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**THERMAL CONDUCTIVITY LABORATORY STUDIES
OF SOME MACKENZIE HIGHWAY SOILS**

BY

E. PENNER, G.H. JOHNSTON AND L.E. GOODRICH

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Thermal Conductivity Laboratory Studies of Some Mackenzie Highway Soils¹

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Thermal conductivities were determined for 10 fine-grained soils obtained from potential borrow pit areas along the proposed route of the Mackenzie Highway, N.W.T., and from the nearly completed section of the Mackenzie Highway, just south of Inuvik. The moisture contents and densities of the test specimens were based on the standard Proctor density curves. The measurements were made by the transient heat-flow method using a line heat source. The values were in good agreement with Kersten's data obtained by the steady-state heat flow method.

Grain-size, mineralogical analyses of the clay-size fraction, Atterberg limits, and standard Proctor density determinations are given for all 10 soils.

La conductivité thermique a été déterminée sur 10 sols à grains fins provenant, de zones d'emprunt possibles le long du tracé proposé de la route du Mackenzie, T.N.O., et d'une section presque achevée de cette route, immédiatement au sud d'Inuvik. Les teneurs en eau et densités des échantillons étaient basées sur les courbes de densité Proctor standard. Les mesures ont été faites par la méthode du flux de chaleur transitoire en utilisant une source de chaleur linéaire. Les valeurs obtenues étaient en accord avec les données de Kersten obtenues à l'aide d'une méthode à flux de chaleur en régime permanent.

La granulométrie, les analyses minéralogiques de la fraction argileuse, les limites d'Atterberg et les densités Proctor standard sont données pour les 10 sols étudiés.

[Traduit par la Revue]

An important problem of highway design over ice-rich permafrost is to estimate accurately the thickness of the embankment required to prevent thawing and the subsequent settlement that causes road unserviceability and costly maintenance. A reasonable prediction of the change in ground temperature can be made for a given location if climatic data are available and the thermal and physical properties of the road fill and underlying permafrost are known. This paper is concerned with the determination of the thermal conduc-

tivity of embankment materials that are likely to be used in the construction of the Mackenzie Valley Highway.

The investigations were initiated at the request of the Mackenzie Highway Environmental Working Group (EWG). The EWG, an inter-departmental committee of the Federal Government, was formed to review designs for the Mackenzie Highway and to assess its impact on all aspects of the environment.

Initial explorations along the proposed route for the highway indicated that coarse-grained materials, usually used for embankment construction, would not be readily available in some areas. It was considered important, there-

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fore, that the thermal behavior of the available fine-grained materials be established in order that the proposed designs could be properly evaluated.

Information on the thermal characteristics of soils is sparse; much less is known for northern soils. The Division of Building Research of the National Research Council of Canada was invited for this reason to undertake a study of the thermal conductivities of some of the fine-grained soils that might be used for the construction of the Mackenzie Highway.

It was intended, originally, that soils for the study would be taken from established borrow sites. This was not possible in most cases, but it is believed that the samples collected are representative of some large fine-grained deposits found in the Mackenzie Valley. It was not necessary to retain the natural structure, *in situ* moisture content, or temperature of the soils because these would change in any case during the construction phase.

Detailed information was not available concerning the conditions that would prevail during construction in particular areas or on the state of the material after placement, *e.g.*, time of year of construction, method of placement (in well-compacted layers or as compacted frozen lumps), and soil moisture content/density relationships. It was decided, therefore, to use the standard Proctor curves to select the sample density and associated moisture content for thermal conductivity determinations in order to give the study greater engineering significance.

Selection of Thermal Conductivity Test Method

Steady-state Method

For the steady-state method a uniform temperature gradient is applied and the sample is allowed to condition thermally until constant heat-flow conditions are attained. Kersten (1949) used this method with a ΔT of 10 F deg (5.6 C deg) across a sample 4.25 in. (10.8 cm) thick. Such conditions can induce thermally activated diffusion of water in both frozen and unfrozen unsaturated soils (Hutcheon 1958). If the sample is of finite thickness, water or ice accumulates at the cold end and drying occurs at the warm end, but the extent to which this occurs depends on the

duration and magnitude of the imposed temperature gradient, the nature of the soil, and the degree of saturation. The process is normally more unpredictable in the field than under precisely controlled laboratory conditions (Hutcheon 1958).

The ice-water ratio imposes further difficulties in thermal conductivity measurements since it is a function of temperature in fine-grained soils (Penner 1970). When samples are subjected to a temperature gradient (as in the steady-state method) the soil sample does not have a constant ice-water ratio throughout its length. Because the thermal conductivity of ice is more than four times greater than that for water, the thermal conductivity of the sample would also not be constant.

Probe Method

The use of the transient heat-flow method for determining thermal conductivities of unsaturated soils is also not without difficulties. The thermal probe or needle is the most common apparatus used in the transient heat-flow technique. The problem of induced moisture flow in an unsaturated system is similar to the steady-state method but may be more critical as the temperature gradients next to the probe can be much greater than those that usually occur in the steady-state method. Woodside (1958) suggested that increasing the diameter of the probe and using low heat inputs would reduce the thermal gradients and thus decrease the induced moisture flow. Large diameter probes are usually not sufficiently long to satisfy the requirement of a line heat source assumed for the development of the simple theory describing their behavior.

Method Employed

In recognition of the difficulties associated with the two main methods, particularly for unsaturated soils, the line heat source probe technique was considered the preferred method. The method and the probe (Fig. 1) used were similar to those used by D'Eustachio and Schreiner (1952), Woodside (1958), and Penner (1963, 1970). The temperature gradient in the vicinity of the probe was kept as small as possible by maintaining a low power input to the heater but consistent with the ability of the temperature measuring equipment to detect temperature changes in the

FIG. 1. Schematic diagram of thermal probe (courtesy Custom Scientific Instruments, Inc.).

probe with acceptable limits of accuracy. An advantage of the probe method, compared with the steady-state method, is that the thermal conductivity determination is of short duration. This is a time-saving feature which also reduces the time that the sample is subjected to thermal gradients — the cause of thermally activated diffusion. In general the apparatus is less expensive than steady-state equipment and is simpler to operate.

The line heat source was a hollow probe,² 8.375 in. (21.27 cm) long, with an outside diameter of 0.02 in. (0.051 cm). It contains a uniformly spaced spiral heating coil with a nominal electrical resistance of about 1600 ohms. A constantan–chromel P thermocouple is located inside the spiral heater halfway along the probe. Some of the probe thermocouples were calibrated by the Division of Physics, National Research Council of Canada. Probes acquired more recently were calibrated by comparing them at several temperatures with those previously calibrated. A further calibration check was made later in the study using a calibrated platinum resistance thermometer and a G2 Mueller bridge with a temperature measuring capability of ± 0.001 C deg.

Power to the probe was supplied with an electronically controlled constant current source. Current constancy was checked by continuously monitoring the voltage across the heater terminals. The voltage output of the probe thermocouple, referenced to an ice bath, was mea-

sured at 20 to 30 s intervals with a multipoint data acquisition system. The signal was pre-amplified by a factor of 100 to obtain greater precision in voltage measurements.

The level of power supplied to the probe heater depended on the thermal conductivity of the soil. For low thermal conductivity samples it was as low as 0.72 W/m;³ for high conductivities it was never greater than about 1.7 W/m. The power supply had to be maintained at a level sufficiently high to give temperature changes that could be measured with reasonable precision and accuracy. A probe temperature change of about 0.06 C deg during the conductivity determination was considered to be the lowest acceptable for satisfactory accuracy. Later in the study an improved signal amplifier was acquired that permitted the temperature rise of the probe to be reduced to 0.024 C deg.

Conductivity was calculated from the temperature rise of the probe using the following equation:

$$[1] \quad k = \frac{Q}{4\pi\Delta T} (\ln t_2/t_1) = \frac{Q}{4\pi} \cdot \text{slope}$$

where t_2 and t_1 are the times corresponding to the probe temperature change ΔT and Q is the power input. Plotting the change in temperature against the logarithm of the time gives a straight-line relationship. The initial temperature rise in the period from 0 to 2 min was not used in the thermal conductivity calculation because the $\ln$ time temperature plot

²The probe shown in Fig. 1 was obtained from Custom Scientific Instruments Inc., N.J., U.S.A.

³Watts per metre.

FIG. 2. Grain-size analysis of soils.

is not linear immediately after the power is turned on.

The computer was used to determine the least squares fit to the $\ln t$ versus temperature measurement, the standard error (S.E.) of measurement, the probe temperatures from the e.m.f. - temperature equations, and the thermal conductivity, k . Pertinent information such as current, power supply per unit length of probe, and standard error in the slope of the linear fit to the measurements are given in tabular form along with the thermal conductivity results.

Material

Soil Sampling

Samples were obtained in late May 1973 at three locations on the newly completed section of the Mackenzie Highway just south of Inuvik, N.W.T. Soil No. 1 was taken from a highway cut at Station 1073 + 00, mile 944; No. 2 from Borrow Pit No. 7, Station 654 + 00, mile 951.5; and No. 3 from the south shoulder of the highway at Station 339 + 00, mile 957.5. In early July 1973, sample No. 4 was obtained from Norman Wells, N.W.T., Nos. 5, 6, and 7 from the Mackenzie Highway 'Training Section' at the Lake of Two Mountains, N.W.T., and Nos.

8, 9, and 10 from the Mackenzie Highway north of Fort Simpson, N.W.T.

Soil Tests

Grain-size Analyses

Hydrometer and sieve analyses (where required) were carried out according to standard Division of Building Research methods which closely follow A.S.T.M. procedures. Sodium metaphosphate was the dispersant and samples were soaked overnight because of previous air drying. Difficulties were encountered in making grain-size analysis for soil No. 3, as it consisted of a poorly cemented friable sandstone. It was not possible to achieve complete breakdown of the material and because of this the hydrometer part of the combined analysis given for this material is not considered to be particularly reliable. Grain-size distribution curves for the 10 soils are given in Fig. 2.

Atterberg Limits

The limits are given in Table 1 for soils Nos. 4 to 10; soils Nos. 1, 2, and 3 were too coarse to give meaningful limits.

Mineralogy of Clay-size Fraction

Samples of the clay-size fraction (<0.002 mm) were separated by sedimentation using Na_2CO_3 as the dispersant. Exchange sites on

TABLE 1. Atterberg limits

Soil No.	Liquid limit at 25 blows, W_L (% MC)	Plastic limit, W_p (% MC)	Plasticity index, I_p (% MC)
1	—	—	No plasticity index
2	—	—	No plasticity index
3	—	—	No plasticity index
4	37	21	16
5	25	18	7
6	30	21	9
7	28	14	14
8	43	24	18
9	33	22	11
10	48	23	25

the clays were saturated with Mg^{++} ions by flocculation with $MgCl_2$ solution followed by washing in the centrifuge to remove excess salts. X-ray diffraction analyses were carried out on oriented samples by allowing a suspension of the clay to dry slowly on a glass slide.

A standard procedure involving four series of diffractograms was followed in the X-ray analyses of the oriented specimens. In the initial series the specimens were X-rayed at a high relative humidity. For the second series the specimens were saturated with a 50/50 glycerol-water mixture and again X-rayed after overnight soaking. For the third series the specimens were heated to 300 °C for an hour in a muffle furnace, cooled, and X-rayed. In the last of the series, samples were reheated to 600 °C for 1 h and again X-rayed on the diffractometer.

Mineralogical analyses were not made on a quantitative basis. Table 2 was prepared, however, to indicate the relative amounts of each mineral species identified.

Compaction

Standard Proctor moisture content/density curves were determined to relate the thermal conductivity values to some standard and recognized engineering test. In addition, the curves provided a method of estimating the moisture content on the dry side of optimum, which aided the selection of moisture content and density for measurements. The unsaturated condition was considered to be the moisture condition that would actually prevail in the constructed road. Figure 3 gives the relationship between moisture content and wet and dry density for all 10 soils.

Thermal Conductivity Determinations

Sample Preparations

The thermal conductivity for each of the 10 soils was determined (with apparatus shown in Fig. 4) at three moisture content/density conditions selected from the Proctor compaction curves. The lowest moisture content for all soils was about 5% by weight; the second was selected about one-half way up the dry side of the Proctor compaction curve; the third moisture content was just short of optimum. These three density and moisture content samples will be referred to as samples 1, 2, and 3 respectively for each soil.

The moisture content of the samples was established by adding the appropriate amount of water as a fine spray and mixing. They were then stored in plastic bags for several weeks in a constant temperature, high relative humidity chamber to attain moisture uniformity.

Samples for the conductivity measurements were prepared in molds using the same compactive effort per unit area of the container

TABLE 2. Relative proportions of minerals in the <0.002 mm size fraction

Soil	Quartz	Illite	Chlorite	Kaolinite	Vermiculite
1	+	+	+	+	—
2	++	++	+	++	—
3	+++	++	—	++	+
4	+++	++	++	++	—
5	+	+	—	—	—
6	+	+	+	+	—
7	++	++	+	++	—
8	+++	+++	++	+	—
9	+++	+++	+	+	—
10	+++	+++	++	++	—

NOTE: + + +, large amount present; + +, moderate amount present; +, small amount present.

FIG. 3. Standard Proctor compaction determinations.

and the same soil layer thickness as in the standard Proctor procedure. The sample molds were PVC pipes (Figs. 5 and 6) 12 in. (30.48 cm) high and 5.7 in. (14.48 cm) in diameter with a 0.5 in. (1.27 cm) wall thickness. The diameter of the mold was shown (by calculation) to be large enough so that no temperature rise was experienced at the outer edge of the sample during the 15 min thermal conductivity determination.

To facilitate insertion of the thermal conductivity probe after the samples had been prepared, a stainless steel wire was tightly held along the center line of the mold between a clamp at the bottom and a rotatable brass yoke at the top during sample preparation. The yoke

was rotated between successive blows during compaction to ensure a uniform density throughout the sample. The sample was built up in layers in this way until it was higher than the length of the thermal conductivity probe. A layer of molten petroleum wax was poured on top of the sample to prevent moisture loss. As indicated earlier, three samples of different density and moisture content were prepared in this way for all soils.

Probe Insertion

The thermal probes were coated with a silicon grease and inserted into the sample from the top as the stainless steel wire was withdrawn from the bottom of the mold (Fig. 5). The

FIG. 4. Apparatus used in thermal conductivity measurements. (1) Constant temperature chamber. (2) Hewlett Packard data logger. (3) Mueller temperature bridge. (4) Galvanometer (Mueller bridge). (5) K_2 universal potentiometer. (6) Galvanometer (K_2). (7) Power source (Mueller bridge). (8) Constant current source (thermal conductivity probes). (9) Ice bath (reference junctions).

FIG. 5. Soil sample mold.

FIG. 6. Sample mold for specimen preparation. (1) PVC sample mold. (2) Wire centering yoke. (3) Stainless steel wire.

hole in the bottom was sealed with wax or grease after the wire had been removed. After waxing the plastic terminal block to fix it in position, the sample and assembly were placed in a constant temperature chamber for conditioning.

Sample Conditioning

All three samples of each soil, after preparation in the molds, were placed in the constant temperature chamber and conditioned to a pre-selected temperature. The samples were insulated at both ends so that thermal conditioning would be attained by radial heat flow. The chamber temperature variation was within ± 0.03 C deg but the variation inside the specimen was less because of the thermal lag caused by the mold wall.

Thermal conductivities were measured at three nominal temperatures, 5, -5 , and -15 °C. It required 24 to 36 h to bring the samples from room temperature to $+5$ °C, about 48 h

FIG. 7. Temperature change, ΔT , in time relationship.

from 5 to -5 °C, and a further 24 to 36 h from -5 to -15 °C. The longer period between 5 and -5 °C was due to the latent heat release during the freezing process.

Density and Moisture Content

The moisture content of each of the samples was determined during preparation by sampling the bagged soil in two or three different places. The wet density was determined from the volume of soil in the mold and the weight of the wet sample after the thermal conductivity runs had been completed.

Results

Figure 7 presents the temperature increase measured at 30 s intervals, during a thermal conductivity run for sample 1, soil 1, at a temperature of -15 °C. The S.E. of the slope, $\pm 0.65\%$, is close to the average for all the determinations. It should be emphasized that the S.E. applies only to the slope of the line through the time-temperature measurements. It does not indicate the overall accuracy with which the thermal conductivity, k , has been determined, which at present cannot be evaluated for unsaturated soils. Of the 90 runs, six had S.E. values in excess of 2%; the lowest S.E. was 0.17%.

The conductivity results for all soils are given in Table 3, along with the relevant soil proper-

TABLE 3. Summary of thermal conductivity and related parameters

Soil	Sample	Saturation (%)	Dry density (lb/ft ³)	Wet density (lb/ft ³)	W_n (%)	Current (mA)	Power (W/m)	K (W/m K)	S.E. of slope (%)	Temperature of soil (°C)	
										Nominal	Actual
1	1	25.6	103.4	109.9	6.10	10	0.756	1.114	± 0.62	+5	4.56
	2	56.6	111.7	123.8	10.79	12	1.113	1.709	± 1.57		4.51
	3	83.2	117.9	134.1	13.74	13	1.279	1.782	± 0.77		4.51
	1		103.5	109.9	6.10	10	0.760	0.917	± 0.46		-5.78
	2		111.7	123.8	10.79	11	0.936	1.853	± 1.18	-5	-5.81
	3		117.9	134.1	13.74	13	1.287	2.540	± 0.87		-5.76
	1		103.5	109.9	6.10	10	0.761	0.973	± 0.65		-15.30
	2		111.7	123.8	10.79	11	0.937	1.766	± 1.23	-15	-15.37
	3		117.9	134.1	13.74	13	1.289	2.407	± 1.22		-15.33
	1	28.9	108.3	114.8	6.09	10	0.753	1.348	± 1.49		4.73
	2	69.1	120.1	133.0	10.73	12	1.089	2.533	± 1.37	+5	4.79
	3	84.8	120.3	136.1	13.10	13	1.212	2.277	± 0.88		4.72
2	1		108.3	114.8	6.09	12	1.093	1.129	± 0.56		-5.29
	2		120.1	133.0	10.73	13	1.285	2.516	± 1.47	-5	-5.23
	3		120.3	136.0	13.10	15	1.614	2.728	± 1.20		-5.27
	1		108.3	114.8	6.09	12	1.094	1.207	± 0.68		-15.50
	2		120.1	133.0	10.73	13	1.288	2.923	± 1.33	-15	-15.43
	3		120.3	136.0	13.10	15	1.616	2.838	± 0.98		-15.48
	1	18.4	106.7	111.0	4.04	11.1	0.880	0.882	± 0.39		4.84
	2	36.0	113.0	120.6	6.72	11.1	0.933	1.953	± 0.86	+5	4.92
	3	71.5	123.0	135.6	10.17	No satisfactory determinations					4.93
	1		106.7	111.0	4.04	11	0.867	0.998	± 0.75		-5.14
	2		113.0	120.6	6.72	12	1.093	2.420	± 1.67	-5	-4.94
	3		123.0	135.6	10.17	14.1	1.526	3.042	± 1.06		-4.91
3	1		106.7	111.0	4.04	11	0.867	1.042	± 0.86		-15.85
	2		113.0	120.6	6.72	12	1.094	2.357	± 0.90	-15	-15.68
	3		123.0	135.6	10.17	14	1.516	2.745	± 1.34		-15.40
	1	18.4	106.7	111.0	4.04	11	0.866	0.908	± 0.58	+5	5.07
	2	36.0	113.0	120.6	6.72	12	1.089	1.895	± 0.66		4.98
	1	23.3	100.6	106.6	5.96	12	1.090	0.707	± 0.45		4.99
	2	45.8	106.5	117.3	10.16	12	1.096	0.818	± 0.90	+5	5.01
	3	82.8	111.5	129.5	16.12	12	1.097	2.273	± 1.56		5.62
	1		100.6	106.6	5.96	12	1.095	0.782	± 0.35		-5.12
	2		106.5	117.3	10.16	10	0.762	1.815	± 4.21	-5	-5.23
	3		111.5	130.0	16.12	12	1.096	2.741	± 1.19		-5.03
	1		100.6	106.6	5.96	10	0.761	0.770	± 0.70		-15.54
	2		106.5	117.3	10.16	11	0.923	1.610	± 1.15	-15	-15.40
	3		111.5	130.0	16.12	12	1.098	2.906	± 1.12		-15.90

TABLE 3. (Continued)

5	1	21.2	105.8	110.9	4.80	12	1.093	1.015	± 0.48	+5	5.09
	2	48.6	113.5	123.7	8.97	13	1.285	1.187	± 0.57		5.13
	3	76.7	115.9	131.4	13.33	14	1.514	1.496	± 0.61		5.22
	1		105.8	110.9	4.80	12	1.089	0.987	± 0.41	-5	-5.07
	2		113.5	123.7	8.97	13	1.288	1.316	± 0.44		-5.05
	3		115.9	131.4	13.33	14	1.515	2.367	± 1.19		-4.90
	1		105.8	110.9	4.80	12	1.096	0.937	± 0.38	-15	-15.12
	2		113.5	123.7	8.97	14	1.496	1.647	± 0.52		-15.11
	3		115.9	131.4	13.33	15	1.743	2.213	± 0.66		-14.94
6	1	26.6	102.5	109.2	6.50	12	1.113	0.853	± 0.55	+5	4.96
	2	55.8	110.4	122.7	11.20	13	1.287	1.012	± 1.03		4.93
	3	79.3	114.0	130.5	14.46	14	1.489	1.898	± 0.61		4.96
	1		102.5	109.2	6.50	12	1.113	0.840	± 0.33	-5	-5.27
	2		110.4	122.7	11.20	13	1.287	1.530	± 0.68		-5.29
	3		114.0	130.5	14.46	14	1.489	2.268	± 0.82		-5.20
	1		102.5	109.2	6.50	12	1.115	0.847	± 0.40	-15	-16.75
	2		110.4	122.7	11.20	13	1.289	1.659	± 1.22		-16.82
	3		114.0	130.5	14.46	15	1.712	2.239	± 0.64		-16.75
7	1	32.8	123.2	128.9	4.65	11	0.933	1.358	± 0.76	+5	4.89
	2	73.7	129.5	141.0	8.52	14	1.515	1.792	± 0.75		5.17
	3	91.8	122.5	138.8	13.30	14	1.486	2.218	± 0.74		5.07
	1		123.2	128.9	4.65	12	1.112	1.168	± 0.42	-5	-5.01
	2		129.5	141.0	8.52	14	1.515	1.877	± 2.34		-5.08
	3		122.5	138.8	13.30	14	1.489	2.581	± 1.19		-5.22
	1		123.2	128.9	4.65	12	1.112	1.257	± 0.59	-15	-15.79
	2		129.5	141.0	8.52	15	1.739	2.418	± 0.96		-15.55
	3		122.5	138.8	13.30	15	1.710	2.750	± 1.26		-15.74
8	1	15.7	86.6	91.4	5.60	12	1.113	0.380	± 0.32	+5	4.33
	2	53.7	97.8	112.1	14.66	12	1.033	0.919	± 0.55		4.29
	3	70.1	97.6	116.4	19.23	12	1.094	1.378	± 1.30		4.23
	1		86.6	91.4	5.60	12	1.113	0.361	± 0.24	-5	-5.93
	2		97.8	112.1	14.66	12	1.033	0.948	± 1.05		-6.04
	3		97.6	116.4	19.23	12	1.094	1.660	± 0.74		-6.04
	1		86.6	91.4	5.60	12	1.113	0.371	± 0.17	-15	-14.97
	2		97.8	112.1	14.66	14	1.406	1.074	± 1.01		-15.16
	3		97.6	116.4	19.23	14	1.489	1.748	± 1.39		-15.16

TABLE 3. (Concluded)

Soil	Sample	Saturation (%)	Dry density (lb/ft ³)	Wet density (lb/ft ³)	W_n (%)	Current (mA)	Power (W/m)	K (W/m K)	S.E. of slope (%)	Temperature of soil (°C)	
										Nominal	Actual
9	1	18.9	89.3	94.9	6.31	10	0.773	0.507	± 2.49	+5	4.90
	2	39.8	94.3	105.4	11.84	10	0.717	0.849	± 7.46		4.90
	3	72.2	102.2	120.3	17.79	10	0.762	1.430	± 7.01		4.94
	1		89.3	94.9	6.31	12	1.114	0.511	± 0.65	-5	-6.38
	2		94.3	105.4	11.84	12	1.033	0.982	± 0.98		-6.40
	3		102.2	120.3	17.79	15	1.714	1.591	± 1.43		-6.29
	1		89.3	94.9	6.31	12	1.113	0.498	± 0.28	-15	-14.72
	2		94.3	105.4	11.84	12	1.033	1.075	± 0.92		-14.78
	3		102.2	120.3	17.79	12	1.095	2.094	± 1.70		-14.67
10	1	20.3	87.4	93.6	7.08	10	0.762	0.504	± 1.19	+5	4.23
	2	38.2	91.2	102.3	12.21	10	0.744	0.683	± 1.40		4.22
	3	53.1	93.1	108.2	16.23	10	0.717	0.818	± 1.85		4.24
	4	80.7	101.7	122.2	20.11	11	0.915	1.400	± 0.98		4.93
	1		87.4	93.6	7.08	12	1.100	0.497	± 1.38	-5	-5.89
	2		91.2	102.3	12.21	10	0.774	0.743	± 1.19		-5.90
	3		93.1	108.2	16.23	12	1.033	0.984	± 1.93		-5.81
	4		101.7	122.2	20.11	12	1.093	1.901	± 1.07		-4.70
	1		87.4	93.6	7.08	10	0.761	0.483	± 1.31	-25	-25.87
	2		91.2	102.3	12.21	11.2	0.777	0.750	± 1.49		-25.40
	3		93.1	108.2	16.23	10	0.717	1.196	± 2.74		-25.89
	4		101.7	122.2	20.11	12	1.095	1.948	± 1.06		-15.78

FIG. 8. Temperature - thermal conductivity relationship for soil No. 1.

FIG. 9. Temperature - thermal conductivity relationship for soil No. 8.

ties. Power input, S.E. of the slope, and initial soil temperature are also listed.

The thermal conductivity of soil No. 1 at the various densities and moisture contents for the three nominal temperatures, 5, -5, and -15 °C, are shown in Fig. 8. In general, the same pattern characterized most of the soils but there were differences. Most of these differences, however, appear to be consistent with the probable effect of soil-water-ice interactions on thermal conductivity.

Most soils (Nos. 1, 2, 5-8, and 10) showed a lower thermal conductivity in the frozen state at the lowest moisture content. The reduction is believed to be due to the location of the ice within the soil matrix. Before freezing, water forms a bridge between soil particles due to surface tension and provides an effective path for heat conduction. During freezing, some of the bridge water is removed. The ice crystals are thought to partially fill the voids between

soil particles; the wide conductivity path between particles is removed during the phase change.

At high moisture contents and densities (greater degree of saturation) the samples showed increased conductivities in the frozen state, probably because the ice now fills the pores more completely. As ice has a higher thermal conductivity than water this leads to an overall increase in k .

Soil No. 1 (Fig. 8) is a coarse-grained soil, 25% clay size, 33% silt size, 25% sand, and 17% in the gravel size range. It would be expected to have much less unfrozen water at below-zero temperatures than a soil, such as No. 8, with 54% clay size and 46% silt. Figure 9 gives the thermal conductivity values for all densities and moisture contents at the three temperatures of soil No. 8. Again, the decrease in conductivity is noted at the low moisture content, when the soil water is frozen. The important difference between these two soils is that at the higher moisture contents (samples 2 and 3) the conductivity increases as the temperature is lowered from -5 to -15 °C because of the corresponding increase in the ice-water ratio. The same applies to soil No. 10 whose thermal conductivity values are shown in Fig. 10.

It should be noted that it is *not permissible*

FIG. 10. Temperature - thermal conductivity relationship for soil No. 10.

FIG. 11. Ratio of k_2/k_1 and k_3/k_1 as a function of saturation percentage for soil No. 8.

to interpolate values of thermal conductivity between 5 and -5°C because of the ice-water phase change at the freezing point. The dashed lines in Figs. 8, 9, and 10, connecting the points, are drawn merely for the sake of clarity. Thermal conductivities of soil in the unfrozen state do not increase by more than about 0.17% per degree Centigrade as the temperature is lowered based on the conductivity of the soil solids. Interpolation is probably permissible between -5 and -15°C , but not necessarily in the straight-line fashion indicated in the graphs by the dashed lines. The increase of thermal conductivity in the frozen state for clay soil has been studied previously for the saturated state (Penner 1970).

The thermal conductivity change in unsaturated soil after freezing is clearly shown in Fig. 11 for soil No. 8. The ratios plotted, k_2/k_1 and k_3/k_1 , where k_1 is the unfrozen thermal conductivity at 5°C , k_2 at -5°C , and k_3 at -15°C , are less than 1 at the low saturation level but increase to greater than 1 at the higher level of saturation. It may be noted also that the ratio k_3/k_1 is greater than k_2/k_1 for all saturation levels. Although the relationships were not nearly as clear-cut for all soils, in general, the pattern was the same.

Some years ago, Kersten (1949) published graphs showing lines of constant thermal conductivity on a plot of moisture content and soil dry density. These graphs have been widely used in practice to obtain values of thermal conductivity for heat-flow studies in the field. Kersten stated that conductivities estimated from such graphs were reliable to within $\pm 25\%$. Figures 12 and 13 show the values for the eight fine-grained soils of the Mackenzie Highway plotted on the appropriate Kersten graphs. Both the frozen and unfrozen conductivity values fall essentially within $\pm 25\%$ of Kersten's values and in most cases the agreement is much better. It would appear, therefore, that although the absolute accuracy of Kersten's values (or of the present data) has not been established, there is a reasonable agreement between the two studies. Kersten's conductivity values were determined at 40°F (4.4°C) and 25°F (-3.9°C). The values from the present study used for the comparison were for approximately 5°C and -5°C .

Reproducibility of Sample Preparation and Thermal Conductivity

Time restrictions during the main part of the project did not permit adequate checks to be made on the reproducibility of sample preparation and the thermal characteristics of the various probes used. Such a study was carried out using soils Nos. 1, 9, and 10 (Fig. 2) with the main emphasis on a comparison of the probes and the influence of the level of power input on the thermal conductivity determination.

Equipment and sample preparation techniques were the same as those already described. An improved signal preamplifier was used, however, when more precise temperature measurements were required for power inputs lower than those applied during the main study. The lowest heater power inputs used in the main study were in excess of 0.72 W/m ; in the reproducibility experiments described here the lowest power inputs were as low as 0.374 W/m giving a temperature rise of 0.024°C deg in the usual 2 to 15 min interval. The results of the reproducibility experiments are given in Tables 4, 5, and 6.

Moisture contents and wet and dry densities are included in each table. Little difficulty was

FIG. 12. Thermal conductivity, k , of unsaturated fine-grained Mackenzie Valley soils (unfrozen).

encountered in obtaining similar densities with the same compactive effort. The largest density difference occurred in soil No. 10 (Table 4) for which the difference between the highest and lowest wet density was 0.55 lb/ft^3 (0.009 g/cm^3). These differences, although usually considered rather small, could not be statistically assessed since only one sample was prepared for each probe for each particular soil.

Table 4 gives comparisons of thermal conductivity determined with two probes at the same power input and at temperatures of approximately 5 , -5 , and -15°C . The standard deviations of three repeats at 5°C , five at -5°C , and four at -15°C are given for each average thermal conductivity value. Consider-

ing all 12 conductivity runs for both probes, no statistical differences were found to exist at the 5% probability level.

Table 5 gives conductivities determined at the same temperature but with different power inputs ranging from 0.374 to 1.496 W/m , a factor of four. There was no statistical difference between readings at the 5% probability level for these tests.

Table 6 gives the results of different power inputs at various temperatures; again, on the basis of paired comparisons at the 5% probability level, no significant differences could be detected between the probes for the temperatures involved.

It may be concluded that the reproducibility

FIG. 13. Thermal conductivity, k , of unsaturated fine-grained Mackenzie Valley soils (frozen).

TABLE 4. Comparison of thermal conductivity measurements—soil No. 9 (No. of samples: 2, similarly prepared; soil temp.: differing; power input: constant; No. of probes: 2)

Starting temp. ($^{\circ}\text{C}$)	Approx. probe temp. rise ($^{\circ}\text{C}$)	No. of runs	Power input (W/m)	Thermal conductivity (W/m K)	
				Probe 6, sample 1	Probe 7, sample 2
5.04 to 5.10	0.074	3	0.763–0.765	1.656 ± 0.020	1.610 ± 0.020
–4.63 to –4.68	0.055	5	0.763–0.765	2.188 ± 0.010	2.202 ± 0.031
–14.13 to –14.21	0.053	4	0.764–0.766	2.295 ± 0.020	2.277 ± 0.037
Total 12				av. 2.046*	av. 2.030*
Moisture content (%)				19.66	19.49
Dry density, γ_d (lb/ft 3)				106.89	106.70
Wet density, γ_w (lb/ft 3)				127.90	127.85

*No statistical difference at the 5% probability could be found between averages of probes 6 and 7 in samples Nos. 1 and 2 of soil 9.

TABLE 5. Comparison of thermal conductivity measurements—soil No. 10 (No. of samples: 3, similarly prepared; soil temp.: constant; power input: differing; No. of probes: 3)

Starting temp. (°C)	Approx. probe temp. rise (°C)	No. of runs	Power input (W/m)	Thermal conductivity (W/m K)		
				Probe 4, sample 1	Probe 6, sample 2	Probe 7, sample 3
4.72 to 4.74	0.073	2	0.370-0.374	0.856 ± 0.034	0.883 ± 0.036	0.850 ± 0.018
4.71 to 4.81	0.135	5	0.759-0.764	0.905 ± 0.017	0.900 ± 0.014	0.872 ± 0.018
4.75 to 5.01	0.265	2	1.491-1.496	0.908 ± 0.004	0.883 ± 0.004	0.864 ± 0.009
Total 9				av. 0.889*	av. 0.889*	av. 0.862*
Moisture content (%)				13.17	13.29	13.21
Dry density, γ_d (lb/ft ³)				99.66	100.94	99.67
Wet density, γ_w (lb/ft ³)				112.78	114.33	112.84

*No statistical difference at the 5% probability level could be found between averages of probes 4, 6, and 7 for samples Nos. 1, 2, and 3, soil No. 10.

TABLE 6. Comparison of thermal conductivity measurements—soil No. 1 (No. of samples: 2, similarly prepared; soil temp.: differing; power input: differing; No. of probes: 2)

Starting temp. (°C)	Approx. probe temp. rise (°C)	No. of runs	Power input (W/m)	Thermal conductivity (W/m K)	
				Probe 6, sample 1	Probe 7, sample 2
5.03 to 5.07	0.030	5	0.374–0.375	2.010 ± 0.023	1.974 ± 0.011
5.05 to 5.08	0.103	2	1.292–1.294	1.994 ± 0.011	1.962 ± 0.006
–4.72 to –4.77	0.024	3	0.374–0.375	2.512 ± 0.020	2.460 ± 0.006
–4.72 to –4.77	0.060	2	0.923–0.926	2.516 ± 0.005	2.450 ± 0.025
–4.77 to –4.78	0.086	3	1.293–1.295	2.379 ± 0.030	2.430 ± 0.040
Total 15				av. 2.282*	av. 2.255*
Moisture content (%)				16.31	16.37
Dry density, γ_d (lb/ft ³)				109.95	110.10
Wet density, γ_w (lb/ft ³)				127.88	128.10

*No statistical difference at the 5% probability level could be found between averages of probes 6 and 7 in samples 1 and 2 of soil No. 1.

with respect to sample preparation was good and that the probes could be interchanged without introducing unreasonable experimental errors. Differences resulting from the level of power input to the probe heater within the range studied did not significantly alter the conductivity values at the 5% level.

The thermal conductivities in the main study were determined at the lowest power input possible that would still result in reliable temperature readings. The results of the reproducibility trials indicated that the power level used did not introduce statistically significant errors.

Discussion

The agreement between the thermal conductivity values determined by the probe method and those determined by Kersten with the steady-state method is encouraging. The authors believe that the reliability of thermal conductivity values available in the literature (mostly derived from Kersten's study) has been enhanced by the agreement shown.

Mass transfer associated with heat transfer remains a problem, for the unsaturated case, that cannot be readily evaluated under the laboratory test conditions described here or in the case of the steady-state method. Although heat transfer by conduction should be independent of temperature gradient, that associated with vapor transfer is greatly dependent on this gradient. The continually changing gradients that occur in nature are seldom the same as

those imposed in the measurement of thermal conductivity. Caution should be exercised, therefore, when using laboratory determined values for unsaturated soils under field conditions.

Sample uniformity, rather easily achieved in the laboratory, seldom occurs in nature. In ice-rich permafrost even greater heterogeneity may exist because of nonuniform ice distribution. The authors consider that comparisons of field thermal conductivities with laboratory measured values could be a useful study.

Conclusions

Since sample densities were fairly reproducible, it could be shown that the use of different probes did not introduce significant errors in the measured conductivities. Similarly, power input did not appear to be a critical factor in the range from 0.370 to 1.490 W/m.

These studies, although covering only a fairly narrow range of soils, show that at low values of moisture contents, the thermal conductivity for seven of the soils was less in the frozen state than in the unfrozen state. This was reversed at higher moisture contents. The factors that determine the moisture content at which this 'change-over' occurs have not been established.

There are no unusual features about the thermal conductivity data determined in this study. The influence of moisture content and density of the soil and ice content were consistent with anticipated behavior.

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