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Frost Action in Soils

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FROST ACTION IN SOILS

By

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ACKNOWLEDGEMENT

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INTRODUCTION

Frost action generally is used, in its broad sense, to include any detrimental effect on engineering works resulting from the penetration of frost below the surface of the ground. Considerable damage is done to roads, airfields, bridges, culverts, pipelines and buildings in regions where the ground and the climatological conditions are favorable to ground freezing and thawing.

The writer has reviewed most of the available material pertaining to frost action in an effort to present the problem in an authentic manner, simple, yet reasonably up to date in theory and application. This study has been made from the stand-point of a highway engineer, since the interests of structural engineers and agronomists might be somewhat different.

The body of the study is divided into six chapters. In chapter I, the problem is presented with particular emphasis on damages and reduction of load carrying capacities in roads due to frost action; also, the nature and the factors of frost action are introduced. In chapter II, one of the most important prerequisites for frost action, namely the soil texture, is discussed. In Chapter III, soil moisture, in the form of liquid,

solid and gas is discussed. Chapter IV deals with soil temperatures. Both internal and external factors, effecting heat conductivity, and heat capacity of soils are discussed. Chapter V gives some basic information about permafrost. Chapter VI briefly mentions some of the remedies that could be taken against frost action.

The study of frost action is a recent one, although ground freezing and heaving was known before the seventeenth century. During the stage coach traffic period of the 1700's people observed the damage caused to culverts and roads as a result of frost heaving.

Only recently, due to the tremendous growth of automobile transportation the technical problem of frost action on roads has become practically and economically significant. Early in the 1920's investigations relative to frost action began in different countries.

Present concepts of frost heaving were developed by Lavelle, Becker and Day, and finally Taber. In 1916, Taber[1] concluded that heaving was caused by the growth of ice crystals into lenses or layers of ice. This is the present concept of frost heaving.

Some early field studies in the United States consisted of soil moisture content measurements. In the early 1920's an experimental road was constructed to

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[1]Stefen Taber, "The Growth of Crystals Under External Pressure", American Journal of Science, Vol. 16, 1916, pp. 544-545

investigate soil heaving by the Illinois Department of Highways.

Michigan Highway Department's studies were also started in the early 1920's. They brought out the relation between soil type, profile characteristics, soil water conditions and heaving.

The study of frost action in Sweden started at about the same time as in the United States. Norwegian investigations were carried out by Riise, Dahle and Brudal. Recently Germany has also become interested in frost-action problems.on roads.

In 1930, Sourwine[1], a highway engineer, interrelated frost occurance to the climatological records, as a means of determination of probable ground freezing occurance. (See figure 1).

Extensive investigations of frost action by the Corps of Engineers which were begun in 1945 constitutes the most comprehensive field and laboratory studies of frost action conducted in this country.

Outside the United States the work of Beskow of Sweden stands high with its original and thorough treatment of the problem.

The phenomenon of frost action in soils is very

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[1]J. A. Sourwine, "A Method of Analysis of Data on Frost Occurance for Use in Highway Design" Public Roads, Vol. 11, 1930, pp. 51-60.

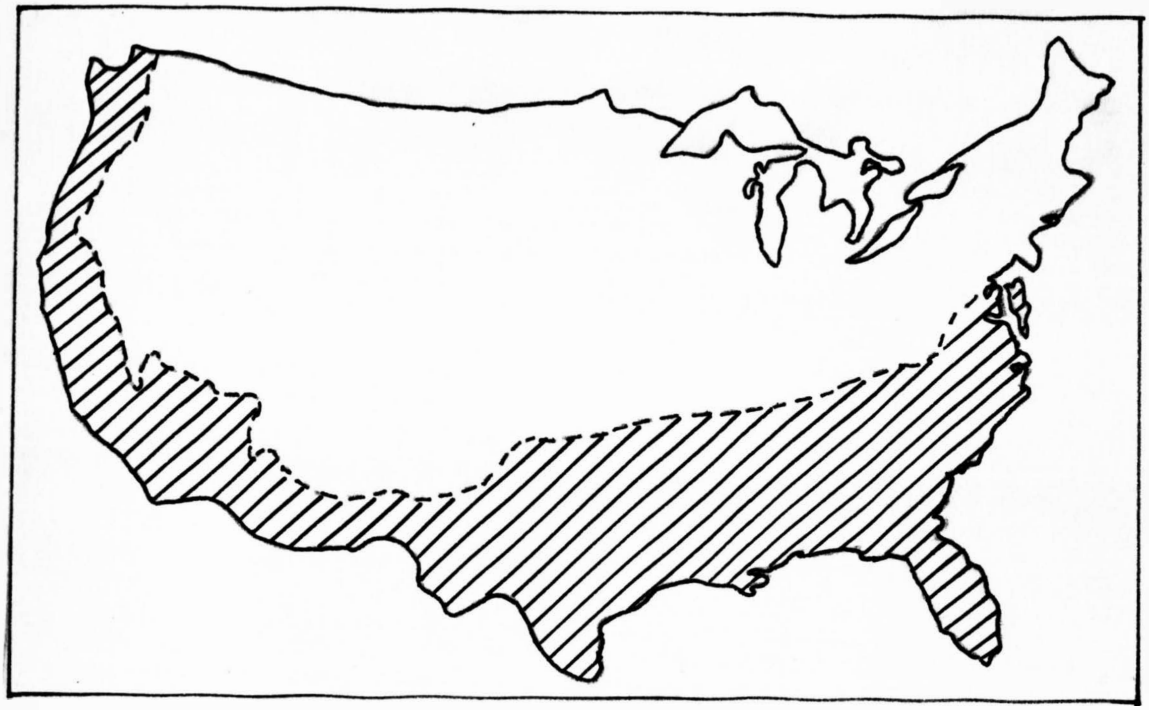

FIGURE 1. Map showing critical index line for highway ground freezing, based on most adverse existing conditions. (From Sourwine)

complex and the investigations are usually conducted: (1) to study the various factors related with soil-moisture and temperature, (2) to know more about the particularly frost susceptible soils under freezing conditions, and (3) to provide observations and test data to establish a method for the evaluation of frost danger to subgrade, base and subbase courses.

CHAPTER II

EFFECTS OF FROST ACTION ON ROADS

It is a known fact that frost action contributes considerably to the rapid deterioration of highways. Pavements are frequently broken up or severely damaged as the subgrades freeze in winter and thaw out in the spring. Pavements of the flexible type, such as clay bound sand and gravel, sand-clay, soil cement, and soil-bitumen are the most vulnerable to damage of this kind. However, rigid type concrete slabs or bituminous surfaces on concrete bases may also crack.

In addition to the physical damage suffered by flexible pavements and the high cost of repairs and maintenance caused by frost action, the economic and social loss to the users of the highway thus affected may be very great. When the frozen soils thaw in spring they become extremely unstable. In order to protect the pavement during this period, it is frequently necessary to place an embargo on the facility to restrict the weight of vehicles using it.

This chapter deals with the effects of frost action on roads and the factors involved in it.

The main effects of frost action on a highway are freezing and thawing. Freezing produces frost heaves, which are caused by the growth of ice lenses between the

soil particles. Differential heaves occur where pockets of frost-susceptible soils are present. So the frost heave can be defined as the raising of the ground surface due to the formation of ice in the underlying soil.

Thawing produces frost boils. They are the breaking of localized sections of a highway pavement under traffic and ejection of subgrade soil in a soft and soupy condition caused by the melting of the segregated ice layers. Frost action also causes loss in load carrying capacity because of subsequent softening of the soil and the localized settlements. On concrete roads, frost forms high joints by freezing the water in the soil below the joint. In addition, frost dislocates and breaks highway drainage pipes and conduits. It is also responsible for uneven settlement of culverts, bridges etc.

It is the abrupt differential heave which causes the most damage. Old rigid type pavements built without longitudinal center joints have often cracked longitudinally due to a greater uplift at the edges. Flexible type pavements likewise fracture both longitudinally and transversely on differential uplift.

A common type of damage to roads regardless of type is the lifting of the crown of the road. This is usually attributed to the snow removal. The snow along the edges of the road acts as an insulator retarding the frost penetration, while the clear areas permit deeper penetration.

Factors Contributing to Damage

It is evident that the factors contributing to damage are many and complex. The major ones are:

1. Climatic conditions, for example freezing and thawing temperatures and their duration.
2. The soil texture itself, particularly soils of high capillarity and capillary conductivity.
3. Precipitation, its nature, duration and intensity.
4. Drainage conditions, both internal and external.
5. Soil moisture, its amount and chemical composition.
6. Position of ground-water table.
7. Vehicle loads, types and intensities.

Magnitude of Frost Heaving on Roads

There is no definite rule to tell the magnitude of heaving in soils, even if the conditions are favorable for ground freezing. It is usually agreed that heaving is a factor of grain size and the ground water table. Some investigators have stated that the rate of heave is inversely proportional to the distance to ground water. It was also found out that the frost heave is greatest at the beginning of winter and later decreases rapidly.

It was found out that frost heaving is entirely independent of the rate offreezing, provided that the pressure is kept constant. (See figure 2).

Capillary and load pressures have a similar effect and the frost heave can be stated in relation to the

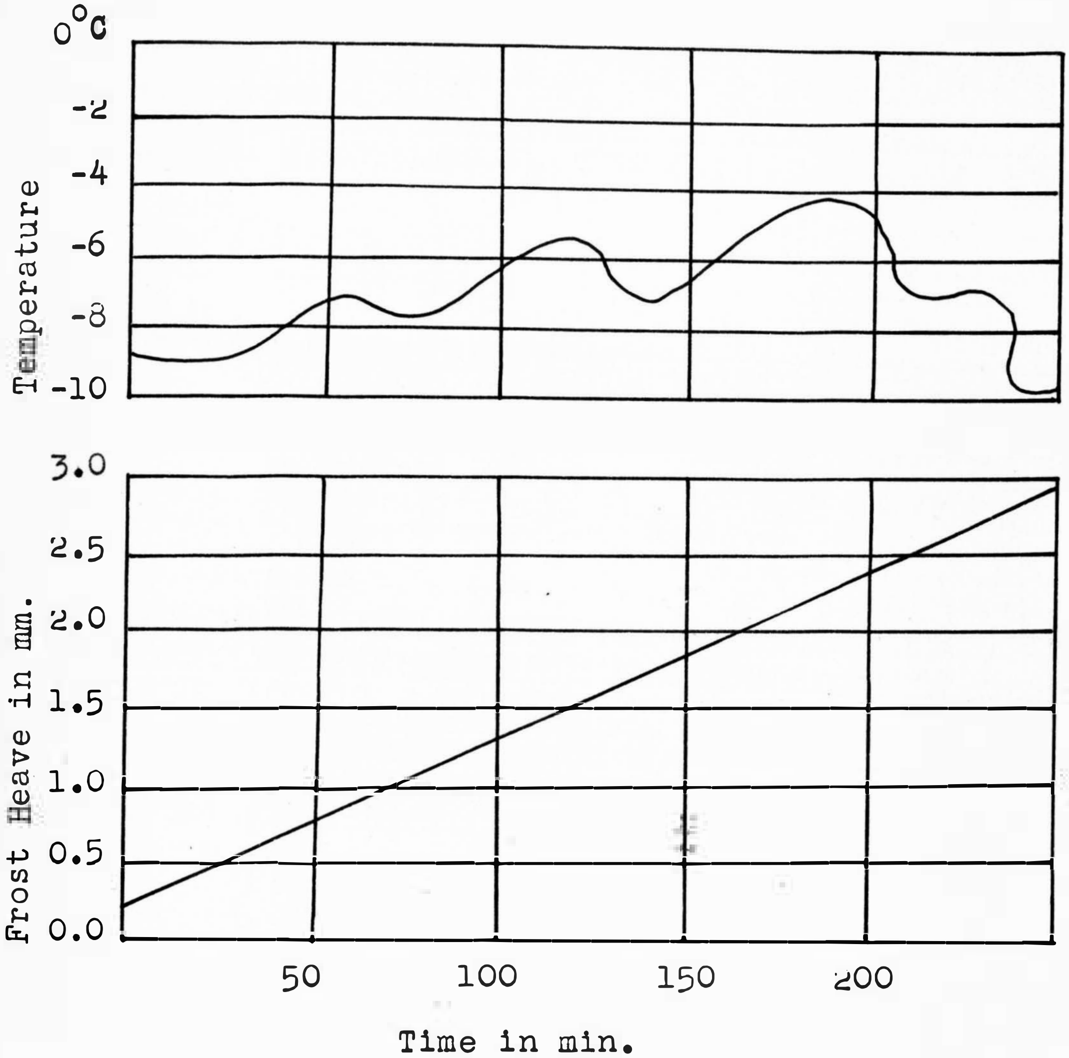

FIGURE 2. Graph showing that frost heave is independent of rate of freezing. (From Beskow)

total pressure action at the frost line, which is the sum of the two. Test results show that the curves for the rate of freezing versus pressure are hyperbolic. (See figure 3). It can be stated that the rate of frost heaving is inversely proportional to the square of the pressure, after the pressure exceeds a certain minimum value. The same curves also illustrate the relation of grain size to the rate of heaving.

A relation also has been found out between the water sucked up to the frost line and the amount of frost heave. The question of how much increase in water is caused by a certain amount of frost heave depends first upon whether the ice in the frozen soil is massive or porous, which in turn depends upon the degree of saturation of the soil, its structure and the magnitude of the load pressure. Considerably larger heave for the same amount of water content increase occurs when the ice is porous. In general it can be stated that the amount of water sucked up to the frost line is equal to or very slightly less than 9/10 of the amount of the frost heave.

Nature of Frost Boils

Frost boils are the result of partial thawing of the underlying frozen layers. In early spring the frozen subgrade usually thaws both from the top and from the bottom. The thawed soil between the pavement and the

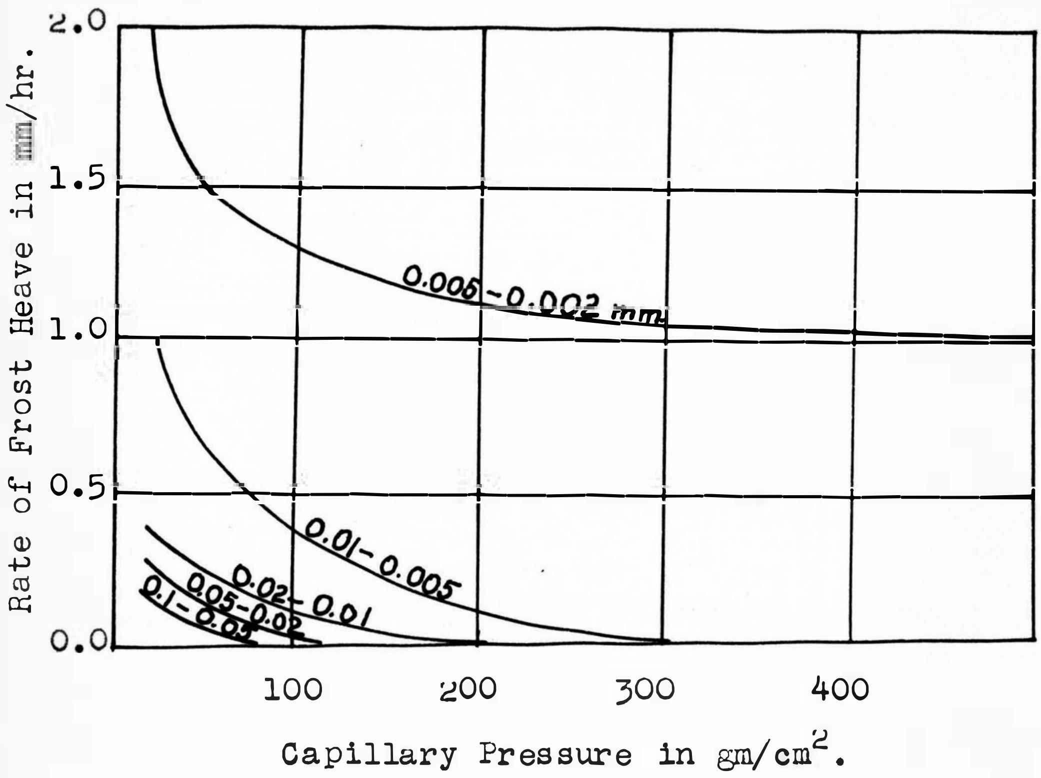

FIGURE 3. Relation between rate of frost heave and capillary pressure. (From Beskow)

frozen layer contains an excess amount of moisture, resulting from the melting of ice. Since the frozen layer of soil is impervious to the water, the thawed soil above it can not drain; and this thawed soil loses practically all of its bearing power because of its super saturated condition. This stage of frost action contributes the greatest damage to roads. If particularly the pavement is non-rigid type and the traffic is allowed to use the road, the wheels of vehicles easily break through the pavement and churn up the soft soupy layers of soil immediately below.

Frost boils are caused by a frozen layer below, so the duration of them will depend upon the thawing of this layer completely. If the weather warms up rapidly, the layer may thaw out in a relatively few days. It has also been found out that rapid warming of the weather contributes to the severity of the damage, due to the liberation of excess water which can not drain in such a short time. But if the thaw is gradual and thawing and freezing weather are interspersed, frost boils may persist several weeks. If a warm rain occurs during the frost-boil-season, the rain water might soak down into the soil and hasten the thawing of the frosen cut-off layer in the subgrade.

There is no practical artificial method of curing a frost boil after it has developed. The usual maintenance

of frost boils consists of removing the frost-susceptible soils and replacing them with granular materials and repatching the wearing courses.

Reduction in Load Carrying Capacity

It is evident that there is a definite reduction in load carrying capacity of roads affected by frost action. However, the loss in load carrying capacity varies with different localities and with different types of pavements.

It is known that the bearing value of the frozen soil is dependent upon the texture of the soil. The order of soils from lowest to highest in bearing value can be stated as: clay, silt-loam, sandy-loam, and sand. That is also the order of bearing value normally expected in those soils in the unfrozen condition. Investigations have revealed that there is a marked increase in bearing value of soils, with decrease in temperature for any initial condition of moisture content and density. This indicates that highways may have high load bearing capacities when the soil is frozen to an adequate depth.

Most investigators seem to agree that the combined factors of freezing and wetting have a detrimental effect on the bearing power of soils. Baver[1] attributes this

[1] L. D. Baver, "Soil Physics", John Wiley and Sons, Inc., New York, 1950, Third Edition, pp. 489.

reduction to the granulating action of alternate freezing and thawing on soil clods. He also states that the aggregation produced by several freezings and thawings decreases rapidly as the number of freezings increases. The aggregation by mechanical means that results from the pressure of ice crystals is also important. A slight reduction in density may affect the bearing capacity tremendously.

It appears that the bearing values tend to increase for a given soil type with increasing thickness of base and surface and decreasing subgrade moisture contents. Also for a given type and thickness of pavement there appears to be an increase in the surface bearing value as the subgrade soils range from clays to nonplastic granular materials. (See figure 4 after Motl[1]).

Several states have conducted tests to determine the reduction in road carrying capacities of roads due to frost action. No matter what testing procedure was used, the pattern of load carrying reduction was quite similar in all of the states with frost problems. However, the test results in bearing capacity obtained by static loads and repetition loads differed to some extent. Corps

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[1]C. L. Motl, "Load Carrying Capacity of Roads as Affected by Frost", Highway Research Board, Bull. No. 54, 1952.

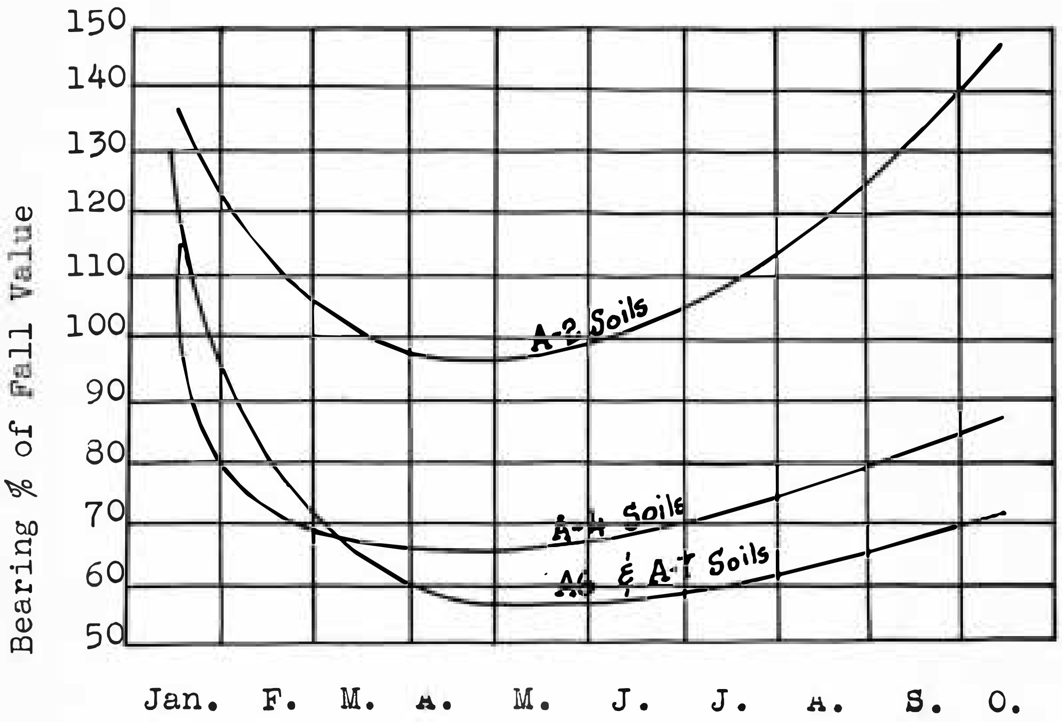

FIGURE 4. Bearing value of different classes of soils in Nebraska, 1952. (From Motl)

of Engineers[1] view in this respect was:

> "The gradually applied load in static load tests allowed escape of water consolidation and build-up of resistance in the subgrade soil."

The Corps of Engineers concluded from their comparative studies of load supporting capacity on Flexible and rigid type pavements that:

> "The ratio of the safe wheel load during the period of maximum weakening due to frost action, to the safe wheel load during the normal period, is approximately 0.3 for flexible pavements and approximately 0.8 for rigid pavements."

The findings of the other states also agree closely with the conclusion of the Corps of Engineers with regard to the safe wheel loads during the critical period of spring months.

Usually in this country the lowest bearing value of the roads is reached sometime in April. As a rule the drop in the bearing value from the highest to the lowest occurs in a comparatively short time. But if the weather warms up very gradually, the consequent thawing of the frozen layers and the reduction in bearing capacity might take place in a longer, period of time. The recovery of bearing capacities of roads takes much longer usually 5 or 6 months, but the critical period for the maximum damage is confined to 2 to 3 months. (See figure 5).

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[1] "Report on Frost Investigations", New England Division, Corps of Engineers, Boston, Mass. 1947.

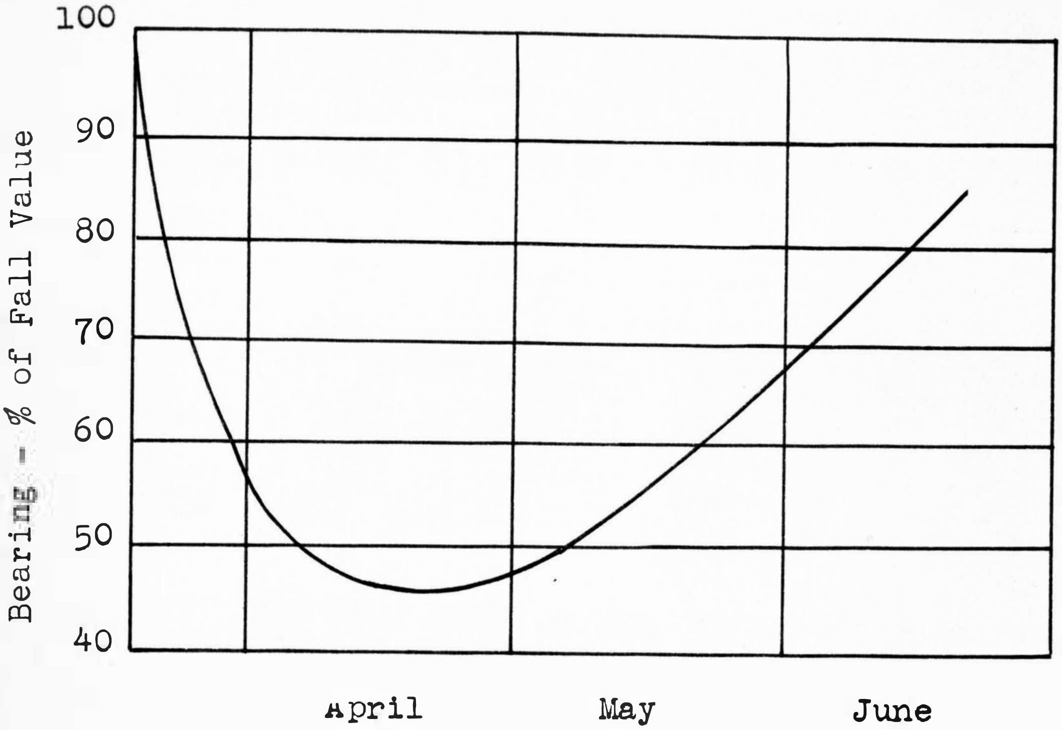

FIGURE 5. Average of ten bearing capacity tests in North Dakota, 1949. (From Highway Research Board Bull. 10-D, 1950)

Load Carrying Capacity Tests

The most commonly used methods to determine the load carrying capacity of roads employ plate bearing apparatus, cone bearing apparatus of North Dakota and the Housel penetrometer.

The plate bearing apparatus consists of a truck or trailer with a Jack equipment to transfer the load from the truck to the bearing plate and gauges for indicating the load increments and deflections of the pavement.

A cone bearing instrument consists of a pointed tool which is forced into the soil by applying loads of 10, 20, 40, and 80 pounds and recording the respective penetrations. The applied load divided by the area of penetration opening is the bearing value.

A Housel penetrometer instrument operates on the same principles as the cone bearing instrument, and the results obtained do not differ very much with the two methods.

CHAPTER III

SOIL TEXTURE

Soil texture refers to the relative proportions of the various size groups, namely clay, silt and sand in a mass of soil. Soil texture is the key to ground freezing as it determines such important factors as moisture retention, capillarity, heat conductivity and heat capacity. The aim of this chapter is to present the relations between soil classification and frost action.

Grain Size and Frost Action

Different investigators are in reasonably close agreement on limiting grain size for non-frost heaving soils, for it has been found out that it requires a certain percentage of fines and gradation in order that a soil might be frost heaving.

The poorest soils from the standpoint of frost damage are those which are sufficiently fine grained to exert a high capillary force, and at the same time are sufficiently coarse grained to have a high rate of capillary conductivity. Soils of this type will transmit relatively large quantities of water in a relatively short time to feed growing ice lenses. Those soils which contain large quantities of silt-size particles are the most objectionable in this respect.

It should be mentioned that it is practically impossible to fix a definite boundary between frost-heaving and non-frost-heaving as far as the exact grain size is concerned because the nature of soil moisture and soil temperature usually effect the final results.

A soil might be frozen but not show frost heaving. This brings us to homogeneous freezing and discontinous freezing as far as the grain size is concerned. It is a long known fact that discontinously frozen soil is much more detrimental to roads than homogeneously frozen soil.

Under ordinary conditions of soil type and climate, the usual frozen soil structure of relatively compact earth is as follows: The fine grained soils in the frozen condition are composed of layers of clean ice which are essentially parallel to each other and parallel to the surface; the coarser the soil is, the less ice there will be, both in thickness and in spacing of the layers. This kind of soil freezing is usually called discontinous freezing since there are unfrozen soil layers between the ice formations.

Beskow[1] states that soils with grain sizes (0.06-0.1mm) freeze totally homogeneously, except for the ice building in pre-existing cavities.

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[1]Gunnar Beskow, "Soil Freezing and Frost Heaving with Special Application to Roads and Railroads", The Swedish Geological Society, Series C., No. 375, Translated by J. O. Osterberg, Northwestern University, Evanston, 1947.

In sandy soils, the cause of ice growth is the existence of discontinuities, usually fissures or oavities. If no fissures or cracks exist, or if there are no thin layers of fine material, no ice layers occur; instead the soil freezes homogeneously. Homogeneously frozen soil is defined as the soil in which water is frozen within the material voids without macroscopic segregation of ice.

It was mentioned that sand was no frost-heaving; but by adding a small amount of clay to the sand, the mixture immediately becomes frost heaving. 5% clay causes a noticable effect, 10% considerable, 20% a very large effect. For inoreased clay content, the heave decreases, for 40% clay it is practically zero. Beskow[1] explains this as follows:

> "For a small amount of clay, the clay particles form a colloidal covering on the sand grains, having the requisities for discontinous freezing, at the same time the pores are open and permeability high. On the other hand when the clay content is very large, it will fill the sand pores, make it practically impermeable, thus the soil cannot suck up water so there is no appreciable frost heave."

<u>Frost Heaving Soils</u>

Several investigators have attempted to classify soils frost heaving or non-frost heaving aocording to grain size distribution or drainage index and capillarity.

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[1]Beskow, op. cit. p. 41.

The natural drainage index is primarily a function of the topographic position of the soil type and of the texture or textures of its profile. It is generally agreed that better drained soils are less susceptible to frost action, whereas soils poorly drained are more susceptible.

Beskow states that soils with capillarity of less than one meter (coarse silts and gravels) are under no circumstances frost heaving. For sediments this is defined as material of which less than 30% passes the 0.062 mm sieve and less than 55% passes the 0.125 mm sieve. For moraine, it is the material of which less than 22% passes the 0.125 mm sieve, all computed in percentage of the material that passes the 2 mm sieve. He also adds that soils with capillarity greater than 2 meters (fine silts and finer sediments of which more than 50% is less than 0.062 mm) are under all circumstances frost heaving.

Taber[1] (1929) stated that "On freezing no segregated ice could be seen in mixtures containing less than 30% clay." Several investigators found out that heaves in excess of a few inches may occur in coarse sands or even in gravelly material providing an excess of water is present, either

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[1]S. Taber, "Frost Heaving", Journal of Geology, Vol. 37, No. 5, pp. 428-461, 1929.

from seepage or from a naturally high water table.

The Corps of Engineers[1] (1951) after experimenting with different types of soils ranging from well-graded sandy-gravel to a medium plastic clay, concluded that the nature, as well as the proportions of fines, influenced heave. They have stated that:

> "In general, the test results available to date in this phase of the investigation indicate that the presently used criterion which states that well-graded soils with less than 3%, by weight, finer than 0.02 mm are not frost susceptible has proven to be a useful rule but other factors, such as the character of the fines, must be considered in recognizing frost susceptible soils with accuracy or in predicting the intensity of ice segregation which may be expected."

According to Haas[2] A-1 and A-3 soils are probably not susceptible to frost action. A-2 soils are moderately to very-highly frost susceptible, and A-6 and A-7 soils are highly to very highly frost susceptible. It must be remembered that lower group indexes also show a higher percentage of gravel and sand.

It was found out that clays, silty clays, silty clay loams, silt loams and loams are very likely to pump. Sands are not likely to pump. It can be concluded that generally frost susceptible soils are also susceptible to pumping.

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[1]Report on Frost Investigations" New England Division, Corps of Engineers, Boston, Mass. 1951.

[2]Wilbur M. Haas, "Drainage Index in Correlation of Agricultural Soils with Frost Action and Pavement Performance Highway Research Board Bull., No. 111, 1955.

The Determination of Soil Texture

The term texture as used in the United States refers wholly to size characteristics of the soil particles. The terms commonly used to indicate texture of soil, such as loam, sandy loam, and silty clay, are wholly arbitrary in origin; and their general meaning and connotation may vary from place to place and from one organization to another, the significance depending on the needs of the organization.

The textural class to which a soil belongs may be determined readily if the grading of the soil is known. The distribution of particle sizes throughout a mass of soil is known as the grading of the soil. For the sand and gravel fractions, the grading is determined by separating a representative sample of the soil into various size groups or separates by shaking it through a nest of sieves, each sieve having a different size of opening or mesh. The smaller size fractions are separated by measuring the settling velocity of the particles when the sample is thoroughly dispersed in a soil-water suspension. Since the larger particles settle out of suspension more rapidly than do the smaller particles, the time rate of settlement provides a measure of the relative size of the fine grains in accordance with the Stokes Law pertraining to the settling velocity of a sphere in a liquid. This principle

is used in the pipette technique of mechanical analysis. The object of the pipette technique is to determine the density of a suspension at a given depth as a function of time. Variations in density are measured by taking out samples of a definite volume at the required depth and determining the dry matter contained therein.

A hydrometer is another instrument used for gradation of finer particles. A hydrometer, which is calibrated to read grams of material per liter, is placed in the soil suspension in a special sedimentation cylinder at the desired time and readings are recorded. Theoretically, the hydrometer measures the density of suspension at a given depth with time.

United States Bureau of Public Roads accepts the following particle sizes as representative of the textural elements. "Sand-size particles-2 to 0.05 mm; silt size particles - 0.05 to 0.005 mm; clay-size particles - less than 0.005 mm.

After finding the relative particle sizes, the textural class is determined mostly by means of a triangular chart, either in the form of an equilateral triangle, or in the form of a right triangle. (See figures 6a and 6b). These charts are based on the textural classification developed by the United States Bureau of Public Roads, and they are widely used by various state highway departments throughout this country.

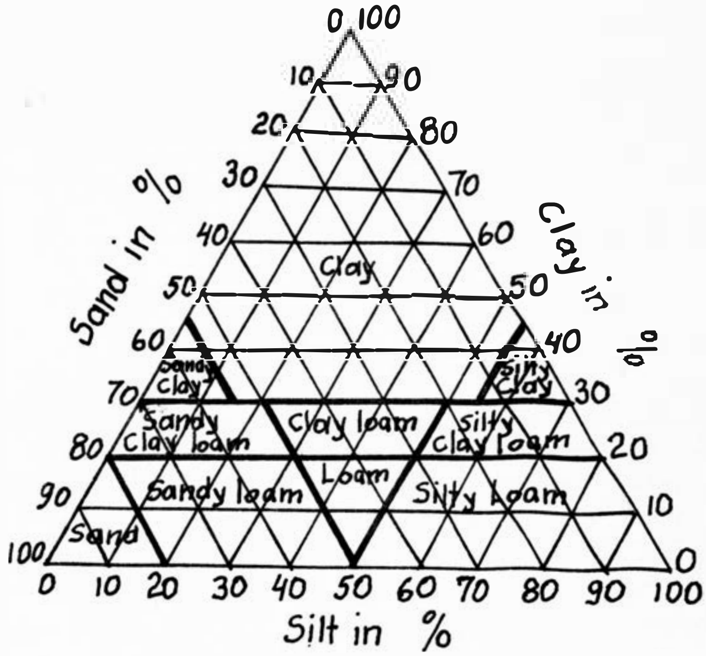

FIGURE 6a. Textural classification chart.
(U. S. Bureau of Public Roads)

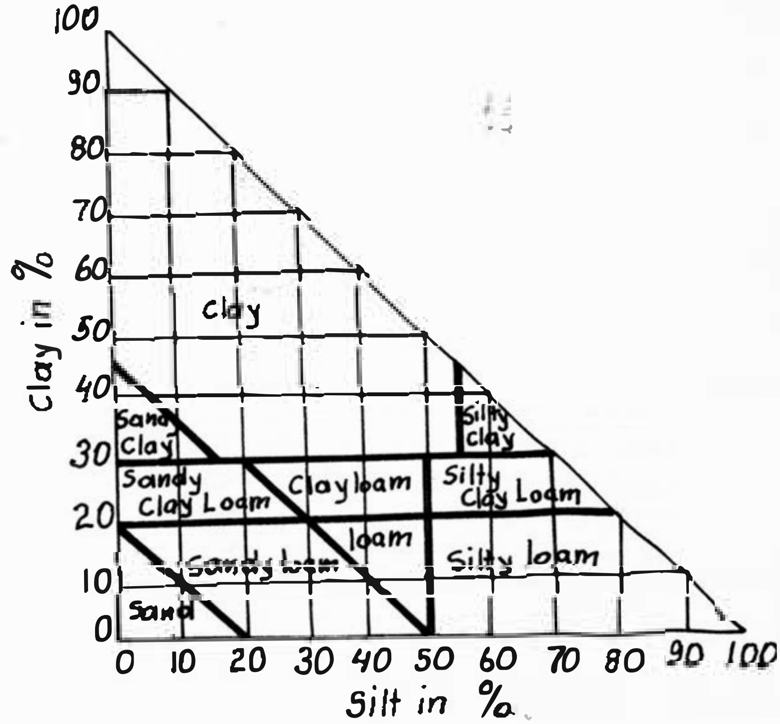

FIGURE 6b. Textural classification chart.
(U. S. Bureau of Public Roads)

CHAPTER IV

SOIL MOISTURE

In frost action the most important variable is water. It is much more complex and variable than soil texture and temperature, since it occurs in three phases and comes in variable amounts which are effected by temperature, drainage, vegetation and soil type. Soil moisture influences coefficient of thermal conductivity, specific heat, radiation and evaporation.

There can be no detrimental frost action without movement of water to the zone of freezing. Water movement takes place through the soil pore space, which is dependent upon the nature of the soil, that is, its grain composition, shape, and grain size distribution. It is also dependent upon soil density, and initial water content, and on soil structure, which controls the size and spacing of fissures in the soil.

It is evident that the basic laws governing the soil moisture and the three phases of the ground water must be understood for the study of frost action. It is the purpose of this chapter to deal with the soil moisture as related with frost-action.

Water movement in soils is very complex; although the literature on this subject is quite voluminous,

there is no single treatment which satisfactorily explains movement under conditions ranging from complete saturation to partial saturation.

Almost all investigators agree that all flow of liquids or gases depends upon the existence of a pressure difference which causes a continuous flow from a higher to a lower pressure.

Some researchers have classified soil moisture into three main types according to their characteristics. They are: hygroscopic or film water, capillary water, and free or gravitational water.

Hygroscopic Water

Hygroscopic water is defined as the water absorbed from an atmosphere of water vapor as a result of attractive forces in the surface of the particles. It is convenient, although not strictly accurate, to think of such water as existing in thin films around the soil particles and flake-shaped colloids. This film water is held to the surface of the colloids with very great force; however, this adsorptive force diminishes rapidly as the distance from the surface of the colloid becomes greater and the total thickness of the adsorbed film may be that of only a few molecular layers.

The study of hygroscopic moisture in soil and the adsorptive forces which primarily control it is to a

very large extent a study of the colloidal fraction of the soil. The term "colloid" is derived from a Greek word, meaning "glue-like", since, colloid material, when isolated, is a mass of gluey, gelatin-like material. The colloidal fraction in a soil may consist of both organic and inorganic substances. The inorganic colloids mainly consist of clays.

It is known that heat is required to remove absorbed moisture films from the colloidal fraction; it also follows that heat is produced during the reverse process of film development. This evolved heat is known as the heat of wetting. The hygoroscopicity of a soil is defined as the moisture content at which heat of wetting is no longer evolved during the wetting process.

Capillary Water:

Capillary water is the water held by surface tension forces as a continuous film around the particles and in the capillary spaces.

The movement and retention of water in the capillary fringe above a ground water table is similar in many respects to the rise and retention of water in a capillary tube. The forces of capillary pressure are known as surface stress condition. The concave menisci (border between air and water) in the pores try to straighten themselves out, and therefore exert a "suction" giving a pressure deficiency, whose magnitude is inversely

proportional to pore diameter. The well known capillary tube formula to express the rise of water in a tube is as follows:

$$h = \frac{2 \cdot \text{Cos}\, A \cdot T}{r \cdot d \cdot g}$$

in which, h = heigh of water rise in centimeters;

r = radius of circular capillary tube in cm;

T = surface tension of liquid, in dynes per cm;

A = anglo of contact between the meniscus and the wall of the tube;

d = density of the liquid, in grams per cubic cm;

g = acceleration of gravity = 980 cm/sec^2.

The attraction which soil has for capillary water may be expressed quantitatively by a stress property called capillary potential. It is defined as the work required to pull a unit mass of water away from a unit mass of soil and represents the security or tenacity with which the soil holds capillary water. Gardner[1] has demonstrated that the capillary potential at any point in a soil mass is numerically equal to the tension in the soil water at the point, but is of the opposite sign.

Gravitational Water

Gravitational Water is the portion of ground water which is not held by the soil but drains under the influence of gravity. The flow of gravitational water in soil is similar in many respects to the free flow of water in a

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[1]Gardner Willard, "The Capillary potential and its relation to soil moisture constants", soil science, 10: 103-126, 1920.

conduit or an open channel in that it is attributable to the gravitational pull which acts to overcome certain resistances to movement or flow of the water. Such resistances are due to friction and viscous drag along the sidewalls of the pore spaces in the case of flow through soils. The driving force which causes water to flow may be represented by a quantity known as the hydraulic gradient. This is defined as the drop in head divided by the distance in which the drop occurs.

The quantity of flow depends upon a soil factor known as the coefficient of permeability. The value of coefficient of permeability depends to a very large extent on the size of the void spaces which in turn depend on the size, the shape, and the state of packing of the soil grains.

Moisture Movement in Soils

The movement of soil water is brought about by the action of gravity or capillary pull, either alone or in combination.

The transportation of water to the freezing layers occurs by capillarity suction. The controlling factors are:

1. capillary pressure;
2. the permeability of the soil;
3. the distance to the ground water table.

The resistance to flow of water through a capillary tube is inversely proportional to the fourth power of the diameter and directly proportional to the permeability. The amount of flow due to capillarity is written as follow:

$$Q = -K \text{ grad } i \text{ (cc/Sec.)}$$

in which Q = amount of flow

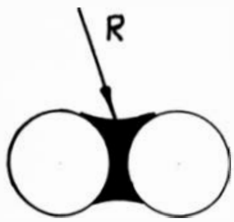
K = capillary conductivity

grad i = capillary potential gradient

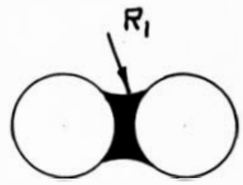
As has been stated before, capillary conductivity depends upon the kind of soil, its state of packing and moisture content. (See figure 7). Capillary conductivity increases with moisture content and decreases with the size of the soil pore space.

Capillary potential gradient can be termed as the driving force arising from the pressure differences. Pressure differences might arise due to differences in moisture content and temperature between two cross-sectional areas in a soil column. The driving force will be greater with large differences in soil temperature and moisture, and thus, more rapid will be the movement of capillary water.

Movement in the vapor phase occurs as a result of vapor-pressure differences within the soil. Water always moves from a higher to a lower vapor pressure region. The movement of water in the vapor phase is sometimes called

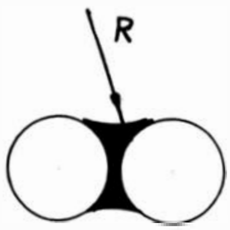


a) Wet soil

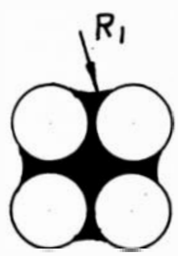


b) Dry soil

Effect of moisture content upon curvature of air-water interface.

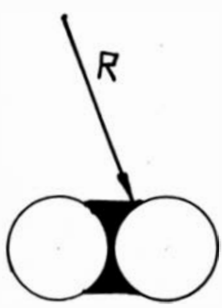


a) Coarse-grained soil

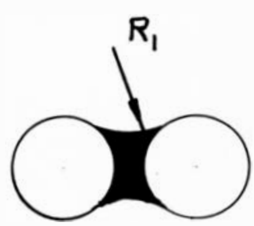


b) Fine-grained soil

Effect of particle size upon curvature of air-water interface.



a) Closely packed soil



b) Loosely packed soil

Influence of state of packing of soil on curvature of air-water interface.

FIGURE 7. Physical conditions of soil particles effecting water adsorption. (From Spangler)

diffusion. Differences in vapor pressure may arise from variations in soil moisture or soil temperature. It has been found that diffusion due to temperature differences is so small that for water flow in frost heaving soils, it is of no importance. This fact is correlated with very small pressure differences for low temperatures close to 0°C.

In clay soils the direct capillary flow is interfered with or broken by a more or less well-developed fissure network. It was found that transverse fissures cause a decrease in the rate of water suction and frost heave. The effect depends on the distribution and magnitude of the points or planes of contact. Water movement across a fissure can only occur over points of direct contact, since it was mentioned that diffusion is practically negligible.

In water transportation through soils, the distance to the ground water table is very important. Particularly sands and coarse grained soils depend upon the closeness to ground water table for capillary suction of moisture. One important phenomenon has been found out in relation with ground water table: The rate of flow decreases very little with increase in distance to water table, to a certain depth, then the flow suddenly decreases to zero.

The Process of Soil Freezing

It has been mentioned that ground water either freezes in the soil pores or between the soil layers, but in either case freezing starts with the portion of water with least force of attraction by the soil particles.

In a fine grained soil such as clay even the freest water in the center of the largest pores is within the radius of influence, and has a considerable freezing point depression. If there exists however a small discontinuity a crack, a fissure, a contained foreign material, insect and rodent holes, etc.--this discontinuity represents a surface of weaker force of attraction on the water, that is a higher freezing point than in the clay itself. Ice crystallization therefore begins in such places; and due to the force exerted by the crystallization the cracks widen and grow sideways, and crystallization of ice continues in the newly made cracks.

In a coarse soil, the freezing point depression in the poros is so exceedingly minute that crystallization can occur practically as easily in the pores as in a discontinuity. Winterkorn[1] and Baver stated that water in a soil capillary is most strongly held at the pore-wall, while in the center of the pore it may be free.

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[1] H. F. Winterkorn, and L. D. Baver, "Sorption of liquids by soil colloids", Soil Science Vol. 38, 1934.

It was found out that a lower temperature was required to freeze the remaining water in clayey soils after the 'more free' water had been moved upward and frozen during freezing of the overlying soil. Bouyoucos[1] found from his early studies that at low moisture content the lowering of the freezing point was extraordinarily high and very different for various types of soil, being lowest in the sandy types and highest in the clay types. Beskow[2] explained that the lowering of the freezing point was due to the "adsorption power" of the soil particles.

Freezing of Fine Grained Soils

It was stated that fine grained soils almost always freeze heterogenously; that is they form on ice-stratified frozen soil. After the freezing has started, in order that growing ice crystals can expand they must push the particles in front, which can only happen if new water molecules can come in between the ice crystals and the particle surfaces against which they rest. This phenomenon is often called frost heaving.

It is assumed that the ice crystals grow from below the already frozen layer due to the direction of the

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[1] G. J. Bouyoucos, "Further Studies on the Freezing Point of Soils", Michigan Agr. College, Exp. Sta., Tech. Bull. 16, 1916.

[2] Beskow. op. cit. p. 76.

water supply. Ice crystals grow by displacing a layer of molecules taken from the adsorption films, so the films become thinner and they in turn get back their thickness by attracting water molecules from the side and underlying particles. In a fine grained soil, the films around the particles are relatively short and thick so the flow of molecules can occur much more rapidly, thus helping the ice layers to get thicker and thicker. It is evident that the growing ice crystals in turn push the soil particles ahead, actually lifting themselves and the overlying mass upwards. The continuation of this situation requires an adequate mobility of the adsorption water films to allow flow of water and moderate rate of freezing. Mobility of adsorption films are dependent upon the pressure. For increasing pressures the films are pressed tightly and the mobility is reduced. In natural ground a soil might show considerable heaving, while the same soil under the road bed would not heave very much.

It is generally agreed that for increased rates of freezing an increase in the mobility of the adsorption water films is necessary.

The effect of pressure for practical purposes can be considered as a situation requiring a small lowering of the freezing point. Bridgeman[1] found that a pressure

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[1] P. W. Bridgeman, "Effect of Pressure on the Freezing Point of Water", Smithsonian Phys. Tables, p. 200, 1921.

of 1000 kg per sq. cm.(14,223 psi) lowered the freezing point 8.8 degrees centigrade.

Taber[1] based his theory to explain the mechanics of heaving on the premise that:

1. all soil water does not freeze at the same temperature which makes it possible for water to move to the growing crystal.

2. the growing crystal displaces material overlying it and thus develops ice lenses.

3. the frost line is relatively stationary during the growth of crystals forming the ice lens or stratum.

Previously, similar points to that of Taber's first two factors have been discussed briefly, but no mention has been made about the frost line.

Frost line is usually termed as the lowest surface of the frozen ground layer. In general the larger the temperature gradient is the more distinct the frost line becomes.

The factors which influence the arrangement of ice layers, or frozen soil structure are the following:

1. pressure, especially its direction and relative magnitude.

2. temperature, especially its direction of isotherms and also temperature gradient and rate of cooling.

3. the soil structure, existence of a jointed or discontinuous structures.

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[1] S. Taber, "The Mechanics of Frost Heaving", Journal of Geology, Vol. No. 38, 1930, pp. 303-317.

Direction of pressure, direction of isotherm and stratification cause a system of parallel ice strata oriented parallel to the ground surface. But there may be divergences from this rule.

In a frozen soil, a small expansion sideways causes enormous pressure increases, since no space exists for this expansion; above however, there is unlimited space, so ice crystallization grows perpendicular to the ground surface and ice stratification becomes parallel to it.

The qualitative importance of the direction of the isotherm is obvious. Generally, in nature, the direction of the isotherm corresponds to the ground surface; that is to say the direction of the temperature drop corresponds to the direction of least resistance. Since crystallization starts close to a definite temperature, it is clear that the ice strata has a definite tendency to grow parallel to the ground surface.

The importance of soil structure is most marked at contact surfaces between different layers. When the change of layers is repetitious as in varved clays, stratification becomes extremely parallel and distinct, with the ice formed in the boundary surfaces.

Under natural conditions the above three main factors work together to cause stratification and frost line to occur parallel to the ground surface.

The principal reason for the occurance of successive ice strata, and not merely a single growing ice layer, has been assumed to be that the rate of flow of water upward to the freezing zone is not large enough to compensate for the conduction of heat away. If the upward water flow was sufficient, a single ice layer would have formed.

Freezing of Coarse Grained Soils

Most of the physical laws and conditions discussed in relation with the freezing of fine-grained soils also apply to the freezing of coarse grained soils.

We have mentioned that generally coarse grained soils freeze homogeneously; the reason might be attributed to the incapability of such soils to supply enough water to encourage the growth of ice lenses.

In a coarse grained soil, such as a sand, the thickness of the adsorption water films is very small in comparison to the grain size. The adsorbed water film becomes much more "squeezed out" due to the fewer points of contact among the sand particles. In a coarse soil the meniscii are very wide, and the water molecules have a longer distance to travel. The rate of transportation of water molecules at a certain limiting grain sizes become so small that the flow of water to the ice surface cannot keep up with the rate of cooling, and the ice crystals freeze solid on the adjacent soil particles.

Ice formation and consequent frost heaving might occur in coarse grained soils under extremely favorable conditions, such as:

1. closeness to the ground water tablo.
2. a very slow lowering of the freezing isotherm.
3. absence of pressure due to overlying layers and surface loads.
4. presence of naturally varved layers.

The opposite conditions also hold true for fine grained soils to produce homogeneous freezing.

Measurement of Soil Moisture

The determination of soil moisture is very important for the study of frost action. The moisture content of a disturbed soil sample can be determined by driving off the water in an oven and representing it on the oven dry basis. In the last several years, a very intensive effort has been made to discover and develope appropriate and reliable soil-moisture determining methods for field use. Bouyoucos[1], the well known soil-moisture authority, lists the following methods in use:

1. The plaster-of-paris-block electrical resistance method of Bouyoucos and Mick and the nylon-electrical resistance method of Bouyoucos.
2. The fiberglas electrical-resistance method of Colman.

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[1]G. J. Bouyoucos, "Soil Moisture and Moisture Movements", Highway Research Board, Special, Report No. 2, Frost Action in Soils, Washington, 1952, pp. 64-72.

3. The electrothermal conductance methods of Shaw, Baver and Johnson.

4. The electrocapacitance method of Fletcher, Anderson, and Edelfsen.

5. The tensiometer method of Richards.

6. The sorption-plug gravimetric method of Davis and Slater.

The electrical-resistance method of measuring soil moisture is based upon the principle of electrical conductivity varying with the moisture content between the electrodes. But the accuracy of this method is doutful, since small changes in the salt content of the soil solution affects the conductivity more than the amount of water that is present.

Heat conductivity in soils is sometimes used as an index of soil moisture; use is made of the principle of the increase in resistance of a wire conductor with increase in temperature to measure the changes in heat conductivity of the soil water system. The relationship between heat conductivity and moisture content is distinct for each soil.

Belcher[1] discusses a new method to measure the soil moisture, making use of scattered neutrons. The method is based on the scattering of neutrons and measuring the

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[1]Donald J. Belcher, "The Measurement of Soil Moisture and Density by Neutron and Gamma-Ray Scattering" Highway Research Board, Special Report No. 2, Frost Action in Soils, Washington, 1952, pp. 98-110.

loss in their energy. The scattering is particularly strong, and the loss of energy marked if the neutrons collide with hydrogen atoms. Those neutrons which have been scattered by hydrogen atoms will have lost most of their energy and return as slow neutrons. Thus in counting the number of slow neutrons at or near to the source, one obtains a measure of the number of hydrogen atoms present, which can be correlated with the amount of water in the soil.

CHAPTER V

SOIL TEMPERATURE

It was mentioned that one of the most important prerequisites for frost action was the presence of freezing temperatures. Moisture movement in soils depends, to a certain extent on the temperature differences, and ice formation is a physical phenomenon associated with the heat conductivity of soils. It is a basic fact that a certain amount of heat is liberated when the water freezes. In order for the ground to freeze, the heat conducted away must be greater than the heat absorbed. For this to happen, a certain minimum temperature gradient must exist. It is evident that soil temperature as a function of soil texture and soil moisture and affected by the climate is very important in understanding the frost action in soils.

Most investigators divide the factors affecting soil temperature into two broad classes, intrinsic and external. The intrinsic factors might be stated as specific gravity, thermal conductivity, radiation, absorption, moisture content, organic content, texture and structure, concentration of salts in solution, evaporation, nature of surface and topographic position. The external factors are meteorological elements such as air temperature,

sunshine, barometric pressure, wind velocity, dew point, relative humidity and precipitation. Some of these factors tend to heat the soil, and others tend to cool it.

Crawford[1] lists the following intrinsic factors as often causing the temperature differences in the soil:

1. Latent heat of fusion of ice.
2. Latent heat of evaporation of water.
3. Ground surface cover.
4. Ground surface color.
5. Topographic position.

The surface factors chiefly influencing the radiation and adsorption of heat and hence soil temperatures are found to be cultivation, moisture content, color of the soil, and presence of vegetation. Dry soils are warmer than moist soils, since they radiate and evaporate less. Sands are the coolest of the dry soils, due to their great radiation.

It is important to keep in mind that those properties which are responsible for rapid absorption of heat rays during the day by dark-colored objects also cause rapid emission of heat during the night. This fact explains the daily variations in temperature under the darker colors.

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[1] Carl B. Crawford "Soil Temperature and Thermal Properties of Soils" Highway Research Board Sp. Report No. 2, 1952.

Frost penetration is more rapid and its disappearance slower under bare conditions, owing to the fact that it is frozen to a great depth. Investigators agree on the insulating effect of plant and snow cover.

It is a long known fact that snow protects the soil from severe frost, but the physical properties of snow are so variable that an accurate analysis of its protective effect is almost impossible. The importance of density of snow cover in effecting the insulating properties is well recognized. The relation of heat conductivity to density is a parabolic one. (See figure 8).

<u>Soil Moisture Content</u>

The effect of soil moisture content is probably the most important and yet the least understood intrinsic factor involved in soil temperature variations. Moisture content has a great effect on the specific heat of soil in place, since water has a specific heat approximately five times as great as dry soil. Dry soils have low conductivity due to poor contacts between the grains, and hence the temperature falls off rapidly with depth. Moisture improves the grain-to-grain contact, and the conductivity increases.

It appears that the soil moisture influences the radiation, evaporation, specific heat, thermal conductivity, diffusivity and heat capacity of soils.

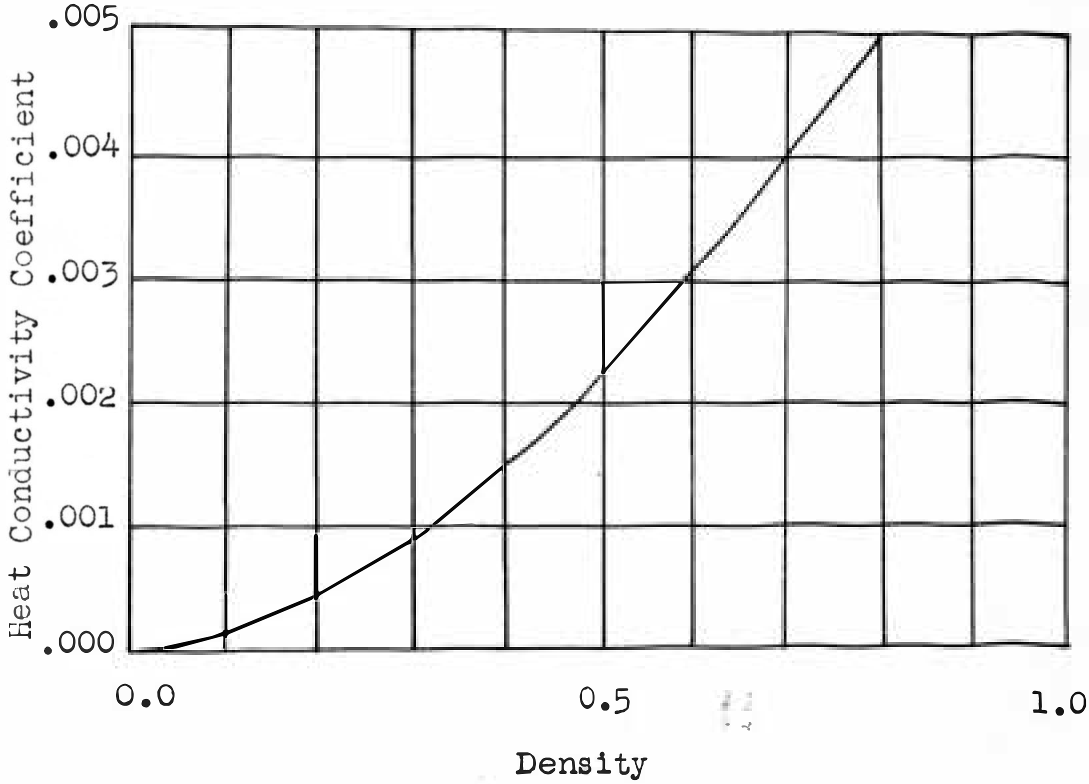

FIGURE 8. Relation between heat conductivity coefficient and the density of snow. (From Beskow)

Thermal Properties of Soils

The specific heat of any substance is defined as the calories of heat required to raise one gram one degree on the centigrade scale. The heat capacity of a given material is equal to its specific heat times its mass. Heat capacity and specific heat of a soil can be calculated by adding together the capacities of the various constituents. The thermal conductivity of a soil is the quantity of heat which will pass through a unit area of unit thickness in unit time under a unit temperature gradient. The thermal diffusivity of a soil can be represented as the thermal conductivity divided by the specific heat times the density. Diffusivity measures the rate of temperature rise under a unit temperature gradient.

Kersten[1], in his recent extensive analysis of the thermal properties of soils, found the conductivity to vary in the following manner:

1. When the soil is unfrozen, it increases with an increase in mean temperature.
2. When the soil is frozen:
   a. With a low moisture content there is very little change with temperature.
   b. With greater moisture contents it increases with a decrease in mean temperature.
3. As the soil changes from unfrozen to frozen:

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[1]Miles S. Kersten, "Thermal Properties of Soils" University of Minnesota, Institute of Technology Bulletin 28, 1949.

a. For dry soils there is no change.

b. At low moisture contents it decreases.

c. At high moisture contents it increases.

4. When the soil is at a constant moisture content, the conductivity increases with an increase in dry density. The rate of increase is fairly constant and independent of the moisture content.

5. At a given density and moisture content it varies, in general, with the texture of the soil. It is high for gravels and sands, lower for sandy loam and lowest for silt and clay.

6. The conductivity differs appreciably for different soil minerals.

It is evident that diffusivity also varies with different moisture contents, since it is a function of conductivity. Patten[1] showed that diffusivity of a coarse quartz powder increased to a maximum with the increase of moisture content and then decreased. Increase is due to an increase in the conductivity and the specific volume. (See figure No. 9). At higher moisture contents the volumetric heat capacity increases and the specific volume decreases. Both changes tend to decrease the thermal diffusivity.

Theoretical Basis for Heat Transfer

Jumikis[2] suggests that, for the treatment of frost problem, heat transfer maybe studied under:

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[1]H. E. Patten, "Heat Transference in Soils" U.S. Department of Agriculture, Bureau of Soils, Bulletin 59, 1909.

[2]Alfreds R. Jumikis, "The Frost Penetration Problem in Highway Engineering", Rutgers University Press, New Brunswick, N.J., 1955, p. 162.

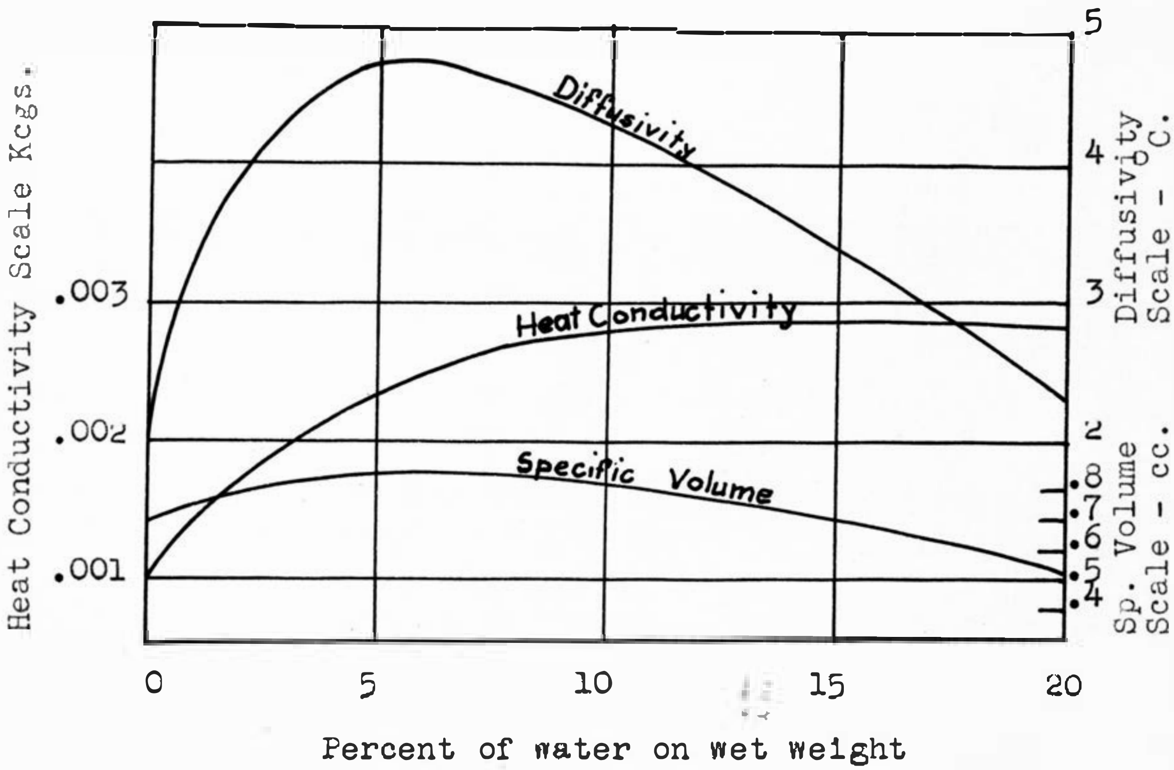

FIGURE 9. Effect of moisture content on volume and thermal behavior of a coarse quartz powder. (From Patten)

1. The steady-state flow of heat.

2. The unsteady-state heat conduction.

3. Neumann's theory.

4. Stefan's theory.

5. The suction force theory.

As a general basis for the analysis of these theories the following laws apply:

1. The quantity of heat in a differential soil element is proportional to its mass and to its temperature.

2. Heat conduction takes place when there is a difference in temperature between points or bodies.

3. Heat flows from a higher to a lower temperature.

4. The rate of heat flow across an area is proportional to it and to the temperature gradient (the rate of change of temperature with respect to distance measured normal to the area) at a point of the area.

5. The streamlines of heat flow are assumed to be parallel.

__The Steady-State Flow of Heat__

In applying the theory of heat flow in the steady state to the treatment of the frost penetration problem, the following assumptions are made:

1. The soil is a homogeneous isotropic material.

2. The geothechnical and thermal properties of the soil are constant.

3. Freezing in soil begins at 32°F.

4. The thermal conductivity of the soil is independent of the temperature. This latter assumption

is partially true because the conductivity of most soil materials is a function of the temperature and of their moisture content, density, prosity, presence of gaseous matter in their voids, etc.

Conduction of heat through a solid is given as:

$$\frac{dq}{dt} = \frac{K.A.dt}{dx}$$

Where $\frac{dq}{dt}$ = rate of heat flow.

K = coefficient of thermal conductivity.

A = cross sectional area.

$\frac{dt}{dx}$ = rate of change of temperature T with respect to the thickness x, of plate through which heat flows.

When the flow of heat in a body has reached a steady state, the flow is constant; thus the temperature at any place is also constant. That is to say:

$$\frac{dQ}{dt} = q$$

$$\frac{dt}{dx} = \frac{T_1 - T_2}{x}$$

Where q is the quantity of heat and T_1 and T_2 are temperatures at the top and bottom of the plate, then:

$$q = K. A \frac{T_1 - T_2}{x}$$

The quantity of $\frac{T_1 - T_2}{x}$ is called the temperature or thermal gradient. It is the ratio of the drop or increase in temperature between two points. Geometrically, thermal gradient represents a straight line (constant slope).

When the profile of a thermal system is composed of physically or thermally different materials in layers in

contact with each other, the profile is termed a compound layer, and the formula to determine the amount of heat transfer per hour is given as:

$$q = \frac{T_n - T_s}{\frac{x1}{AK_1} + \frac{x2}{AK_2} + \dots + \frac{xn}{AK_n}}$$

Where T_n is the temperature of the (n)th layer and T_s the surface layer, K_1, K_2, K_n represent the conductivity of respective layers.

Heat Conduction in the Unsteady State

The process of heat flow in a case where temperatures vary with both time and position is term heat conduction in the unsteady state. The formula:

$$\frac{dQ}{dt} = K.A. \frac{dt}{dx}$$

is now applied to a differential volume in the interior of the body of a soil layer. Now let us assume that this differential volume is located between two parallel laminae, called the isothermal surfaces, which are (∂x) distance apart. At the top and bottom of the differential volume, temperatures ($T + \partial T$) and (T) prevail, respectively. Then, according to the law by Fourier, during a time element dt, the quantity of heat which flows through the layer is

$$dQ = -K \frac{\partial T}{\partial x} dA.dt$$

where $-\frac{\partial T}{\partial x}$ = the temperature gradient at any point.

The minus sign indicates that the temperature decreases as the distance (x) in the direction of heat flow increases. It is important to note that $\frac{\partial T}{\partial x}$ varies with time as well as with distance.

Fourier's general partial differential equation for heat conduction in rectangular coordinates is given as:

$$\frac{\partial T}{\partial t} = D \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right)$$

where $\frac{\partial T}{\partial t}$ is the partial differential of temperature with respect to time and D is the diffusivity.

This equation expresses the conditions which govern the flow of heat in subgrade soils. In treating frost penetration problems in highway soils, we may assume that the flow of heat takes place in one dimension only, namely vertical, then the general equation becomes:

$$\frac{\partial T}{\partial t} = D . \frac{\partial^2 T}{\partial x^2}$$

The solution of this equation involves the determination of the temperature T as a function of the time and space coordinates in such a manner that

$$T = f(t_1 x)$$

must satisfy the general differential equation and other conditions which are characteristic of each particular problem.

Neumann's Theory

Originally Franz Neumann developed his theory to study the formation of ice upon freezing of still water. However, by properly fitting geotechnical soil constants into this theory it can be applied also to the frost penetration problem in soils.

It is assumed that the initial temperature T_0, of such a soil is positive and constant. Then by a sudden lowering of the surface temperature, T_s to a new constant and freezing value, the cooling process is inaugurated. The two partial differential equations are:

1. For the frozen part of the soil $(0 < x < E)$

$$\frac{\partial T_1}{\partial t} = D_1 \cdot \frac{\partial^2 T_1}{\partial x^2}$$

2. For the unfrozen part $(x > E)$

$$\frac{\partial T_2}{\partial t} = D_2 \cdot \frac{\partial^2 T_2}{\partial x^2}$$

where E is the maximum frost penetration.

Boundary Conditions:

1. The initial conditions: at $x\ 0$, $t \geq 0$, $T1 = T_0 =$ Const.
2. The fixed boundary conditions.

a. at $x = 0$, $t \geq 0$, $T_1 = T_s$
b. when $x \rightarrow \infty$, $t \geq 0$, $T_2 \rightarrow T_0 =$ Const.
c. The condition at the advancing isothermal surface of the frozen layer downwards.

at $x = E$, $t > 0$, $T_1 = T_2 =$ Const. $= T_f = 32^oF$.

where $T_f =$ freezing temperature.

Determination of Frost Depth:

Several investigators have found a resonably close relationship between climate and both penetration of frost and magnitude of heave, when climate (quantity of cold) is expressed in terms of its combined duration and intensity. Some use the term of degree-hours of temperature while others have used degree-days as the measure of duration and intensity of cold.

Degree days are the number of degrees that the mean temperature is below freezing during one day. The sum of these daily values for the winter season is sometimes called the "Freezing index".

There are two approaches to the frost penetration problem: theoretical and practical. There are two practical field methods for determination of frost depth, in general use. One is the thermocouple; the other the auger.

In the theoretical approach to the frost depth, various soil coefficients are either assumed or determined experimentally; and the depth is calculated by making use of a given formula.

When the surface temperature of the pavement drops below freezing, frost penetrates the soil or pavement. The greater the drop in temperature, and the greater the coefficient of thermal conductivity of the material is, the faster the frost penetrates the soil. On the other

hand, the greater the specific heat of the material the slower the frost penetrates.

In the case of heat conduction through a single layer, the frost penetration depth (E) can be calculated approximately, assuming the thermal conductivities of frozen and unfrozen soils are approximately equal. The the formula is:

$$E = \frac{T_f - T_2}{\frac{T_1 - T_2}{x}} = \frac{T_f - T_2}{i}$$

However, when the assumption that K (frozen) = K_u (unfrozen) cannot be made, then the frozen and unfrozen layers of the soil should be treated considering heat flow through compound layers which are in horizontal contact with each other. Than the following formula applies:

$$E = \frac{T_f - T_s}{i_u} \cdot \frac{K_f}{K_u}$$

where T_f = Freezing temperature = 32°F.

T_s = Surface temperature.

iu = Thermal gradient of unfrozen layer.

Kf = Conductivity of frozen layer.

Ku = Conductivity of unfrozen layer.

The thermal gradient (iu) is to be established in each locality for each particular soil by field observations. Also (Kf) and (Ku) are to be known. One difficulty in

using the above formula is that (Kf) varies as the frost penetrates.

Of practical interest to highway engineers is the insulating effect of the various protective covers. The problem is: How deep will frost penetrate through the cover into the soil?

The insulating effect of concrete and snow with respect to frost penetration can be demonstrated by means of an example:

Assume a concrete pavement thickness of 8 inches with K(constant) = 0.54 B.T.U. per ft.hr. °F. Suppose that a drop in temperature took place over the road surface from 52°F to 12°F in 5ft. For soil conductivity assume Ks = 0.83 B.T.U. per ft. hr. °F. The thermal resistance of concreto is $\frac{X}{A.Kc} = R$ If the pavement slab is not covered with snow, then the frost will penetrate the soil through the slab by:

$$E = \frac{Tf - T_2}{\frac{T_1 - T_2}{x}} - R. Ks$$

$$E = \frac{32 - 12}{\frac{52 - 12}{5}} - \frac{8}{12.(0.54)} \cdot (.83)$$

$$E = 2.50 - 1.0 = 1.5 \text{ ft.}$$

In case a concrete road is not kept free of snow, the frost penetration will be:

$$E = \frac{Tf - T2}{\frac{dt}{dx}} = Rc.Ks = Rsn.Ks$$

where Rc = thermal resistance of concrete.

Rsn = thermal resistance of snow.

In order to investigate the effect of two different covers with respect to frost retardation, the following proportionality holds:

$$\frac{X_1}{X_2} = \frac{K_1}{K_2}$$

This relationship permits one to calculate, for example, the thickness of snow cover equivalent to a known thickness of concrete cover:

$$Xsn = Xc. \frac{Ksn}{Kc}$$

Frost Pentration Under Bituminous Pavements

For a treatment of frost penetration under bituminous pavements the modified Stefan equation is a useful tool. The information required for its use includes texture and moisture contents of the soil profile, density determinations by tests or estimates, the average daily air temperatures during the freezing season.

Consider a layered system, such as a bituminous mat, gravel base, and layers of underlying soil, numbered from the top down.

The degree days required to freeze layer 1 are:

$$F_1 = \frac{L_1 \cdot x_1^2}{48\ K_1} = \frac{L_1 \cdot x_1}{24} \cdot \frac{R_1}{2}$$

in which F_1 = degree-days required

L_1 = volumetric latent heat of fusion in B.T.U. per cu.ft = 1.434 w.d.

W = Moisture content of soil in per cent.

d = dry density of soil in lbs. per cu.ft.

K_1 = thermal conductivity in B.T.U. per sq. ft. per degree F per ft. per hr.

R1 = termal resistance $\frac{x_1}{K_1}$

For Layer 2

$$F_2 = \frac{L_2 \cdot x_2}{24} \cdot (R_1 + \frac{R_2}{2})$$

For layer (n) $F_n = \frac{L_n \cdot x_n}{24} \cdot (R1 + R2 + + \ldots\ldots + R(n-1) + \frac{R_n}{2}$

$$F_n = \frac{L_n \cdot x_n}{24} \cdot (\Sigma R(n-1) + \frac{R_n}{2})$$

in which $\Sigma R(n-1)$ = the summation of the thermal resistances of all layers above layer n.

Example from Kersten[1]

$$F = \frac{L\ X}{24} (\Sigma R(n-1) + \frac{R}{2})$$

$$F = \frac{540\ (0.20)}{24} (0.38 + \frac{0.30}{2}) = 5 \text{ deg-days}$$

in which 540 = the volumetric latent heat of fusion of sand and gravel

0.20 = the thickness of this layer.

0.38 = the thermal resistance of the overlying bituminous mat.

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[1]Miles S. Kersten and Rodney W. Johnson, "Frost Penetration under Bituminous Pavements" Highway Research Board Bull. 111, 1955.

0.30 = the thermal resistance of the sand and gravel.

$\frac{0.30}{2}$ = the average resistance for the layer during its becoming frozen.

Kersten stated that predicted depth of frost penetration by the modified Stefan equation was less than actual depth.

CHAPTER VI

PERMAFROST

Permanently frozen ground, or "permafrost," is defined as a deposit of soil or rock of variable thickness and depth in which subfreezing temperatures exist throughout the year.

According to many theories, the origin of permafrost can be traced to the period of refrigeration of a large portion of the earth's surface at the beginning of the Pleistocene or Ice Age, perhaps a million years ago. Validity of this glacial origin theory has not yet been proved, however.

Observations show that apparently because of climatic changes, permafrost deposits vary in their thickness and areal extent. Where the mean annual temperature is below freezing, permafrost may be forming even at the present time. Permafrost underlies approximately one-fifth of the land area of our globe. Permafrost areas include about 80 percent of Alaska, half of Canada, a considerable port of Siberia, and some areas in China.

Basic features of Permafrost: The top and bottom surfaces of permafrost deposits are not horizontal. The irregular top surface of a permafrost deposit is the permafrost table. All ground above the permafrost table is designated as the active zone. The upper part of the

active zone is subject to intermittent freezing and thawing and is called the frost zone. Where seasonal freezing penetrates to the permafrost table, both frost zone and active zone coincide; otherwise, between the bottom of the frost zone and the permafrost table there is unfrozen soil known as talik. If a cold summer is followed by a cold winter, a frozen layer may develope at the bottom of the active zone, which might remain unthawed during one or more summers is called pereletok. (See figure 10 for the illustration of permafrost termindogy).

Seasonal thaw in the frost zone might penetrate from 1 to 10 ft., depending on insulation, drainage, and type of soil or rock material. The active zone might vary from 2 to 14 ft. or more. According to Krynine and Judd[1], the perennially frozen layer itself might be from several inches to about 2000 ft. thick, as in some parts of northern Siberia.

The expression "thermal regime" of the permafrost in a given locality means the state of certain equilibrium of the active zone under given environmental conditions including a constant position of the permafrost table.

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[1]Dimitri P. Krynine, and William R. Judd, "Principles of Engineering Geology and Geotechnics", Mc Graw Hill Book Company, Inc, New York, 1957, pp. 389-419.

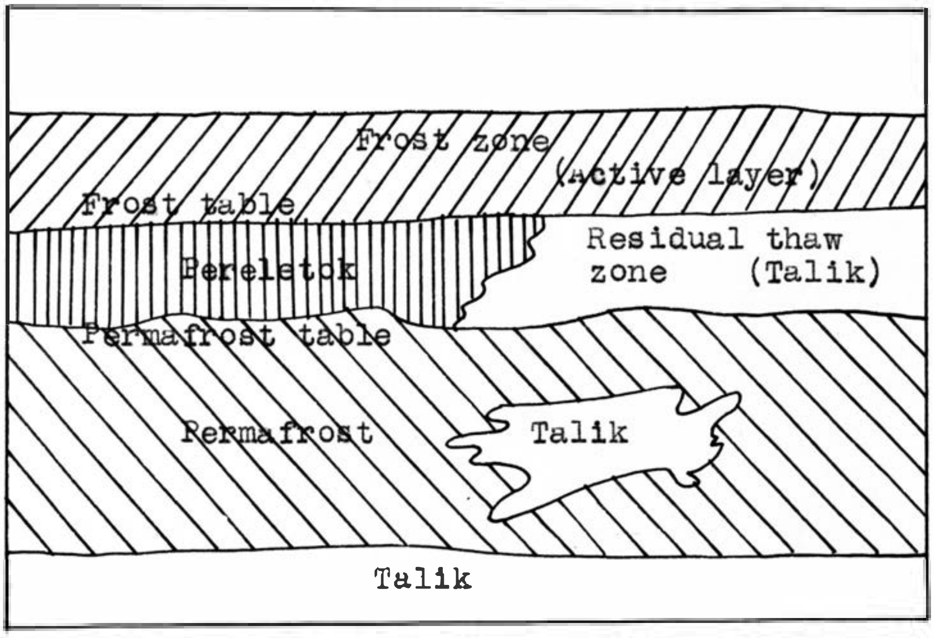

FIGURE 10. Permafrost terminology.
(From Krynine and Judd)

The thermal regime may be affected not only by natural factors but also by the activities of man, such as stripping vegetation, building cuts and fills, and drainage. When the thermal regime is upset, the permafrost table may be shifted upward or downward, often with undesirable consequences.

Ground Water and Icing in Permafrost Areas: Ground water may be above, within, and below the permafrost.

1. Water above the Permafrost

In warm months this may be a source of limited water supply, and it usually disappears in winter. If the active layer consists of impervious materials, ground water may be trapped between the active zone and the permafrost table. In such occurances the trapped water under pressure may move horizontally and contribute to the formation of "hydrolaccoliths", which are oversized heaves.

2. Water Within the Permafrost

Such water generally occurs in alluvium near rivers, abandoned river channels, or thawed gravel beds. It may also occur in small thawed areas lying between masses of permafrost. Other common occurances are in or near standing bodies of water, south-facing hillsides, and places where insulation has been removed, vegetation stripped.

3. Water Below the Permafrost

Such water generally occurs in large quantities mostly in alluvium under the permafrost, but it may also be found in joints, channels, and other available space in the bedrock. In hilly regions, ground water under the impervious permafrost may stand under high pressure, and flowing wells may result.

As the winter freezing of the soil at the surface sets in, the ground water in the active zone is placed under pressure. The pressure gradually increases, since the amount of ground water grows up but the space available for it shrinks because of the ice formation. Finally the hydrostatic pressure causes the water to force its way to the surface, where it spreads and freezes in successive sheets of ice. The "ice fields" or "icings" thus formed are parallel to the ground surface and attain a thickness of 3 to 10 ft., and more. Ground icing is very troublesome in the arctic, as the ice sheets may cover a highway for thousands of feet.

Icing control may consist of drainage and proper provision for the shifting of ice fields. Ice fences and heating also have been used to prevent the encroachment of ice sheets upon the highways.

Construction in Permafrost

There are two known methods of construction in permafrost:

1. The passive method, wherein the thermal regime, including the level of the permafrost table, is preserved, and
2. The active method, in which permafrost is completely removed by thawing and excavation.

The active method is used if the permafrost is thin and the ground after thawing will have satisfactory bearing power to support the structure.

In the construction of runways and roads, both the passive and the active methods are used. The passive method, where practicable, is preferred because atmospheric heat will not penetrate so fast or so deep through a natural vegetal cover as through artificially placed materials, and therefore the permafrost will not thaw in the summer. The insulating capacity of the construction materials should be at least the same as that of the natural cover. Furthermore, in winter time, cold should not be allowed to penetrate into the ground to such a depth as to affect the flow of ground water and disturb the existing thermal regime. This leads to the necessity of placing a substantial insulating layer under the riding surface. Very briefly the passive method in such construction is to push the moss and brush over the proposed site to form a base;

this is packed and subbase placed over it. Under such circumstances, the permafrost table will hold and may even rise.

In the active method of construction, the entire active zone is removed and replaced with porous granular material, such as coarse gravel, and the roadway or runway is placed directly upon this material. This method generally is applicable only in arctic areas where the mean annual temperatures are at or near freezing. Otherwise, on the days during which the temperature rises considerably above the freezing point, the permafrost will thaw owing to the lack of insulating cover, and pavement damage is likely to occur.

Generally in locating runways and highways in permafrost areas, cuts should be avoided, because (1) excavation of permafrost is difficult and thus expensive, and (2) if ground-water channels are intercepted, the thermal regime may be disturbed and ice fields may be created. Embankments should be built as far as possible from places where they may produce ice fields, as for instance, along brooks or close to valley bottoms.

As it is everywhere else, the problem of drainage is important in the permafrost areas for both runways and roads, and even more important for the latter, since as a

rule, they traverse much rougher terrain. The side ditches should be as far from the crown of the road as practicable; also, narrow, deep ditches are preferred to wide, flat ones. Narrow ditches provide more protection from cold air and are less susceptible to icing. Bridges and culverts should be high enough to clear stream ice, which can build up quite rapidly during the winter and during the spring break-up.

CHAPTER VII

SOME REMEDIAL MEASURES

The troubles caused by frost action may be quite different for different structures. Heaving usually causes destruction. The damage depends mainly on unevenness of heaving, different degrees of heaving at different parts of the structure, causing breakage and deflections.

Sometimes, as in the case of most buildings, it is necessary to prevent all or nearly all movement, usually excavation to "frost-safe-depth" and refilling with non-frost heaving material.

On the other hand, the main frost damage to roads is due to the softening of soil from melting of ice lenses, causing a decrease of bearing strength in the soil.

The following are the most common preventive measures as generally applied to eliminate or minimize frost damage:

1. Relocation of route.
2. Chemical treatment of Soils.
3. Drainage.
4. Replacement of frost-susceptible soils.
5. Insulation courses and membranes.
6. Frost-safe depth.

Relocation of Route

Sometimes where some road sections are subjected to detrimental differential heaving, under favorable terrain conditions, relocation can be considered. In a hilly terrain, the relocated sections if possible should be built along the southern side of a hill or in such a manner as to escape from improper accumulation of snow drifts. In most cases however, the relocation is impractical.

Chemical Treatment of Soils

The chemical treatment is the newest and most promising method of preventing damage from frost action.

Substances reducing the thickness of soil water films or giving the soil particles hydrophobic (water hating) characteristics would reduce frost heaving. Tests have been made on road fills with such substances as sulphite leach, calcium chloride, sodium humate. For frost action the treatment must affect a rather thick sub-grade soil layer. The substance must invade at least two ft. of soil. It must be movable in the soil-water system, and yet gradually become absorbed in order to avoid washing out with time.

A recent chemical compound experimented with is the aniline furfural. Sheelar[1] concluded that the aniline

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[1]J. B. Sheelar, J. C. Ogilvie, D. T. Davidson, "Stabilization of loess with Aniline Furfural", Highway Research Board Proceedings, 1957.

furfural stabilized soils had low moisture adsorption and hydrophobic character. A minimum of 2% by weight aniline-furfural was required for resistance to weathering.

Some chemicals, for example salts and sodium silicates, when injected into frost susceptible soil, lower the freezing point of the soil, thus have a retarding effect with respect to formation of ice lenses. Yoder[1] found calcium chloride quite effective in lowering the freezing point of the soil moisture. The presence of calcium chloride in the soil lowers the freezing point so that a lower temperature is required to produce the ice lenses that cause frost heave. It was found that the freezing point of pure water is lowered from 32°F. to 23°F. by the addition of 10 percent of chloride. Any fraction or multiple of this percentage will lower the freezing point a corresponding amount, that is, the freezing point lowering is directly proportional to the amount of chemical present. However, a soil containing 10 percent solution will have a freezing point well below 23°F. because soil itself begins to freeze at lower temperatures than pure water.

It should be noted that a solution of calcium chloride does not freeze solid at, or just below, its freezing point, only a few crystals of ice are formed. This ice is composed of nearly pure water, which upon being frozen,

[1]E. J. Yoder "Freezing and Thawing Tests on Mixtures of Soil and Calcium Chloride" H. R. Bd. Bull. 100, 1955.

releases its calcium chloride. The extra chloride is added to the remaining solution making it more concentrated and thus lowering its freezing point. This low solid-freezing point permits the use of relative small percentages to be effective in minimizing frost damage.

In northern climates, sometimes road construction has to continue during below-freezing temperatures. Calcium chloride has proven effective for treating newly prepared foundations and subgrades to prevent freezing during the period of grading and placing of the construction material. The method new recommended to permit uninterrupted paving is to apply $1\frac{1}{2}$ to 2 lb. calcium chloride per sq. yd. bladed or mixed into the top 2 to 3 in. of subgrade material. This provides protection for the normal period between grading and paving, at minimum temperatures of 10 to 15°F.

However, the effec t of treating soils chemically seems to be temporary, as the chemicals slowly leach away. Up until now, not very much has been known about chemical treatment of soils.

Drainage

If the excess water saturates the pore spaces of the soil, either because of a high water table or because of an accumulation of gravitational water in the upper soil layers, the process of removal by downward flow through

the soil is referred to as "internal drainage."

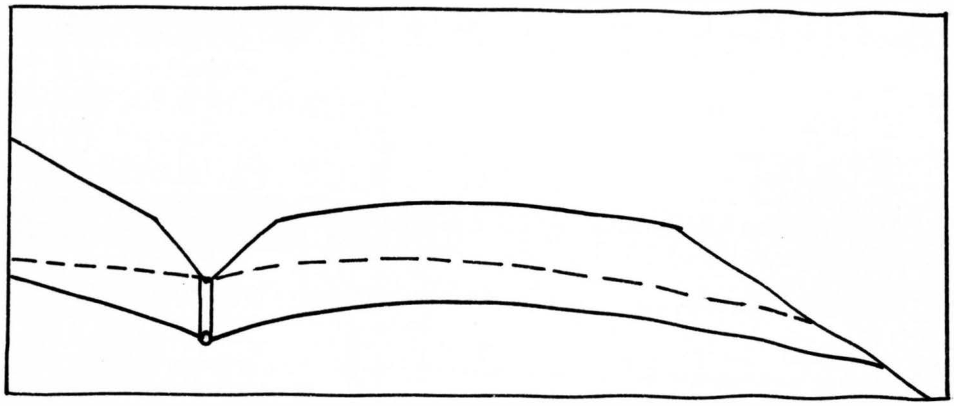
Effective drainage is of primary importance to all roads. The object of drainage installations is to lower the ground water table or to intercept seepage flows which upon accumulation in highway roadbeds may under adverse freezing conditions cause troublesome heaves.

In order to lower the ground-water table, drainage facilities should be installed below the present water table, but not within the zone of the capillary fringe. The reason for this is that only gravitational water can be drained off.

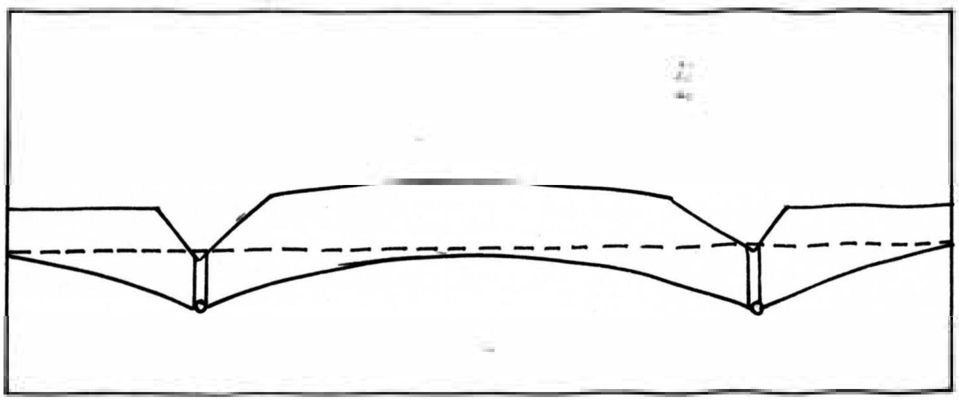
The terrain conditions favorable for drainage are roads with side slopes. Here a deep drainage placed along the upslope side will cut the ground water flow, forcing the ground water level down to the drainage level. Thus only one deep drain is required along the roadside. (See figure 11).

If the country is flat or the road is going in the direction of slope, deeper double drains one on each side of the road are required.

Very extensive experience has shown that for preventing frost boils, the effective depth of drainage below road surface has to be at least 6 ft in silts, and 5 ft in clay and moraine soils. Of course, the effect of deep drainage in each actual case could be predicted



a) Single drain (Sloping up).



b) Double drain (Flat country)

FIGURE 11. Effect of tile drains on the ground water table.

more exactly by studying changes in ground water depth during the freezing period.

A recent technique employed to lower the water table is called electroosmosis. It was found that the passage of direct current through the soil between embeded electrodes causes the water in the soil to move from the positive electrode toward the negative electrode. It a well-point is used as the negative electrode, the water which collects at the electrode can be pumped out, thus effecting drainage of the soil. Kondner[1] states that cathodes can be located with vertical sand drains, thus causing a flow of water in a radial direction towards the sand drains.

Replacement of Frost-Susceptible Soils

Excavation of frost-susceptible soils to replace them by non-susceptible types or at least satisfactory granular backfill to the depth of frost boundary is probably the most common and rigorous measure to eliminate serious road damage. The depth of excavation depends upon the type of soil, climatic conditions, backfill material and the required degree of safety.

A subbase should be as coarse grained as possible

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[1]Robert L. Kondner, and Walter C. Boyer, "Research on the Use of Electroosmosis in the Stablization of Fine Grained Soils" Highway Research Bd. Proceedings, 1957.

and poorly graded; that is it should not have fines, which might fill the voids and provide capillary channels around the large particles. Crushed stone is an ideal material for cutting off the capillary flow of water. A subbase need not extend below the maximum probable depth of frost penetration. For example, according to Spangler[1], in the corn belt of the United States, frost rarely pentrates the soil to a depth greater than 4ft, and this would represent a maximum effective thickness of subbase as a barrier against ice growth . This method is an expensive one, but it is the safest.

Insulation Courses and Membranes

By insulating courses are meant capillarity or suction-breaking layers. Pebbles, sand, and gravel can be used for secondary roads. Brushwood mats, moor and straw are used in Europe for the same purpose. These courses also serve as heat-insulating layers to retard the frost penetration. On top of these insulation courses the excavated frost susceptible soil is backfilled again. The thickness of these layers depend upon their thermal insulating properties. The object of such courses is to achieve maximum resistance to frost penetration with a minimum thickness.

Another principle to achieve an insulating effect

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[1] M. G. Spangler "Soil Engineering" International Textbook Company, Scranton, 1951.

is to combine an upper layer of soil material possessing a low heat conductivity with a second layer with a high frost-storing capacity. Then the upper layer acts as a heat insulating course which preserves, as long as possible, the heat strorage capacity of the lower by water-saturated material.

The function of the sand fill as a non-frost sensitive subbase material is quite simple. But sand is also effective as a rather thin bottom layer. In this case, the sand layer has a real insulation function, namely cutting the capillary connection between the overlying soil and the subgrade. In order to secure a non-interrupted, open porosity all over the area, a minimum thickness of 1 ft. is stipulated. The refill of very frost sensitive material (Silt) should never exceed 2 ft. thickness. The water level should be about 1 ft. below the sand layer.

Another principle is to provide a capillary cut-off blanket of fairly well graded non-swelling clayey material under the pavement. Because of its high clay content, such a material may have a high capillary potential; however, by reason of the same fine grained characteristic, the rate at which capillary water moves through the soil may be very low to feed the growing ice layers.

Membranes are understood to be impermeable and frostproof materials, such as heavy paper, tarred felt, bituminous fabrics or sheet metal. These materials break the upward flow of soil moisture towards the ice lenses during their growth. They must be placed below the maximum frost penetration depth; otherwise ice lenses will form underneath the membranes. The disadvantage of membranes is that the surface waters cannot escape. A better condition is achieved if the membranes are installed with a transverse grade on both sides of the center-line, like a sharply broken roof. Another disadvantage of the membrane method is its high cost.

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