THE THERMAL CONDUCTIVITY OF SOILS

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SYNOPSIS

Equipment and methods of test to determine the coefficient of thermal conductivity of soils at various conditions of moisture content and density are described.

Tests were made on nineteen different soils which represented a wide textural variety, gravel, sand, sandy loam, silt loam, and clay, as well as some crushed rocks and a fibrous peat. Moisture contents for tests varied from air-dry to values greater than the optimum moisture content; densities varied from a loosely-poured condition to the maximum obtainable by heavy ramming.

Soils were tested at several mean temperatures. The most important influence of temperature depends on whether it is above or below freezing. For moisture content increases above about 6 to 12 percent, the conductivity of frozen soils becomes progressively greater than that of the unfrozen soil.

Density affects the thermal conductivity of a soil in about the same manner for all soils, at any moisture content, and for either the frozen or unfrozen condition. On the average each one-pound per cubic foot increase in density increases the thermal conductivity by about 3 percent.

An increase in moisture content causes an increase in thermal conductivity. This is true up to the point of saturation.

The thermal conductivity of a soil, at a given density and moisture content, varies in general with the texture of a soil, being relatively high for coarse textured soils and relatively low for fine textured soils. The mineral composition of the soils also effects the conductivity. Quartz tends to give high values whereas minerals such as plagioclase feldspar and pyroxene, which are constituents of basic rocks, tend to give low values of thermal conductivity.

Four charts are presented to aid in the estimate of the thermal conductivity of a soil. Two of the charts are for sands or sandy soils, and two for silt and clay soils. One of the charts for each type of soil is for the frozen condition, the other for the unfrozen. It is expected that these charts will give conductivity values within an accuracy of 25 percent.

Knowledge of the thermal conductivity of soils should be helpful in many phases of highway engineering. Thorough understanding of the action of frost on highway pavements and embankments is dependent upon this knowledge. The design of insulation layers beneath pavements to retard frost penetration or to prevent thawing of underlying materials depends upon the thermal properties of the materials. Thermal conductivity information on soils is also useful in such engineering problems as the design of basement walls, the calculation of heat losses from floor slabs constructed directly on the ground, heat transfer from cables to the ground, or refrigerant lines to ground, calculation in connection with "heat pumps," and many others. A wealth of information on thermal conductivity is available for most materials used in construction except for the most common—that is, soil.

The Corps of Engineers, U. S. Department of the Army, initiated in 1945 a study of the problems encountered in construction of airfield pavements, buildings, and other structures in regions of permafrost, or permanently frozen ground. In planning the program, it was recognized that interpretations of many field observations and the solution of various design problems would be dependent upon a knowledge of the thermal properties of soils. Arrangements were made with the Engineering Experiment Station of the University of Minnesota for the performance of laboratory studies on this subject. This paper is a report on the main part of that investigation—the determination of the thermal conductivity of a variety of soils at various conditions of moisture content and density.

UNITS OF MEASUREMENT

The units used in this presentation are as follows:

Thermal Conductivity, k, represents the amount of heat expressed in British thermal units transmitted per hour through 1 sq. ft. of soil 1 in. thick per degree Fahrenheit difference between the two surfaces. Values of conductivity thus expressed may be converted into British thermal units per hour per square foot 1 ft. thick per degree Fahrenheit difference by multiplying by 0.08333, or into the C.G.S. units, calories per second per square centimeter per centimeter thickness per degree Centigrade difference between the two surfaces, by multiplying by 0.0003446.

All temperatures are expressed in degrees Fahrenheit, unless otherwise noted.

Density is the weight of a material per unit volume. In this paper it is the weight of dry soil in pounds per cubic foot.

Moisture content is expressed as a percentage of the dry weight of the soil.

TEST EQUIPMENT AND METHODS

Equipment.—The design of the apparatus used to measure the thermal conductivity of soils was patterned in part on apparatus which was in use at the Engineering Experiment Station, University of Minnesota, for testing building materials and insulation. The testing of soils, however, posed many problems not encountered in the testing of building materials, such as the need for placing soils at a variety of moisture content and density conditions; consequently, it was necessary to design and construct an entirely new apparatus.

The apparatus may be divided into the following parts for purposes of description:

1. A tubular soil container consisting of a central pipe containing heaters and an outside cold jacket enclosed by an insulated box to keep heat losses at a minimum;
2. A motor-generator unit with an exciter and voltage regulator for supplying steady D.C. power to the heaters;
3. A condensing unit, cooling and mixing tanks, and a circulation system for supplying alcohol to the cold side of the soil container, with provision for controlling the alcohol temperature to obtain the desired soil temperature on the cold face;
4. A system of power and temperature measurement and control.

A general view of the test apparatus is

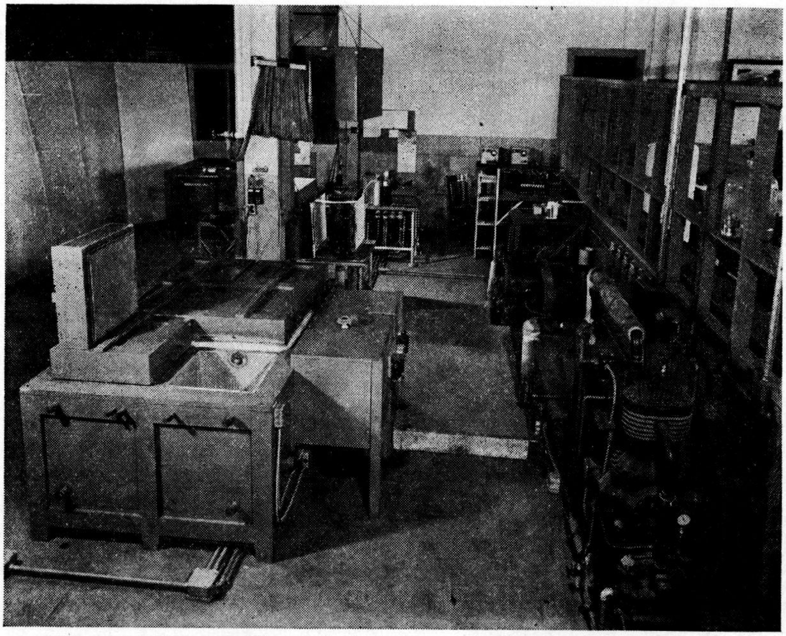

Figure 1. General View of Soil Thermal Conductivity Apparatus

shown in Figure 1. In the photograph, the cooling and mixing tanks are at the left front. These tanks were originally constructed to operate four soil containers, but only two containers have been built. The alcohol cooling tank is in the center, with two mixing tanks on each side. The condensing unit for the main tank is at the right front. The soil containers are at the left behind the tanks; one, with the insulated cover down, is behind the column. The control table is to the rear beyond the soil containers. At the right and beyond the condensing unit of the alcohol cooling tank is a smaller condensing unit for cold plates adjacent to the soil containers. Beyond this is the motor-generator unit, and against the wall, are two photo-electric relay units.

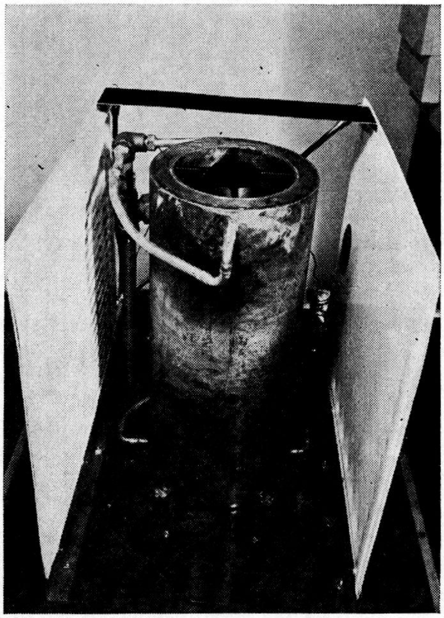

Figure 2. Tubular Soil Container and Refrigeration Plates

A close-up view of a soil container is shown in Figure 2. Figure 3 shows the general assembly of this unit which was made up chiefly of concentric sections of three sizes of copper pipe. The smaller pipe is divided into 3 sections and contains three cartridge type electric heaters. The center one is the main heater for the test section; the other two are called "Guard Heaters" and their purpose is to regulate conditions in the two ends so that there is no tendency for heat from the central section to flow upward or downward.

The two outer cylinders form the cooling jacket. Alcohol circulates in this chamber to maintain the desired cold side temperature.

The soil being tested is placed in the annular space between the central column and the cooling jacket. Thermocouples mounted at two points on the center column and two points on the inside face of the cold jacket give the temperatures on the hot and cold sides, respectively, of the soil.

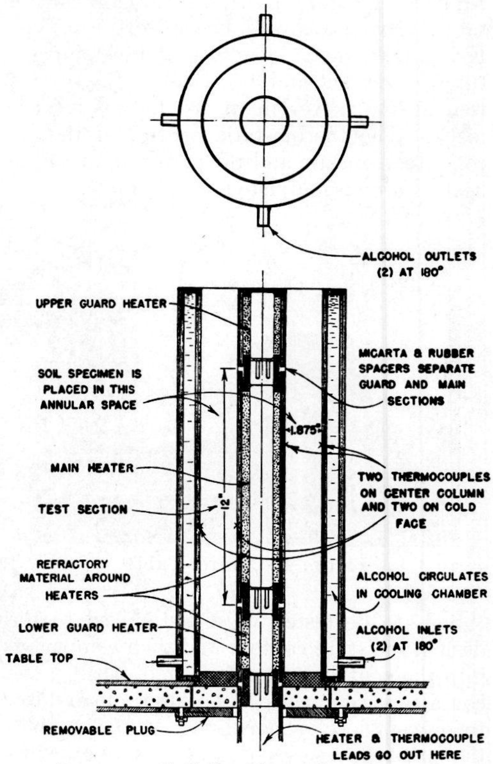

Figure 3. Soil Container for Thermal Conductivity Tests

Each soil container is enclosed by an insulated cover. Two refrigeration plates are mounted beside each container within this cover to aid in maintaining low temperatures.

The cooling and mixing tank unit consists of separate mixing tanks for each soil container and a common central cooling tank, which is kept at a low temperature by a 5-hp. condensing unit. Separate circulation systems are provided between each mixing tank and soil container. The alcohol in each tank is thermostatically controlled to a selected temperature.

Power for the heaters in the control section of the soil container is provided by a motor-generator set. Because of the accuracy required in the maintenance of specified temperatures and the rate of heat applied to the soil, the voltage is controlled by a voltage regulator. Figure 4 is a view of the control table. By means of a Leeds-Northrup type K-2 potentiometer, readings of the temperatures on the hot and cold sides of the soil, as well as the power input to the heaters are made. The thermostatic control of the alcohol temperature and the power input to the heaters are also adjusted at this table.

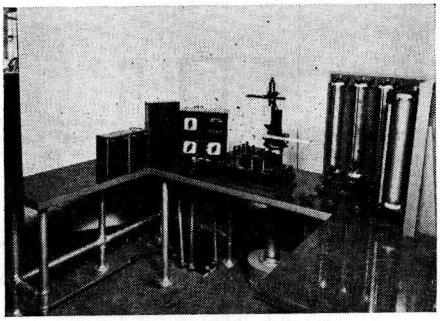

Figure 4. Control Table

Soils to be tested were first mixed to the desired moisture content and then compacted into the container at the desired density; the containers were sealed at both bottom and top to prevent loss of moisture. At the completion of a test, a series of samples were taken to determine the final moisture distribution.

The thermal conductivity tests were run at several mean temperatures, in most cases at four: 70, 40, 25, and −20 deg. F. For each test a differential of 10 deg. was used; thus the 70-deg. mean temperature run had a cold face temperature of 65 and a hot face temperature of 75.

Runs were started by adjusting the cold face temperature to approximately 65 deg. and by regulating the rheostats until the hot face temperature was approximately 75 deg. Adjustments were made until the temperatures were within about a quarter of a degree of the desired temperatures. Readings of the four thermocouples were taken every 15 min., and the balancing couples were also checked at these intervals. Voltage and amperage readings were made every hour. When the readings leveled out and showed only small changes, thermal conductivity coefficients were calculated for each hour's run. When these values showed less than 1 percent variation for a 5-hour period, the test was considered satisfactory.

The flow of heat through the soil in the soil container is similar to that through a pipe covering or any other hollow cylindrical specimen. The equation for the flow of heat for such a condition may be written as follows:

$$q = \frac{k\left(\frac{A_2 - A_1}{2.3\ \log_{10}(A_2/A_1)}\right)(T_1 - T_2)}{t}$$

in which:

q = rate of flow of heat in Btu per hour;
k = coefficient of thermal conductivity in Btu per square foot per inch per hour per deg. F;
A_2 = area of outside face of soil test cylinder in square feet;
A_1 = area of inside face of soil test cylinder in square feet;
T_1 = temperature at inside face in deg. F;
T_2 = temperature at outside face in deg. F;
t = distance between inside and outside faces of cylinder in inches.

In the test runs q is determined by readings of the voltage and amperage on the main heater: the product of these i.e., the watt input to the main heater, is multiplied by 3.415 to obtain Btu's per hour. Substituting the physical dimensions of the test section the equation can be reduced to the form:

$$k = \frac{6.172EI}{T_1 - T_2}$$

in which:

k, T_1, and T_2 are as noted above, and
E = voltage on main heater
I = amperage of main heater

This is the formula used to calculate the conductivity coefficients given in this paper.

SOILS

Nineteen soils were included in the test program; five were sands or gravel, six were materials of heavier texture varying from sandy loam to clay, seven were minerals or crushed rocks, and one was an organic soil. For convenience in presentation, all the materials have been termed "soils" and have been given soil numbers. All are listed in Table 1 with their mechanical analyses and physical constants. This table is in approximate order of texture, with the coarser materials such as gravel, crushed rocks, and sands first, followed by soils of progressively finer texture. The textural class names given for the soils are those defined by the U. S. Bureau of Chemistry and Soils, and are based on percentages of sand, silt and clay in the soils. The peat soil is listed last. The following paragraphs give a brief description of the soils.

Soil P4601, Chena River Gravel, is a material composed largely of quartz and basic igneous rock and is from the Chena River at Fairbanks, Alaska. It was used in base course construction in the Permafrost Research Area near Fairbanks, Alaska. The gravel sample obtained from the field had many stones up to about 2 in. in size. Because of the size of the thermal conductivity test apparatus, all stones larger than ¾ in. were eliminated and replaced with a like weight of ¼- to ¾-in. stone. The grading given in Table 1 is that of the altered material. The original sample had 56 percent gravel and 22 percent coarse sand, but otherwise was similar to the grading given.

The next seven materials in Table 1 were included in the test program as a part of the study of the effect of mineral composition. They are not natural soils.

Soil P4703 is a quartz obtained from the Consolidated Feldspar Corporation at Keystone, South Dakota. The material as received was in angular pieces up to a pound size, plus or minus. It was passed through a jaw crusher (and some of it through a ball mill) in order to reduce it to the grading at which tests were made.

Soil P4704 is crushed trap rock or basalt screenings from the Trap Rock Company at Dresser Junction, Wisconsin. This sharp angular material was tested as received with no further crushing.

Soil P4705 is crushed potash feldspar ob-

TABLE 1
GENERAL PHYSICAL PROPERTIES OF SOILS

Soil No.	Soil Designation	Mechanical Analysis[a] (Percentage by Weight)							Physical Constants						Textural Class[c]
		Gravel	Coarse Sand	Medium Sand	Fine Sand	Silt	Clay	Silt and Clay	Liquid Limit	Plasticity Index	Modified Optimum Moisture Content	Modified Maximum Density	Specific Gravity	Absorption (percent)	
		Over 6.68[b]	0.84 to 6 68	0.177 to 0.84	0.05 to 0.177	0.005 to 0.05	Under 0 005	Under 0 05							
P4601	Chena River Gravel	56.0	26.0	14.0	3.4			0.6		N.P.			2.70	0.75	Gravel
P4703	Crushed Quartz	0.0	44.5	37.3	12.7			5.5		N.P.			2.65	0.26	Coarse Sand
P4704	Crushed Trap Rock	0.0	59.0	24.2	6.8			10.0		N.P.			2.97	0.20	Coarse Sand
P4705	Crushed Feldspar	0.0	51.8	34.2	9.8			4.2		N.P			2.56	0.75	Coarse Sand
P4706	Crushed Granite	0.0	47.8	32.4	13.0			6.8		N.P			2.67	0.56	Coarse Sand
P4702	20–30 Ottawa Sand	0.0	0.0	100.0	0.0	0.0	0.0			N.P.			2.65	0.17	Coarse Sand
P4701	Graded Ottawa Sand	0.0	0.0	98.3	1.6			0.1		N.P.			2.65	0.19	Medium Sand
P4714	Fine Crushed Quartz	0 0	0.0	89.0	11.0	0.0	0.0			N.P.			2.65		Medium Sand
P4709	Fairbanks Sand	1.0	34.5	53.5	8.5			2.5		N.P.	12.0	122.5	2.72		Medium Sand
P4604	Lowell Sand	0.0	14.0	80.0	6.0	0.0	0.0			N.P.	12.2	119.0	2.67		Medium Sand
P4503	Northway Sand	1.6	5.4	86.0	7.0	0.0	0.0			N.P.	14.0	112.8	2.74		Medium Sand
P4502	Northway Fine Sand	0.0	0.5	43.5	53.0	3.0	0.0			N.P.[d]	11.4	116.0	2.76		Fine Sand
P4711	Dakota Sandy Loam	0.0	18.2	34.8	15.8	21.2	10.0		17.1	4.9	6.5	138.5	2.71		Sandy Loam
P4713	Ramsey Sandy Loam	0.0	6.0	29.0	19.0	27.5	18.5		24.6	9.3	9.0	127.5	2.68		Sandy Loam
P4505	Northway Silt Loam	0.0	1.0	2.0	19.0	64.4	13.6		27.3	N.P.	15.7	112.0	2.70		Silt Loam
P4602	Fairbanks Silt Loam	0.0	0.1	0.5	7.0	80.9	11.5		34.0	N.P.	15.5	110.0	2.70		Silt Loam
P4710	Fairbanks Silty Clay Loam	0.0	0.0	1.0	8.2	63.8	27.0		39.2	12.4	18.0	102.0	2.71		Silty Clay Loam
P4708	Healy Clay	0.0	0.3	0.7	0.9	20.1	78.0		39.4	15.0	17.0	108.0	2.59		Clay
P4707	Fairbanks Peat									N.P.					Peat

[a] Aviation Engineers; Manual TM5–255.
[b] Size in millimeters.
[c] U. S. Bureau of Chemistry and Soils
[d] N.P. = non-plastic.

tained from the Consolidated Feldspar Company at Keystone, South Dakota, the same source as for the crushed quartz. The test samples were prepared by screening the material through a No. 4 screen and rejecting the part retained.

Soil P4706 is crushed gray granite. The sample was obtained from the Howard Monument Company in Saint Paul, Minnesota, from material which originally came from the quarries at Saint Cloud, Minnesota. The test sample was prepared by passing it through a jaw crusher. A portion of it was further pulverized by putting it in a ball mill.

Soil P4702 is Standard 20 to 30 Mesh Ottawa Sand from the Ottawa Sand Company at Ottawa, Illinois. It is a pure, washed silica sand, and it meets the requirements of the A.S.T.M. Specification, C77-39.

Soil P4701 is Standard Graded Ottawa Sand from the same source as P4702. It conforms to the A.S.T.M. Specification, C109-37T.

Soil P4714, is crushed quartz from the same source as P4703 but prepared to a grading approximately the same as that of P4701.

Soil P4709, Fairbanks Sand is a siliceous sand which was used as a fill material in the test runway sections at Fairbanks, Alaska.

Soil P4604, Lowell Sand, is a material furnished by the Corps of Engineers, New England Division. It is a cohesionless, siliceous sand from a glacial outwash deposit at South Lowell, Massachusetts. Thermal conductivity tests were also made by the Frost Effects Laboratory at Boston, so that the tests on this material afford a means of checking the results at Minnesota.

Soils P4503, Northway Sand, and P4502, Northway Fine Sand, are from Northway Airfield, Alaska. The sands are similar in appearance except for their difference in grading. They are black and are composed largely of basalt or fine-grained gabbro.

Soil P4711, Dakota Sandy Loam, is a local soil from Dakota County, Minnesota. It was included in the test program since no soil of similar texture was obtained from Alaska.

Soil P4713, Ramsey Sandy Loam, is a local soil from Ramsey County, Minnesota. It was included in the program for the same reason as P4711. It is the heavier of the two sandy loams, with both the plasticity index and the clay content about twice those of P4711.

Soil P4505, Northway Silt Loam, is from Northway Airfield and is a non-plastic, silty soil with a brownish-gray color.

Soil P4602, Fairbanks Silt Loam, is from the research area at Fairbanks, Alaska. It is similar in appearance to the other silt loam, P4505, and it has a gray color. It has a somewhat higher silt content than the Northway Silt Loam.

Soil P4710, Fairbanks Silty Clay Loam, is an Alaska soil from the housing area at Fairbanks. It is similar to P4602 in appearance, but it has a greater clay content.

Soil P4708, Healy Clay, was obtained from the Healy coal mine at Healy, Alaska.

Soil P4707, Fairbanks Peat, is a fibrous, brown peat from the vicinity of Fairbanks, Alaska.

RESULTS

It is not the intent here to give all the detailed test results on all the soils tested, but rather to give certain typical relationships which were found to exist. The test program resulted in about 1000 individual thermal conductivity determinations.

Effect of Temperature.—Tests on all soils were made at two mean temperatures above the freezing point, 70 and 40 deg. F. and on at least two below freezing, 25 and −20 deg. Because many soils in regions of permafrost exist at temperatures close to the freezing point, the conductivity values at 40 and 25 deg. are perhaps the most important.

Considering first the tests at the two temperatures above freezing it was found that the 70-deg. mean temperature conductivity was, on the average, about 4 percent greater than the value at 40 deg. Only in a very few tests was the 40-deg. value greater than that at 70 deg.

The relationship of the conductivity values at the temperatures below the freezing point, 25 and −20 deg., appears to be dependent upon the moisture content. For tests made on all soils, excluding the peat, the ratio of the conductivity at −20 deg. to that at 25 deg. for moisture contents of 0 to 5 percent (121 tests) averaged 0.99; 5 to 10 percent (22 tests), 1.01; 10 to 15 percent (21 tests), 1.05; 15 to 20 percent (13 tests), 1.06; and 20 percent or more (15 tests), 1.04. Thus it may be stated that on the basis of averages of a large number of tests, the conductivity of frozen soils does not vary markedly in a temperature range from 25 to −20 deg. The conductivity at

−20 deg. becomes somewhat greater than that at 25 deg. as the moisture content increases. Further inspection of the data indicates that the increase in conductivity of frozen soils for a drop in mean temperature is greater for a soil with a high density than for the same with a low density. The foregoing facts may be explained by the decrease in conductivity of soil solids and the increase in conductivity of ice with a decrease in mean temperature. The resultant effect is a function of the amount of moisture present.

The most important relationship in a consideration of the effect of mean temperature upon thermal conductivity is the change in conductivity which occurs in passing through the freezing point. Tests on all soils were made just above freezing; i.e., hot side, 45 deg., cold side 35 deg., mean, 40 deg. and just below freezing; i.e. 30 and 20 deg. with a mean of 25 deg. It was found that the difference in k values at these two points was chiefly dependent upon the moisture content. On relatively dry soils, for example, those in the air-dry condition, very little difference was found. As the moisture content was increased, the k value at 25 degrees became less than that above freezing. With a further increase in moisture content the below freezing value became progressively greater than that above freezing. The ratio of the frozen to unfrozen value also depended somewhat on the density of the soil, the ratio in general being greater for a high density than for a low density at the same moisture content. Figure 5 illustrates the relationship between the ratio of the conductivity of the frozen soil to the conductivity of the unfrozen soil and the moisture content for one soil, P4602, Fairbanks Silt Loam. Curves such as that of Figure 5 are drawn without the individual test points in Figures 6 and 7 for the other soils with which tests were made at high moisture contents.

Effect of Density.—It was found in tests on all soils that an increase in density resulted in an increase in thermal conductivity. This was the case for any given moisture content and for any given temperature.

The thermal conductivity was found to vary with density according to the following equation:

$$k = A(10)^{B \cdot \text{Density}}$$

A and B being constants. Such an equation

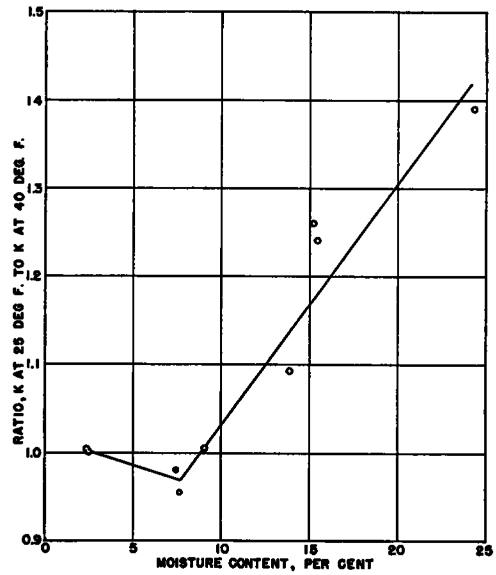

Figure 5.—Relationship of Ratio of Conductivity of Frozen Soil to Conductivity of Unfrozen Soil and Moisture Content. Soil P4602, Fairbanks Silt Loam.

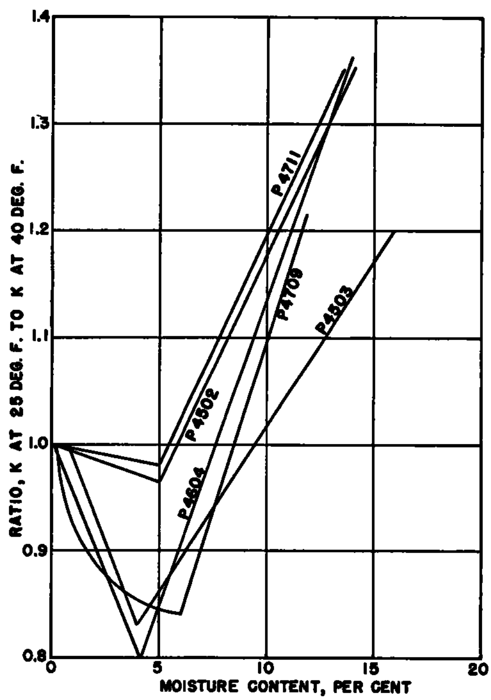

Figure 6. Relationship of Ratio of Conductivity of Frozen Soil to Conductivity of Unfrozen Soil and Moisture Content. Sandy Soils.

plots as a straight line on semilogarithmic paper, the density being on the arithmetic scale and the conductivity on the log scale.

The rate of increase of conductivity with an increase in density is approximately the same at any moisture content for a given soil. Figure 8 is an example of the results on one soil at a mean temperature of 40 deg. It may be noted that all five curves have about the same slope indicating the same percentage increase in conductivity per pound per cubic foot increase in density for moisture contents as high as 25 percent.

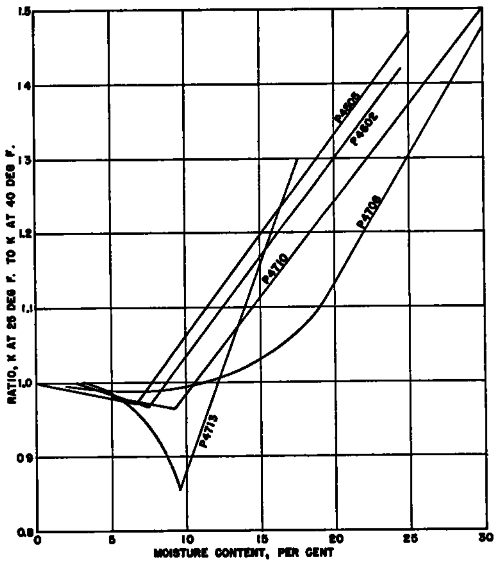

Figure 7. Relationship of Ratio of Conductivity of Frozen Soil to Conductivity of Unfrozen Soil and Moisture Content. Fine Textured Soils.

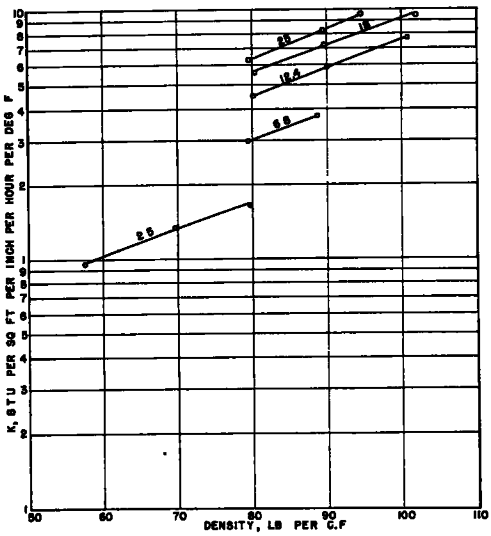

Figure 8. Relationship of Thermal Conductivity and Dry Density of Soil. Mean Temperature, 40 F. Soil P4710, Fairbanks Silty Clay Loam. Values on Curves Give Moisture Content in Percent.

Similar curves were made for all soils tested for mean temperatures of 40 and 25 deg. With the exception of the curves on the peat soil, P4707, and two or three isolated curves for other soils, all of the curves have approximately the same slope. The percentage increase in k for 1 lb. per cu. ft. increase in density varies from 1.2 to 4.4 with four exceptions and averages 2.8 for tests at 40 deg. For the frozen soils, the values vary from 1.6 to 4.6 with seven exceptions and average 3.0 percent. About 70 percent of the values at both temperatures are within the range from 2.0 to 3.5 percent increase in k for a 1-lb. increase in density.

Effect of Moisture Content.—The effect of moisture content upon the thermal conductivity of a soil is an important one, and this factor has been studied with many of the soils. Tests were normally made at several moisture contents varying from the air-dried condition, which was usually less than 1 percent in the sands and 2 or 3 percent in the fine grained soils, to several percent more than the modified optimum moisture content. On the clay soil, P4708, for example, which has a modified optimum moisture content of 17.0 percent, tests were made at 35 percent moisture content. On the sand soils, tests were possible at moisture contents up to a maximum of 17 percent. Tests on the crushed rock materials, the Ottawa sands, and the Chena River Gravel were made at moisture contents of about 4 percent or less; consequently, the results on these soils are of somewhat limited value in the study of the effect of moisture content. Four sand soils and six heavier soils had tests at moisture content ranges of more than 10 percent, and the study is based largely on these ten soils.

Figure 9 is a plot of the data on one soil, P4709, Fairbanks Sand on semi-log graph paper. Such plots ordinarily give straight lines for that part of the data above a moisture content of approximately 1 or 2 percent for the sands and about approximately 7 percent in the silt or clay soils. The points at 2.6 percent moisture are somewhat high for the lines drawn in Figure 9. In most instances, however, deviations of test data from such a straight line were small. Equations for the thermal conductivity for such curves are of the form:

$$k = A \log (\text{Moisture Content}) + B$$

cussed thus far have all been in terms of percentage of dry weight of soil, the common method of such expression. Use of another means, the percentage of saturation, is helpful in making further deductions from the moisture-content thermal-conductivity graphs. The percentage of saturation is defined as the percentage of the void space of a soil occupied by water. It is dependent upon the density of the soil, the specific gravity of the soil particles, and the moisture content.

The curves for Soil P4709 in Figure 9 for the moisture contents above 1.3 percent have been redrawn in Figure 10 with the moisture expressed in terms of percentage of saturation;

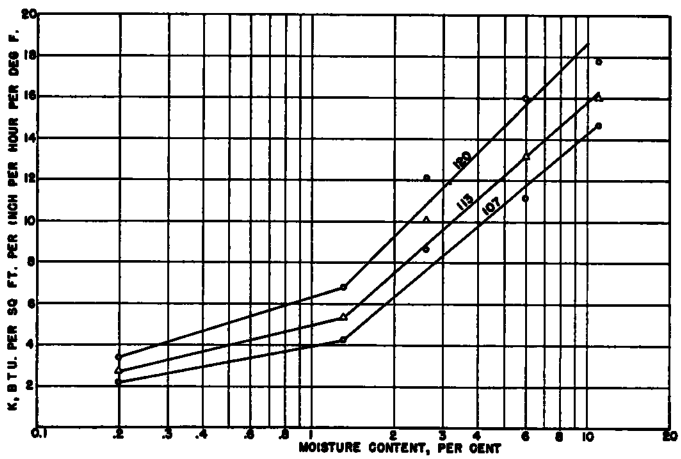

Figure 9. Relationship of Thermal Conductivity and Moisture Content of Soil. Mean Temperature, 40 F. Soil P4709, Fairbanks Sand. Values on Curves Give Density in Pounds per Cubic Foot.

Such curves as Figure 9 give an approximate idea of the effect of moisture content upon thermal conductivity. For the four sands, P4709, P4604, P4503, and P4502 at a density of 110 lb. per cu. ft., the average k at 2.5 percent moisture would be about 6.8; at 5 percent, 8.9; and at 10 percent, 11.2. For five of the soils of finer texture (P4713, P4505, P4602, P4710, and P4708) at a density of 100 lb. per cu. ft., k at 10 percent moisture is approximately 6.7; and at 20 percent, 9.5. Thus doubling the moisture content within the ranges cited increases the conductivity by approximately 30 or 40 percent. At higher moisture contents, the percentage increase would be less.

The moisture contents in the graphs dis- the test points have not been included but are not essential. In Figure 10, the straight line curves have been extended (dash lines) to reach 100 percent saturation.

For frozen soils, i.e. mean temperature 25 deg., the thermal conductivity and moisture contents give a straight line relationship on arithmetic graph paper. Such a relationship is shown for Soil P4709, Fairbanks Sand in Figure 11. Equations for such curves are of the form:

$$K = A + B\ (\text{Moisture Content}).$$

The following averages are indicative of the rate of increase in conductivity for an increase in moisture content, the density remaining constant. For a density of 100 lb. per cu. ft., the increase in conductivity for a 1 percent increase in moisture averages approximately 1

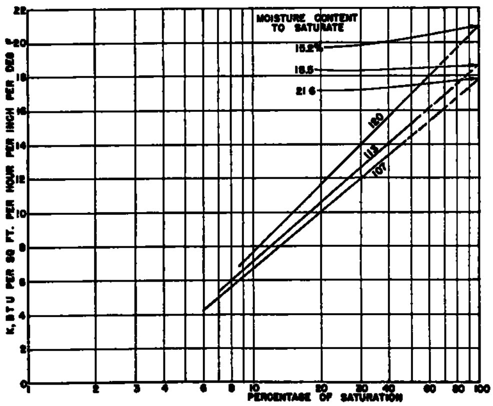

Figure 10. Relationship of Thermal Conductivity and Percentage of Saturation of Soil. Mean Temperature, 40 F. Soil P4709, Fairbanks Sand. Values on Curves Give Density in Pounds per Cubic Foot.

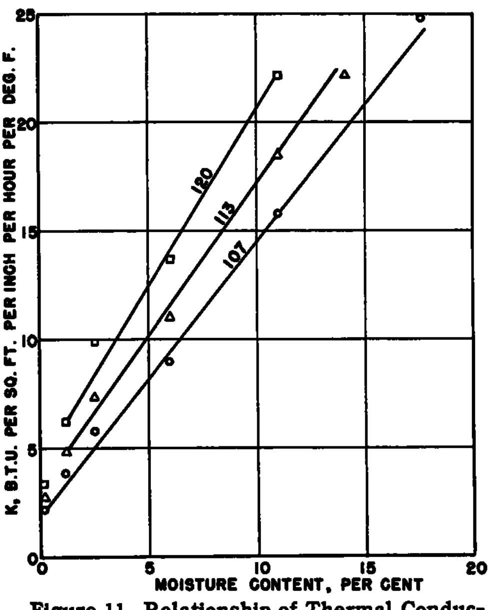

Figure 11. Relationship of Thermal Conductivity and Moisture Content of Soil. Mean Temperature 25 F. Soil P4709, Fairbanks Sand. Values on Curves Give Density in Pounds per Cubic Foot.

for the sands and approximately 0.5 for the soils of heavier texture.

If moisture contents are expressed as a percentage of saturation, curves such as those of Figure 12 are obtained. The curves are extrapolated to reach 100 percent saturation (dash lines).

Effect of Saturation.—By means of curves such as those of Figure 10, it was possible to make a study of the conductivity of saturated soils at temperatures above freezing. The curves for ten soils tested at high moisture contents all showed that a decrease in density

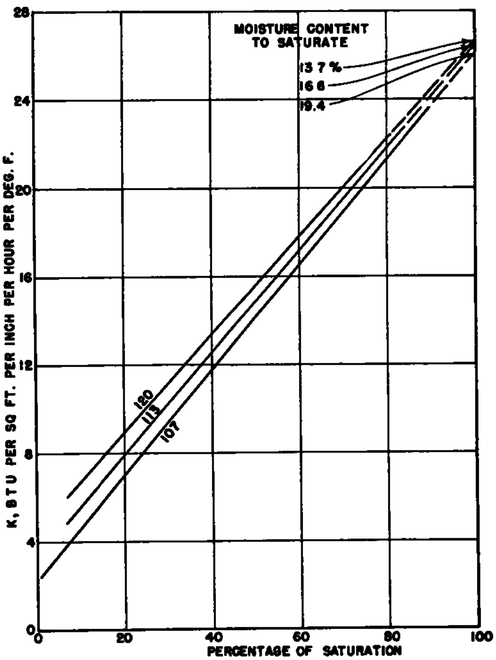

Figure 12. Relationship of Thermal Conductivity and Percentage of Saturation of Soil. Mean Temperature, 25 F. Soil P4709, Fairbanks Sand. Values on Curves Give Density in Pounds per Cubic Foot.

results in a decrease in conductivity for a condition of 100 percent saturation. It should be recalled that a decrease in density corresponds to an increase in moisture content, expressed as a percentage of the dry weight of the soil, for saturation. The thermal conductivity of water is about 4.[1] Thus, the decrease in conductivity for decreasing densities appears to be entirely rational. One might expect the values to approach 4 as a minimum value for extremely low densities.

A general relationship of the decrease in con-

[1] Kent—Mechanical Engineers' Handbook Power, 11th Edition, p. 3-28.

ductivity of saturated soils with a decrease in density is shown in Figure 13. In this graph, the conductivity values for 100 percent saturation has been plotted versus their corresponding densities for eight soils. Two soils, the Northway Sands, P4502 and P4503, have been omitted; these soils gave unique results for sands. (This point will be considered later). The data of the eight different soils definitely show the decrease in conductivity for a density decrease. It would seem that soils at even lower densities than those in Figure 13 and in a saturated condition would have conductivity values of 8 or less.

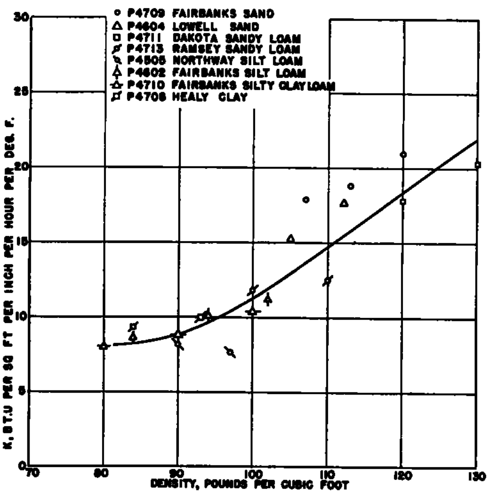

Figure 13. Relationship of Thermal Conductivity of Saturated Soils and Dry Density. Mean Temperature, 40 F.

For frozen soils which are saturated, a study of conductivity values indicates a division into two groups. Seven of the soils, including all those with high silt or clay contents, give conductivity values for saturated soils in the range from 11 to 17 with an average of 14. The two Northway sands, P4502 and P4503, and the Ramsey clay loam, P4713, which contains 46 percent of silt and clay, are within this group. The other three soils all have conductivity values between 21 and 27; these soils are all sandy, and, excluding the two Northway sands, are the three sandiest soils in the group of ten being considered.

Ice has a conductivity value of about 15[2]. Thus, one might expect the conductivity of saturated frozen soils to approach this value as the density decreases. The fact that the tests at several different densities for seven different soils give an average conductivity of 14 would seem to be significant. It would seem that as densities became less the conductivity for frozen saturated soils would not change markedly. This is borne out in part by tests on one soil, P4602, Fairbanks Silt Loam; tests at densities of 102, 94, 83, and 77 lb. per cu. ft. all have conductivity values between 14.0 and 16.8 for saturation.

Sandy soils which are predominantly quartz have high conductivities when saturated and frozen. Three such sandy soils tested all show conductivity values of 21 or greater for saturation (See Figure 12 for results on one sand.) Although it seems reasonable to assume that, with a decrease in density the conductivity values would decrease and approach 15 for saturated sands, the curves indicate only slight reductions in the k value for a lowering of density. It appears that, in order to obtain conductivity values of 15 or slightly higher, the densities of such sand soils would have to be quite low, and such soils do not ordinarily occur at low densities.

Effect of Texture.—The soils tested in this program were of a wide textural range, varying from a rather coarse gravel and several crushed rocks with about 50 percent retained on a No. 20 sieve down through several sands and two sandy loams to such fine grained soils as two silt loams, a silty clay loam, and a clay. This wide range permits a study of the effect of soil texture upon conductivity. Such a comparison should preferably be made for tests conducted under similar conditions of moisture content and density. As might be expected, however, the densities at which the sandy soils could be placed for test purposes were relatively greater than those to which the silt and clay soils could be compacted; also, the range of moisture contents at which the sands could be tested was less than that for the fine grained soils. Consequently, it is impossible to select any density-moisture content combination at which tests were made on all soils.

In Table 2, the soils have been listed in approximate order of magnitude of thermal conductivities from greatest to least, with the thermal conductivity values at a mean temperature of 40 deg., for eight different

[2] Ibid.

density-moisture content conditions. The moisture contents range from 4 to 20 percent, and the densities range from 90 to 120 lb. per cu. ft. The conductivities are also given for the condition of maximum density and modified optimum moisture content. Some of the conductivity values in this table have been determined by extrapolation and are consequently approximate. In all instances, values have been approximated to the closest one-half unit, if possible. Blank spaces in the table indicate that the density or moisture content or both are such that no tests were possible for that condition or sufficiently close to it so that a reasonable extrapolation of the data could be made. For example, at 4 percent moisture content, it was not possible to compact the silt loams to a density as great as 100 lb. per cu. ft.; consequently, no conductivity value is given for the silt loams in this condition. The test results at 10 percent moisture content and 110 lb. per cu. ft. density facilitate the textural comparison greatly in that some of both the coarse and the fine grained soils are included.

TABLE 2

TABULATION OF THERMAL CONDUCTIVITY (k) VALUES OF SOILS IN APPROXIMATE ORDER OF DECREASING VALUES

Mean Temperature—40 Deg. F.

Soil No.	Soil Designation	Moisture Content, %							Mod. Opt.[a]
		4	4	4	10	10	20	20	
		Density lb. per cu. ft.							
		100	110	120	90	110	90	100	Maximum[a]
P4714	Fine Crushed Quartz	12.0	16.0						
P4703	Crushed Quartz	11.5	16.0	22.03					
P4701	Graded Ottawa Sand	10.0	14.0						
P4709	Fairbanks Sand	8.5±	10.5	13.5		15.0			19.0
P4604	Lowell Sand	8.5	11.0			13.5			17.5
P4601	Chena River Gravel		9.±	13.0					
P4705	Crushed Feldspar	6.0	7.5	9.5					
P4706	Crushed Granite	5.5	7.5	10.0					
P4711	Dakota Sandy Loam		6.5	9.5		13±			19.0
P4704	Crushed Trap Rock	5.0	6.0	7.0					
P4713	Ramsey Sandy Loam	4.5	6.5			10.0			16.5
P4502	Northway Fine Sand	4.5	5.5			8.5			9.5
P4503	Northway Sand	4.5	6.0			7.5±			8.5
P4708	Healy Clay	4±			5.5	9.0±	8.0	10.0	11.5
P4602	Fairbanks Silt Loam				5.0	9.0±	7.5	10.0	12.0
P4710	Fairbanks Silty Clay Loam				5.0	9.0±	7.5	9.5	9.5
P4505	Northway Silt Loam				4.0±	7.0±	6.0±	7.0±	9.0

[a] See Table 1 for values of modified optimum moisture content and maximum density for each soil.

Soil P4702, 20–30 Ottawa Sand is not included in the table since no tests were made at moisture contents of more than 2 percent.

The order of soils in Table 2 permits some generalizations. For one thing, three quartz materials head the table followed by three siliceous sands. This immediately suggests the probability of mineral composition being of importance. This factor is considered in the next section. The sand content of soils also appears to be important. Sand soils, such as Fairbanks Sand, (P4709) and Lowell Sand (P4604), are high in the list of conductivities. Dakota Sandy Loam, (P4711), which contains 69 percent of the sand fraction and Ramsey Sandy Loam (P4713) with 54 percent sand are midway in the table. The clay (P4708), the silty clay loam (P4710), and the two silt loams (P4505 and P4502), all with less than 22 percent of sand fraction, have the lowest conductivity values. The two Northway sands (P4502 and P4503) are seemingly out of order in this consideration of sand content; the low conductivity of these two materials may be due to their distinctive mineral composition, as will be pointed out subsequently. In general, however, it appears that at equal moisture contents and densities, thermal conductivities vary with texture, being greater for coarse grained, or sandy materials, and lower for the finer grained soils such as silt loams or clays.

If the conductivity values at the modified optimum moisture content and maximum density are considered, the values are in a somewhat different order. This is due both to the difference in moisture content and the variation in density. One of the sandy loams (P4711), for example, has a greater conductivity value than the Lowell Sand (P4604). This sandy loam had a maximum density of 137 lb. per cu. ft. whereas the Lowell Sand had 119.

It might also be noted that although the Chena River Gravel (P4601) has conductivity values approximately equal to the Fairbanks Sand (P4709) and Lowell Sand (P4604), it can be compacted to higher densities than either of these soils, resulting in the attainment of high conductivity at relatively low moisture content. At a moisture content of 4 percent and a density of 129 lb. per cu. ft., for example, a conductivity of over 16 is obtained on the Chena River Gravel.

Effect of Mineral Composition.—To determine the variations in thermal conductivity of common soils constituents, tests were made on four materials which were: No. P4703, crushed quartz from Keystone, South Dakota; No. P4704, crushed trap from Dresser Junction, Wisconsin; No. P4705, crushed potash feldspar from Keystone, South Dakota; No. P4706, crushed granite from St. Cloud, Minnesota.

An attempt was made to prepare these materials so that approximately similar gradings would be obtained. All materials passed a No. 4 sieve. The amounts of minus No. 270 mesh material varied from 4.2 to 10.0 percent.

Conductivity tests were made at two densities, about 103 and 120 lb. per cu. ft., and at four moisture contents, between 0 and 4.0 percent. The conductivity results for the 103-lb. density are shown in Figure 14. It will be noted that there is a marked difference in conductivities at equal moisture contents for the four rocks, particularly between the quartz and the other three. The order of thermal conductivities from least to greatest is trap rock, granite, feldspar, and quartz. The approximate ratio of magnitude, taking trap rock as 1.0 are: trap rock 1.0, granite 1.3, feldspar 1.4, and quartz 2.5.

On the basis of mineral and rock composition, all of the soils tested may be divided into fairly distinct groups. These are: (1) soils in which the quartz content is high; (2) soils which have a high basic rock content with such minerals as plagioclase feldspar, pyroxene, amphibole, and olivine; (3) soils whose mineral composition is intermediate between acid and basic rock; and (4) soils with an appreciable quantity of kaolinite and other clay minerals. The soils and their mineralogical data are arranged into these four groups in Table 3.

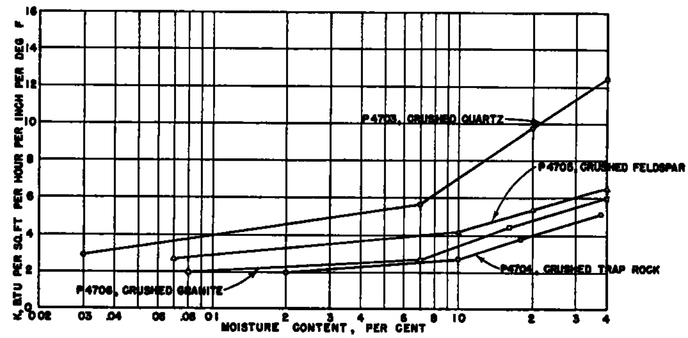

Figure 14. Relationship of Thermal Conductivity and Moisture Content for Four Crushed Rock Soils. Mean Temperature, 40 F.

The first group includes nine soils which are all granular in nature. The two sandy loams, P4711 and P4713, are the soils having the finest texture in this group. These soils are characterized by high contents of quartz, felsite, and orthoclase feldspar. Quartz and orthoclase feldspar are indicative of acidic rocks. Felsite is not a mineral but a rock whose chief constituents are quartz and orthoclase feldspar. The soils have relatively small quantities of plagioclase feldspar, pyroxene, amphibole, olivine, and basic igneous rock fragments.

The second group of soils in Table 3, which includes only two soils, consists of the two Northway sands. These soils are characterized by relatively high percentages of plagioclase feldspar, pyroxene, amphibole, and olivine, which are minerals, and of basic igneous rock grains which contain these minerals.

Silt Loam, has a high percentage of the basic rock minerals.

The significance of this mineralogical grouping of soils may be obtained by study of Table 2 in which the soils were listed in an approximate order of thermal conductivities. The first six soils in this tabulation, which are those with the highest conductivities, are all within the mineralogical group of high quartz content. The second and third groups have low quartz content and a relatively high percentage of plagioclase feldspar and basic igneous rock fragments. When considered together as a single group, they have markedly lower conductivities than the quartz group. The two natural sands, P4502, Northway Fine Sand, and P4503, Northway Sand, have conductivity values of approximately half those of the three natural granular materials in the quartz group: P4709, Fairbanks Sand, P4604,

TABLE 3

GROUPING OF SOILS ON BASIS OF MINERAL AND ROCK COMPOSITION

(Percentage by Weight)

Soil No.	Soil Designation	Quartz: By Petrogr. Exam.	Quartz: By X-ray Analysis	Orthoclase Feldspar	Felsite	Plagioclase Feldspar	Pyroxene, Amphibole, and Olivine	Basic Igneous Rock	Kaolinite, Clay Minerals, and Clay coated Minerals	Hematite and Magnetite	Mica and Coal	Others
						Group I[d]						
P4702	20-30 Ottawa Sand	99 plus[c]										
P4701	Graded Ottawa Sand	99 plus[c]										
P4703	Crushed Quartz	95 plus[a]										
P4714	Fine Crushed Quartz	95 plus[a]										
P4604	Lowell Sand	72.2		20.5			3.0				1.3	3.0
P4709	Fairbanks Sand	59.4		3.6	5.0	6.3	8.0	10.0		2.5	0.1	5.1
P4711	Dakota Sandy Loam	59.1		12.9		1.0	12.1		12.4			2.5
P4713	Ramsey Sandy Loam	51.3		11.8		5.6	12.6		15.9			2.8
P4601	Chena River Gravel	43.1		11.6		12.9	27.0				2.1	3.3
						Group II						
P4503	Northway Sand	7.5			11.5	9.0	7.5	51.0				13.5
P4502	Northway Fine Sand	12.0			7.0	18.0	12.0	40.0				11.0
						Group III						
P4704	Crushed Trap Rock	3.0		10.0		50.0[b]	34.0			2.0		1.0
P4705	Crushed Feldspar	15.0		55.0		30.0						
P4706	Crushed Granite	20.0		30.0		40.0						10.0
						Group IV						
P4708	Healy Clay	22.5							55.0		22.0	0.5
P4710	Fairbanks Silty Clay Loam	4.6	59.5				2.2		28.9	1.6	3.2	
P4602	Fairbanks Silt Loam	13.3	40.3						28.3		18.1	
P4505	Northway Silt Loam	1.5				31.5	19.5	4.5	27.5	10.0		5.5

[a] By visual inspection; impurities less than 5 percent.
[b] Andesine feldspar.
[c] By visual inspection; impurities less than 1 percent.
[d] For definition of groups, see text, Page 403–404.

The third group consists of three crushed rock materials. They are characterized by low quartz content and high sodium content in the feldspars. The andesine feldspar of Soil P4704 is a component of rocks which are near the dividing line between acid and basic rocks.

The fourth group includes four soils of fine texture which have from 25 to 55 percent of clay minerals. Two of the soils, P4602, Fairbanks Silt Loam and P4710, Fairbanks Silty Clay Loam, also have a large percentage of quartz; whereas another, P4505, Northway

Lowell Sand, and P4601, Chena River Gravel. The two natural sandy loams in the quartz group, P4711 and P4713, also have greater conductivities than the Northway Sands.

The four fine grained soils, or those which contain 25 percent or more of clay minerals, occupy the positions of lowest conductivity in Table 2. It may be significant that, of these four, the one with the lowest conductivity is also the one with the lowest quartz content and the largest quantities of plagioclase feldspar, pyroxene, amphibole, and olivine, which are constituents of basic igneous rock.

It may be concluded from this study that the thermal conductivity of granular soils is affected by mineral composition. Sands with a high quartz content tend to have a high thermal conductivity as compared to sands which have a high basic rock content composed of such minerals as plagioclase feldspar and pyroxene. Fine textured soils with appreciable quantities of kaolinite or other clay minerals have low conductivities.

Prediction of Thermal Conductivity.—The thermal conductivity tests on 19 different soils gave a great variety of results; nevertheless, they are useful in formulating predictions of thermal conductivity values for any soil. As noted in Table 2, the values may vary by more than 100 percent for two soils at the same moisture content and density, but, by taking into account such items as grading, mineral composition, and other characteristics, the possible error in an estimate may be lowered. Although the test results for all 19 soils are informative, those on eight particular soils are most useful. Of the other 11 soils, 8 were tested only at moisture contents of about 4 percent or less. One was a peat which could not be compacted to a density greater than 21 lb. per cu. ft., and two (The Northway sands, P4502 and P4503) were of such a unique mineral composition that they would be considered uncommon.

Considering first the conductivities of unfrozen soils, i.e., a mean temperature of 40 deg., any general overall equation would of necessity be in considerable error for some soils. An inspection of Table 2 will verify this statement. It would seem expedient to divide the soils into two groups: one, the fine grained soils containing, in general, those soils with 50 percent or more silt and clay; and two, the sands and sandy soils. Soil P4713, Ramsey Sandy Loam, which contains 47 percent of silt and clay, has conductivity values more similar to the fine grained soils; whereas Soil P4711, Dakota Sandy Loam, which has 37 percent of silt and clay, should be included with the sandy soils. The two Northway Sands, P4502 and P4503, actually have conductivity values more similar to the fine grained soils than to the sands and should not be considered as characteristic of ordinary sands.

Considering first the fine textured soils, i.e.: P4708, Healy Clay; P4710, Fairbanks Silty Clay Loam; P4602, Fairbanks Silt Loam; P4505, Northway Silt Loam; and also P4713, Ramsey Sandy Loam, a common equation for thermal conductivity may be formulated which yields results not more than about 25 percent in error for all test results except one and much closer than this in most instances. The equation is a combination of those derived for moisture content and density variations and is as follows:

$$k = [0.9 \log (\text{Moist. Cont.}) - 0.2]10^{0.01D}$$

k being for a mean temperature of 40 deg., and D being the dry density in pounds per cubic foot. The equation only applies to moisture contents of 7 percent or greater. A chart of the equation is produced in Figure 15. The k curves of the chart are drawn only up to the zero air-voids curve which indicates the 100 percent saturation point for any density.

Figure 15 should serve as an aid in estimating the thermal conductivity value of any soil which contains about 50 percent or more of silt and clay.

The foregoing equation gives results which are too low for granular soils such as P4709, Fairbanks Sand, P4604, Lowell Sand, and P4601, Chena River Gravel. Soil P4711, Dakota Sandy Loam, also gives higher values. A general equation which best suits such soils is:

$$k = [0.7 \log (\text{Moist. Cont.}) + 0.4]10^{0.01D}$$

k being for a mean of 40 deg. and the moisture content being not less than 1.0 percent. Conductivity values obtained by this equation check test results very well for the three clean sands or gravel mentioned above. Only 2 of 35 tests have differences of more than 25 percent. Values from the chart are as much as 50 percent too great for some tests on the Dakota Sandy Loam.

The equation is charted in Figure 16. This diagram should be used for sandy or gravelly soils of normal composition, i.e., mineralogically they should be predominately quartz. The chart will give too high a result for sandy loam soils or those that contain from 20 to 50 percent of silt and clay.

As previously noted, the conductivity values for the two Northway sands, P4502 and P4503, agree more closely to the results of the equation advocated for silt and clay soils than to that for sands.

For soils in a frozen condition, the tests at a mean temperature of 25 deg. are considered. Here again, the soils are divided into two groups, the fine textured and the sandy ones. For frozen soils, the relationship between conductivity and moisture content has been shown to be that of a straight line. A study of the curves of this relationship shows that both the zero moisture content intercepts and the slopes are a function of the density. For the fine texture soils, the general equation which best fits the data is:

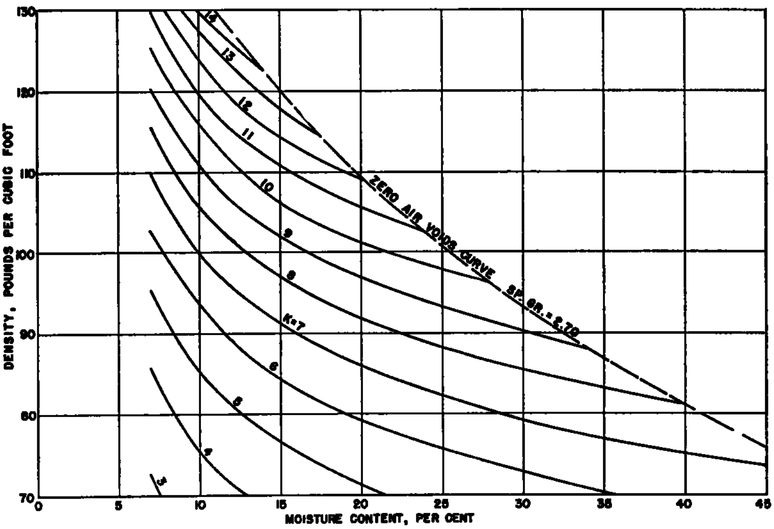

Figure 15. Diagram of Thermal Conductivity for Silt and Clay Soils. Unfrozen. Mean Temperature, 40 F.

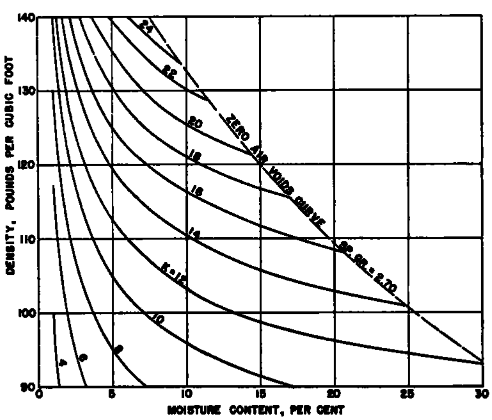

Figure 16. Diagram of Thermal Conductivity for Sandy Soils. Unfrozen. Mean Temperature, 40 F.

$$k = 0.01(10)^{0.02114D} + 0.025\,(10)^{0.014D}\ (\text{Moist. Cont.})$$

k being at a mean temperature of 25 deg. and D being the dry density in pounds per cubic foot. The equation holds for moisture contents from approximately 7 percent to saturation. Figure 17 is a chart of the equation. This chart may be used for soils which contain about 50 percent or more of silt and clay. Sandier soils will have conductivity values greater than those of this chart. Values from this diagram check more than 90 percent of the test results for soils P4708, Healy Clay; P4710, Fairbanks Silty Clay Loam; P4602, Fairbanks Silt Loam; P4505, Northway Silt Loam; and P4713, Ramsey Sandy Loam, within 25 percent, and much closer in most instances.

A general equation for the granular soils, P4709, Fairbanks Sand; P4604, Lowell Sand; P4601, Chena River Gravel; and P4711, Dakota Sandy Loam, is as follows:

$$k = 0.011(10)^{0.0214D} + 0.026(10)^{0.0146D} \text{ (Moist. Cont.)}$$

k and D being as before and the moisture content being not less than 1 percent. This equation is only slightly different from that for the fine grained soils but gives somewhat greater values of conductivity for a given might have conductivity values in the range between those indicated by the two charts. By proper consideration of the texture of the soils, conductivity values with an error of not more than 25 percent should be obtained.

Since conductivity does not vary much in the range of ordinary air temperature, and since the same is true for the below freezing range, it should not be necessary to make any changes in the chart values for any normally existent air temperatures.

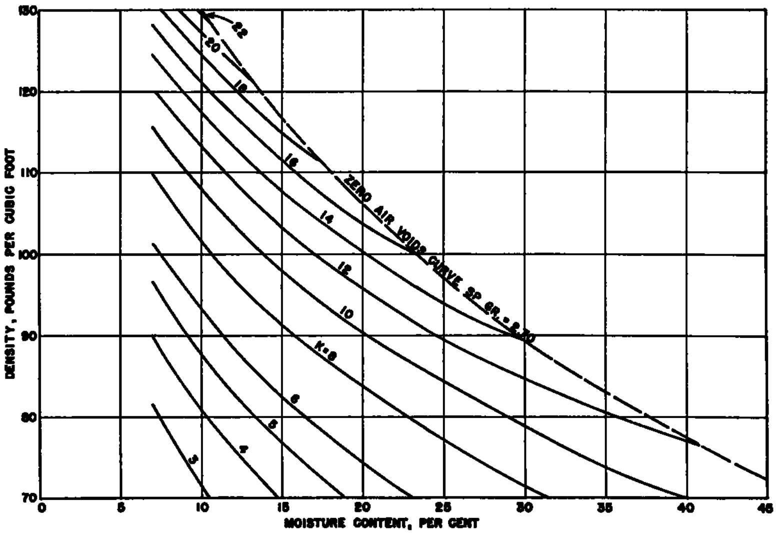

Figure 17. Diagram of Thermal Conductivity for Silt and Clay Soils. Frozen. Mean Temperature, 25 F.

density and moisture content. Figure 18 is a chart of the equation. Values from this diagram are checked by test results of the four enumerated soils within about 25 percent, except for some tests on two of the sands at moisture contents of 5 percent or less. This chart should serve for any other sandy soils of similar mineral composition.

The four charts, Figures 15, 16, 17, and 18 serve as a means of prediction of the thermal conductivity of any soils. Two of the charts are for frozen and two for unfrozen soils; two are for sandy soils and two for silt or clay soils. The division point in texture may be based on the silt and clay contents. Soils with more than 50 percent of silt and clay are in the fine textured group. Soils which have a somewhat smaller silt and clay content

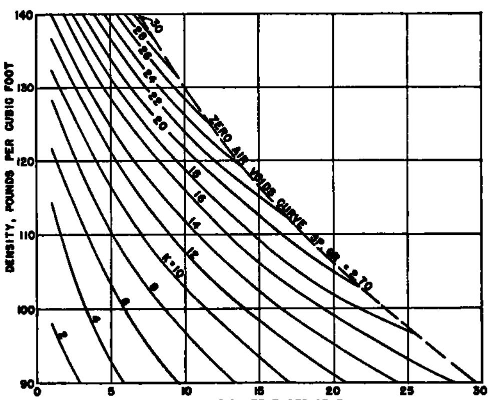

Figure 18. Diagram of Thermal Conductivity for Sandy Soils. Frozen. Mean Temperature 25 F.

CONCLUSIONS

Consideration of the test results leads to the following conclusions:

1. The coefficient of thermal conductivity of soils above the freezing point increases slightly with an increase in mean temperature. Values at 70 deg. F. average approximately 4 percent more than those at 40 deg.

2. In most cases, the coefficient of thermal conductivity does not vary appreciably in a mean temperature range of from +25 to −20 deg. At higher moisture contents, the −20-deg. value becomes progressively greater than the +25-deg. conductivity. For all tests made with moisture contents greater than 20 percent, the low temperature values average 4 percent more than 25-deg. results.

3. The difference in thermal conductivity above and below the freezing point is dependent upon the moisture content of the soil. For air-dry soils there is practically no difference in the two values. For moisture contents up to about 6 percent in sandy soils or 12 percent in fine textured soils, the conductivity is lower below freezing than above. With further increases in moisture content, the conductivity of frozen soils becomes progressively greater than that of the unfrozen soil. At the modified optimum moisture content, the conductivity below freezing averages about 17 percent greater than that above freezing. At a moisture content of 5 percent more than the modified optimum, it is about 35 percent greater.

4. At a constant moisture content, an increase in density results in an increase in conductivity. The rate of increase is about the same at all moisture contents, and is not markedly different for frozen and unfrozen soils. On the average, for each 1 lb. per cu. ft. foot increase in density, the conductivity increases 2.8 percent for unfrozen soils and 3.0 percent for frozen soils.

5. At a constant density, an increase in moisture content causes an increase in conductivity. This is true up to the point of saturation and holds for frozen as well as unfrozen soils.

6. For saturated, unfrozen soils, the conductivity decreases for a decrease in density. For saturated, frozen soils, the data indicate no well-defined relationship between density and conductivity. Sand soils in such a condition and at densities normally obtainable gave higher conductivities than soils with relatively high silt and clay contents.

7. The thermal conductivity varies, in general, with the texture of soils. At a given density and moisture content, the conductivity is relatively high on coarse textured soils such as gravel or sand; somewhat lower on sandy loam soils, and the lowest on fine texture soils such as silt loam or clay.

8. The thermal conductivity of a soil is dependent upon its mineral composition. Sands with a high quartz content have greater conductivities than sands with high contents of such minerals as plagioclase feldspar and pyroxene, which are constituents of basic rocks. Soils with a relatively high content of kaolinite and other clay minerals have relatively low conductivities. This may be due to the fine texture and is not necessarily the result of the presence of these minerals.

9. The conductivities of crushed rocks of similar gradings vary according to type of rock. The order of conductivities of four crushed materials tested, from least to greatest, is trap rock, granite, potash feldspar, and quartz. The approximate relative magnitudes are 1.0, 1.3, 1.4, and 2.5 respectively.

10. For purposes of prediction of thermal conductivity, soils should be divided into two groups, sands or sandy soils and silt and clay soils. The line of division, in general, is based on the silt and clay content: soils with 50 per cent or more of silt and clay are in the fine textured group. The thermal conductivity also differs according to whether the soil is frozen or not. The four equations for these conditions are:

1. Silt and clay soils, unfrozen

$$k = (0.9 \log (\text{Moist. Cont.}) - 0.2)10^{0.01D}$$

2. Silt and clay soils, frozen

$$k = 0.01(10)^{0.02114D} + 0.025(10)^{0.014D} (\text{Moist. Cont.})$$

3. Sandy soils, unfrozen

$$k = (0.7 \log (\text{Moist.Cont.}) + 0.4)10^{0.01D}$$

4. Sandy soils, frozen

$$k = 0.011(10)^{0.0214D} + 0.026(10)^{0.0146D} (\text{Moist. Cont.})$$

In these equations, the moisture content is a percentage of the dry soil weight, and D is the dry density in pounds per cubic foot. The equations for the silt and clay soils apply for moisture contents of 7 percent or more; those for the sandy soils, of 1 percent or more.

The equations for sandy soils are largely based on tests on fairly clean sands. For sandy soils with a relatively high silt and clay content (for example 40 percent), conductivity values intermediate between those calculated by two equations might be a reasonable prediction. It is expected that judicious use of the equations with an understanding of their limitations, will give conductivity values not more than 25 percent in error.

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EFFECT OF MATERIAL RETAINED ON THE NUMBER 4 SIEVE ON THE COMPACTION TEST OF SOIL

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SYNOPSIS

The purpose of the investigation was to determine the effects of larger size fractions of gravel in soil on maximum density and optimum moisture content, and to ascertain if it would give satisfactory results to make the compaction test on samples containing the material retained on the No. 4 sieve up to ¾ in. The common practice is to make the test on the material passing the No. 4 sieve and make a correction for the effect of the larger material.

Comparative tests were made on samples containing the material retained on the No. 4 sieve and samples passing the same sieve. In these tests the samples containing the coarser material gave greater values for maximum density and smaller values for optimum moisture than did the material from which the coarse particles had been removed. This indicates that data from samples containing all fractions as received are necessary for application to field conditions.

The use of larger molds was investigated without disclosing any variance from the foregoing results.

In the standard method of determining moisture-density relations in soil[1] only that portion of the soil sample passing the No. 4 sieve is used in the compaction test. This results in the portion of the soil sample retained on the No. 4 sieve not being tested, and inasmuch as the purpose of the test is to simulate field compaction conditions, it is desirable that the soil to be tested in the laboratory have the same gradation that is to be used in the field. While it is realized that an upper limit must be placed on the top size of material that can be tested in small quantities such as are used in the Proctor mold of 1/30 cu. ft. volume, it was hoped that some investigation into the use of larger material would show that the top size could be raised from material passing the No. 4 sieve to some other maximum size.

[1] ASTM Tentative Method of Test for Moisture Density Relations of Soils, D-698-42T and AASHO Standard Laboratory Method of Test for the Compaction and Density of Soil, T99-38.

CORRECTION FOR LARGER SIZE MATERIAL

When any appreciable portion of the soil sample is retained on the No. 4 sieve, a procedure often used is to run the compaction test on the soil finer than the No. 4 and then make a correction for the effect of the stone or gravel present. This correction is necessary because the presence of larger material will increase the apparent density due to the higher specific gravity of the stone or gravel as compared with the bulk specific gravity of the