SOIL TEMPERATURE AND THERMAL PROPERTIES OF SOILS

SOIL TEMPERATURES, A REVIEW OF PUBLISHED RECORDS

Carl B. Crawford, Junior Research Officer
Division of Building Research, National Research Council of Canada

Frost action in soil results from a critical change in temperature at some depth below the surface. Any study of frost action therefore must be closely linked with a detailed study of the variation of temperature in soil at increasing depth below the surface and throughout the cycle of the year. This basic characteristic of soil in place might appear at first sight to be a relatively simple matter. Due, however, to the many variable factors involved, not the least of which is the character of the soil in question, the problem is actually most complex.

The Division of Building Research of the National Research Council of Canada has embarked upon a long-term study of soil temperature variations in view of their economic importance in many fields of engineering. An earlier paper by Legget and Peckover (56) reviews some of the detailed problems involved in the study of soil temperature variations and outlines work which is at present in progress in Canada. The present paper marks the completion of the initital stage of this project and is now contributed, since it presents in review a brief record of previous considerations of many of the factors dealt with in this symposium.

The usual research project of this kind starts with an extensive review of the literature in order to establish what is already known and proven. On this basis, an experimental program is carefully built up, avoiding the pitfalls exposed by previous investigators and steering the shortest path to the goal which has been set. In the present instance, the customary procedure was at first reversed, and some field experiments were started before past work was reviewed in detail. This was necessary because the time cycle of the experiments involved is one full year, and a delay in commencing field work would have meant much loss of time. It is therefore hoped that in addition to providing the necessary background for Canadian experimental work this paper may be a guide to the fund of information on soil temperatures which is available in scientific literature.

This paper contains references only to publications in English. Indirect references are made to some of the available papers on the subject published in Germany and Scandinavia, but time did not permit these being studied. About 200 papers in English appear to exist, which deal with the subject to some degree. About 80 of the more important of these papers were carefully read, studied, and abstracted. Fifty-seven of the papers were found to be of direct interest, and the following record is essetnially a summary of the information and records which they contain. The bibliography of A. W. Johnson of the Highway Research Board was of great assistance in the long quest for relevant papers.

In each section of the paper, an effort has been made to give an accurate review of the more important aspects of the work of various investigators. These reviews have been put in chronological order under each subject for the sake of uniformity. It might be expected that this procedure would bring into prominence the studies of some early scientist who had managed to look into the problem thoroughly enough to discuss many of the factors involved. This is indeed the case, and it will be found that almost every section of the paper starts with a review of the work of Dr. G. J. Bouyoucos of Michigan State College, who from 1913-1922 stated most of the problems encountered in the study of soil temperatures, and analyzed many of them. Most of the important references since that time refer to his pioneer work, which is still an essential starting point for current studies.

Historical Note

It is not surprising that scientists of the seventeenth century were interested in the action of frost in the ground. But it is remarkable to find soil temperature records such as those observed by Forbes (1) over one hundred years ago (Fig. 1). Forbes began measurements in January 1837 at three locations 1/ near Edinburgh. Readings were obtained at depths of 3, 6, 12 and 24 French ft. (24 French ft. = 25. 6 English ft.), using specially constructed mercury in glass thermometers. These thermometers were as much as 26 ft. in length with a capillary bore down the center. One degree F. change in temperature at the bulb moved the mercury five feet in the capillary tube, so an enlarged bore was added at the scale to facilitate reading. Corrections were applied to compensate for the temperature of the stem and the readings were taken to one-hundredth of a degree Fahrenheit.

Forbes reports that soil temperature observations to a depth of 8 ft. were taken near Edinburgh by Sir John Leslie from 1815-1819. Records were also obtained in India at 3, 6 and 12 French ft. from 1842-1845. Forbes credits Lambert, a German mathematician, with the first systematic analysis of soil temperatures.

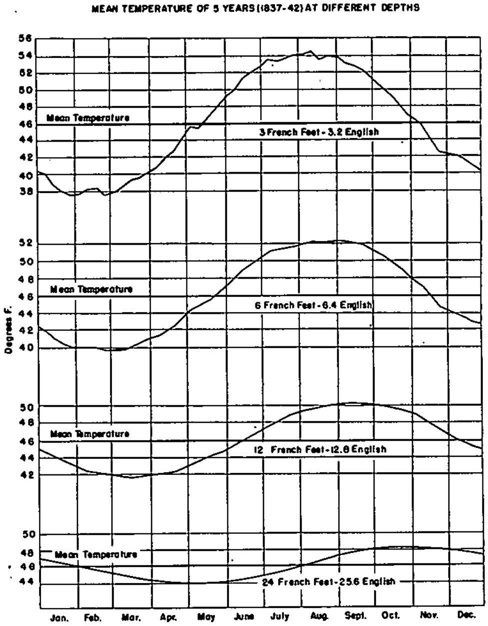

Figure 1. Mean Temperature of Soil at Different Depths with Time, from Forbes (1)

Beskow (30) reports reference to the "freezing up of stones from the ground" as early as 1694, but the first explanations of frost heaving were offered about the middle of the 18th century.

The advent of modern measuring instruments has greatly simplified the study of subsurface temperatures. At the close of the last century Professor Callendar began measurements at Montreal using electrical resistance thermometers. This new method permitted a relatively sturdy instrument to be left in the soil and periodic readings to be taken or even continuously recorded. Naturally an improvement in instrumentation was all that was needed to start a number of new investigations.

Up to the present time there have been more than two hundred papers published in English on soil temperatures and frost action. In addition, there are, of course, many others published in other languages. Unfortunately for engineers, most of the work on soil temperatures has been done for agricultural purposes. The data so obtained are often difficult to apply to engineering problems but are nevertheless valuable. From available records it is clear, however, that there exists a need for further study, in view of the many associated engineering problems.

Economic Aspects

The economic importance of a study of soil temperatures is clearly shown in engineering literature. Mabee (33) for example, reported that about 2,000 (2. 7 percent) of the private service lines in Indianapolis were frozen during the severe weather in the early part of 1936. At that time, Indianapolis suffered the most severe winter in a 65-year period.

1/ Editor's Note: Only the readings for one location, Craigleith, are shown in Figure 1, inasmuch as the three sets of readings are quite similar.

The necessity of soil temperature data for an analysis of flat-slab construction is indicated in a report of the National Bureau of Standards (69).

Hieronymus (48) and Shanklin (17) have pointed out the necessity of soil-temperature observations in order to evaluate the ability of soil to dissipate heat generated by losses from power cables. Economical calbe design is dependent on a knowledge of the earth's temperature at various seasons and depths and a knowledge of soil heat capacity.

Algren (55) considered observations essential to the study of heat-pump operation, the perimeter and ground-slab loss for floor-panel heating systems and the ground losses and floor-slab temperatures of basementless houses.

In addition to the above references, a publication by Legget and Peckover (56) lists important associated problems: cold storage plants, vegetable storage, city snow clearance, permafrost conditions, and of course, highway and airport construction.

Some Factors Affecting Soil Temperatures

In a review of literature such as this, it is necessary to consider the various factors which may affect the temperature of the soil and to treat individually the most important of these factors. This has been done as far as possible, but in many cases there is a natural overalp from one section to another.

Bouyoucos (8, 12), in his thorough and systematic review, divided the factors affecting soil temperatures into two broad classes, intrinsic and external. The intrinsic factors he denoted as specific heat, 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.

These factors are related to soils in varying degree. Peat, for example, has a black color, low heat conductivity, and a high water-holding capacity. These properties are reversed in sand. Thus these factors usually compensate to a surprising degree and result in very similar temperature variations in various soils. Differences do occur, however, when factors are unbalanced. According to Bouyoucos, the intrinsic factors which most often become unbalanced and cause temperature differences are: (1) Latent heat of fusion of ice, (2) Latent heat of evaporation of water, (3) Ground surface cover, (4) Ground surface color, and (5) Topographic position. The first four of these variables are discussed in other sections in some detail. The fifth may conveniently be dealt with here.

The effects of topographic position are readily apparent. Bouyoucos (12) observed temperatures in various degrees of exposure over a small area. He found that from March to September at 3-in. depth, the temperature on a south slope was about 2 F. higher than that on a north slope, and temperatures on the top of a hill were 5 or 6 F. higher than at a lower elevation on a river bank. From October and through the winter all positions had about the same temperature. Atkinson and Bay (37) indicated that there will probably be a greater frost penetration on north exposures than on south.

Bouyoucos found that it was impossible to analyze the interrelation of minor meteorological factors. The only factors which can be closely correlated with soil temperature are air temperature and summer sunshine. Air temperature has the most important influence since many other factors tend to cancel out. During the winter months (until March) the average air temperature is lower than the soil temperature at depth. The reverse is true for the rest of the year. The greatest difference is usually in January, the least in December and March.

Absorption of solar energy from the sun is another important factor that has a perceptible influence on soil temperatures. It causes the maximum surface temperature of the soil to be higher during the day than the maximum air temperature immediately above it. Baver (52) has stated that the temperature of the soil is primarily dependent on radiant energy received from the sun. All other sources of heat are relatively unimportant. The heat absorbed in the soil from the sun's radiation is in turn dependent on the latitude of the location and slope of the ground. He adds that in warm weather vegetative cover protects the soil from direct rays from the sun, reducing the maximum temperature. On the other hand, during the cold season, it acts as an insulating blanket reducing the heat loss from the soil. Baver also noted that large bodies of water tend to stabilize soil temperature due to the high specific heat of water, acting as a heat reservoir which offers great resistance to temperature changes.

Franklin (14) pointed out that a low relative humidity will lower the soil temperature a great deal due to rapid evaporation, particularly when accompanied by high winds. He observed that fluctuations in air temperature are normally followed by fluctuations in soil temperature. However, a frozen layer at the surface will damp out these fluctuations since the bottom of the frozen layer maintains its temperature at the freezing point.

Effect of Rainfall and Melting Snow

There appears to be some disagreement regarding the influence of rainfall and melting snow on soil temperatures. Callendar (4) regarded rainfall and percolation to be one of the greatest single factors influencing soil temperatures. He observed in Montreal that a heavy rainfall on November 3 caused a rapid decrease in temperature in sandy soil. The drop was checked on November 10 by a 4-in. snowfall. A severe frost on November 19 froze the soil to a depth of 4 in. The fall of temperature near the surface was accelerated on November 23 by a rainfall percolating through the half-frozen soil. The most remarkable sudden fall of temperature began on December 12 and was caused by a rainfall which melted 2 or 3 in. of snow and percolated rapidly through the dry and partially frozen soil. This type of fall in temperature differs entirely in character from that due to thermal diffusion in being very rapid and nearly simultaneous at all depths.

After this a fortnight of dry, cold weather froze the ground to 13 in. and was followed by a 1-ft. snowfall on December 27, which remained until April 11. The protective cover of snow was found to be very significant in reducing further frost penetration. Heavy rains accompanied by melting snow then caused a sudden fall in temperature at the lower depths. Although the water could not easily penetrate the frozen soil, it found its way to the lower strata by devious means. Final thawing of the soil took place at a depth of 10 in. on April 19. This allowed full-scale penetration of water, which again caused a sudden drop in the lower temperatures. Callendar drew special attention to the insulating effect of snow and the effect of heavy rainfall in diffusing heat and equalizing temperature in porous soils at different depths.

Rainfall was found to raise the value of thermal diffusivity considerably. For instance, during the interval of the measurements described, April 21 to 23, 1/2-in. of rainfall occurred and the diffusivity was raised to 0.011, although the average annual value is about 0.004 for this soil. This increase in the value was assumed to be due to percolation. On the basis of a three-year record, Callendar and McLeod (6) found that the diffusivity of the soil during February, when the ground was so frozen that there was practically no percolation, had a value of about 1/3 the annual average. It was concluded that the February value represented the diffusivity due to pure thermal conduction and that more than half the average value is therefore due to the effect of percolation.

Bouyoucos (8), whose views differ from Callendar's, suggested that the importance of rainfall had been over-estimated. He has stated that although rain is commonly considered a warming agent, his records reveal that spring rain lowers the soil temperature not only by eliminating sunshine but by subsequent evaporation of the rain.

Franklin (14) considered rain a great equalizer of temperature between the surface soil and that at depth, due to percolation. In sand, due to rapid percolation of rain, the subsurface temperature will change very rapidly during a rainfall and afterwards return to normal. These changes take place with decreasing rapidity in loam and in clay.

Keen and Russell (16) felt that rainfall not only cooled the soil in summer due to lower temperature but also prevented warming of the soil due to associated cloudiness.

It was their belief that rain reduced the maximum summer temperature but tended to raise the minimum autumn temperature. The effect on the mean temperature was therefore somewhat less than might have been expected. They suggested that direct relationship might be found in the amount of moisture in the soil rather than in the amount of rainfall.

Smith (22) found rainfall to have marked effects on soil temperature. When rainfall was above normal soil temperatures showed distinct variations. Keen (25) pointed out that rain is usually at a lower temperature than the soil and will therefore have a cooling effect. Rain may percolate through the soil, distributing the temperature more evenly. The water movement will, of course, change the diffusivity as well. Atkinson and Bay (37) observed rainfall to have a hastening effect on the time of frost thaw in spring. It was noted also that the rainfall was usually accompanied by higher air temperatures.

Although opinions of its importance differ, it appears that rainfall has a definite modifying effect on soil temperatures, promoting both cooling and warming depending on the season and the soil condition. Some observers have felt that a rainfall map could be closely correlated with a frost depth map. Permeable soils are of course affected to a greater extent than impermeable ones due to the free percolation they permit. Percolation seems to have the effect of equalizing the temperature of the soil at various depths. The increase in moisture content resulting from rainfall naturally raises the value of thermal diffusivity considerably.

To a certain extent the effect of rainfall can be controlled. Modern highways prevent the percolation of rain, and drainage therefore determines the extent to which rainfall will affect the soil moisture conditions. Further studies may show that control of rainwater is an important determinant of soil temperatures.

Snow Cover

All investigators agree that snow is a leading factor in protecting the soil from severe frost, but the physical properties of snow are so variable that an accurate analysis of its protective effect has probably never been made. From an engineering standpoint this is not vitally important, since no amount of snow can be depended upon for any particular winter. Furthermore, it is often necessary to remove the snow from the very area that requires protection.

Bouyoucos (8) considered snow to act as a blanket, reducing the loss of heat because it is a poor conductor and because it prevents convection and wind currents from contacting the soil. He found very marked differences between covered and bare soil. Under a 5-in. snow cover and with an air temperature of -1 F., the temperature was 29.6 F., whereas on bare soil it was 6 degrees lower. Results showed conclusively that snow protected soil from rapid temperature changes and maintained higher soil temperatures. In reverse, it retarded warming of the soil in spring.

Thomson (29) noted that soil temperatures near the surface varied slightly under snow cover, whereas in summer when the air temperature reached 100 F., the soil surface temperature (bulb just covered to avoid direct sunlight) would reach 80 F. with a lag of one hour. At 4-in. depth the lag was 3 hr. with less extreme variation. At 40 in. extreme variations in daily air temperatures were scarcely noticed. He noted also that when snow cover was removed and cold weather followed, the soil temperature often dropped to the minimum for the winter. This same effect was also detected in December before snow cover was produced.

For a three-year period, average temperatures at Winnipeg at all depths were surprisingly similar, with the overall average 41.6 F., (10-in. average 42.0 F., 15-ft. average 41.1 F., with a spread of only 0.9 F.) For the same period the air-temperature average was 36.9 F., showing the soil to average 4.7 F. higher than the air (see Fig. 2). This was attributed to the prevention of radiation from the earth by the snow cover in winter and to the heat of fusion of ice.

In a report on soil temperatures in Saskatchewan, Harrington (21) observed that the common temperature approached by the envelope of the maximum and minimum curves with depth was considerably higher than the mean of the extremes at the 1-ft. level. He attributed this difference to the outflow of heat from the earth and to the supposition that lower air temperatures are less sustained than higher ones. As supposed by Thompson, snow cover probably caused part of the difference. Harrington reported also that daily fluctuations were noticed, particularly at a depth of 1 ft. and to some extent at 2 ft. when there was no snow cover. In December and January, when there was considerable snow cover, daily fluctuations were practically non-existent at any depth.

Mail (31) illustrated the value of snow cover during the exceptionally cold winter commencing in January 1936 in Montana. In spite of great variations in air temperature, soil temperature varied very little under a snow covering of 8 to 15 in. The minimum surface temperature under the snow was - 19 F., although the minimum air temperature was -49 F. The frost line stayed at 3-ft. depth for 23 days.

Atkinson and Bay (37) found the depth of frost penetration to decrease in direct proportion to the depth of snow. It was observed in their analysis that in two out of three cases where there was 10 in. or more of snow the frost depth decreased. Where there was less than 10 in. of snow the frost depth increased correspondingly. In another experiment three plots were covered with 6, 12 and 24 in. of snow respectively and two others were left bare. At the start there was a slight frost in the ground. Frost disappeared under the 12-in. and 24-in. covers but continued to deepen under the 6-in. cover and the bare plots. The two bare plots were consistently of the same temperature, so 12 in. of snow was added to one, and within a few days the frost began to soften and there was a gradual rise in the frost depth, although this remained the same under the bare plot.

Many investigators have noted, but only mentioned, the insulating effect of snow. Belcher (40) considered that the type of cover was of prime influence in the depth of frost penetration. Since snow provides excellent insulation, frost penetration below cleared highways would be greater than in adjacent fields covered by a blanket of snow. Belotelkin (41) found very noticeable effects on soil-temperature measurements if the snow cover was trampled near the measuring instrument. Berggren (46) estimated that with a 4-in. cover of fresh snow the depth of frost penetration for a given time was only about one-sixth as great as with no snow cover.

The importance of the density of snow cover in affecting its insulating properties is well recognized. It was illustrated by observations of Bouyoucos on one cold day when the minimum temperatures at 3-in. depth were 7.5 F. under bare soil, 15.6 F. under compact snow cover, 27.0 F. under uncompacted snow cover, and 32.3 F. under uncompacted snow and a layer of vegetation.

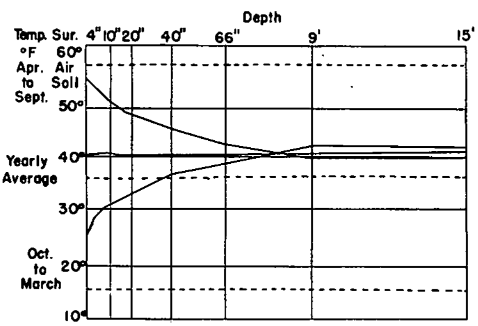

Figure 2. Yearly and Seasonal Comparison of Average Air and Soil Temperatures, from Thompson (29)

Beskow (30) has presented data obtained by H. Abels showing the monthly variation of the average density of snow cover. In addition, he has published a curve of the variation of the heat conductivity of snow as a function of its density. This is a graphical summary of data from Landolt-Bornstein and, especially, Jansson (1901). From this information Table 1 was prepared to illustrate the insulating effect of snow cover during a normal winter. It is seen that both the thermal conductivity and density of snow increase rapidly in early spring.

During the early part and the middle of the winter, the snow conductivity is about one-tenth that of soil. Franklin (14) estimates the average conductivity of snow to be about one-fifteenth that of soil.

TABLE 1

Variation of the Average Density and Thermal Conductivity of Snow Cover

Month	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.
Average Density of Snow Cover	.139	.182	.193	.189	.233	.279
Thermal Conductivity*	.00029	.00033	.00037	.00035	.00045	.00057

* Cal./cm./sec./°C.

TABLE 2

Moisture Content of Soil with Different Amounts of Organic Matter (%)

5 inch depth

	Organic Content					
	1.81%	2.01%	3.32%	5.47%	6.95%	Peat
April 3	16.96	12.95	21.80	26.90	32.53	256.5
July 27	2.08	3.69	6.78	12.83	17.42	236.4
Nov. 4	2.46	5.85	8.63	14.46	21.8	247.8

The protective effect of snow in reducing frost penetration and soil-temperature fluctuations has been realized for many years. Unfortunately, as previously pointed out, it is an unreliable protection and may have to be removed. Nevertheless, in some engineering work the insulating effect of snow cover should be considered for the sake of economy. It is clear that the density of snow will have a considerable effect on its protective qualities. Even so, one foot of snow cover will normally provide as much protection against frost penetration as several feet of soil. Snow cover on roads is, of course, much more dense than the above figures would indicate.

Surface Cover

From the literature studied it appears that Bouyoucos has been the only person to study systematically the effect of surface cover on subsurface soil temperature. In his initial paper (8) and a subsequent one (12) he emphasized the importance of color and type of cover. Although these observations were taken for agricultural purposes their importance in an engineering analysis is readily apparent.

It was observed that heat penetrated more rapidly into uncultivated than cultivated soil and most slowly into sod-covered soil. The greater moisture content of the latter two undoubtedly had some retarding effect. In an experiment using surface covers of white quartz sand and black (dyed) quartz sand, it was found that heat from the sun was transmitted both horizontally and vertically but in greater amounts vertically. This was attributed to increased moisture content with depth. The soil with the black surface had a higher temperature at 5 in. than the white covered soil had at 3 in.

In order to find the effect of color on radiation and absorption, Bouyoucos used these same two quartz sand. He found color to have little or no effect on radiation (less than two percent difference on all colors) but quite an appreciable effect on absorption. He found black sand to average about 11 F. warmer just below the surface than white sand after a day's sunshine (maximum temperatures 105. 7 to 94. 3 F. and 99. 7 to 89. 1 F. respecitvely). In addition, he found that a dry surface radiates considerably less than a moist surface (7 to 9 percent less for mineral soils, 15 percent less for peat). He then found that dry soils radiate quite differently according to type (peat 20 percent less than sand). From these observations Bouyoucos concluded that: (1) Radiation is independent of color; (2) In the dry state, sand is the best radiator, followed in order by gravel, clay, loam and peat; (3) Water exhibits the greatest radiating power with all soils, when well moistened, radiating equally; and (4) The different rates of cooling and warming of soils depend on their moisture content and hence on their specific heat.

Bouyoucos mixed natural sand with various amounts or organic matter. The natural sand contained 1. 8 percent organic matter and the mixtures ranged up to 6. 9 percent organic matter. He then had soil samples with various shades of color and various moisture holding properties. He placed these samples in the field along with a similar sample of peat. The moisture content of the samples increased in proportion to organic content. In July and November the 8. 95 percent soil contained about nine times as much water as the 1. 8 percent soil and the peat about 120 times as much. (See Table 2). Nevertheless, the temperature of the dark sand was somewhat higher than that of the uncolored, natural soil whose reflection was great and whose moisture content was small. The temperature of the peat would have been higher but for its great moisture content.

In order to investigate the temperature under field conditions of the most common types of soil, viz, gravel, sand, loam, clay, and peat, Bouyoucos (8) placed these soils in the field in the same manner as for his investigation of organic content. In his first year of study, Bouyoucos covered the soil samples with a thin layer of white sand. In his second year the sand was removed. In the third year the soil was again covered and in the fourth year the cover was removed. He found that without the covering only the sand and gravel attained higher average temperatures in the summer. This illustrated that soils of high moisture content are kept somewhat cooler in spite of dark color) due to increased evaportation when not covered. With the sand cover all soils maintained about the same average temperature. Results of the first and third years of study were in close agreement, as were the results of the second and fourth years. He believed that it was the inequality in the amount of evaporation, therefore, that caused the various types of soil to have different degrees of temperature when the sand cover was removed.

The effect of surface conditions was also noted by Belcher (40) who stated that the color and type of road surface undoubtedly influenced the trend of frost in the subgrade, especially in the early spring when the initial thawing commences. Many investigators have written of the insulating effect of vegetation. Algren (55) observed average temperature in September at 1-ft. depth under barren ground to be 7. 6 F. higher than under sodded ground. The difference at 16 ft. was still 3. 6 F. In winter the reverse was true. Soil temperatures below barren ground were more readily affected by variations in air temperatures.

Smith (20) found that frost occurred sooner in marshes when they were poorly drained or covered with vegetation, because the soil could not heat up during the day. At the same time it was stated that vegetation inhibited radiation, and in a forest the mean annual temperature was observed to be 2. 7 F. warmer than outside, and the mean daily range in the forest was 7. 3 F. less than outside. Belotelkin (40) also observed forest litter to be very effective in delaying frost penetration. Atkinson and Bay (37) found that frost penetrated twice as deeply in an open pasture area as in a protected woodlot area, although snow cover was the same in both cases.

TABLE 3

Soil	Specific Gravity	Specific Heat	
		Equal Weight	Equal Volume
Sand	2.664	.1929	.5093
Gravel	2.707	.2045	.5535
Clay	2.762	.2059	.5686
Peat	1.755	.2525	.4397

Those 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. Cultivation seems to damp out small variations in soil temperature. Moisture content of the soil is fairly important, and dry soils are generally warmer than moist soils, since they radiate and evaporate less. Sands are the coolest of the dry soils, due to their great radiation.

Color and vegetation are both very important in influencing soil temperatures, the latter when present either as surface vegetation or forest cover. It is noteworthy that both of these factors are controllable to a certain extent, and their importance is worth remembering in such possible engineering applications as hastening frost retreat or increasing heat storage for heat-pump operation.

Soil Moisture Content

The effect of soil-moisture content is probably the most important and yet the least understood intrinsic factor involved in soil temperature variation. A change in the amount of water present in the soil will alter almost all its intrinsic properties.

It seems appropriate to describe in some detail the experiment conducted by Bouyoucos using soils with varying amounts of organic matter. Organic matter in a soil alters its color and water holding properties, and it was the intention to study the extent to which these two properties would oppose each other. With increasing organic content the soil color darkens and the water-holding capacity increases. The test was prepared by placing wooden boxes 3-by 3-by 3-ft. in a trench 3-ft. wide and 3-ft. deep. Sand with various amounts of organic matter was placed in each box, and one box was filled with peat. Table 2 shows the amount of organic matter in each sample as found by the ignition method. The natural soil contained 1. 8 percent organic matter and it was covered with a thin layer of white-quartz sand to give maximum reflection. The variation of percentage moisture content with season of the year for these soils is shown in Table 2. The striking effect of organic content on moisture content is readily seen in this table.

At depths of 5 and 18 in., the soil with 3. 3 percent organic content had the highest temperature in spring and summer, followed in order by the soils containing 2. 0, 5. 5, 6. 95, and 1. 8 percent organic matter and peat. With the exception of the 1. 8 percent soil, the temperature in the fall was practically the same for all soils. In winter the 1. 8 percent soil had the lowest temperature, peat had the highest, the others were intermediate or at about the same temperature. On a yearly average the 1. 8 percent soil and the peat were of about equal temperature but less than that of others, which themselves were about equal. Throughout all seasons the soil with 3. 3 organic matter had the largest amplitude of temperature, followed in order by the 2. 0, 5. 5, 6. 95, and 1. 8

TABLE 4

Effect of Moisture on Soil Temperature

Soil	Weight of a cu. ft. (lb.)	Percent Moisture	Specific heat by equal weight	Rise of Temp. of dry soils by 100 heat Units	Rise of Temp. of moist soils by 100 heat Units
Sand	102.7	16.96	.1915	.011170°C.	.005876°C.
Gravel	109.2	10.45	.2045	.009854	.006520
Clay	76.35	29.16	.2059	.013990	.005790
Loam	72.93	40.7	.2154	.014010	.004848
Peat	36.76	256.5	.2525	.023740	.002127

percent soils and the peat.

Four years of observations showed that soils either white and with low moisture content or black with high moisture content had a lower average temperature during the spring and summer than soils with these properties in medium proportions. From these observations it would appear that both surface color and moisture content have considerable influence on soil temperature. From the point of view of color the peat should absorb the greatest amount of heat and the natural soil the least. On the other hand, the natural soil has a low specific heat and should therefore change temperature more readily. Notice that the 3.3 percent soil became warmest in summer and had the greatest yearly amplitude. This is probably caused by the most favorable balance between surface color and specific heat due to moisture content. The effect of moisture content on temperature changes in the soil is discussed in more detail later in this section and in the section on Thermal Conductivity and Diffusivity.

Bouyoucos (8) gives the specific-heat properties of soils shown in Table 3. This table shows significant properties of the soils. It is seen that peat has the lowest specific heat by volume and yet the highest specific heat by weight. It is the specific heat by volume that is important when considering soil temperature variation with depth.

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. As shown by Table 4, dry peat will heat or cool about twice as readily as sand or gravel, with equal application of heat. In its natural wet condition it will heat or cool only about one-third as readily. Hence it is seen that the moisture content will overshadow in importance density and specific heat of dry soil to a great degree.

Although sand and gravel have a higher specific heat by volume than peat and thus will heat or cool more slowly in the dry condition, Bouyoucos deduced that when field moisture content is considered, the sand and gravel will cool or heat three times as rapidly as peat (Table 4). For this reason the sand and gravel would be expected to warm more rapidly in the spring and cool more rapidly in the fall. This is true in the spring because the air temperature has a daily upward trend and the sand and gravel warm up early, but the peat, having the greatest heat capacity, warms up slowly and finally reaches the temperature of the sand and gravel. In the fall the trend of air temperature is downward on the average but the fluctuations are great. On certain days the temperature falls very low and the sand and gravel cool most. Next day the temperature may rise considerably and the sand and gravel will heat most. These alternate cold and warm days tend to keep the sand and gravel as warm as the other soils. If, however, there were a sudden continual drop in air temperature the sand and gravel would cool faster than the other soils. The other soils referred to are clay, loam, and peat.

Keen (25) points out that dry soil has a 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; but the specific heat also increases, so the actual rise in temperature is small. Moreover, the vaporization of water will slow the warming up, since the latent heat of water is about 500 calories per gram. The latent heat may even cool the soil. The greatest temperature rise from a given application of heat occurs between the extremes of wet and dry soil where the conductivity increases more rapidly than the specific heat.

Smith (27) attributes variation in temperature lag at depth from year to year to variation in moisture content. Belotelkin (41) observed that frost penetrates deeper and remains longer in poorly drained soils than in better-drained soils. Fine-textured soils resemble, in their influence on soil-freezing, poorly-drained soils; coarse-textured soils resemble better-drained soils.

Smith (44) states that a factor which is far more important than the variation of mechanical composition, or particle arrangement, is the moisture content of the soil. He observes that although the influences of moisture content can be sorted out and dealt with in order without difficulty, they are so interdependent that in field conditions the total effect is very complex.

Water has such an important influence on soil temperature that reference to soil moisture content is made in almost every section of this paper. It appears that soil moisture influences the radiation, evaporation, specific heat, thermal conductivity and diffusivity, and heat capacity of the soil. Organic content and density control soil moisture content, to a certain extent, and therefore have considerable influence on this important property. Moisture content is by far the most important intrinsic factor affecting soil temperatures. This conclusion is suggested by review of the published records of many investigations. Legget and Peckover (56), following Winterkorn, have suggested that the mechanism of water-vapor movement in soil is possibly the main determinant of soil temperature variation.

Moisture Migration

The effect of temperature on moisture movement in soils was studied by Bouyoucos about 35 years ago. He deduced that moisture movement was directly related to the changes in viscosity and surface tension of water with temperature (Table 5). Notice that the decrease in viscosity is considerably greater than the decrease in surface tension as the temperature rises. It was believed that as the temperature increased the reduced surface tension permitted the water to be drawn to regions of higher surface tension. The reduced viscosity would also have aided the process.

In order to measure moisture migration Bouyoucos (9) used brass tubes 8-in. long filled with soil of uniform moisture content. One end of each tube was placed in a cold bath and the other in a warm bath. This was done with the tubes both horizontally and vertically. Both arrangements gave essentially the same results, illustrating that the effect of gravity is negligible.

According to the laws of surface tension and viscosity the amount of water moved should be independent of the moisture content, provided that the soil mass exerts no influence upon the water. Since the soil does exert an adhesive force, the thermal transfer of moisture would be expected to increase continually with a rise in moisture content. This did not happen. Rather the thermal transfer of moisture increased with increasing moisture content to a certain point and then began to decrease. Bouyoucos termed the soil moisture content which allowed the greatest amount of water movement from warm to cold, the "thermal critical moisture content."

Bouyoucos also studied vapor movement in the soil. He found that when a moist,

TABLE 5

Variation of Surface Tension and Viscosity with Temperature (9)

Temperature	Surface Tension	Viscosity
0°C.	100.00%	100.00%
10	97.96	73.32
20	94.32	56.70
30	91.62	45.12
40	88.46	36.96
50	85.52	30.17

warm column of soil was separated by an air space from a dry, cold column of soil, the percentage of moisutre movement across the air space was insignificant, indicating that little moisture will move in the form of vapor.

In a recent and extensive investigation of moisture movement in soils, Smith (47) questions the procedure of Bouyoucos in measuring thermal transfer of moisture. He points out that soil in the warm and the cold cylinders are at the temperature of their respective baths and that a temperature gradient occurs only across the partition between the two baths. There is little transfer of moisture outside the region of the partition, and since Bouyoucos' results are referred to the soil over the whole cylinder, the magnitude of the effect is, therefore, considerably masked.

Smith's experiments were conducted on a relatively thin soil specimen with the temperature gradient produced across the small dimension. Samples for moisture-content analysis were taken from the cold and the hot faces of the soil. The results obtained by Smith were similar to those of Bouyoucos, but the moisture transfer was much greater.

The physical condition of the soil, undisturbed or fragmented, was found to influence greatly the amount of moisture migration under small-temperature gradients. When the structure was granular, from the A-horizon, fragmentation moderately increased the moisture transfer. When the structure was blocky (cube-shaped grains with low porosity), from the B-horizon, fragmentation increased the moisture transfer up to seven times. In the C-horizon fragmentation doubled the moisture movement.

The same apparatus used to measure moisture migration was employed to measure vapor movement and subsequent condensation in the soil. Smith agreed with Bouyoucos that a negligible amount of moisture was transferred by vapor movement.

Capillary action and vapor movement were found to be individually incapable of producing moisture transfer along a temperature gradient. Smith explains that moisture in soil is distributed in minute capillary bodies.

Franklin (14) claims that water vapor diffuses downward by day, when the surface is hot and upwards at night, when the surface is cold. The vapor which rises at night is trapped in vegetation and condensed, liberating latent heat, which partially balances the outgoing radiation.

Only two investigators, Bouyoucos and Smith, have made a detailed study of moisture migration, although many have noticed the phenomenon. Moisture movement is regarded as a particular nuisance in the laboratory study of thermal properties, but it has a most important influence on the heat transfer in soil in the field. Any transfer of water in the soil will not only carry heat but will alter the thermal properties by its movement.

Soil Density

Practically all observers of soil temperature fail to record any effect of density. The significance of density on frost penetration in one instance was reported by Legget and Peckover (56). It was noted that most investigators measured soil temperatures in undisturbed ground, whereas for practical engineering purposes data for disturbed soil is usually required. For this reason a comparative study was begun at Toronto, Ontario, taking temperature measurements in both disturbed and undisturbed soil. The degree of compaction normally employed in trench backfill was used to obtain the disturbed condition.

Results obtained from this installation were so striking that it was thought some factor other than density was influencing the temperatures. Nevertheless, it did appear that density was an important factor since frost penetration was much greater in disturbed soil than in undisturbed soil. Further experiments are being conducted under various conditions in an attempt to establish the true effect of density.

Winn and Rutledge (38) found soil density to have a great effect on frost heaving. They found heaving to be greatest at a certain critical density and to decrease rapidly at lower or higher densities. This was attributed to a favorable combination of permeability and capillarity.

Soil temperatures would be affected to some extent by this critical density due to the latent heat of water. It may be that density control could result in moisture control and consequently temperature regulation. Density certainly seems to be one of the few controllable factors which can affect soil temperatures.

Thermal Conductivity and Diffusivity

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. It is usually expressed in British thermal units transmitted per hour through one square foot of soil one inch thick per degree Fahrenheit difference between the two surfaces, or in calories per second per square centimeter per centimeter thickness per degree Centigrade between the two suraces. The thermal diffusivity of a soil is the thermal conductivity divided by the specific heat times the density. The specific heat is the heat required to raise unit weight of the soil one degree. Thermal diffusivity may be expressed as the thermal conductivity divided by the volumetric heat capacity. The volumetric heat capacity is equal to the density times the specific heat of the soil.

The thermal properties of soils have been under study for a great many years. In 1846 Forbes (1) noticed that the rate of increase in temperature with depth varied according to the type of material. The rate of increase was greatest in porphyritic trap rock, followed in order by pure sand and sandstone. This is also the order of increase in their conductive powers. Hence, he attributed the various rates of increase in temperature with depth to differences in conductivity and consequent differences in the rate of heat conduction from the interior of the earth.

In 1860 Thompson (2) calculated the soil diffusivity using the amplitude of temperature variations at depth. He further calculated the conductivity using a value of specific heat (presumably with soil in the dry state). Everett (3) also determined diffusivity and conductivity using methods similar to those of Thompson.

Callendar (4) calculated the thermal diffusivity of the soil in place using the temperature gradient with depth to determine the heat absorbed by the soil between various depths. This process was equivalent to a graphical integration of the differential equation for heat flow. The changes in the thermal diffusivity of the soil throughout the year could be traced in this manner. In a later paper Callendar and McLeod (5) presented additional calculations.

Some of the most comprehensive early work on the thermal properties of soils was published by Patten (7) in 1909. He expalined that the conductivity of soil is increased by the addition of water, due to the better thermal contact between soil grains produced by the moisture film. If the water content is still further increased, the temperature of the soil will rise more slowly, in spite of better conductivity, due to the high specific heat of water, which is almost five times that of dry soil. (See Figs. 3 and 4). Beyond a certain value the moisture content becomes the predominating factor and the conductivity of the mixture gradually falls to the value for water.

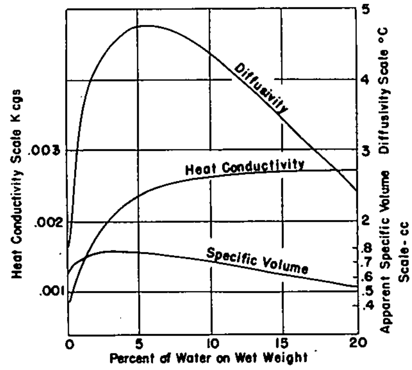

Figure 3. Effect of Moisture Content on Volume and Thermal Behavior of a Coarse Quartz Powder, From Patten (7)

With increasing moisture content, the conductivity increases for the reason already given. The diffusivity, which measures the rate at which the temperature rises under a unit temperature gradient, increases to a maximum and then diminishes. The increase is due to an increase in the conductivity and the specific volume. At higher moisture contents the volumetric heat capacity increases and the specific volume decreases. Both changes tend to decrease the thermal diffusivity. Between the extremes of dry and wet soil is a range of moisture contents wherein the volumetric heat capacity of the moist material increases less rapidly than the conuctivity. Within this range is obtained maximum conduction of heat and the greatest temperature rise for a given application of heat.

In 1913 Bouyoucos (8) attempted to measure thermal conductivity of soil by the hot-plate method, but he was troubled with moisture migration in the sample. In the field he found relative values of conductivity by observing the time for heat to penetrate soils which had a similar layer of sand on their surfaces.

He also noticed variations in the temperatures of different soils during the summer (when no surface sand was present), but this difference almost disappeared by mid-September. From then until December the soils cooled at about the same rate. He believed that this even rate of cooling and equal average temperature in the fall and winter months (even when covered with sand or not covered) indicated there are no intrinsic factors which predominate and cause variations in these different soils.

Bouyoucos and McCool (18) state four principal factors may be responsible for the difference in frost occurrence between organic and mineral soils. These are differences in color, temperature of the air at various elevations, specific heat by volume of the soil, and heat conductivity.

Color of the surface has already been discussed under the section on surface effects. Muck and peat, under field conditions, possess a much greater specific heat than mineral soils, due to large moisture content. It would be expected, therefore, that organic soils should have less frost penetration, but the opposite was found to be true. The heat conductivity of mineral soils is much greater than that for organic soil. Bouyoucos deduced from his experimental results that this is the factor responsible for the difference in frost occurrence between mineral and organic soils.

Shanklin (17) experimented with the thermal conductivity of soils in order to study the heat distribution around buried electrical cables. He found the conductivity to increase with moisture content, and he noticed moisture migration. In discussion it was pointed out that a knowledge of the soil heat capacity is important since cables are hot for a relatively short period during the day.

Keen (25) discussed the theory of heat flow in a conducting material. He based his analysis on the common equation for heat flow applied to flow through the soil. At the same time he took into account the migration of moisture from a warm to a cold area. The shift of water alters the thermal conductivity and the volumetric heat capacity of the soil, and these, in turn, influence the rate and amount of heat movement. Therefore, since the conductivity and heat capacity are not constant, the simple theory does not apply exactly.

Beskow (30) points out that conductivity of ice is three or four times greater than that of water. However, the conductivity of a frozen soil is not greatly increased over that of unfrozen soil, because ice banding decreases the contacts of the soil particles. Therefore, the conductivity of moist (non-saturated) soils is increased only slightly. For coarse soils the increase in conductivity is not normally greater than 20 percent. For clays the conductivity of frozen soil is seldom greater than that for unfrozen soil.

Using a hot-plate apparatus, Smith and Byers (34) found the thermal conductivity of dry soils to depend greatly on the organic content and texture. Sandy soils are the best conductors, clay soils medium conductors, and highly organic soils are poor conductors. The conductivity of the actual dry-soil material was found to be practically constant for all soils, but the conductivity varied with porosity. The least heat transfer occurred with the greatest porosity. In the above analysis all the samples were similarly treated by rolling, sieving, and oven-drying.

Smith (44) concluded that the ability of a dry soil to transmit heat depends on the character of the solids that form the framework of the soil and of the liquids and gases that fill the voids throughout the framework. A formula was evolved which yields the effective conductivity of a dry soil, provided the porosity of the soil and the heat conductivity of the soil particles are known and the effect of structure can be evaluated.

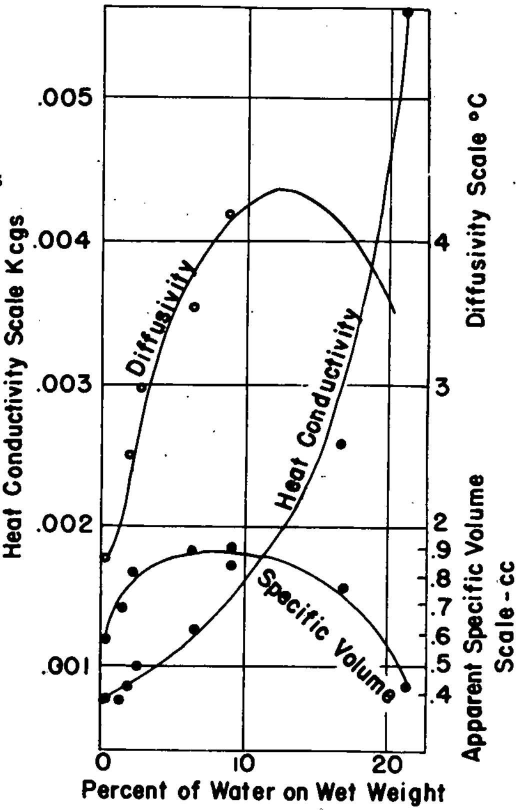

Figure 4. Effect of Moisture Content on Volume and Thermal Behavior of a Fine Sandy Loam, From Patten (7)

Shannon and Wells (51) found thermal conductivity to depend primarily on water content and whether the soil was frozen or unfrozen. The conductivity, frozen or unfrozen, approached a common value as the water content approached zero. Thermal conductivity increased with increasing moisture content. At high moisture contents the conductivity of frozen material was generally about 50 percent greater than for unfrozen material. Thermal conductivity was found to increase with increases in unit weight of the material.

Kersten (53), in this recent extensive analysis of the thermal properties of soil, 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:

(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 constant dry density it increases with an increase in moisture content.

(6) At a given density and moisture content it varies, in general, with the texture of

the soil. It is high for gravels and sand, lower for sandy loam, lowest for silt and clay.
(7) The conductivity differs appreciably for different soil minerals.

Moisture migration has always been a problem when one attempts to measure thermal conductivity of soil. Smith (36) in his initial work on the conductivity of moist soils found moisture migration to be a great problem. Griffiths (45) experienced the same trouble in testing building materials. Recently Allcut (54) was similarly troubled with moisture migration in his conductivity testing.

The British Electrical and Allied Industries Research Association (32) has advanced a method of measuring thermal resistivity of the soil in place, employing a heating sphere. Resistivity may be converted to its reciprocal, conductivity. Very recently Dr. Misener has successfully experimented at London, Ontario , with a heating sphere method of measuring soil conductivity in place. At the present time, Hooper and Lepper (57), of the University of Toronto, are experimenting with a heated probe for measuring conductivity. These modern methods appear to be the answer to the problems of measuring thermal conductivity of soil, since the experimental time is reduced to a few minutes and therefore moisture migration does not take place.

Much attention has been given to the study of thermal properties of soils. It now seems that the new methods of measuring thermal properties of soils in situ will add much valuable information to the general study. The thermal diffusivity is, of course, the intrinsic factor controlling soil temperature, and it in turn is controlled largely by the moisture content. Therefore, it is evident that quick, easy determinations of thermal diffusivity of soil in situ are valuable. Moreover, by following changes in diffusivity, changes in moisture content can be calculated.

Freezing Temperature of Soils

It is known that most soils freeze at temperatures somewhat lower than 32 F., but there appears to be some doubt as to the exact causes of this lowering of the freezing point. The fact that the temperature is below freezing in a soil does not mean the soil is frozen. It was observed by Bouyoucos (15) that soils could withstand considerable supercooling before freezing. The degree of cooling which soils and artificial materials could withstand without freezing when they were kept perfectly still and with the water content at about the saturation point was: Sand, loam, and clay: 7.6 F. below normal freezing point; Peat, muck: 9 F. below normal freezing point; Water, silica, carbon black, gelatin, agar: 10.8 F. below normal freezing point.

Since the water freezes at about the same degree of super-cooling as the artificial materials, it would appear the water controls the degree of super-cooling and the materials have no effect on it. It was found that clays do not have a greater super-cooling than sands.

Bouyoucos (8) reports that Ulrich in 1897 found the temperature of soil freezing was generally lowered by the addition of salts. This lowering increased with the salt concentration. Ulrich observed that when the soil water froze the temperature rose immediately to 32 F., remained there for a time and then gradually fell. Some salts retarded this fall of temperature while others hastened it.

In his own analysis, Bouyoucos found that salt concentration lowered the freezing point considerably. Bouyoucos points out that as a treated soil freezes, the remaining liquid becomes more concentrated, and therefore lowers the freezing point further. The reverse is true during thawing. Bouyoucos also studied the effect of salt solution on soil temperatures during the summer. He observed that salt-treated soils became as much as 7 or 8 F. warmer than untreated soils. This appeared to be due to a decreased amount of evaporation from the treated soil due to an increase in surface tension and a lowering of vapor tension. After a time the untreated soil became dry due to evaporation, and the soil treated with salt solution was still moist. Then the salt-treated soil became cooler than the reference soil, since evaporation was continuing.

Beskow (30) believes that lowering of the freezing point is not due to dissolved salts alone. He has shown that particle size has a direct bearing on the lowering of freezing point. This is caused by the attraction of the water molecules to the soil particles.

The attraction is termed adsorption power, and the action of the force is expressed as hygroscopicity. The water molecules form a thin film around the soil particles, and the force of attraction decreases with distance from the particle. During freezing an additional force is required to pull the water molecules from the hygroscopic film, and the freezing point is consequently lowered. The water molecules immediately adjacent to the soil particles are frozen last. This phenomenon explains why the freezing point is continually lowered as the water progressively closer to the soil becomes frozen. Finer soil particles have a larger area per unit volume, and there is therefore greater adsorption power and consequently a lower freezing point.

Lowering of the freezing point of soils has been variously ascribed to super-cooling, salt concentration, and particle size. Bouyoucos and Beskow disagree on the effect of particle size, but it is likely that this property has some effect on the freezing point.

Daily Temperature Variations

The mean clearness of the atmosphere or the intensity of radiation for each day and night is reflected by the amplitude of diurnal variation in soil temperatures at shallow depths. It is shown by Callendar (4), using a summation curve of sunshine, that for every change in the sunshine graph there is a corresponding change in soil temperature at 20 in., with a time lag of one day.

Keen and Russell (16) point out that only the sunshine effect before noon should be considered, since sunshine after that time could not affect the maximum temperature in the soil. For the first 6 months of the year they believe that the number of hours of sunshine largely determines the mean soil temperature, but in the latter part of the year the hours of sunshine have less effect; cooling by radiation at night then becomes dominant.

During the winter, Keen and Russell found very little daily variation in temperature. Towards the end of January daily variations began to occur. In general, soil temperatures fell from 5:30 p.m. until morning. The fall was greatest on clear nights. Rain in autumn retarded the fall. The cooling of the soil never proceeded as far as that of the air temperature.

Keen (25) explains that the winter conditions of low temperature and small fluctuations are due to: (a) lower elevation of the sun and corresponding reduced radiation from the sun; (b) higher soil moisture content, and therefore higher specific heat; and (c) radiation from the soil on cold clear winter nights.

The spring conditions of increasing average temperature and increasing fluctuations are due to: (a) increased radiation; (b) reduced specific heat of the soil due to evaporation of moisutre; and (c) warm winds and overcast nights, which inhibit the usual nightly fall of temperatures.

The summer and autumn conditions of increases of average temperature and daily fluctuations of temperature to a maximum, followed by a decrease in these values, are due to: (a) increased sunshine leading to drying out of the soil, reduction in specific heat, and greater temperature range; (b) a decrease in heat conductivity as the soil dries out; and (c) a reversal of the conditions in (a) as the altitude of the sun decreases.

Bouyoucos (8) found the minimum daily temperature at a depth of 6 in. for gravel and sand to occur about 7 a.m., the clay and loam about noon, and the peat at 6 p.m. In later work (12) he observed that unless the soil is frozen there is almost always a temperature gradient with depth. During the day the temperature decreases with depth and during the night it increases with depth due to reversion of the air temperature. In the early morning the surface is cool, and as the sun rises the surface heats, and a warm wave is started downward. At the same time, a cold wave descends at a lower depth, and a time lag occurs. The lag of the maximum and minimum epochs tends to be approximately proportional to the depth in all types of soil. (At a 6-in. depth during June, the daily temperature amplitude in sand and gravel was 20 F., in peat 5 F.) The daily amplitude of oscillation of temperature decreases in geometric progression as the depth increases in arithmetic progression.

Belcher (40) points out that soil temperatures rise and fall as a sine wave, and the amplitude of the wave varies inversely with depth. The diurnal temperature variation is not generally noticed below two or three feet. In his investigation of surface soil temperatures, Smith (20) developed a special thermometer. Using the instrument, which he considered to be more accurate than an ordinary thermometer, he found several interesting features in the surface temperatures. Just before sunrise the surface soil was generally cooler than the air 1/2-in. above it. Peat was seldom more than 1.5 F. colder, but mineral soil was often as much as 4.5 F. lower than the air above it. When the air temperature was near freezing no great differences were noted. On calm spring nights, especially when the humidity was high, the surface of mineral soils was as much as 5.1 cooler than air.

Diurnal changes in temperature were observed to a depth of 12 in. Maximum temperature at a depth of 12 in. occurred about three hours later than the maximum surface temperature. The minimum at 12 in. occurred five hours later than the minimum surface temperature. In a subsequent publication Smith (27) points out that air changes in volume by 1/491 of its original volume for every degree Fahrenheit change in temperature. For this reason, air is inhaled and exhaled by the soil due to diurnal and seasonal temperature changes. This air coming from the atmosphere would tend to equalize soil and air temperatures.

The amplitudes and depths of daily temperature variations are, of course, largely determined by geographical location and local weather conditions. Sunshine, rainfall, and air temperature variation would be expected to have the greatest effect. In general, daily temperature variations do not occur below a depth of 2 ft.

Temperature Inversion with Depth

The temperature inversion due to temperature lag with depth is familiar to all who have studied soil temperatures. More than 100 years ago, Forbes (1) demonstrated temperature overturn at depths of 3, 6, 12, and 24 ft. (See Fig. 1). Forbes observed a decrease in temperature range and a retarding of maximum and minimum temperatures with increase in depth below the surface. Owing to these differences, the temperature curves systematically lag as the depth increases. In trap rock and sand, the range at a depth of 24 ft. was found to be 1/10 that at 3 ft. and the maximum temperature was retarded five months. In sandstone the range at 24 ft. was 1/5 that at 3 ft. and the maximum was retarded only three months. These observations illustrate the appreciable influence of the increased conductivity of sandstone. Theoretically, the annual range ought to decrease in geometric progression as depth increases uniformly. This was shown to be true by Forbes' Observations, and it was calculated that the annual range would be reduced to .01 C. in trap at 57.3 French ft., in sand at 66.6 French ft. and sandstone at 98.9 French ft.

At Winnipeg, Manitoba, Thomson (29) observed (Fig. 5) that the lowest temperature in the upper 20 in. was reached on March 13, at 40 in. on March 20th, at 66 in. on March 27, at 9 ft. on May 8 (a lag of three months), at 15 ft. on July 3 (a lag of 6 months). The highest temperature at 9 ft. occurred early in October, and at 15 ft. about December 15. The temperature range at 9 ft. was 14 F., at 15 ft. was 4 F., and at 20 ft. he presumed that no variation would occur (although the extreme air temperature range is 140 F. in this region).

On the average, Thomson found that temperature overturn in soil at Winnipeg began at the end of March in the upper depths and was completed to a depth of 15 ft. by the beginning of July, (a period of 14 weeks). The fall overturn began at the end of October and was completed to 15 ft. before the end of December (a period of 17 weeks).

Bliss, Moore, and Bream (43) observed that temperature overturn in Southern California occurred regularly in the fall and spring to a depth of 7.5 ft. In the fall, September or October, it was characterized by gradual temperature changes taking from 5 to 7 weeks, while in the spring temperature overturn began in March or April and lasted 7 to 16 weeks.

Hieronymous (48) found no apparent response to seasonal variation of air temperature at a depth of 24 ft. in silt loam. He found time lag at various depths to vary with the kind of soil at different locations and at different depths at a given location.

At Minneapolis, Algren (55) observed a three-week lag behind air temperatures at a depth of one ft. under bare ground. Variation at one ft. was 48 degrees, from 75 degrees, to 27 degrees F. At 16 ft. the variation was 8 degrees, from 54 degrees to 46 degrees F. At the 16-ft. depth the maximum temperature occurred in November (lag of three months), minimum occurred in April. He deduced that the annual variation at a depth depth of 28 ft. would be 2 F., with an average temperature of 50 F. at this depth.

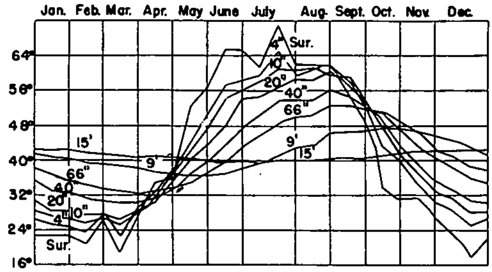

Figure 5. Soil Temperature with Time at Various Depths, From Thompson (29)

Smith (22) found the temperature lag to vary from 1/2 hour at 1/2-in. depth to 80 hours at the 36-in. depth. In a subsequent publication (27) he found the annual average soil temperatures, at depths ranging from 6 in. to 12 ft., to be from 65 to 67 F. The annual mean air temperature was 58. 8 F.

Smith (27) reported that McClatchie in Arizona estimated constant temperature at 50 ft. He found the annual range at 5 ft. to be 20 to 25 F., at 10 ft. to be 15 to 20 F., at 15 ft. to be 10 to 15 F. From his own observations Smith (25) found an annual range of 27 F. at a depth of 4 ft., 22 F. at 5 ft., 18 F. at 6 ft., 14 F. at 8 ft., 12 F. at 10 ft., 9 F. at 12 ft., in a soil varying from sandy loam to coarse and fine sand. The minimum at 12 ft. occurred 16 weeks later than the minimum at one ft., and the maximum at 12 ft. occurred 15 weeks later than the maximum at one ft. The maximum and minimum at depths ranging from one ft. to 12 ft. was practically a straight line function of the depth.

At Montreal, Callendar and McLeod (5) found annual temperature ranges of 34 F. at 20 in., 26 F. at 40 in., 19 F. at 66 in., and 11 F. at 108 in. in a turf-covered area of loose sand. Bouyoucos (8) found that the greatest seasonal amplitude occurred in the summer with autumn, spring, and winter coming next in order. The yearly average temperature was practically the same for all soils at depths of 6, 12, and 18 in. On a yearly basis, sand had the greatest range, followed in order by gravel, clay, loam, and peat.

Lauchli (10) found temperature amplitude to decrease with depth. In Georgia, he observed a constant temperature of about 61. 5 F. at a depth of 45 ft. Rambaut (11) at Oxford, England, observed a range of 9. 5 F. at a depth of 10 ft. in gravelly soil with grass cover. On an annual average Keen and Russell (16) found the warming of the soil to be much more rapid than the cooling. The soil warms rapidly in the spring, probably due to drying and increased sunshine. Cooling in the winter is retarded due to increased moisture, and radiation on clear fall nights probably accounts for most of the cooling effect.

In comparing Saskatcheqan and Kansas soil temperatures, Harrington (21) noticed that the annual temperature variation at the 6-ft. depth was 21. 5 F. for Saskatchewan and 28. 5 for Kansas, whereas at the one-ft. level the ranges were 67. 5 F. and 52 F. respectively. This apparent inconsistency is explained by the fact that in Saskatchewan the air temperature varies between greater extremes, as indicated by the one-ft. curves, whereas the general swings indicated by the 6-ft. curves, which are unaffected by daily weather fluctuations, indicate a substantially greater uniformity in mean temperature.

Bliss, Moore, and Bream (43) found the mean weekly air temperature in summer to be considerably higher than the soil temperature at a depth of one ft. This agrees with Harrington (21) but disagrees with Kimbal, Rhunke, and Glover (28) and Smith (22).

The above observations clearly illustrate the wide variations of temperature with depth. Geographical location is certainly a prominent factor influencing temperatures at depths of several feet. Thermal conductivity and moisture content also must have an appreciable effect. It is certain that temperatures at depths within the scope of most engineering work vary throughout the year, and there seems to be no way of estimating closely either the variation or the average without field data obtained in the general area concerned. In temperate climates there is little variation at a depth of 25 ft., and the average temperature is reasonably close to 50 F.

Frost Penetration and Retreat

To most engineers the understanding of frost action is the most important aspect of soil temperatures. A great deal of work has been done in this field, but in this paper frost action will be dealt with only in its relation to soil temperatures.

Thomson (29) noted that frost penetration begins early in November at Winnipeg. In the spring the frost begins to retreat at the surface and at its lower level at about the same time. The last frost in the soil is found at about a depth of 4 ft. late in April or early in May. In a severe winter frost penetrated about 20 in. a month to a depth of about 7 ft.

Beskow (30) describes the frost line as an isotherm that has a very large resistance to movement due to the large amount of heat absorbed or extracted during freezing or thawing of the soil water. Thus, great temperature variations in the surface soil are absorbed at the frost line as it slowly penetrates.

According to Keen (25), if the temperature begins to fall below freezing at the lower frost line, more ice is formed and the temperature returns to freezing, due to the evolution of latent heat. The net result, therefore, is a slow increase in the depth of frozen soil. Lang (42) noticed that when the air temperature became warmer at various times during the winter, the soil thawed at the bottom.

Harrington (21) reports frost penetration to a depth of 6 ft. in Saskatchewan. It was believed that the depth reached by the frost line is largely controlled by such factors as the depth of snow, character and amount of vegetation, kind and texture of soil, and severity and duration of the winter. Since the 8-ft. depth reaches its minimum temperature in April or May, the danger to water pipes at this depth is greatest in the spring. This conclusion is borne out by experience.

In 1930 Sourwine (24) attempted an analysis of frost occurrence on a broad scale using available meteorological records to predict average frost penetration over various areas of the United States. Considerations of modifying effects on ground temperatures due to type of soil, density, moisture content, topography, or surface cover were neglected. Rather, the intensity, duration, and frequency of low air-temperature occurrence over a period of years was chosen as a criterion for analysis. The determined values were subject to modification according to local conditions.

The depth of frost penetration may be approximated by a correlation between the accumulated degree-days of temperature below a given point and actual measurement of the frozen layers. This relation was first noticed by Casagrande (26) in 1931. Belcher (40) realized from a study of the rate of change of temperature and the temperature penetration curves that there may be some correlation between the more rapid accumulation of temperature below freezing, producing a greater depth of penetration per time-temperature unit. At Winnipeg the average number of degree-days per in. of penetration is 48 at depths of 10, 20, 40, and 65 in.

Shannon (49) considers the main factors influencing frost penetration to be the magnitude and duration of below-freezing air temperatures, the thermal properties of the soil, the surface cover, and the temperature conditions within the soil at the start and during freezing. The summation of the magnitude and duration of air temperatures is termed the freezing index. Thermal properties of soil vary with type, moisture content, density, and whether frozen or unfrozen. Naturally, frost will penetrate deeper if the soil temperature is near freezing when freezing begins. The depth of frost penetration can be related to the freezing index and Shannon's study presents a comparison. Freezing index frequently can be calculated from available meteorological records and a probability curve plotted. From the probable freezing index, the depth of frost can be estimated. Moisture and cover conditions vary from year to year and will alter empirical deductions using the freezing index.

A theoretical treatment is given to the "freeze" penetration into soil by Berggren

(46). It is difficult to apply Berggren's analysis in practice, since thermal characteristics and temperature conditions of the soil must be known. Nevertheless, some interesting conclusions may be drawn. Firstly, for a fixed sub-freezing temperature suddenly applied at the surface, the depth of soil frozen increases with the square root of time. Departure of the initial temperature-distribution from uniformity has little effect on the rate of penetration, because the soil heat-capacity is ordinarily small, relative to the latent heat of fusion. The frost layer increases at a smaller rate for wetter soils, because of greater heat of fusion and despite greater thermal conductivity. Secondly, in the frozen zone and for an equal distance beyond the temperature distribution may, for practical purposes, be considered linear (though having different slopes in each zone). Shannon's computations indicate that Berggren's formula yields frost penetrations that are about 50 percent too great.

In the study of frost penetration Fuller (39) observed that air temperatures penetrate gravel more rapidly than clay. At Portland, Maine, frost penetrated to 45 in. in gravel and remained there from February 27 until March 7, when the ground began to thaw at the bottom. In clay, frost penetrated to a depth of 48 in. The frost penetrated much more rapidly into the gravel at the commencement of freezing, but at the beginning of January the frost line in clay overtook the frost line in gravel. Frost depth had a close relationship to the cumulative degree-days of below-freezing air temperature. It took about half as long for the frost to leave the ground as it did to penetrate to the low point. A similar observation was made by Keen and Russell (16). A chart was prepared which could be used to estimate changes in the frost line using degree-days of below-freezing air temperature.

Highland (19) made a survey of observed frost penetration under streets in American and Canadian cities and towns. In addition, he obtained a record of the depth at which water mains are placed in these areas. In 1938 the maximum frost penetration recorded in 100 cities was published in "Heating and Ventilating" (35) together with a frost penetration map of the United States.

A five-year program investigating temperature variations in concrete pavement and the underlying subgrade has been reported by Swanberg (50). Frost penetration was correlated to degree-days of freezing air temperatures. Cycles of freezing and thawing at various depths were noted.

Shannon and Wells (51) state that from the point of view of thermal conductivity, it would seem that frost penetration would be greater in wet soil than in dry soil. This was not found to be the case however. A change in moisture content from 5 to 10 percent will increase the sum of the volumetric heat and the latent heat by about 100 percent and will increase the conductivity only about 20 percent. Thus the depth of frost penetration will generally be greatest in a given soil at zero moisture content and will become less with increasing moisture content.

Frost penetration and retreat is an important engineering problem. The depth of frost penetration is of vital importance to waterworks departments in northern latitudes. In recent years several attempts to forecast the depth of frost penetration have been made with reasonable success. The methods employed by Fuller (39) and Shannon (49), both based on the criterion of "freezing index," appear to be the most notable. Once again moisture content is the complicating factor. No method has yet been advanced which would take into account soil moisture in frost predictions, although it is probably next to air temperature in importance.

Conclusion

This review shows clearly that a wealth of information is available in published records on even such a specialized subject as soil-temperature variations. Correspondingly, the survey of the available published information shows evident gaps in the overall picture of soil-temperature phenomena and points the way quite clearly to a number of relevant questions still unanswered. All the records of soil-temperature variation with depth which have been examined follow the pattern which would be expected from the basic physics of the problem, having regard to the internal heat of the earth on the one hand and the variations in air temperature and solar radiation on the other. Variations in soil temperature close to ground surface, however, show themselves to be susceptible to a number of other factors, some of which are controllable. Study of these factors is one direction in which more research is needed with reference to frost action.

Dominating all intrinsic factors which affect soil-temperature variation is the moisture content of the soil. As studies of this matter have progressed, it has become clear that the water present in soil affects internal heat flow in a much more complex manner than its presence might ordinarily suggest. The full implications of the dynamics of moisture-vapor movement in relation to soil temperatures have still to be investigated, and this fact directs attention to the significant omission from almost all records of any reference to the position of the ground-water table at the experimental site. Of equal significance is the almost complete neglect of the density or state of compaction of the soils in which records have been taken. Much study and experimentation will be necessary before the true role of these factors can be evaluated. Enough is now known, however, to render possible the suggestion that upon these two factors in particular depends to a large extent the full understanding of frost action in soil.

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SOME FIELD MEASUREMENTS OF SOIL TEMPERATURES IN INDIANA

E. J. Yoder, Research Engineer, and C. R. Lowrie, Jr., Research Assistant
Joint Highway Research Project, Purdue University

Synopsis

This report covers the results of field measurements of soil temperatures made under an asphaltic pavement. Temperature gauges which actuated automatic recording instruments were installed at various depths below the pavement.

The progression of heat waves through the soil, the depth of 32 F. (mean temperature), and the depth of minimum temperatures of 32 F. have been plotted against time. During the winter months measurements were made manually of depth of frost penetration, depth of snow cover, ground water fluctuations, and moisture content of the soils.

No definite conclusions have been drawn from the data other than verification of several important facts brought out by previous investigators. It is indicated, however, that more attention should be directed towards considering minimum daily temperatures in a study of this type. Since this type of research is of necessity a long range study, the accumulation of data over a period of years is desirable in order to better correlate the factors affecting soil temperature.