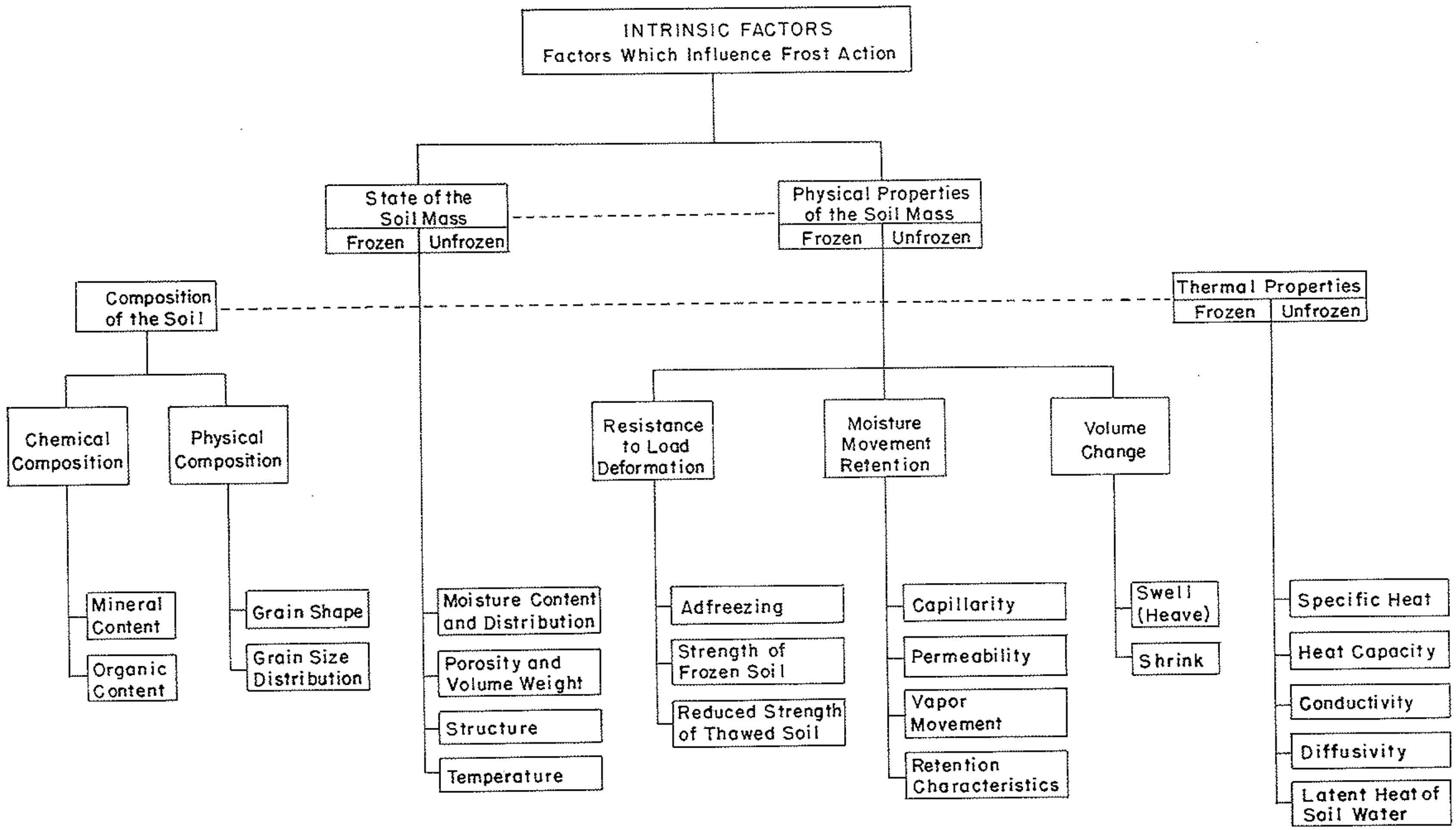

INTRINSIC FACTORS
Factors Which Influence Frost Action
State of the Soil Mass
Frozen
Unfrozen
Physical Properties of the Soil Mass
Frozen
Unfrozen
Composition of the Soil
Thermal Properties
Frozen
Unfrozen
Chemical Composition
Physical Composition
Resistance to Load Deformation
Moisture Movement Retention
Volume Change
Mineral Content
Organic Content
Grain Shape
Grain Size Distribution
Moisture Content and Distribution
Porosity and Volume Weight
Structure
Temperature
Adfreezing
Strength of Frozen Soil
Reduced Strength of Thawed Soil
Capillarity
Permeability
Vapor Movement
Retention Characteristics
Swell (Heave)
Shrink
Specific Heat
Heat Capacity
Conductivity
Diffusivity
Latent Heat of Soil Water

Figure 3.

contact with a water supply. The results indicate that well-graded gravelly soils having sufficient fines to permit detrimental frost action show an intensification of ice segregation with increase in degree of compaction up to a critical density about equal to 95 percent of modified AASHO maximum density. Above that critical density, further densification reduces ice segregation. Intensity of ice segregation increases in inorganic silt soils right up to 100 percent of AASHO modified maximum density. Uniformly-graded frost susceptible sands are little affected by variation in degree of compaction (see Fig. 4).

As in the case of soil moisture, density may have a double effect. Although a soil may be compacted to a density in excess of the critical density (maximum ice segregation), a single freezing may cause sufficient ice segregation to reduce the density and increase the porosity so that subsequent frost action effects become more intense.

The external load (surcharge) carried by the soil also may influence the magnitude of heaving (13, 8); thus, the density of the soil above the freezing zone may have some small influence on heaving.

The problem is one of determining the critical porosity (or density) at which different soils show maximum intensity of frost action under different degrees of saturation. Possessing such information, compaction specifications for subgrades and granular bases can be written to require a degree of compaction consistent with the best performance. That best performance should result in the least permanent change from the as-built to the in-service condition and from season to season after adjustment to the new environment. The following studies are suggested:

1. Continuation of laboratory studies on a wide range of soil types to determine the influence of degree of densification on not only ice segregation and heaving but also on magnitude and rate of reduction in load-carrying capacity following the beginning of the thawing period.

2. Supplementary field studies to permit correlation of and make possible better interpretation of the data from laboratory tests.

3. Determination of influence of degree of densification on soils treated with various admixtures which have possibilities for the reduction of frost effects or the improvement of strength properties.

4. Corollary study: There is currently in development a method using radioactive materials in the determination of soil density (10). There is need for continuation of development of in-place test methods and apparatus to determine soil density and periodic and seasonal changes in this density.

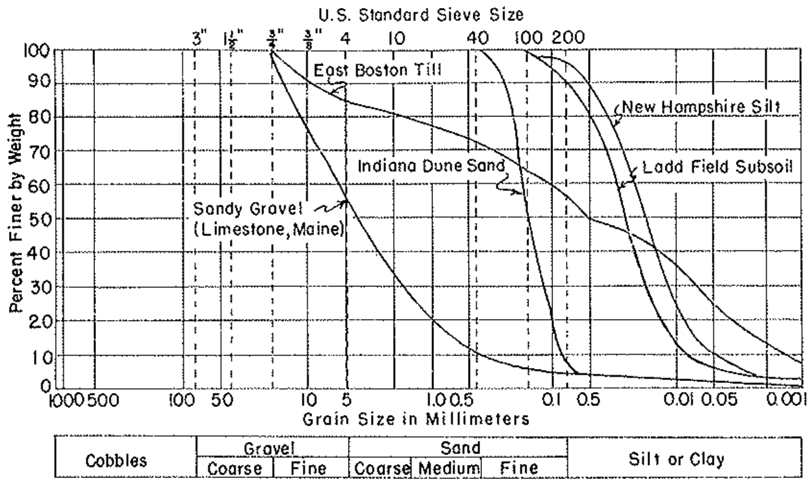
EFFECT OF STRUCTURE

Unfrozen State

Normally the term structure is used to denote the arrangement of soil particles into soil aggregates forming granular, prismatic, blocky, platy, or other types of aggregation. Structure is used here as a comprehensive term which also includes arrangement of soil into (1) large irregular masses of different textures; (2) strata of different texture; and (3) into soil horizons which are developed in the natural processes of soil formation.

Structural arrangement and rearrangement of soil into aggregates occurs only in the upper few feet which also constitutes the frost zone. Aggregation occurs only in clayey soils. Aggregation has many effects, one of which is the formation of fissures along the boundaries of the aggregates (13). These fissures give clayey soils the capacity to contain free ground water in much the same state as water in sands, except in lesser quantities. That ground water may aid appreciably in producing intense frost action.

The existance of textural differences in soil may create nonuniform soil-moisture conditions, that is, local zones of saturation or bodies of ground water (see Fig. 5). The occurrence of very thin layers of silt or clay in sand (Fig. 6) vary in lake deposited materials, textural differences from one soil horizon to another, pockets or "lenses" of sand, silt, or clay, any contact boundary of deposits which differ in texture, aggregation or porosity (and thus differ in ability to retain or transport water and to conduct heat) are examples of conditions where soil struc-



Material	Maximum Dry Density-pcf.
East Boston Till	131(2)
Indiana Dune Sand	107(1)
Ladd Field Subsoil	100(3)
Sandy Gravel (Limestone, Maine)	139(1)
New Hampshire Silt	107(2)

(1) Providence Vibrated Density
(2) Modified AASHO Method
(3) Standard Proctor Method

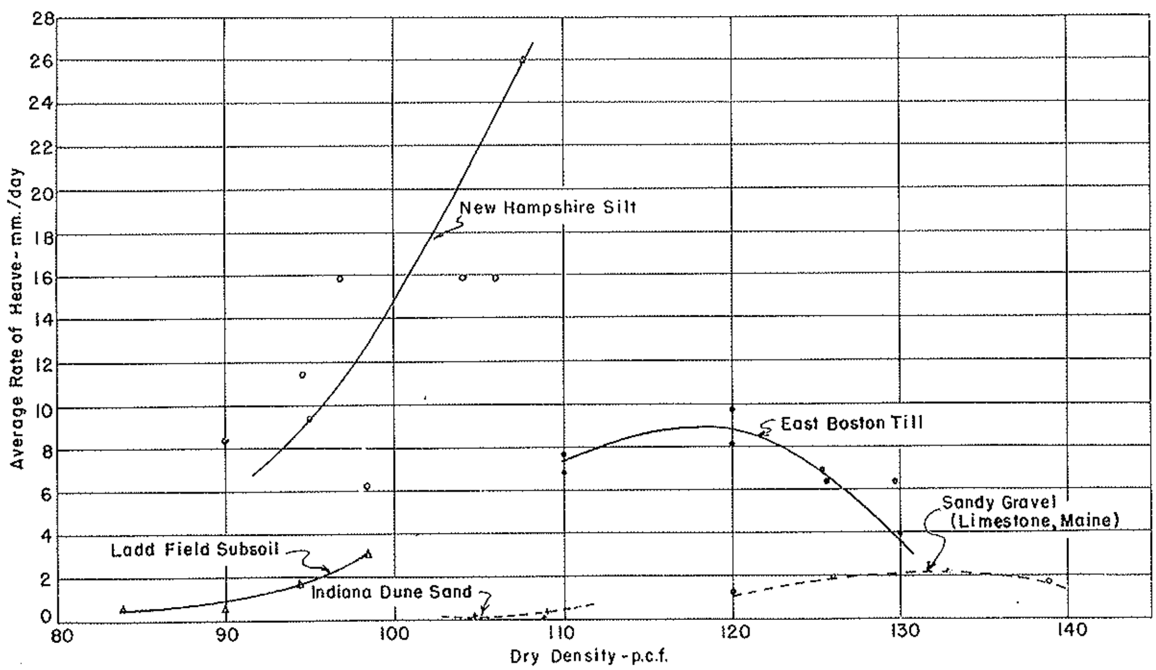


Figure 4.

ture may foster differential frost action (14, 15, 13, 16).

Some investigators have found it practical to correlate frost-action intensity with pedological soil series and type (17). Others (14, 18) have correlated geologic origin and degree of frost susceptibility. The occurrence of ledge rock, boulders, or stumps within or near the zone of freezing has been recognized to be productive of local and often intense frost action.

The effects of stratification, as in varved soils, on flow of moisture to or from a freezing zone have received only limited attention (13, 19).

Not only does soil structure influence frost action, but frost action may modify soil structure. Freezing and thawing may, due to pressures and fissuring produced by ice formation, foster development of soil aggregates and permanent fissures. Intense frost action of the type found in permafrost regions may produce a stirring or mixing of soil materials

(20). Fossil remains (such as involutions in soil horizons) indicative of intense frost action have been observed in areas on the perimeter of the most recent glaciation in the United States.

Frozen State

Frozen ground assumes a structure which reflects the intensity of the processes of freezing and thawing on the inherent nature of the soil and its associated water conditions. The influence of environmental factors of slope and cover are sometimes strongly reflected in such structure.

Seasonally frozen ground is usually classified according to the nature and distribution of the ice it contains. Massive or homogeneous structure denotes soil water frozen in the soil pores and normally occurs in coarse-grained soils, and in fine-grained soils of low moisture content, or those frozen at a rapid rate. Stratified or discontinuous-type structure contains visible ice segregation in lenses, wedges, veins, or needles and is usually associated with wet, fine-grained soils. However, appreciable ice segregation is observed in coarse-grained soils under conditions of great water availability and favorable rates of freezing, particularly cyclic freezing and thawing.

The Corps of Engineers (21) has developed a preliminary nongenetic classification and description system for frozen soils, which is intended to contain adequate detail for engineering purposes. This classification subdivides homogeneous structure into: (1) well-bonded frozen soils in which the ice firmly cements the material together and (2) poorly-bonded to friable materials. Under the stratified or heterogeneous-type structure this system notes several different types of ice concentrations: (1) stratified ice lenses or layers, (2) irregularly oriented lenses, veins, etc., (3) coatings of ice on individual particles, and (4) individual ice crystals within the soil mass. The occurrance of these various subtypes of frozen structure has been correlated in a general way with soil gradation and freezing conditions.

Perennially frozen ground (Permafrost) structures are normally classified on the basis of continuity of the frozen mass below the active layer. One type is continuous, meaning that the ground mass is frozen to full depth without unfrozen inclusions. The other is discontinuous, and contains alternate layers of frozen and unfrozen materials, or islands of frozen ground within an unfrozen matrix. Permafrost has been mapped on an areal scale as continuous, discontinuous, and sporadic (22, 23). The structure of the permafrost proper may be homogeneous or stratified, just as the structure of seasonally frozen ground. If the heterogeneous structure is such that large ice masses are present, description and classification must deal not only with the distribution and shape of the ice accumulations but also with the characteristics of the ice proper.

Frozen-ground structure may often be identified through surficial polygonal delineations, which are usually underlain by wedge-like ice masses. Theories differ as to the formation and growth of these and other types of "patterned" ground attributed to freezing and thawing influences. The various types of patterned ground and their possible origins have been summarized (24). Recent studies (25) have devoted attention to the airphoto identification and classification of various of these patterns as indicators of soil texture, moisture conditions, and the presence of permafrost. One very recent but unreported study by the U. S. Geological Survey examined the genesis and morphology of ice wedges in arctic Alaska.

The problems associated with structure as a factor in frost action are twofold. There is need for (1) better recognition of different soil structure conditions and their potentials for producing frost action and (2) determining the most effective methods for preventing detrimental frost action in the various types of soil structure. The following studies are suggested:

1. The efforts to formulate a practical engineering classification of soil structure in terms of its influence on the intensity of frost action should be continued and expanded. The classification should envelop both frozen and unfrozen ground so a correlation could be made of structure and water availability to permit better prediction of the relative amounts and distributions of ice. Further study of patterned

ground common to permafrost regions is justified, as such study will reveal additional details of the association of such patterns with soil texture, drainage conditions, and depth to permafrost. Surficial evidences of ground-ice formation and modification, such as polygonal ground, are particularly adaptable to further analysis and classification as indicators of ground condition.

2. Practical, in-place field studies to determine, for an extended time period, the relationship between various soil structure types and intensity of frost action are also needed. Such studies would yield useful data, pertinent not only to natural soil structure but also to artificial soil structures consisting of bases of various texture on subgrade soils of various textures.

3. Experimental studies to determine the feasibility and effectiveness of various methods (for example subgrade drainage) to reduce or eliminate frost action for various soil structure conditions are required.

4. Future emphasis should also be placed upon the effects of stratification on water movement, particularly capillary movement. Variations in moisture content with height above the water table and rate of capillary flow are especially needed for such soils as silts with organic streaks or laminations as are common to permafrost regions.

Effect of Temperature

If there is to be improvement in accuracy of prediction of ground freezing and thawing from climatic data, there must be available more adequate data on depth of ground freezing and thawing to use as bases for correlation with climate. Data on depth of the line of freezing and thawing taken at frequent time intervals over a long period of time for a variety of soil types and a wide range of soil states under various thicknesses of different types of pavement and surface vegetation and snow cover would be necessary to complete correlation. Some recent data (26, 7, 27, 28) have covered these variables over a brief time period.

It is obvious that because of difficulties of observing depth of freezing with present methods, data on depth of freezing and thawing are costly to obtain. Therefore, until better methods are available, correlation must be through the use of soil-temperature data.

Published data relative to soil temperature is voluminous. However, reviews (1, 2, 29) have shown a meager amount of soil temperature data useful in the study of frost action in bases and subgrades for highway and airfield pavements. Generalized charted data are available showing average annual and maximum annual depths of frost penetration. However data on type and state of soil, type of cover, and conditions of exposure all needed to make the data really useful, are lacking.

This brings out the obvious need for reliable methods for obtaining soil temperature data, and installations for collecting temperature data. Both recording-type thermometers and thermocouple installations can yield data of sufficient accuracy for the primary needs of knowing where and when soil freezing and thawing occur. Resistors are available which can distinguish frozen from unfrozen ground. The problem concerning data on ground freezing and thawing is therefore, one of determining depth of freezing and thawing and accurate appraisal of conditions of exposure, ground cover, and subsurface soil type and state which, together with climatic conditions, have been responsible for the conditions of freezing and thawing.

The following suggestions are offered as means of extending the field of useful knowledge in this regard: (1) Install temperature-measuring apparatus in locations of common or typical conditions. (2) Determine depths of freezing and thawing by means of excavation or by electrical resistance means. (3) Evaluate pavement type, soil type, and soil state for places of temperature or ground-freezing observations. (4) Corollary Studies: (a) Continue development of automatic temperature-recording devices for installations for frost studies and (b) develop automatic devices for determining time of soil freezing and soil thawing. Possibly present resistance type devices can be further developed so they can record automatically when freezing and thawing occur.

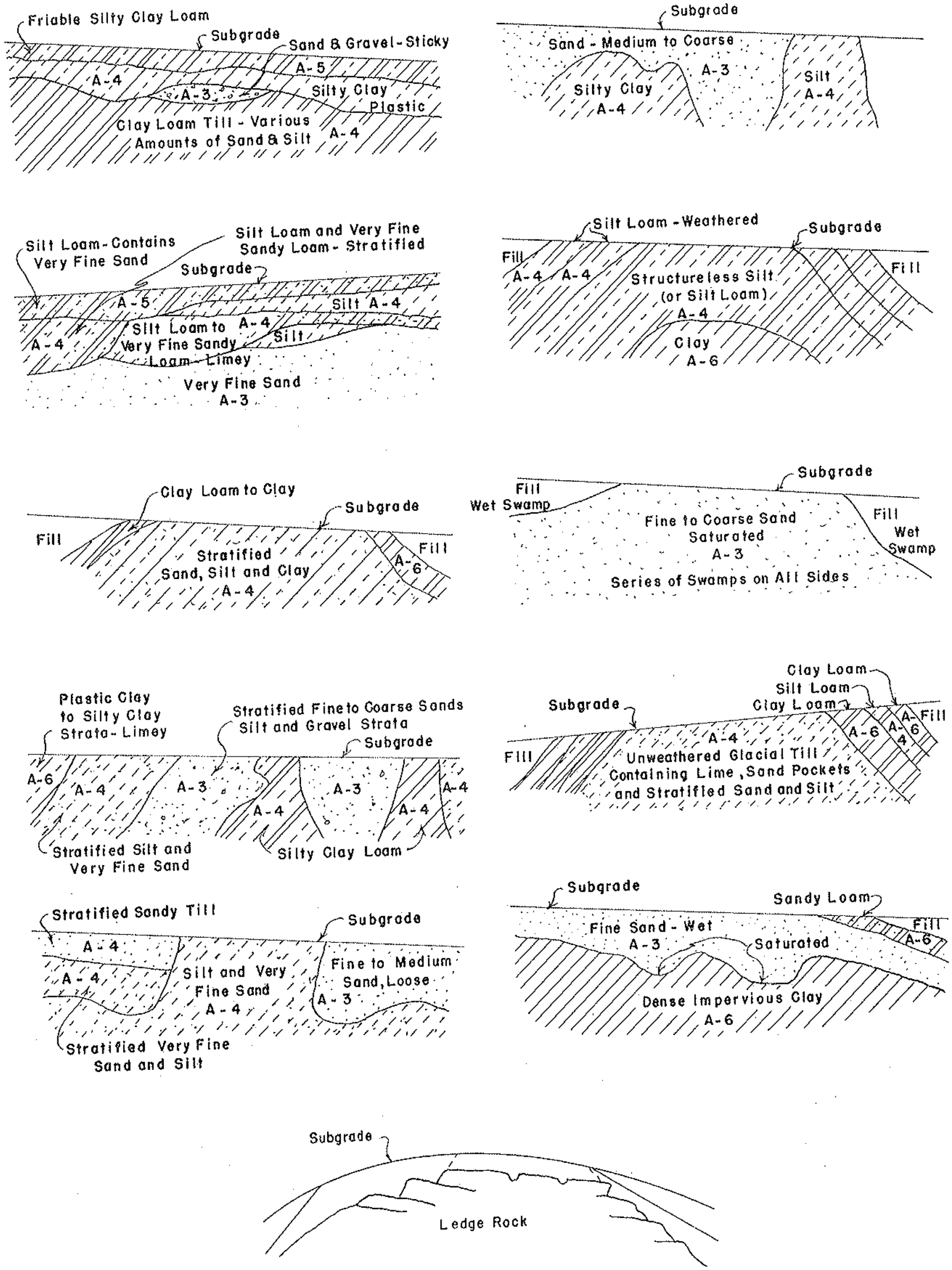
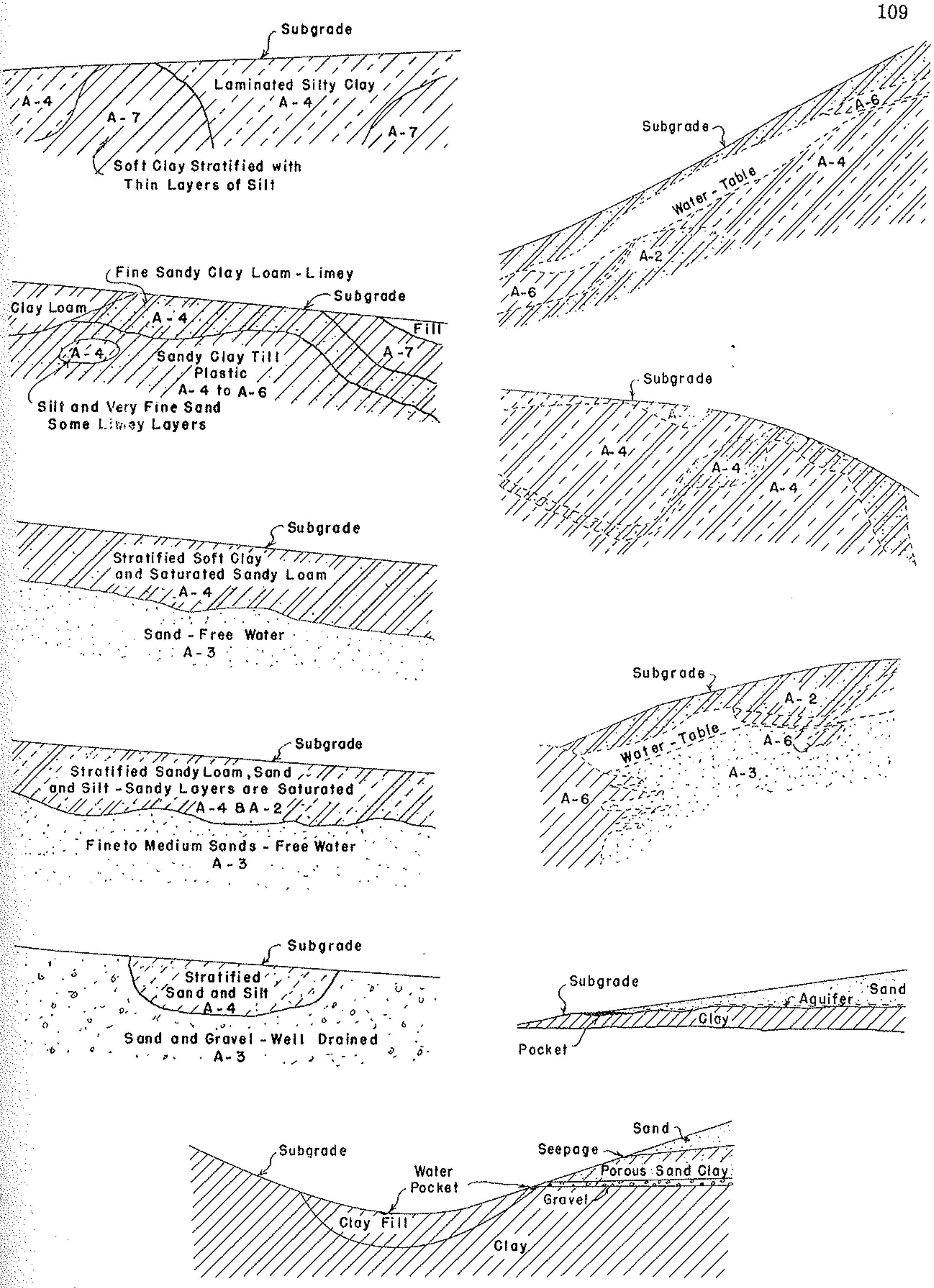


Figure 5. Soil Profiles in Which Detri-



mental Frost Heave has been Observed.

COMPOSITION OF THE SOIL

Water and temperature are the dynamic elements in frost action. The soil solids may either facilitate or restrain movements of water and freezing temperatures, both of which are necessary for frost action. The problem as it concerns the soil solids portion of the soil mass is to determine which qualities or characteristics of their makeup have the greatest influence in producing or in preventing frost action. In attempting to find those qualities, it is necessary to relate frost susceptibility to the inner or chemical composition, as well as to the outer or physical composition, for collectively they determine both the thermal and physical properties of soil.

Chemical Composition

Chemical composition is usually expressed in terms of content of different minerals which make up the soil fines and organic matter. Clay minerals differ greatly in the degree in which the particles adsorb water to their surfaces. The clay mineral montmorillonite, for example, has high surface area and great capacity to adsorb and hold water in a state not considered fluid or mobile enough to feed growing ice crystals. The mobility of the water is governed in a large measure by the nature of the adsorbed ion. Kaolinite, on the other hand, has relatively low adsorption capacity and thus can contain a more mobile supply of water. Thus, for soils made up entirely of fine particles, one being composed largely of kaolinite-type mineral would be more susceptible to segregation of water and detrimental freezing. However, although several investigators have agreed on this, they also agree that, regardless of the types of minerals present, if the soils are dominantly fine grained they are sufficiently susceptible to frost action to be considered dangerous.

The problem becomes one of determining the influence of mineral (and organic) content on frost action in sandy and gravelly soils which contain borderline proportions of fines. Investigations made to date have failed to show clearly the effect of mineral and organic contents, singly or in combination.

It appears that chemical composition may need to be analyzed not only in terms of mineral and organic makeup but also in terms of the nature of the ion carried. Also, the chemical composition needs to be interpreted in terms of the proportions of fines of different types and their joint influences on the mobility of soil water with respect to forces operating in the freezing and thawing processes.

The increasing use of differential thermal analysis, X-ray diffraction and colorimetric methods to identify type and proportions of clay minerals; various methods including the electron microscope, to determine relative grain shape and size distribution; and methods for determining the affinity of soil particles for water, indicate these tools have potential use as aids in determining why soils differ in degree of frost susceptibility.

Physical Composition

The most-common means for distinguishing frost susceptibility of soils is to relate intensity of heaving with size distribution in the fine-grain fraction. This has been done on a more or less general basis through some soil classification systems, (and for a specific soil in terms of the percentage passing the No. 200 sieve or the percent finer than 0.02 mm. in diameter).

Some use has been made of the pedological system as a means of defining soils of low frost susceptibility (17, 30). The results of testing and experience with sands of some natural soil series have shown them to be suitable for subbases and bases where low frost susceptible materials were desired.

Percent of Fines. The percent passing the No. 200 sieve has been used most widely by highway departments to relate to frost susceptibility. Maximum values specified for low-frost-susceptibility materials normally range from about 5 to 10 percent. This is in substantial agreement with military-airfield practice, which specifies maximum values of 3 and 10 percent finer than 0.02 mm. in diameter for well-graded and uniformly graded gravels, sands, and sand-gravels, respectively. The Corps of Engineers (31) has further classified frost-susceptible soils according to texture into four F groups of increasing susceptibility, the group F4 having greatest susceptibility.

Swedish practice is somewhat similar to that of airfield practice in that it permits a higher proportion of fines in the more-uniformly graded sediments than in well-graded morainic materials. Generally, the finer the grains (in the fine-grain fraction), or the greater the proportion of colloidal sizes, the more effective the fine soil fraction is in producing ice segregation (8). The presence of plasticity is an indication of the possibility of greater ice segregation.

The standard specifications of several state highway departments and federal agencies recognize frost susceptibility, although indirectly, in the grading requirements for granular bases and subbases, as they reflect experience in areas where frost action has been a serious problem.

Size and Proportion of Coarse Materials. The focus of attention on proportions and types of the smaller frost-susceptible sizes has tended to obscure the influence of the coarser particles, both as to their influence on ice segregation and on stability following thawing. The latter is brought out under "Resistance to Load Deformation."

The proportion of stone or coarse aggregate bears a definite relation to the nature of frost action. Laboratory tests (8) have shown that for a given soil, increasing the coarse aggregate content decreases the rate of ice segregation in proportion to the corresponding reduction in fines. The same tests showed formation of ice lenses on the under side of the coarser aggregates, similar to those found in nature under stones.

The influence of the overall grading of the coarse fraction (retained on No. 200 sieve) on the decrease in strength following thawing has been largely neglected. That is true particularly with respect to their use in granular bases covered with thin bituminous surfacing.

Although durability and wear tests are in common use for aggregates for concrete and bituminous surfaces, it has been a common concept that any gravels which met grading and plasticity requirements are suitable for use in granular base courses. Some engineers are now questioning the suitability of aggregates which appear to degrade under construction traffic or to disintegrate under freezing and thawing under service conditions and thus foster more intense frost action than that which is expected from preconstruction tests.

To summarize, much has been done to refine and improve simple grain-size distribution criteria for use in definition of frost susceptibility. The present criteria are certainly much more accurately descriptive than in the past. However these criteria are still not able to evaluate the effect of the character of the finer fraction and thus lend themselves to further refinement and study.

The problem associated with the effect of composition on frost action is essentially one of means of identification of materials according to their susceptibility to frost action. Knowledge of the basic chemical composition may aid in identification. However, it is evident that evaluation of chemical composition must go hand in hand with evaluation of the effect of the grain-size distribution within the fine fraction.

The following field and laboratory studies are suggested:

Chemical Composition. 1. Determine the relative effect of organic matter, particularly in natural sands which are being used more frequently as bases and subbases under rigid and flexible types of pavement, respectively.

2. Continue study of chemical composition of the soil grains as a means of identifying frost-susceptible soils. This may involve differential thermal analysis, X-ray diffraction, colorimetric and electron-microscopy methods. The study should go beyond mere identification of type of mineral; it should include the effect of various ions. The influence of a mineral may differ markedly with the proportions present; hence, evaluation of the effect of chemical composition should be in terms of the grain-size distribution within the fine fraction and the proportions of fines in the total material. Along with fundamental research, a practical type of research studies on materials based on their parent rock may have value. For example: Of soil fines derived from quartz,

feldspar, limestone, schist, which are associated with the least frost action? Which clays are the most effective in small amounts sodium, hydrogen, calcium, potassium? Are there different critical grain sizes for different chemical compositions? To what extent are fines having plasticity a measure of their frost susceptibility in granular mixtures?

which are productive of frost action and (2) relate wear and soundness with degradation under construction and in service traffic with frost susceptibility.

THERMAL PROPERTIES

Soil freezing occurs when sufficient heat is withdrawn to reduce the temp-

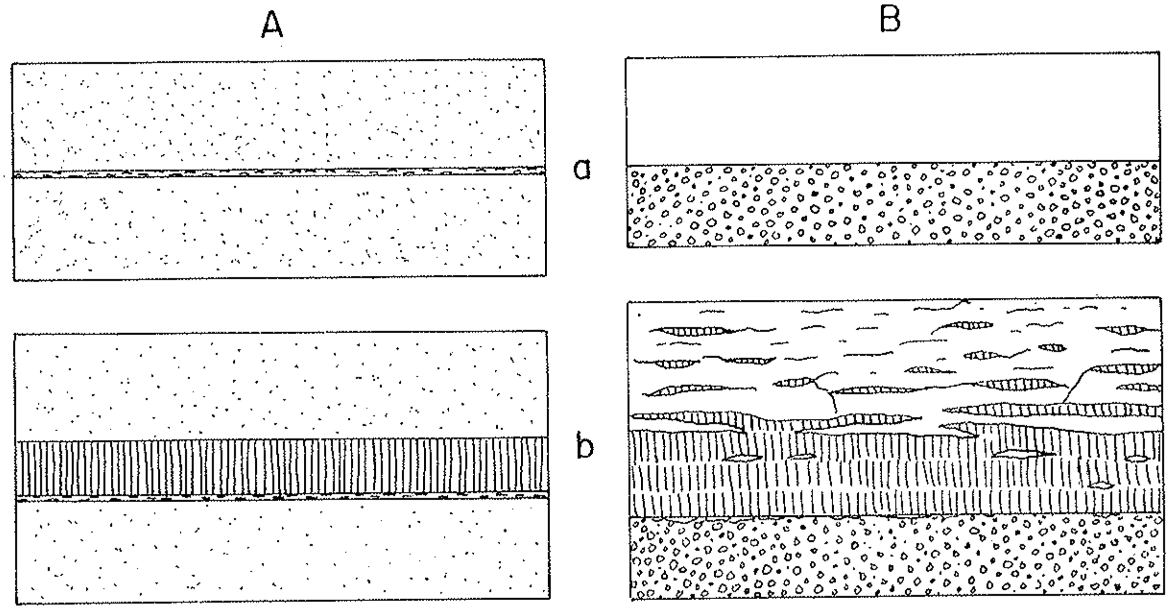


Figure 6.

Physical Composition. Continue studies to evaluate the influence of grain size distribution, primarily on materials which may be suitable for subbases and bases.

1. Are the maximum permissible proportions of frost susceptible fines identical for well-graded materials having different maximum size? For example, maximum proportions of fines for a given degree of frost susceptibility for a fine aggregate sand-gravel (all passing No. 4 sieve) compared to maximum proportions for similar frost susceptibility in a 3-in. maximum size material.

2. Relative frost susceptibility of different gradings from contained water at various degrees of saturation (without a source of free ground water).

3. Relate grain-size distribution in both coarse and fine fractions more closely to load-carrying capacity in before-frozen and after-thawed conditions.

Corollary Studies. (1) Develop quick field aids to identification of soil fines

erature of the mass to a point where at least a part of the soil water solidifies. Finely grained soil first solidifies at some temperature below 32 F. The soil continues to gain strength as its temperature is further reduced and more soil water freezes (32, 31). The rate at which the freezing temperature moves into the soil (diffusivity) is dependent on: (1) the specific heat of the soil water and of the soil solids; (2) the amount of heat which must be removed from a given volume to reduce the temperature to freezing (volumetric heat capacity; temperature difference); (3) the latent heat of the soil water (which depends upon the percentage of the soil water frozen at a given temperature); and (4) the rate at which the heat can be conducted through the soil (conductivity).

Knowledge of these thermal properties of soils and pavements plus climatic conditions makes possible calculation of depth and rate of freezing in unfrozen soils and depth and rate of thawing in frozen soils. Much work has been done in recent years (33, 34, 35, 36) in the study of thermal properties of soils and factors which influence those properties. These studies have evaluated more adequately than in the past the relationships between thermal properties and variations in temperature (above and below freezing), moisture content, porosity, texture, composition, and natural structure.

Difficulties have long been encountered in laboratory determinations of soil thermal properties. Principal among these difficulties is the migration of moisture under maintenance of an applied thermal gradient. The increase in temperature at the hot face produces an increase in vapor pressure of the soil water, a decrease in surface tension and viscosity, and a flow or a vapor movement of moisture to location of cooler temperature, lower vapor pressure, and higher surface tension (37, 38). The establishment of this undesirable moisture gradient may be minimized, but not eliminated, through use of small, short-time-applied thermal gradients, the effects of which are measured over an increment of thickness located as far as is feasible from the hot and cold faces.

A number of field or in-place techniques of determining soil thermal properties are being developed (39, 40, 29). These techniques employ a heater, usually electric, at whose surface temperature change is measured under controlled energy output. If experimental time is short, moisture migration is slight. The theoretical heat-flow equations for a source of no dimension within a homogeneous, infinite medium are at variance with actual conditions; but these equations may be applied and errors kept very small by proper attention to such variables as time interval and effective radius of measurement. The thermal probe and the cylindrical heater have been studied as line heat sources and small spherical shapes as approximations of a point source.

The problem associated with thermal properties is to develop reliable thermal data on various types of soil existing under a wide range of conditions of moisture content and density in both frozen and unfrozen state and also to develop thermal data on various types of cover, including pavements and bases. The data need to be sufficiently inclusive that practical calculations can be made for almost any condition encountered.

The following suggestions are made for future studies:

1. The correct value for latent heat of water depends on the proportion of the soil moisture frozen at different temperatures below 32 F. Knowledge of the freezing point, or rather the range of freezing temperature of soil moisture, is inadequate. Studies of a highly practical nature need to be undertaken with typically fine-grained materials of common occurrence to ascertain the proportions of moisture frozen within these materials at various sub-32-F. temperatures. Not only should moisture, density, and rate of temperature change be incorporated as variables in these studies, but also the character of the clay minerals present and of the adsorbed ions should likewise be incorporated. These determinations of percentage of water frozen could be translated into further engineering meaning by conducting strength tests on the soil specimens at various sub-32 F. temperatures (the percent moisture frozen at these temperatures being known).

2. Values of the thermal properties at conditions of low density and for high degree of saturation are relatively unknown. This is of course largely due to inadequacies of laboratory thermal instrumentation. Since many of our more serious thermal problems deal with wet, low-density materials (particularly in the permafrost regions), efforts should be made to improve instrumentation and to study these ranges.

3. The increase in thermal conductivity expected from the presence of ice strata in soil may be further increased where consolidation of soil occurs between ice strata or counteracted where freezing is associated with a general loosening of the soil. The effect of various ice-stratified frozen structures on thermal values can well receive more study.

4. Laboratory determination of thermal properties is further complicated by moisture migration, which is activated by

application of a thermal gradient. Techniques of minimizing or compensating for moisture migration can well receive additional attention.

5. Continued development of the thermal probe and other in-situ thermal instruments to permit field measurement of thermal values representative of in-place moisture content and density values in existing soil profiles is justified.

6. Corollary Studies: Study further the forces operating in depressing the freezing point of soils. This study could well be integrated with a fundamental study to determine the nature of depressants which can be mixed with and retained by soils to improve their resistance to frost action.

PHYSICAL PROPERTIES OF THE SOIL MASS

The soil properties which more nearly express the dynamic nature of the soil also have a critical bearing on the nature of frost action. Frost action, in turn, alters the measure of those properties. The properties which permit the soil to transport moisture against gravitational forces by capillary "suction," or vapor movement and distillation, or to move soil water laterally or vertically under hydrostatic head or gravitational pressure are of greatest single influence in determining the magnitude of frost-action effects.

The intensity of frost-action effect may be measured in terms of magnitude of volume change on freezing, swell (the surficial manifestation of which is heave), or shrinkage. The ability of a frozen or of a thawed soil to resist deformation under load is another measure of frost effect, whether this ability be expressed as capacity to support loads, to resist frost-activated slope movements, or to grip, through adfreezing, foundation or pavement members (see Fig. 7).

Moisture Movement

During Freezing. The susceptibility of a soil to ice segregation and heaving is governed by its capacity to retain moisture and to move moisture to a freezing zone.

Disagreement exists as to the nature of forces operative in moving moisture to the freezing zone. It is generally believed that the forces effective in the immediate zone of freezing bringing water into the growing ice crystal are those of molecular cohesion in the film water (16, 41). This results in a drying

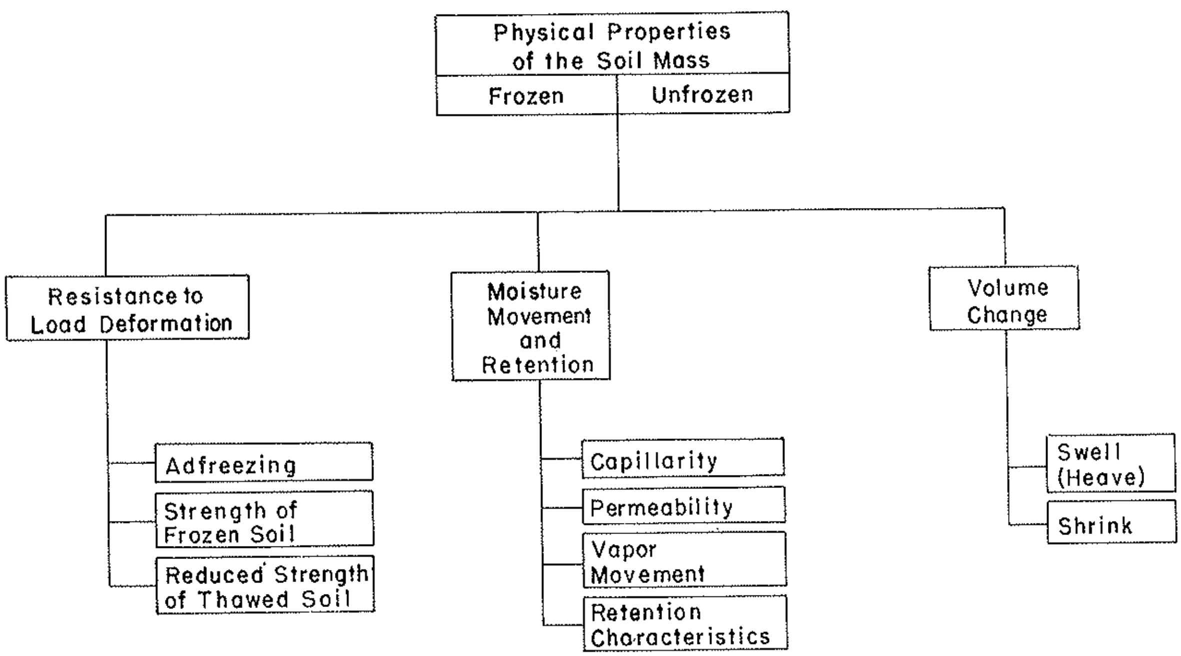


Figure 7.

out (42, 13) near the frost line in the manner that evaporation reduces moisture content near the surface of the ground. Consequently the reduced moisture content causes a water suction and capillary flow. The magnitude of molecular cohesion forces are so great that they will permit ice to grow under restraining forces approaching the crushing strength of ice (43). Regardless of the exact nature of the forces, the water supply to the freezing zone does not move through channels of capillary size, and detrimental amounts of ice segregation depends on adequate water contained in the soil or from a ground-water source near the freezing zone.

Freezing of moist soil in nature for practical purposes is always associated with some ice segregation, either in the form of crystals or lenses. The ice is not always visible, although it is usually detectable in terms of water gain. That gain may be limited to very thin strata, so thin that they are often overlooked in routine sampling of depths of 6 or 12 in. or more.

The effectiveness of vapor flow as a means of moving significant amounts of moisture to the freezing zones is a matter of some controversy. Limited laboratory experimental results available (13, 44, 45, 8) indicate that small amounts of soil water are moved in the form of vapor and that those amounts are of no consequence in frost heaving. It is not clear exactly how important vapor movement is as a continuing process of moving and building up soil moisture in subgrades to a degree which makes frost action (in the form of reduced strength) significant.

Following Thawing. When the soil has thawed the increased water content, whether limited to relatively thin strata or prevalent throughout the frozen depth, seeks to redistribute itself in a manner to satisfy forces which prevail. Regardless of the magnitude of moisture gain, its release on thawing creates a soil state different from that which existed prior to freezing. That water may be restrained from downward movement by the relatively impervious frozen soil beneath or, on completion of thawing, by saturated soil beneath. In the latter case, reduction and redistribution of moisture to prefrozen condition must be accomplished by forces of gravity and evaporation. If no ground-water source was available during freezing and all moisture gain above was at the expense of moisture loss below, the normal forces of soil suction will bring about redistribution.

The rate of that redistribution is dependent upon (1) the length of time during which it was moved upward by thermal forces due to below-freezing thermal gradients, (2) the duration of the freezing period, and (3) the relative effect of all forces operative during freezing. It may be that the time for redistribution following thawing is proportional to (1) and (2) above. However, if the forces operative in moving moisture to the freezing zone are, as one investigator (41) holds, greatly in excess of the forces causing its redistribution, that redistribution may be a much slower process than was the period of active freezing.

The problem here is one of a clearer understanding of the forces which prevail throughout both freezing and thawing processes and how the elements of time and those forces effect soil moisture movements. A clearer understanding of the two-stage process of freezing and thawing should make possible better base and pavement designs and better application of load restrictions for roads which become seasonally inadequate.

The following studies are suggested toward bringing about a better understanding of water movements, as related to freezing and thawing:

1. Establish more clearly the forces operative in moving water during freezing. Also, establish the relative distances through which the forces are effective and the influence of time on their relative effectiveness in soils of differences in texture and chemical composition and for different degrees of saturation. Evaluate the forces operative in causing a redistribution of water following thawing and the influence of time in changing soil moisture condition.

2. Establish more clearly, by both field and laboratory experiments, the real significance of water movement in the form of vapor. It is recognized that it is difficult to conduct small-scale laboratory tests which bring all natural forces into play with the same propor-

tional effect as occurs under pavements under natural conditions. Therefore, laboratory experiments need be supplemented with full-scale field experiments which include all natural variables and not just those of temperature difference.

Volume Change

Swell (Heave). Frost action in soil has two major detrimental effects of prime interest to engineers responsible for building of airfields and roads. One of these is differential volume change. The other is its effect on load-carrying capacity, both in the frozen and in the thawed condition.

The gain in moisture content associated with the freezing of most soils is associated with an increase in volume, which is spoken of as heaving if it occurs in visible amounts. When heaving differs markedly within short distances or in limited area, those differences in magnitude recognized as abrupt heaving are capable of causing severe damage to pavement and culvert structures. Such heaves are usually associated with abrupt changes in soil texture or soil water conditions and are readily recognized by most engineers experienced in construction in regions where deep freezing may occur.

Heaving is intensified in arctic regions where permafrost occurs. Deep freezing in soil whose drainage is retarded by the underlying permafrost is provacative of destructive heaving (46). The condition is most severe in the subarctic, where it is difficult to build without degrading the permafrost, thus tending to increase the depth subject to seasonal freezing and thawing and the intensity of heaving.

Hydrostatic conditions (47, 60) further increase the intensity of ground-surface movements. In the fall season, penetration of frost may trap large quantities of ground water between the seasonally frozen layer and the permafrost. Under such conditions the ground may bulge, ice may form in the core of the upheaval, and the upheaval may crack open and discharge quantities of water. Many conspicuous manifestations of surficial heaving are observed in permafrost regions. Such features as pingoes, frost blisters, icing mounds, peat mounds, and mud boils are indicative of intense ground freezing in areas where ground water is available in large amounts.

Minor heaving, although the actual increase in the elevation of the pavement profile may range from $^3/_4$ to 2 in. or more, is seldom detected by visual means. Consequently, many engineers are unwilling to recognize its presence or to appreciate its significance. It does not crack pavements, but it does cause reduced load-carrying capacity and also produces a more insidious effect in roughening the riding surface of pavements, particularly to the thinner pavements.

The problem, as it concerns major heaving, is principally one of defining different degrees of heaving according to degree of detriment and identifying and classifying ground conditions which are pertinent to different intensities of heaving. This needs to be done in a systematic manner. This problem is only partly satisfied by information in present literature, partly because of differences in terminology and partly because the information can be obtained only from numerous sources not available to many engineers.

Shrinkage on Freezing. Shrinkage, associated with soil freezing may occur in different forms. Shrinkage below the zone of freezing may occur due to soil consolidation on removal of water as it is drawn into the freezing zone. This form of shrinkage is never seen in nature and normally has little significance beyond the appreciation that it reduces total heaving so that heaving is not directly proportional to the thickness of ice lenses obtained and that it contributes to developing fissures in the soil.

A second form of shrinkage has far greater significance. Such shrinkage (48) results from freezing water-saturated, well-compacted, heavy clay soils. The shrinkage manifests itself in the form of marked downward movement of the soil surface (49) and for the development of large and often deep transverse cracks (50) coincident with cracks or joints in the pavement. Such shrinkage cracking may be detrimental in that it permits early spring rains to increase the soil moisture content. This type of shrinkage

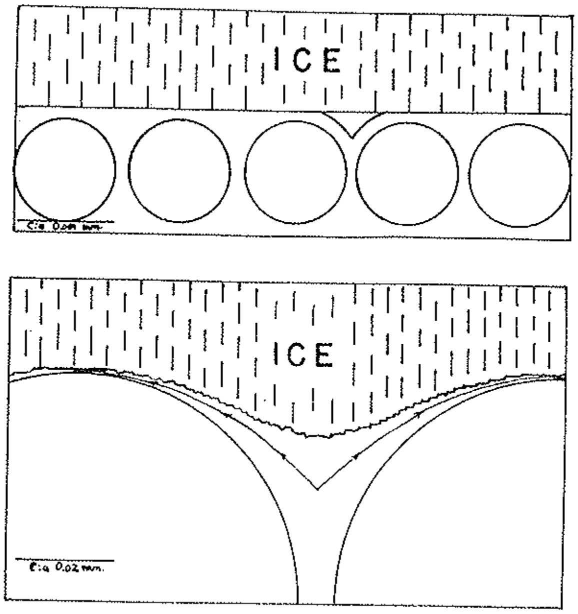


Figure 8.

has been attributed to a change from water to a high pressure form of ice (48) and to the natural contraction (50) of the pavement on cooling which also moves the frozen soil believed to be firmly attached to the pavement.

The greater range in temperatures below freezing in northern to arctic regions makes shrinkage increasingly more significant in the colder climes (24, 58).

The problem concerning soil shrinkage attributable to frost action is essentially that of identifying conditions which causes the shrinkage and establishing the degree in which it is detrimental, so it can be prevented in new construction where economically feasible to do so.

The following studies are suggested to bring about better understanding of soil shrinkage:

1. Conduct laboratory tests to determine the temperature, moisture content, and density conditions necessary to bring about shrinkage of the type associated with cracking of the ground surface.
2. Conduct full-scale field tests to determine the validity of criteria established above and the climatic and soil conditions under which they obtain. This project should have sufficient scope to establish (1) the extent in which they become detrimental and (2) whether or not it is practicable to prevent their occurrence on the types of soil in which they occur.

Resistance to Load Deformation

Frost action has two and opposite effects on the capacity of soils to carry loads. In the frozen state it provides a rigid pavement which may develop tremendous load-carrying capacity. But in the early thawed state the soil may lose up to 70 or 80 percent of the strength it had prior to freezing.

Frozen Soil. There is a great accumulation of information available concerning the elastic and plastic properties and strength of unfrozen soils. However, there is relatively little known of the strength characteristics of soil in the frozen state. These strengths may be of considerable significance where permafrost exists or where seasonally frozen ground layers of appreciable depth are maintained over the cold season. Foundations and bases may derive principal support from permafrost layers. Seasonally frozen layers may make possible increased loads on pavements and cross-country travel over ground which has low carrying capacity when unfrozen. Most effective use of frozen ground in these and other ways requires that its strength properties be more conpletely known.

The compressive, tensile, and shear strengths of frozen ground have been studied to some extent by the Russians (47). These foreign studies have recently been supplemented by American research (21, 32). These latter studies have attempted to evaluate in an orderly manner the effects of temperature, texture, moisture, density, etc. , on frozen strengths.

The Corps of Engineers study (21) revealed that: (1) strength of frozen soils increases with decrease in frozen temperature, (2) clean, cohesionless materials have highest frozen strengths and clays have lowest, and (3) clean, uniformly graded sand has greater frozen strengths than more-well-graded sand and gravel soils. (The specimens tested were frozen slowly in one direction under conditions of full saturation with free access to water).

Among other findings of interest (21), the following are noted: (1) At temperatures just below freezing (26 to 30 F) even very small compressive loads produced continuous plastic deformation and (2) crystal structure of ice specimens frozen simultaneously with soil specimens was not indicative of the crystal structure in segregated ice lenses in naturally frozen soil. Strength properties may be expected to vary appreciably with successive thawings and refreezings. Strength properties of frozen ground are definitely and closely related to those of ice. Unfortunately, the available data for the ultimate strengths and for the elasticity, plasticity and viscosity of ice are rather unsatisfactory (51).

The grip or bond of frozen ground to a pile or foundation wall or pavement is termed "adfreezing force." This bond tends to produce a lifting of the foundation member as the ground freezes and heaves and to crack pavements where differential uplift occurs. Tangential adfreezing strength, a measure of the resistance that must be overcome to produce sliding of an object with respect to ground to which it was frozen, varies for any building material with temperature, composition, texture, and moisture content of the surrounding ground. The surface roughness of the foundation member itself is an additional factor. Few values of adfreezing strength are available from other than Russian sources (47). However, at the present time the St. Paul District of the Corps of Engineers is engaged at a subarctic location in rather extensive pile-loading and extraction tests which should yield valuable data.

The following studies are suggested:

1. Additional evaluation of the tensile, compressive, and shear strengths, plus elastic and plastic constants, of frozen soils of various compositions, textures, porosities, and moisture contents and distributions, under ranges of subfreezing temperatures is needed. Effects of rate and direction of freezing must also be considered.

2. Adfreezing strengths inherent to frozen contact between various subgrade, base, and pavement materials should be developed. Particular attention should be devoted to the rates of development of this adfreezing strength under known thermal influences.

Load-Carrying Capacity. One of the most outstanding studies relative to frost action in soils has been the recent investigations of load-carrying capacities of roads and airfields. Investigations have been reported by eight state highway departments (52, 53, 54, 55) and the Corps of Engineers (56). Additional studies are reported under way in permafrost areas. Highway studies were limited to flexible pavements, while the airfield investigation included both flexible and rigid types. The investigations had two purposes. Highway studies were made primarily to determine the degree of reduction in load-carrying capacity on which to base load restrictions during the spring season. The airfield study was pointed toward evaluating pavements on specific airfields for all season use. The findings are significant and in general agreement, and show a marked reduction in load-carrying capacity of the average order of 40 to 50 percent of the fall season value.

Reduction in load-carrying capacity is associated with a soil condition of increased moisture, decreased density, and perhaps, altered soil structure. Soils in which much water is accumulated and segregated into ice lenses during freezing will ordinarily undergo great reduction in load-carrying capacity on thawing. However, observations (57, 53) have revealed that significant reductions may occur with relatively small water gain and little ice segregation on freezing. Most of the data thus reported were from tests after thawing and for rather large depth increments.

Intensity and duration of the reduction are greatly dependent upon the rate and depth of freezing or thawing. Distribution of the ice within the frozen soil is critical. Rates of freezing which produce large segregations of ice near the surface and deep frost penetrations, in combination with early and rapid thawing to shallow depths, produce the most unfavorable condition of supersaturation above a residual frozen layer. It is then to be expected that the impedance to internal drainage effected by underlying frozen soil, plus the presence of large accumulations of ice in the frost zone and also, perhaps, great depths of this zone, produce a condition conducive to large reductions in the soil's bearing capacity. Further, reductions can be expected to have longer durations in permafrost areas than prevail in seasonally frozen ground regions. Settling and caving actions are also in frequent occurrence.

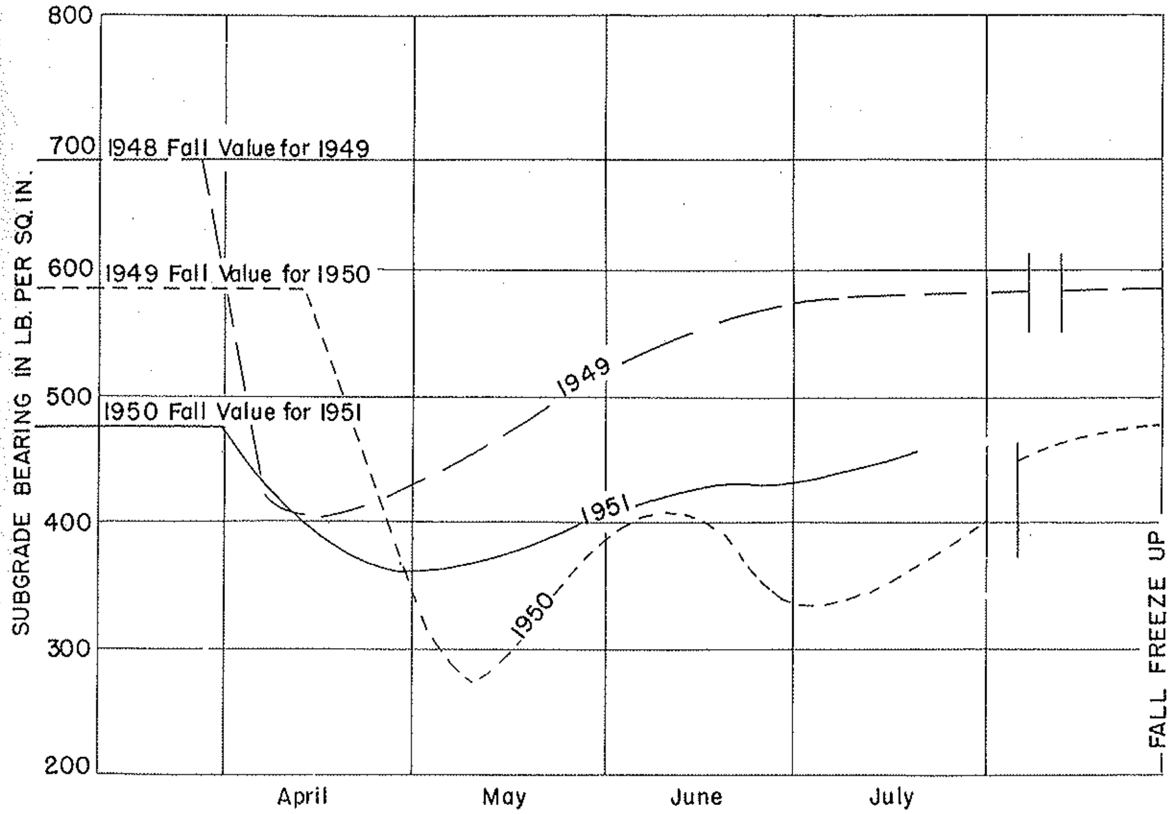


Figure 9.

Efforts to evaluate reductions in load-carrying capacity and the adequacy of various subgrades and base and pavement courses during the frost-melting period have utilized accelerated traffic tests, plate-bearing tests, in-place California Bearing Ratio tests, and other penetration or instrument tests. A great deal of plate-load testing has been accomplished; however, such tests are criticized (56) because the gradually applied load allows escape of water, consolidation, and build-up of resistance in the subgrade. In addition, these tests do not reflect the weakening due to subgrade disturbance under repetitive loadings of the nature imposed by traffic. It is significant to note that the ratios of weakening as determined by static plate tests on rigid pavements (rupture tests on slab corners) are reported (56) to be comparable to ratios determined by actual traffic testing. However, such agreement has not been achieved in the case of plate loading of flexible pavements.

Certain small instrument tests, the North Dakota cone, the Housel penetrometer, and the Iowa subgrade-resistance meter are being studied by several state highway departments under the coordination of a committee of the Highway Research Board (52, 55). Emphasis has been placed upon correlation of these instrument tests with field plate-bearing tests. No extensive or conclusive results have been reported as yet.

A statement of research needs would include:

1. Present comprehensive programs being conducted in determination of reductions in load-carrying capacity on thawing and in validation or formulation of design criteria are producing significant results. Complementary studies in point of soil areas and climatic coverage are needed, particularly in the subarctic. Measured reductions in carrying capacity for various soil textures and moisture conditions under closely observed climatic conditions should be correlated with: (1) Amounts of ice segregation and heave. (2) Degree of saturation before freezing. (3) Changes in soil condition from prefrozen to thawed; (a) increase in moisture content, (b)

increase in soil porosity, (c) modification of soil structure. (4) Position and movement of water table.

In making measurement of reductions, attention should be given to the cycles of climatic variation for the region in question. It is hazardous to evaluate measurements for any particular year, without knowledge of whether that year was very mild, very severe, or about normal, climatically speaking.

2. Although the success achieved to date in correlating the results of traffic, plate, and instrument test evaluations of load-carrying capacity are somewhat limited, it is anticipated that efforts to achieve such correlation will be continued and expanded. There is obvious need for a testing technique that requires little time and light equipment for performance. Modification of test instruments to more closely simulate traffic loading should be given further consideration.

EXTRINSIC FACTORS WHICH INFLUENCE FROST ACTION

Two major external factors have vital influence on the nature of frost action in soil: climate and load. The more important of these is climate, which exercises control over ground temperature. The major elements of climate in normal order of relative importance of influence are: air temperature, precipitation and humidity, sunshine, and wind. Climatic influences may be considered to be modified by location, degree of exposure, and the nature of surface cover.

The effect of location may be evaluated through the elements of latitude, altitude, and proximity to bodies of water. Degree of exposure to sunshine and wind is largely governed by slope and aspect. Surface cover may be composed of vegetation, snow or ice, highway or airfield pavement or other structures. Load (whether in the form of surcharge weight, such as overlying subgrade, base and pavement, or as moving wheel loads) has somewhat less influence than climate but is, nevertheless, an important factor.

Obviously, an attempt to evaluate the relative influences of these factors on frost action would necessitate a lengthy summary. They are merely mentioned here to emphasize that study of the intrinsic factors constitutes only a portion of the overall needs.

PRACTICAL DESIGN AND CONSTRUCTION PROBLEMS

Emphasis in this outline of needed research has been placed upon an understanding of the fundamental technology of freezing and thawing processes. It is felt that improved understanding of these fundamentals is prerequisite to marked improvement in engineering practice relative to frozen ground. However, the development of such basic data does not mean that practical problems of design and construction should be neglected. There is need for field verification of findings by investigations of full-scale construction of embankments, subgrades, bases, pavements, insulation courses, subsurface - drainage installations, etc. This phase of study should be carried on concurrently with the fundamental investigations. There is great need for correlation of traffic testing with normal laboratory testing, in order that the benefits of increased knowledge of laboratory performance may be properly reflected in field design and construction.