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THERMAL CONDUCTIVITY OF SOIL

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SUMMARY.

Thermal conductivity tests have been conducted on fourteen different soils at a wide range of densities, moisture contents, and mean temperatures. The effect of the various factors upon the thermal conductivity is discussed. In general, it is found that the thermal conductivity of soil varies in the following ways:

1. Above freesing, increases for an increase in mean temperature;
2. Below freezing, shows very little change;
3. From below to above freezing, varies according to the moisture content;
4. At a constant density, increases with an increase in moisture content;
5. At a constant moisture content, increases with an increase in density;
6. Is dependent upon the grading and particle shape of the soil;
7. Differs appreciably with respect to different soil minerals.

INTRODUCTION.

During the past two years a research program for determining the thermal conductivity of soil has been in progress at the Engineering Experiment Station of the University of Minnesota. This work has been sponsored by the Corps of Engineers, Department of the Army, as a part of their research study of construction problems in regions of permafrost, or permanently frozen ground.

The purpose of the study was to determine the effect of such items as temperature, density, moisture content, and mineral composition upon the thermal conductivity of soil, as well as to obtain coefficients of conductivity of soils from test installations in Arctic regions. The data serve as a basis for predicting thermal conductivities of other soils.

The tests were made with apparatus designed and built for the investigation at the University 1). The soil was packed into the tubular soil container of this apparatus at various densities and moisture contents, the densities varying from that obtained by loose pouring to the modified maximum density obtained by heavy ramming 2) and the moisture contents varying from air-dry to a few per cent above the optimum moisture content. Tests were made at mean temperatures ranging from 70 to -20° F.

The units used in this report are as follows:

Thermal conductivity, k, represents the amount of heat expressed in British thermal units transmitted per hour through one square foot of soil one inch thick with a 1° F temperature difference between the two surfaces;

All temperatures are Fahrenheit;

Density 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.

The thermal conductivity tests were made with a temperature differential of 10° between the hot and cold faces. A test with a hot temperature of 75° and a cold temperature of 65° is reported as having a mean of 70°; a test with 45 and 35 is reported as having a mean of 40°, etc.

In some tests a part of the contained moisture migrated toward the cold face. In such tests a series of 12 moisture samples were taken from the soil in the tubular container at the end of the test, and an average was determined. The moisture contents reported herein are therefore in some instances average rather than uniform values.

SOILS TESTED.

The soils tested have been furnished by the Corps of Engineers. Most of them are from Arctic regions. The 14 materials tested thus far are listed together with their grading and other physical constants in Table I. Included are several sandy soils and a gravel, three fine grained soils, a peat, and some crushed rock materials.

RESULTS.

More than 600 thermal conductivity tests have been made on the 14 soils tested thus far; consequently, it is not possible to present the detailed results herein. It is intended rather to discuss the results in general and to point out the effect of the several factors influencing the results.

Effect of Mean Temperature.

Thermal conductivity tests were made at four mean temperatures: two above freezing, 70 and 40°, and two below freezing, 25 and -20°. Considering first the values at the temperatures above freezing, the conductivity at 70° averaged about 5 per cent greater than that at 40°. Only in a very few instances was a higher value found at the lower temperature.

The tests below the freezing point showed no marked variation, particularly at low moisture contents. In some tests with moisture contents equal to or greater than the optimum moisture content, the conductivity at -20° was 5 to 10 per cent greater than that at 25°. In general, however, the two values varied by less than 5 per cent.

The most important relationship in a consideration of the effect of mean temperature upon thermal conductivity is the change which occurs in passing through the freezing point. Tests on all soils were made just above freezing, with a mean of 40°, and just below freezing, with a mean of 25°. It was found that the difference in conductivity at these two temperatures was chiefly dependent upon the moisture content. On relatively dry soils, for example those in the air-dry condition, there was practically no difference. As the moisture content increased a few percentage points, the conductivity at 25° became less than that at 40°, but with a further increase in moisture the below-freezing value became progressively greater than that above freezing. At the modified optimum moisture content the frozen soil has a conductivity of approximately 20 per cent greater than the unfrozen soil.

Effect of Moisture Content.

The effect of moisture content upon conductivity has been investigated for the various soils by attempting to run series of tests with a common density but with different moisture contents. Seven soils, including the two silt loams, the clay, and the peat, were tested with moisture contents of more than the optimum. The other soils were tested at moisture contents up to only approximately 4 per cent. Based on these tests with the dry density constant, the best relationship between conductivity and moisture content is of the form

$$k = A \log (\text{moisture content}) + B,$$

A and B being constants determined for the given soil and density. Such an equation plots as a straight line on semi-logarithmic paper. A relationship such as the above fits the results down to a certain moisture content, ordinarily 1 or 2 per cent for the sands and somewhat higher for the finer textured soils, below which a further decrease in moisture content causes only a small decrease in the thermal conductivity.

The value of the constant A in the equations for the various soils and densities, which represents the change in conductivity in one cycle of log paper, i.e., 1 to 10 per cent, 2 to 20 per cent moisture, etc., varies from as low as 4 to as high as 15, with an average of about 8. The conductivity of a soil of average density at 1 per cent moisture content is about 6; thus, an increase of moisture from 1 to 10 per cent more than doubles the conductivity.

Tests were not conducted on any soils at moisture contents greater than 36 per cent; on the sands 17 per cent was the greatest value. Consequently, the effect of very high moisture contents on conductivity is not known. It may be stated that to the point that tests were made, any increase in moisture resulted in an increase in conductivity.

Effect of Density.

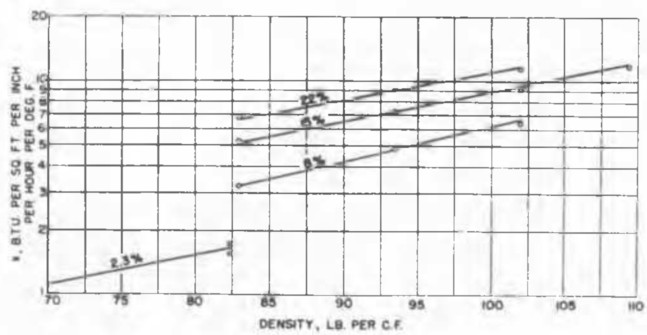
The effect of density was studied on all soils by making series of test at a common moisture content and different densities. Figure 1 is a plot of the results of such tests on one soil. The relationship is expressed by the equation,

$$k = A\,(10)^{B \times \text{density}},$$

A and B being determined by the type of soil and the moisture content. It was found that the rate of increase of conductivity with an increase in density was approximately the same for any moisture content for a given soil. This is illustrated by the uniformity of the slopes of the curves in Figure 1. The rate of increase was found to be quite similar for the 14 soils tested. The rates varied from $1\frac{1}{2}$ to 4 per cent increase in conductivity for each 1 pound per cubic foot increase in density and averaged about $2\frac{1}{2}$ per cent.

Effect of Particle Size and Shape.

Tests were made on three different samples, all pure quartz but with different gradings or particle shape. Soils P4701 and P4702 were standard Ottawa sands from Ottawa,



Variation of thermal conductivity with dry density of soil. Soil P 4602, Fairbanks silt loam, mean temperature 70° F. Values on curves give constant moisture content.

FIG.1

Illinois; P4701 was a fine graded material, and P4702 was 20 to 30 mesh material. Both had rounded particles. P4703 was a crushed angular quartz, grading from ¼ inch down to dust. The comparison of the conductivities is presented in Figure 2 for a density of 98 pounds per cubic foot and at a mean temperature of 70°. The two rounded sands, P4701 and P4702, gave quite similar results, but the crushed quartz was found to have conductivity values as much as 50 per cent greater for the moisture range tested. This one series of tests would indicate that grading and particle shape have a marked effect on conductivity.

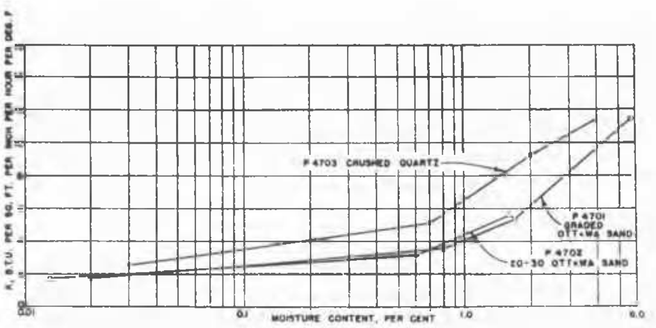
<u>Effect of Mineral Composition.</u>

To determine the variation in thermal conductivity of common soil constituents, tests were made on four crushed rocks: quartz, trap rock (basalt), potash feldspar, and granite. All four materials had approximately similar gradings. (See Table I) Figure 3 shows the test results on these materials at a density of 103 pounds per cubic foot and at a mean temperature of 70°. There is a marked difference in conductivities, particularly with respect to the quartz and the other three materials. The order and approximate ratio of magnitudes of thermal conductivity for these materials are as follows: trap rock, 1.0; granite, 1.3; feldspar, 1.4; and quartz, 2.5.

The differences found for the crushed minerals were also encountered in the tests on natural sands. For example, the thermal conductivity values for the two Northway sands, which consist largely of basalt are relatively low, whereas the Lowell sand which has a higher quartz content gives high values.

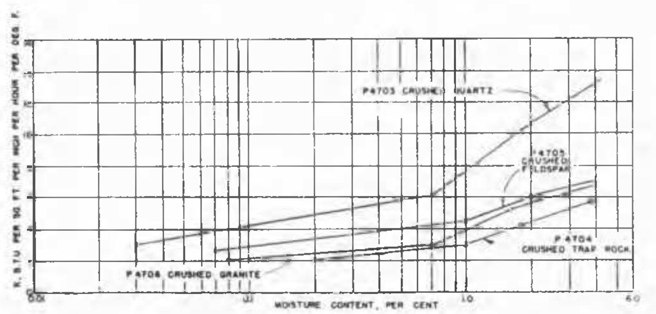
In discussing mineral composition, the results of the tests on the peat are of interest. This soil, which from appearances was almost entirely fibrous organic material, gave lower conductivity values than any other soil tested. At 9 per cent moisture content and 22 pounds per cubic foot density (the highest obtainable), the conductivity was only 0.4; no other soil gave values less than 1.0. At 300 per cent moisture content the conductivity of the peat increased to almost 4, still a relatively low value.

Some of the highest conductivities obtained thus far are for the gravel, P4601. This is due in part to the high density to which this material may be compacted. At a



Comparison of thermal conductivity of three quarts soils P 4701, P 4702 and P 4703. Density 98 lb. per c.F., mean temperature 70° F.

FIG.2



Comparison of thermal conductivity of four soil constituents P 4703, P 4704, P 4705 and P 4706. Density 103 lb. per c.F., mean temperature 70° F.

FIG.3

TABLE I

Soils Tested

Soil No.	Soil Desingation	Gravel Over 6.68 xa)	Coarse Sand o.84 to 6.68	Medium Sand 0.177 to 0.84	Fine Sand 0.05 to 0.177	Silt 0.005 to 0.05	Clay Under 0.005	Liquid Limit	Plasticity Index	Specific Gravity	Textural Class xb)
		Mechanical Analysis x)						Physical Constants			
P4502	Northway Fine Sand	0.0	0.5	43.6	53.0	3.0	0.0	—	N. P. xc)	2.76	Fine Sand
P4503	Northway Sand	1.6	5.4	86.0	7.0	0.0	0.0	—	N. P.	2.74	Med. Sand
P4505	Northway Silt Loam	0.0	1.0	2.0	19.0	64.4	13.6	27.3	N. P.	2.70	Silt Loam
P4601	Chena River Gravel	56.0	26.0	14.0	3.4	-0.6-		—	N. P.	2.70	Gravel
P4602	Fairbanks Silt Loam	0.0	0.1	0.5	7.0	80.9	11.5	34.0	N. P.	2.70	Silt Loam
P4604	Lowell Sand	0.0	14.0	80.0	6.0	0.0	0.0	—	N. P.	2.67	Med. Sand
P4701	Graded Ottawa Sand	0.0	0.0	98.3	1.6	-0.1-		—	N. P.	2.65	Med. Sand
P4702	20-30 Ottawa Sand	0.0	0.0	100.0	0.0	0.0	0.0	—	N. P.	2.65	Coarse "
P4703	Crushed Quarts	0.0	44.5	37.3	12.7	-5.5-		—	N. P.	2.65	Coarse "
P4704	Crushed Trap Rock	0.0	59.0	24.2	6.8	-10.0-		—	N. P.	2.97	Coarse "
P4705	Crushed Feld Spar	0.0	51.8	34.2	9.8	-4.2-		--	N. P.	2.56	Coarse "
P4706	Crushed Granite	0.0	47.8	32.4	13.0	-6.8-		—	N. P.	2.67	Coarse "
P4707	Fairbanks Peat	--	—	--	—	--	—	—	N. P.	—	Peat
P4708	Healy Clay	0.0	0.3	0.7	0.9	20.1	78.0	39.4	15.0	2.59	Clay

x) Aviation Engineers Method, Manual TM5-255.
xa) Size in millimeters.
xb) U. S. Bureau of Chemistry and Soils.
xc) N. P. = Non-plastic.

density of 125 pounds per cubic foot and 3 per cent moisture content, a conductivity of 17 was obtained at 70°.

CONCLUSIONS.

Thermal conductivity tests on 14 soils warrant the following conclusions:

1) The coefficient of thermal conductivity of soils above the freezing point increases with an increase in mean temperature. Values at 70° average about 5 per cent more than those at 40°;
2) In most cases the coefficient of thermal conductivity does not vary appreciably in a mean temperature range from -20 to + 25°;
3) The difference in thermal conductivity above and below the freezing point is dependent chiefly upon the moisture content of the soil. For air-dry soils there is practically no difference in the two values. At slightly higher moisture contents (2 per cent in sands, 5 to 10 per cent in fine grained soils)the conductivity is lower below freezing than above. With further increases in moisture content the conductivity of frozen soil becomes progressively greater than unfrozen. At the modified optimum moisture content the conductivity below freezing is on the average about 20 per cent greater than that above freezing;
4) At a constant density an increase in moisture content causes an increase in conductivity. On the average, the conductivity of a soil at 10 per cent moisture is more than twice that at 1 per cent;
5) At a constant moisture content an increase in density results in an increase in conductivity; the average increase is about 2½ per cent per pound per cubic foot increase in density;
6) The thermal conductivity of a given material is dependent upon its grading and particle shape as well as its density and moisture content. Tests on three materials, all pure quartz but with different gradings and particle shape, showed that at common moisture content and density an angular well-graded material had a conductivity of from 20 to 50 per cent greater than rounded, poorly-graded materials;
7) The thermal conductivity of crushed rock minerals of approximately similar gradings differ appreciably. The order of conductivities of four materials tested, from the least to the greatest, is: trap rock, granite, feldspar, and quartz; the relative magnitudes are: 1.0, 1.3, 1.4, and 2.5.

ACKNOWLEDGEMENT.

The tests were made under the supervision of the writer at the Engineering Experiment Station, University of Minnesota, Professor Frank B. Rowley, Director.

For the Corps of Engineers, St. Paul District, Mr. E.J. Evans was in charge of laboratory tests for density and moisture control, and Mr. Harry Carlson was coordinator of activities under the direction of Mr. H.J. Manger, Engineer in charge of the Permafrost Investigation, and Colonel W.K. Wilson, Jr., District Engineer.

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FOR A SYSTEMATIC STUDY OF THE PROPERTIES OF SOILS AS RELATED TO THEIR PERMANENT CHARACTERS AND TO THEIR NON-PERMANENT CHARACTERS (STRUCTURE AND MOISTURE CONTENT)

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1. INTRODUCTION.

Among the numerous factors which affect the physical and mechanical properties of soils, are be considered:

1. the permanent characters : physico-chemical composition, shapes of particles, kind of their surface, particle size distribution, etc.
2. the structure and the moisture content, supposed uniform, which are capable of free variation within certain limits.

The moisture content is easy to determine by the measure of the difference between the wet weight P_h and the dry weight P_s of a sample of soil having the apparent volume V, from which are deduced:

the specific gravity of the wet soil: $\delta_h = P_h/V$ and the specific gravity of the dry soil: $\delta_s = P_s/V$.

Hence:
$$e = \frac{P_h - P_s}{P_s} = \frac{\delta_h - \delta_s}{\delta_s}$$

The structure is much more difficult to define and even to conceive. It is relative to the arrangement of the particles and of the intersticial liquid in the soil. It is not sufficiently characterized by the measure of the real specific gravity of the soil δ_r which permits to cipher the 3 fractions c, ℓ and a of an unitarian volume occupied by the solid, the liquid and the air. This measure permits to define the value of the compacity:

$$e = \frac{\delta_s}{\delta_r}$$