SUB-SECTION II g

MISCELLANEOUS

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SPECIFIC HEAT TESTS ON SOILS

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SUMMARY

A method is described in detail for making specific heat tests on soils. The results of tests on twelve soils are presented and the following relationships found:
1) The specific heats of a veriety of soils are approximately equal.
2) The specific heat of soils vary with temperature.
3) The specific heat of soil-water mixtures may be computed by proportion.

INTRODUCTION.

As a part of a research program for determining the thermal properties of soils being conducted at the University of Minnesota by the Engineering Experiment Station under a contract with the Corps of Engineers, Department of the Army, a series of specific heat tests have been conducted on a number of different types of soils. These and additional tests are being made to aid in the interpretation of soil temperature data being collected in regions of permafrost and to furnish constants needed in the design of structures to be built in such areas. The results should be of interest to anyone concerned with problems of heat flow in soils.

The specific heat of a substance is the ratio of its thermal capacity to that of water.

SOILS TESTED.

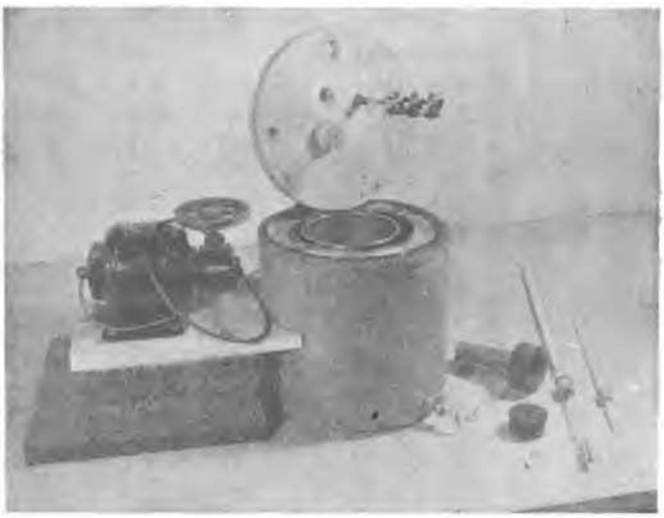
Twelve different soils have been tested; the grading and other physical characteristics are listed in Table I. The soils may be divided into three groups. Four are gravelly or sandy materials; Soils P4502 and P4503 are sands from Northway Airfield in Alaska and are composed largely of basalt or fine grained gabbro; Soil P4601 is a gravel from the Chena River at Fairbanks, Alaska, and Soil P4604 is a siliceous sand derived from a glacial outwash deposit at Lowell, Massachusetts. Two of the soils, P4505 and P4602, are silt loams from Alaska; the other six soils are minerals or crushed rocks. P4601 and P4602 are Ottawa Sands (quartz) from Illinois, P4603 a quartz from South Dakota, P4604 a trap rock (basalt) from Wisconsin, P4605 a potash feldspar from South Dakota, and P4606 a Minnesota granite.

TEST EQUIPMENT AND PROCEDURES.

It was desired to conduct the specific heat tests by as simple a method as possible and to use readily available laboratory equipment rather than to construct special apparatus. Essentially, the apparatus consisted of the following:
1) A copper calorimeter, equipped with an electrically driven stirrer;
2) Thermometers, one calibrated to 0.02° C;
3) Small metal dippers, about 1¾ inches in diameter by 6 inches in depth, with tight rubber stoppers;
4) A steam bath;
5) Two temperature controlled water and alcohol baths, one at approximately 130° F, and

Steam bath and calorimeter for specific heat tests.

FIG. 1



Calorimeter with top off. soil dipper at right.

FIG. 2

TABLE I

Soils Tested

Soil No.	Soil Designation	Mechanical Analysis x) Gravel Over 6.68 xa)	Course Sand 0.84 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	Physical Constants Liquid Limit	Plasticity Index	Specific Gravity	Textural Class xb)
P4502	Northway Fine Sand	0.0	0.5	43.5	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	Medium 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	Medium Sand
P4701	Graded Ottawa Sand	0.0	0.0	98.3	1.6	-0.1-		—	N.P.	2.65	Medium Sand
P4702	20-30 Ottawa Sand	0.0	0.0	100.0	0.0	0.0	0.0	—	N.P.	2.65	Coarse Sand
P4703	Crushed Quartz	0.0	44.5	37.3	12.7	-5.5-		—	N.P.	2.65	Coarse Sand
P4704	Crushed Trap Rock	0.0	59.0	24.2	6.8	-10.0-		—	N.P.	2.97	Coarse Sand
P4705	Crushed Feldspar	0.0	51.8	34.2	9.8	-4.2-		—	N.P.	2.56	Coarse Sand
P4706	Crushed Granite	0.0	47.8	32.4	13.0	-6.8-		—	N.P.	2.67	Coarse Sand

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

one at approximately -40° F;
6) Miscellaneous scales, ovens, etc.

Figures 1 and 2 illustrate some of the apparatus. The calorimeter had a capacity of about 2,500 mls. The jacket consisted mainly of a compartment filled with water and insulated on the outside; the cover was made of ¾-inch plywood.

Several different variations of test procedure were used for different parts of the test program. Essentially, all methods were similar; the basic scheme was as follows:

The soil to be tested was first oven-dried at 220° F and cooled to room temperature in a dessicator. A known weight of water was placed in the calorimeter and its temperature measured. A known weight of soil in a dipper was heated (or cooled) in a bath to a temperature different from that of the water in the calorimeter and was then suddenly taken from its bath and poured into the water in the calorimeter. The temperature change of the water was noted and, by a series of heat balance calculations, the specific heat of the soil was determined.

In order to obtain specific heat values for different mean temperatures, the soil was brought to different temperatures before being poured into the calorimeter, which was ordinarily such that the final temperature would be close to room temperature. Heating the soil in a steam bath at about 212° F gave a resultant mean temperature of test of about 140°. The 130°-bath gave a mean temperature of approximately 100°; the -40°-bath, about 15°. Soils at room temperature added to water below room temperature gave a mean of about 65°.

It was recognized at the start of the specific heat tests that the results would be affected by the heat of wetting of the soils. If a dry soil at a given temperature is placed into water having the same temperature, heat is evolved and causes a rise in temperature. This value must be known in order to calculate the true specific heat. The method of determining the heat of wetting of the soils was about the same as for the specific heat determination, except that the temperature of the dry soil sample was made to conform as closely as possible to that of the water in the calorimeter. Upon the addition of the soil to the water, the rise in temperature was noted. Any change not accounted for by a cooling of the soil (the soil was occasionally a degree or so different from that of the water) was the result of the heat of wetting.

The calculation of the specific heat required the determination of three temperatures: T_i, the initial temperature, or that of the water in the calorimeter before addition of the soil; T_s, the soil temperature before its being poured into the calorimeter; and T_f, the final temperature of the mixture. T_s was ordinarily determined by readings of the thermometers inserted in the soil dippers. In the case of samples in the steam bath, this recorded temperature was checked against the boiling point, computed from a corrected barometric reading.

T_i and T_f, the initial and final temperatures in the calorimeter, were determined by a series of temperature readings taken from about 12 minutes before the addition of the soil and up to 45 minutes after the addition. The resultant temperature change curve was analyzed in order to obtain the temperature of the water just before the soil addition and that which would result if the temperature rise occurred instantaneously by a method making use of Newton's law of cooling, and also by an approximate method similar to that sometimes employed in the use of a bomb calorimeter.

The specific heat, uncorrected for heat of wetting, may be calculated by the equation

$$(W_w + E)(T_f - T_i) = W_s (S)(T_s - T_f)$$

in which

W_w = weight of water in calorimeter, grams
E = water equivalent of apparatus, grams

W_s = weight of soil, grams

S = specific heat of soil

and the T values are as previously stated.

Taking into consideration the heat of wetting, the above equation would be written

$$(W_w + E)(T_f - T_i) = W_s (S)(T_s - T_f) + W_s (H)$$

in which

H = heat of wetting of soil, calories per gram.

Then,

$$S = \frac{(W_w + E)(T_f - T_i)}{W_s (T_s - T_f)} - \frac{H}{(T_s - T_f)}$$

RESULTS.

The results of specific heat tests on dry soils are tabulated in Table II. Each result given is an average of from three to six tests.

Since all of the soils were tested at a common mean temperature of approximately 140° F, the specific heat values at that temperature may be observed for a comparison of the various soils. It will be noted that all of the values are within a remarkably small range; Northway Fine Sand has the largest value, 0.197, and Lowell Sand the smallest, 0.188. The average is 0.192. The average values for the three quartz soils--P4701, P4702, and P4703-- at 140° are remarkably close. Thus, the differences in grading and particle shape (two are rounded sands, the other an angular crushed material) have no apparent effect. The four crushed rock materials-- quartz, trap rock, feldspar, and granite--are within a range of from 0.189 to 0.193. Therefore, the tests do not show any significant differences in the specific heat of the common soils and crushed rocks tested.

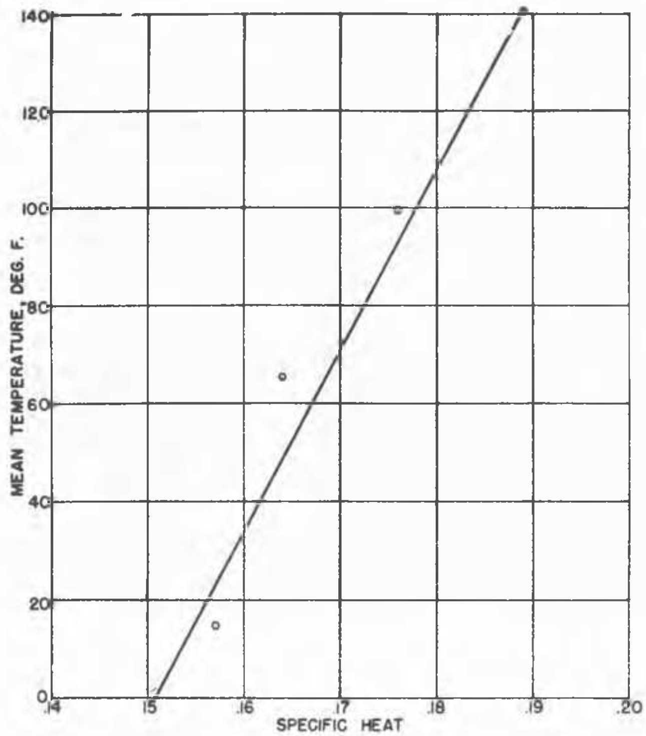
Specific heat tests were made at three mean temperatures on five soils and at four on another. All of these tests show an increase in specific heat for an increase in temperature. The relationship has been approximated as a straight line for all of the soils. Figure 3 shows the curve for one of the soils, and in Figure 4 the curves for all six soils have been reproduced without the individual test points. As can be seen, these curves are quite similar. The average specific heat ranges from 0.19 at 140° F to 0.16 at 0° F, or approximately equivalent to an 11 per cent decrease for a 100° F drop in temperature.

Specific heat tests were made on one soil, P4701, Graded Ottawa Sand, with a variety of moisture contents. This study introduced some difficulties not encountered in the tests on dry soils. For example, it was difficult to pour the damp soils out of the dippers into the calorimeter. The results of these tests, corrected to a common mean temperature, are

TABLE II

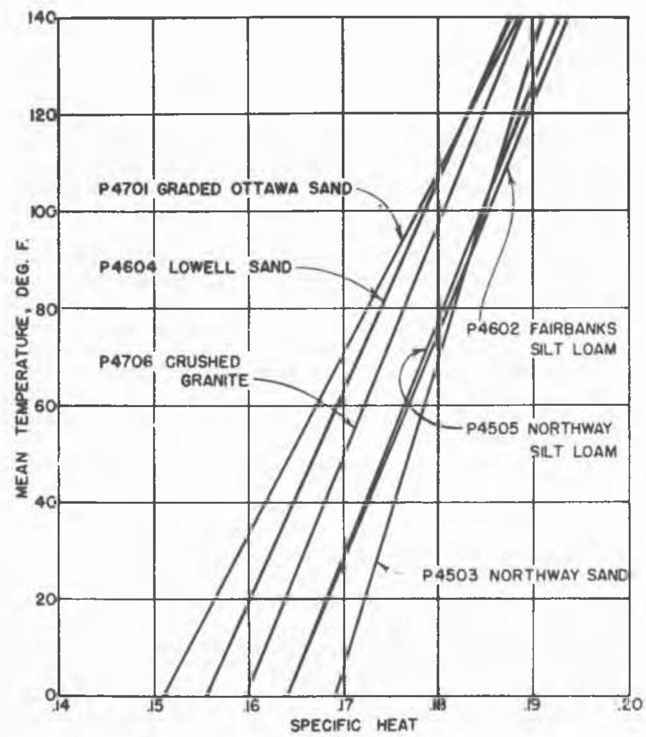
Average specific heat values--Dry soils

Soil No.	Soil Designation	Mean Temperature Deg. F	Specific Heat
P4502	Northway Fine Sand	141.8	0.197
P4503	Northway Sand	19.9 65.7 140.2	0.171 0.185 0.191
P4505	Northway Silt Loam	13.3 68.7 140.7	0.168 0.176 0.193
P4601	Chena River Gravel (Passing No. 4)	141.8	0.194
	(Passing 3/4 inch, retained No. 4)	140.7	0.196
P4602	Fairbanks Silt Loam	16.9 65.8 142.3	0.164 0.183 0.194
P4604	Lowell Sand	14.9 67.5 141.6	0.159 0.188 0.188
P4701	Graded Ottawa Sand	14.9 65.3 99.7 140.5	0.157 0.164 0.176 0.189
P4702	20-30 Ottawa Sand	99.9 139.8	0.183 0.189
P4703	Crushed Quartz	141.6	0.190
P4704	Crushed Trap Rock	139.8	0.193
P4705	Crushed Feldspar	138.7	0.190
P4706	Curshed Granite	8.1 66.9 141.6	0.161 0.174 0.189



Variation of specific heat with mean temperature. Soil P 4701 graded Ottowa sand.

FIG.3



Variation of specific heat with mean temperature Curves for six soils.

FIG.4

given in Table III; the corrections for mean temperature were made by means of the relationship shown in Figure 3. If it is assumed that the specific heat of a soil-water mixture is proportional to the percentages by weight of the two components and their respective specific heats, one may write

$$\text{Specific Heat, mixture} = \frac{(100 \times \text{Spec. Heat, Soil}) + (\text{Moisture Content} \times 1.00)}{100 + \text{Moisture Content}}$$

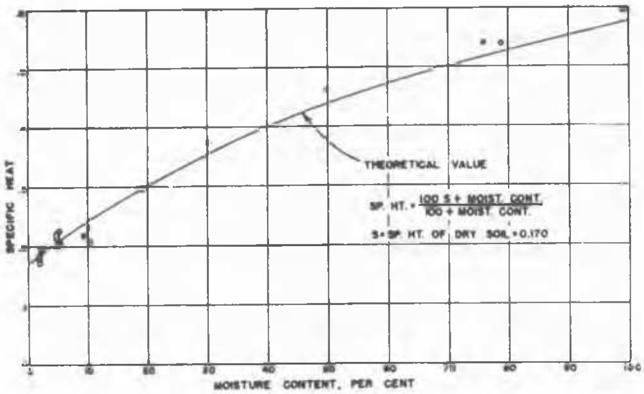
the moisture content being expressed as a percentage of the dry weight of the soil. The values of Table III have been plotted in Figure 5, together with a theoretical curve calculated by the above equation with a specific heat of 0.170 at 0.0 per cent moisture content. Inspection of this curve shows a fairly close agreement between the individual test points and the theoretical curve, although some variations are to be expected due to test difficulties with moist soils. The tests at 10 per cent moisture content were particularly difficult, and this probably accounts for the poor correlation at that point. The tests with respect to this one soil indicate that one may calculate the specific heat of soil-water mixtures according to the proportion by weight of the two components and their respective specific heats.

The heat of wetting values determined for the 12 soils varied from 0.0 for the coarser grained materials to as high as 2.6 and 2.2 calories per gram for the two silt loams, respectively. Values such as those for the silty soils were found to make a considerable difference in the final specific heat values and must therefore be considered in the calculations. In tests on the silt loams at a 140° mean temperature, for example, a specific heat of about 0.23 would have been obtained rather than 0.19, if this factor had been ignored.

TABLE III

Specific heat of moist soils. Values reduced to common mean temperature of 70° F
Soil P 4701, Graded Ottawa Sand.

Moisture Content Per Cent	Specific Heat at 70° F
1.78	0.184
1.85	0.180
1.92	0.180
1.97	0.171
2.06	0.196
4.7	0.221
4.8	0.214
4.9	0.199
5.2	0.226
5.4	0.204
9.4	0.218
10.2	0.232
10.4	0.208
18.7	0.298
19.1	0.296
19.2	0.299
30.1	0.374
49.8	0.463
75.8	0.541
78.7	0.540
99.0	0.595



Relationship of specific heat of soil-water mixtures and moisture content.
Soil P 4701 graded Ottawa sand. Mean temperature 70° F.

FIG.5

CONCLUSIONS.

1. The specific heats of a variety of soils- (sands, silt loams, and crushed rocks)-differ by only a small amount (about 0.01) and average 0.19 at 140° F.

2. Specific heat values of soil decrease with a decrease in temperature. In a temperature range of from 140° to 15° F, the change amounts to approximately 11 per cent for a drop in temperature of 100° F.

3. Based on tests on just one soil, it may be stated that the specific heat of soil-water mixtures may be calculated by proportion according to the percentage by weight of the two components and the respective specific heats.

4. In making specific heat tests by the addition of soil to water in a calorimeter, the heat of wetting of the soils must be taken into account in the calculations.

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APPARATUS FOR MEASURING THERMAL CONDUCTIVITY OF SOIL

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GENERAL DISCUSSION

As a part of a comprehensive program of research on problems encountered in building structures, such as runways and buildings in arctic regions where a condition of permafrost, or permanently frozen ground, exists, the University of Minnesota, Engineering Experiment Station, under contract with the Corps of Engineers, Department of the Army, undertook a study of the thermal conductivity of soil. Since soil is a material with properties entirely different from those types of materials which had previously been subjected to thermal conductivity tests, such as building materials and insulation, an entirely new apparatus was designed and built for these tests. The apparatus had now been in use for about two years, and since it is thought to be unique and possibly useful in other fields of research, it is described herein.

The design of the apparatus was patterned in part on the hot-plate equipment in use at the University of Minnesota for testing materials used in insulating buildings and in part on apparatus used by the U.S. Bureau of Reclamation for tests on concrete. The testing of soils called for a test chamber into which the material could be compacted to any desired density and at any selected moisture content. For this reason a tubelar type container was selected.

For purposes of description, the apparatus may be divided into the following parts:

1) A tubelar soil container consisting of a central pipe containing heaters and an outside cold chamber, together with a refrigerated, insulated box to keep heat losses at a minimum;
2) A motor generator with an exciter and voltage regulator for supplying power to the heaters;
3) A condensing unit, cooling and mixing tanks, and circulation system for supplying alcohol to the cold side of the soil container, with provision for controlling the alcohol temperature to attain 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 shown in Figure 1. In the photograph the cooling and mixing tanks are at the left front. This was originally constructed for four soil containers, but only two have been built. The alcohol cooling tank is in the center, with two mixing tanks on the opposite sides. 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 operating table is in the back beyond the soil containers. At the right and beyond the condensing unit of the alcohol tank is a smaller condensing unit for the soil containers. Beyond this is the motor generator unit and against the wall are two photo-electric relay units.