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CLIMATIC ASPECTS OF FROST HEAVE AND RELATED GROUND FROST PHENOMENA

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Synopsis

Frost heave is a freezing-ground phenomenon created by the compounding and sequencial influences of several climatic and other environmental factors causing ground heat loss. The most important of these factors are: radiation, convection, conduction, evaporation, vegetation and snow cover, soil type, and accumulation of soil water in the "vernal active zone." (Spring freeze-thaw zone above winter frozen sub-soil.)

By the use of climatic and geographic data, already available, it is possible to map the distribution of frost-heave elements and to predict the timing and severity of heave forces for areas through which highways are projected.

An index using the percentage of the total annual hourly frequency of temperatures below 30 F., the temperature difference between the freezing point and the temperature of the minimum 1 percent frequency level, and an adjustment for surface insulation cover appears to provide a means of predicting probable average maximum depths of winter frost penetration. Similar indices may be possible for the determination of probable time and force of heave by consideration of soil type, precipitation, and accumulation of soil moisture to depths favoring frost heave.

An understanding of the climatic mechanism of frost heave makes it possible to establish positive control measures to protect highways and other structures. Such control measures include drainage and insulation techniques heretofore commonly neglected. Highways are generally good

thermal conductors, especially when cleared of insulating snow cover; hence frost penetration beneath them will be abnormally deep as compared to adjoining surfaces. Solar heat absorbed by highways in daytime and intensive outward radiation at night intensifies the freeze-thaw action of the vernal active zone. Sub-highway insulation would lessen the depth of winter freeze as well as lessen the diurnal activity in the vernal active zone. Frost heave results from the freezing expansion of excessive water accumulating in the zone above the upper horizon of the winter frozen ground. Highways form dams and troughs beneath them in respect to contours of upper and lower surfaces of the frozen sub-soil. Drainage may be controlled either by lateral blocking on up-hill sides of slopes or by means of by-passes below the frost line. In flat country vertical sumps to absorptive soils below the level of winter frost penetration should eliminate soil water accumulation and consequent frost heave below pavements.

Radiation

The lowering of incoming solar energy due to seasonal and latitudinal variations is evident. During long, winter nights more radiated heat escapes than can get away on shorter, summer nights. And conversely, solar heat builds up faster in the longer daytime in summer than it can lose by radiation during the short nights. Of course, the sun shines through a greater thickness of atmosphere in winter than in summer, due to differences in elevation of the sun. On a very cold winter night in a locality like Minneapolis, Minnesota, average net loss of radiation is about .07 cal. per sq. cm. per min. This is sufficient in itself to account for freezing about 3 in. of surface water.

Many factors influence the exact rate of heat loss. Emissivity of the surface, bare, dark ground and rocks will radiate more heat, for example, than snow. Warmer surfaces will lose more heat in a given time than colder ones. Cloud cover reradiates heat back so that surface temperatures will not fall as rapidly as under clear conditions, because the clouds are warmer than the clear sky. High humidity in the air inhibits the rate of heat loss. Dew or frost condensation of the surface radiating heat gives up its heat of condensation and fusion tending to cancel off the heat being removed from the surface itself. Air motion tends to mix the air at the surface and thereby cancel some of the extreme effects of radiation.

Frost heave occurs most often in spring after the advent of a cold wave, or after a cold, calm night of radiant cooling. The spring occurrence is due to a moisture build up through fall and winter and to the fact that frost penetration has reached its maximum depth. In the spring the solar heat balance is rapidly shifting to the positive or incoming side. By about mid-March, heat received is equivalent to mid-September solar heat, which is still recognized as respectably warm. The frost ground thaws on the surface during the day and refreezes at night by the combined action of heat radiation from above and absorption from below. The freeze-thaw action tends to give rise to accumulation of water and ice bands in the soil above the impermeable layers of frozen soil that do not temporarily thaw by the spring freeze-thaw action, and in due time give rise to frost heave of serious proportions.

Conduction and Convection

Loss of heat from the ground by means of conduction is strictly the flow of heat by direct contact of one surface with another. However, from a practical standpoint, it is difficult to separate the intimate relationship of outgoing radiation from that of conduction into the air. The incoming radiation supplying heat to the surface tends to blend itself with the functions of conduction back into the air or down into the ground. The ground itself is a storehouse for heat, and at a level some 30 ft. or so below the surface in normal ground, temperature tends to become isothermal, i. e., it maintains a constant temperature which is, for all practical purposes, the same as the mean or average annual temperature for the area. This value is usually provided by the Weather Bureau statistics and is frequently calculated as the mean between the average temperature of the warmest months and the average temperature of the coldest month or the simple average of all the months. It also closely approximates the mean of the highest and lowest temperatures. In some areas of the country where winter cold extends well into fall and spring, the ground temperature is likely to be lower than would be indicated by the average of extreme temperatures, and the reverse is true for areas with extremely long summers.

Figure 1. Approximate Distribution of Deep Ground Isothermal Temperatures Based on Mean Annual Temperatures Degrees Fahrenheit. At levels 15 to 30 ft. below the surface, temperatures as shown remain constant and relatively unaffected by variations in atmospheric temperatures throughout the year. At levels above the isothermal zone stored heat from the previous summer tends to inhibit the cooling and freezing of the ground.

When winter sets in, ground temperatures have built up to their maximum. The surface heat of the ground is rapidly reduced, however, due to the insulating effect of the ground itself. The remnant temperatures of summer still remain apparent in the ground to the extent that at certain intermediate levels between the surface and the deep isothermal layer, ground temperatures are higher in winter than in summer due to this lag effect. This produces an apparent temperature anomaly. The thermal conduction factor of the soil determines the rate at which the heat will be dissipated from the ground. In a soil of high insulating value or low thermal conductivity the surface will cool rapidly by radiation and conduction with a sharp rise in temperature a few feet below the surface in early winter. The frost line at the surface gradually penetrates this soil as the heat is conducted upward. In high conductive materials where the conduction of heat is more rapid, the thermal gradient is less steep and frost penetration consequently is more rapid. Thermal capacity of materials also plays an important part as to the total amount of heat stored in the summertime and gradually given up in winter.

It is clear from the foregoing, that throughout the early winter a supply of heat is being constantly conducted upward towards the surface, and therefore, the surface layers are being warmed both from the top and the bottom on sunny days.

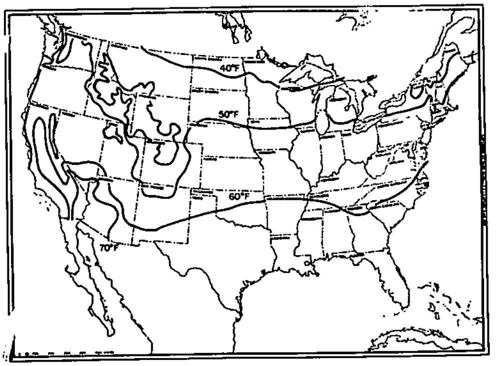

Figure 2. Estimated Approximate Ground Temperatures Degrees Fahrenheit Six to Eight Feet Deep at Start of Fall Cooling Period. At this level, well above the isothermal zone, temperatures which represent stored heat from the previous summer tend to inhibit the cooling and freezing of the ground.

Changes of temperature in winter are principally caused by the migration of great air masses varying widely in temperature. The coldest air masses arrive in the United States from the northwest and are frequently accompanied by clear weather, admitting solar heat to the ground surface in the daytime and creating conditions for excessive radiant cooling throughout the longer winter nights (which is in excess as noted under radiation and therefore negative in its net heat exchange). Air masses aided by radiation determine the temperature of the air figuring in conduction heat losses from the ground. These air masses frequently have extremely low temperatures, well below zero in the northern United States, but

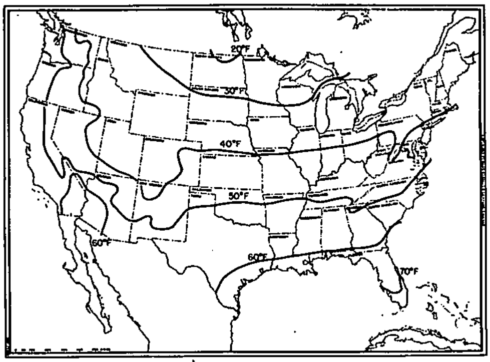

Figure 3. Estimated Approximate Ground Temperatures Degrees Fahrenheit Six to Eight Feet Deep at Time Spring Freeze-Thaw Period Begins. After mid-winter has passed, temperatures at these levels have reached the coldest levels likely to occur and will remain a deficit until reheated by the summer sun.

gradually become moderated southward until approaching the Gulf and southeast Atlantic Coast temperatures generally remain above freezing. Also the preponderance of warm air masses are greater in this latter area than to the north. At the f ronts between the air masses, it is usually cloudy and there are frequent, continuous, gentle rains or snowfalls. The presence of precipitation in itself affects the thermal picture.

Under extremely still air conditions, heat loss by radiation is generally greater than heat loss from the surface into the air by conduction. However, when the air is set in motion and thereby aided by convection, the combined conductive and convective heat loss rapidly exceeds radiation losses per se. For example, under still air conditions the heat loss is of a magnitude of 5. 56 Kg-Cal. per sq. m. per hr. per deg. F. between the temperature of the surface and the air. As air movement increases to one mile an hour, this heat loss or wind-chill factor increases to approximately 9. 27 Kg-Cal. per sq. m. per hr. per Deg. F. At between 2 and 3 mi. per hr. the rate of heat loss is double that of still air. As the wind velocity increases, the effectiveness heat loss by conduction and convection decreases so that at 9 mi. per hr. the value is only about 2-1/2 times the still air value, at 20 mi. per hr. about 3 times, and at 45 mi. per hr. only about 3-1/2 times the still air value.

In order to understand the magnitude of heat loss, let us assume a surface ground temperature of 32 F. and an air temperature of 0 F. The rate of heat loss of combined convection, conduction and radiation would amount to:

Wind Velocity Mi. per Hr.	Rate of Heat Loss Kg-Cal. per sq. m. per hr.
Calm	180
1	300
5	410
10	480
20	560
30	600

The actual occurrence of the foregoing conditions is dependent upon the rate that heat can be conducted to the surface through the soil from below. If the surface layers have considerable insulating effect, the high rates of heat absorption potential will drop rapidly, and of course, if the surface cooled to the air temperature itself, there would be no transfer of heat. On the other hand, if the surface temperature is lower than air temperature, the ground will tend to heat by the reverse values here given. That is, a 10 mi. per hr. wind at 32 F. would tend to heat the surface which had been previously cooled to zero at the rate of 480 Kg-Cal. per sq. m. per hr.

From a practical standpoint it is difficult to illustrate the primary elements of intensity and duration of air temperatures for a geographic location. For many areas, Weather Bureau statistics provide such values as the mean annual temperature which can serve adequately as the probable isothermal temperature deep in the ground, although there will be many local or microclimatic anomalies due to variations in the elevations, texture, and cover of the surface. Figure 1 shows the general distribution of this average annual or deep ground temperature value over the United States.

The Weather Bureau statistics covering mean monthly temperatures and mean monthly extremes and absolute extremes are available but their direct application to our problem has many deficiencies. The maps show a more important aspect based on this data as to the probable temperature of the ground at 6 to 8 ft., which is taken as the average between the annual mean temperature or deep ground constant temperature and the average temperature of the month.

At this level, well above the isothermal zone, temperatures which represent stored heat from the previous summer tend to inhibit the cooling and freezing of the ground (Fig. 2).

After mid-winter has passed temperatures at these levels have reached the coldest levels likely to occur and will remain a deficit until reheated by the summer sun (Fig. 3).

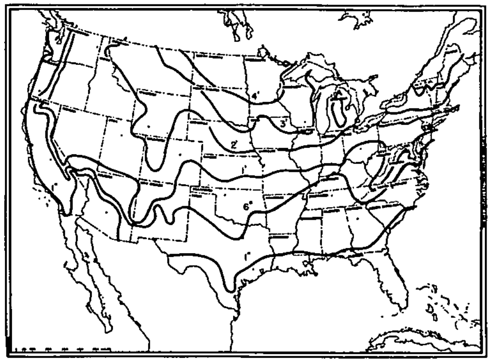

Figure 4. Approximate Average Depth of Frost Penetration in Feet and Inches. (Modified after Climate and Man, Agriculture Year Book 1941, p. 747). The values shown here are reasonable estimates of the depth to which frost is likely to penetrate. Local conditions, however, such as valleys, hills, vegetation cover, ground mantle, solar and wind exposure, etc., create wide variations.

Figure 4 has data collected unofficially and published in the Agricultural Year Book, 1941, entitled "Climate and the Man," which shows the average depth of frost penetration. It can be seen that there is a great relationship between the 6-to 8-ft. level temperatures and frost penetration.

From recent statistical work on temperature frequencies, it has been possible to produce two interesting additional maps that further supply important elements of our frost heave problem. This frequency data is based upon the number of hours in the course of a year that temperature occurs at each degree. It has been observed that the probable and more practical extremes can be more safely calculated by establishing the 1 percent value. That is, Figure 5 shows the minimum temperature recommended for design wherein only about 88 hr. on an average year will have temperatures lower than the minimum here shown. In some areas absolute extreme temperatures may run to more than 20 deg. lower than this value but will be of such short duration that deep effects will be unlikely. This map can therefore be considered as illustrative of intensity of cold.

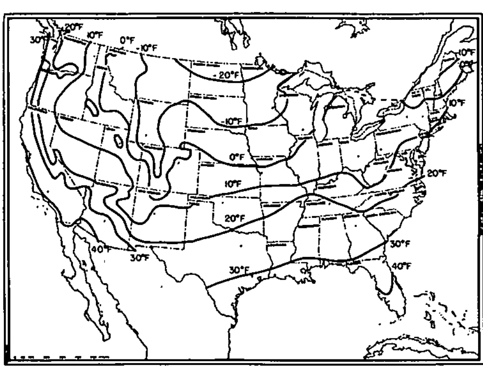

Figure 5. Intensity of Winter Cold (Minimum Design Temperatures Degrees Fahrenheit). Not more than about 1 percent hr. of the year have temperatures lower than shown here, although absolute extremes have been 20 F. or lower. The intensity of cold taken together with the duration of sub-freezing temperatures form principal factors in estimating the depth of frost penetration.

In Figure 6 is another treatment of the frequency data which shows the duration of cold. Here, for convenience, I have used the occurence of temperature of below +30 F., instead of 32 F. Although the data for both these maps was based upon the relatively few stations available, it at least gives a clear indication of the period of time over which frost actions are probable. Here the duration is expressed in percent of hours of the year and cannot be taken as concurrent but rather as values spread over periods of time. It would be valuable to study the frequency of temperatures for

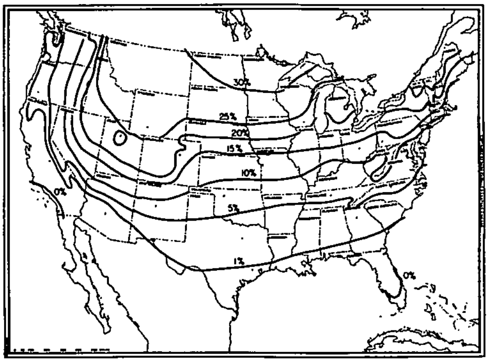

Figure 6. Duration of the Freezing Period. Percent Hours of the Year that the Temperature Falls Below 30 F. Because of the character of data available for this map, it proved more convenient to use 30 instead of 32 F., and although the percentages would be higher at 32 than shown here, they would be of the same relative distribution.

more minute relations to the frost heave problem and would give us encouragement that observations of intensity and duration, correlated with depth of frost penetration, can eventually provide a clear concept of the physical phenomena involved.

Figure 7 shows a graph plot of data for about 40 stations using statistics from Figures 4, 5, and 6. There appears to be a direct relation between the plot of intensity and duration of winter temperatures and that of the depth of frost penetration.

Moisture Problems

Frost heave is dependent upon the presence of water in substantial accumulation near the surface. The study of frost heave has progressed to the point that we are fully aware that moisture accumulation to create serious frost heave damage occurs generally where there is an appreciable amount of free water present. There are four principal ways by which this water can accumulate. The first is by transportation, that is, where the land is on a slope, water may flow under gravity or pressure from a higher elevation or across the surface or through the sub-soil. This water may bring with it varying temperatures from that of the ground.

The second method of water accumulation is by direct precipitation or in the form of rain or melted snow. Where the land is on a slope, some of this water may drain off over the surface or through the sub-soil but in flat areas, it is likely to remain on the surface and in the sub-soil. Evaporation during the winter period is extremely low, and through gravity the water will tend to sink into the soil until it meets an obstruction. Where the ground has been frozen, higher temperatures of spring and solar heat may thaw the top soil, thus permitting the water to penetrate to the upper horizon of the sub-frozen soil. Here it will be blocked by the frozen ground which has become impenetrable. The soil becomes saturated and, due to periodic if not diurnal freezing, begins to work the soil and deform it if there is space for a considerable amount of water. This gives rise to the dangerous lenses which, upon freezing, are known to contribute heavily to the actual frost heave.

The third method of water accumulation has been discussed by Benkelman and Olmstead, and others, as a phenomenon related to capillary action of water brought up from below.

It is the theory of the writer, however, that the full mechanism of water brought up from below is not to be understood only by capillary action. Benkelman and Olmstead, 1932, demonstrated that no ice bands tended to form when their samples were frozen at a constant rate. Banding did occur when the temperature was varied. That is, they kept the surface temperature constant and heated the bottom of their sample tubes to temperatures a little above freezing.

Apparently these workers overlooked

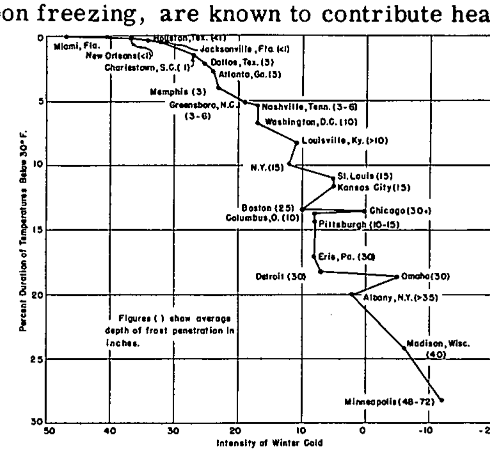

Figure 7. Frost Penetration as Compared to Plotting of Duration and Intensity of Winter Temperatures.

the fact that another transfer mechanism (the fourth method) was present which would account for a transfer upward of water to soil near the surface of the ground. As we noted earlier, deep ground temperatures are considerably warmer than air temperatures and surface temperatures in winter. Therefore, moisture in the ground at greater depths will have a much higher vapor pressure than will the colder temperature soils near the surface, thus it is suggested that these soils are actually evaporating moisture which in the form of vapor rises through the interstices in the soil until reaching the dew point where it is again condensed. It appears difficult, however, either with the capillarity or vapor transfer to the surface, to account for extensive formation of ice lenses, for in both cases the temperature will generally have to be above freezing for this action to take place readily. Therefore, as soon as moisture has accumulated to any extent, gravity would tend to pull it back down and therefore tend to eliminate the excessive accumulation. Thus, it is concluded that the primary source of water to produce ice lenses is that which is either trapped by transported water in depressions of impenetrable sub-layers or by ice-blocked drainage from above. Nevertheless, it is reasonable to assume that vapor accretion can supply sufficient moisture to fill interstices and voids between soil grains with water and ice until the soil is rendered impervious.

Moisture transfer through soil by means of vapor migration has perhaps received too little attention. I have witnessed it as a common phenomenon in glacial regions, such as the neve of Antarctica, where vapor passing among the snow grains causes crystals to grow, cement, and dissipate by this process. Of course, fine-grained soil is less porous than nevê snow but the process of moisture migration can be little different in principle than for migration of moisture through insulation of walls, winter clothing, refrigerators, etc. The phenomenon is closely related to the condensation of dew and frost on window panes in winter and to the reason why basements are dry in winter and humid in summer. This moisture migration by vapor transfer cannot be considered a winter phenomenon only, for in spring and summer when the ground is colder than the surface it is reasonable to assume that vapor moves downward to hasten drying the surface soil in addition to drainage and surface evaporation.

Although this paper has treated only a portion of the climatic aspects which bear upon the ground frost phenomena, two conclusions are apparent. First, that the climatic factors are numerous and complex but are sufficiently well understood that through cooperation of climatologists, highway research personnel and soils mechanics specialists it should be possible to predict frost heave hazards, and make preventive solutions.

Second, despite the innumerable climatic factors which all play a part in the frost heave problems, the single factor of moisture is the most important on which to concentrate control. Most all other climatic factors by themselves do not produce a hazard, but water in the subsoil, by whatever manner it gets there, is the essential element that creates frost-heave damage upon freezing. If we can but find positive measures of keeping water out from under roadway structures to the depth of frost penetration, frost heave will be eliminated. Surface seepage could be controlled by an impervious cover on the surface, but lateral migration of water is more difficult to handle economically. Most difficult of all is to handle moisture which rises from below whether by capillarity or vapor transfer. It is possible that by recognizing the vapor transfer mechanism, later investigators will discover that the present method of highway construction over gravels or crushed rock with large drainage voids is an ideal media for vapor transfer and that beneath the pavement is a situation like a giant window pane on whose undersurface condensation builds up thick masses of ice until the subgrade gravels are cemented in and form an impervious layer. In such circumstances, local thawing under the pavement could cause accumulations of puddles which are entirely unexpected and quite close to the underpavement surface. The subgrade cannot drain properly, for it has been rendered impervious by ice filling the drainage voids. Thus, when the puddles freeze the pavement is heaved. Although the best method of reversing a vapor migration gradient, namely heat, appears as an impractical approach to a solution, we have but scratched the surface of our ability to harness solar heat, but some day we may learn how to capture it to control winter frost heave.