THERMAL PROPERTIES OF SOILS

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Calculation of depth and rate of frost penetration or depth and rate of thaw of frozen soils requires a knowledge of the thermal properties of soils. These properties include thermal conductivity, specific heat and volumetric heat capacity, and thermal diffusivity. Definitions of these terms, together with the units used in this paper follow:

The coefficient of thermal conductivity, k, is a measure of the quantity of heat that will pass through a unit area of unit thickness in unit time under a unit temperature gradient. It is common in this country to express k in British thermal units transmitted per hour through a body 1 sq. ft. in area and 1 in. thick with a temperature differential of 1 deg. F.

Specific heat, S, is the ratio of the quantity of heat required to raise a unit mass of a substance 1 deg. to the quantity required to raise a unit mass of water 1 deg. Numerically, S may be considered as calories per gram per deg. C. or Btu's per lb. per deg. F.

Volumetric heat capacity, C, is the amount of heat required to raise a unit volume of material 1 deg. With soils, a unit of Btu's per cu. ft. per deg. F. is commonly used. Volumetric heat capacity of a soil is dependent principally upon its density, moisture content, and temperature (frozen or unfrozen).

Thermal diffusivity, h^2, is an index of the facility with which a material will undergo temperature change. It may be calculated by the basic equation

$$h^2 = \frac{k}{C}$$

With units of k and C as previously noted, the equation becomes

$$h^2 = \frac{0.08333k}{C}$$

with h^2 in ft.^{2} per hr.

Specific Heat and Volumetric Heat Capacity

The specific heat of the various rocks and minerals present in soils can be found in various handbooks (see Bibl. 2, for example.) On the basis of such tabulations many investigators have selected a value of about 0.19 or 0.20 as being characteristic for the general run of soils. Shannon and Wells used such values in their determination of thermal conductivity values (12). A series of specific heat tests made at the University of Minnesota (5, 7) indicates that such values are entirely reasonable at a temperature of 140 F., plus or minus, but are too high for temperatures close to the freezing point. Figure 1 shows a plot of the results of four tests made on a single soil at four different temperatures. Figure 2 gives such curves for six soils with the individual test points omitted. These figures clearly indicate the decrease in specific heat for a decrease in temperature and that 0.16 or 0.17 is probably a reasonable value to assume for soils when temperatures close

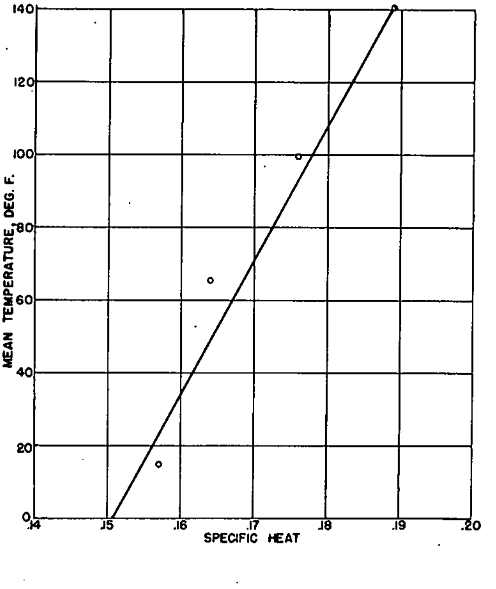

Figure 1. Variation of Specific Heat With Mean Temperature. (Soil P4701 Graded Ottawa Sand).

to the freezing point are being considered. The Handbook of Physical Constants of the Geological Society of America (2) indicates a similar change of specific heat with change in temperature for various rocks. Many of the rocks listed have a specific heat of about 0.17 at 32 F.

The soils shown in Figure 2 represent a variety of mineral compositions and textures. Tests were also made on six other soils but at only one temperature; these gave values similar to those shown. On the basis of these tests it would seem reasonable to assume a specific heat of about 0.17 at 32 F. for most soils.

The volumetric heat capacity of a dry soil may be computed, if its specific heat and density are known, by the formula

$$C = S \cdot \delta$$

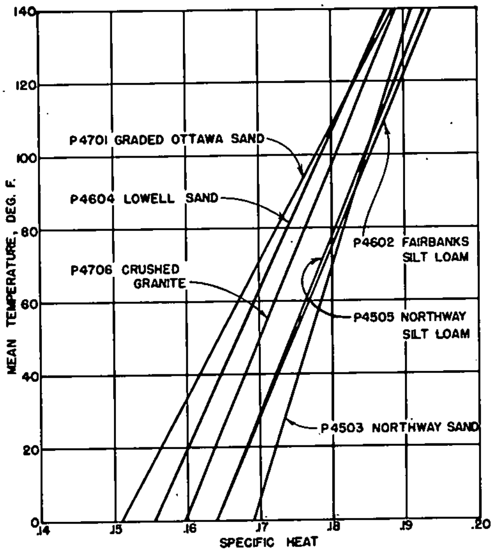

Figure 2. Variation of Specific Heat With Mean Temperature. (Curves for Six Soils).

wherein C is the volumetric heat capacity in Btu's per cu. ft. per deg. F., S is the specific heat, and δ the density in lb. per cu. ft.

It has been shown (5, 7) that the specific heat of a soil-water mixture may be computed by proportion according to the percentages by weight of the soil and water and the specific heats of the components. Thus one may write

$$S_m = \frac{100 \cdot S + w \cdot 1.0}{100 + w}$$

wherein S_m is the specific heat of the mixture (wet soil), S the specific heat of the dry soil and w the moisture content of the soil expressed as a percentage of the dry weight.

The 1.0 in the above equation represents the specific heat of the water. If the soil is frozen, the specific heat of ice should be substituted. This is about 0.5. Thus, for frozen soils:

$$S_m = \frac{100 \cdot S + w \cdot 0.5}{100 + w}$$

If S is assumed to be 0.17 for soils close to the freezing point these equations become

For unfrozen soils, $S_m = \frac{17 + w}{100 + w}$

For frozen soils, $S_m = \frac{17 + 0.5\,w}{100 + w}$

The volumetric heat capacities would be

For unfrozen soils, $C_m = \left(\frac{17 + w}{100 + w}\right) \delta \left(1 + \frac{w}{100}\right)$

For frozen soils, $C_m = \left(\frac{17 + 0.5\,w}{100 + w}\right) \delta \left(1 + \frac{w}{100}\right)$

C_m is in Btu's per cu. ft. per deg. F., δ is the dry density in lb. per cu. ft., and w is the moisture content as a percentage of the dry weight.

Thermal Conductivity

There have been numerous investigations to determine the coefficient of thermal conductivity of soils. The earliest extensive results were reported by H. E. Patten (9). Comprehensive reports have been made by W. O. Smith (13, 14, 15), W. L. Shannon and W. A. Wells (12), and M. S. Kersten (6, 7). Gunnar Beskow has given a rather complete discussion of the important factors to be considered in soil conductivity (2). Recently studies of thermal properties of soil, including conductivity, have been undertaken in connection with work on heat pumps. Such investigations are now being made, for example, at the University of Kentucky (10) and Texas A. and M. College (17).

As would be expected, the thermal conductivity of a soil is dependent upon many factors, including density, moisture content, temperature, (above or below freezing point), texture, structure, and mineral composition. The influence of each of these factors will be briefly discussed and the general range of soil conductivities noted in the following paragraphs. This discussion is based largely on the investigation conducted at the University of Minnesota which was sponsored and financed by the Corps of Engineers (6, 7). The general results are in agreement with the studies of the New England Office of the Corps of Engineers (12). In some of the other investigations the soils information reported is not sufficiently complete or does not cover a sufficient range to yield exact relationships.

Temperature

The important aspect of temperature on the thermal conductivity of soil is whether the soil is frozen or not. The difference in conductivity of frozen and unfrozen soils is chiefly dependent on moisture content. On relatively dry soils no change in the coefficient k occurs in passing through 32 F. At low moisture contents, i. e., 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, however, the k of frozen soil is greater than that for unfrozen. Tests indicate that at the so-called modified optimum moisture content, the k below freezing averages about 17 percent greater than that above freezing; at 5 percent of moisture above this point, the frozen k is 35 percent greater. Shannon and Wells (12) state that "for highwater contents the thermal conductivity of the frozen material is (with the exception of one material tested) approximately 50 percent greater than the corresponding value for the material unfrozen." Beskow is also in general agreement with these results if the soils are sandy, but not for clays. For sandy soils he concludes that the increase in k when a soil freezes "is about 10-15 and at the most 20-30 percent." (2). Data cited by Muller (8) show an increase of about 50 percent for clays and an even greater increase for extremely wet sands.

Density

Tests have shown that an increase in the dry density of a soil, the percentage of moisture remaining the same, results in an increase in thermal conductivity. The rate of increase is about the same at all moisture contents and is not particularly different for frozen and unfrozen soils. As a general rule, it may be assumed for a given soil that a change in dry density of 1 lb. per cu. ft. will result in a change of 3 percent in its thermal conductivity.

Moisture Content

The moisture content of a soil has a very important effect on its thermal conductivity. At a constant dry density, any increase in moisture results in an increase in conductivity. This result has been obtained by all investigators. (6, 9, 11, 12, 15) A characteristic sandy soil, for example, might have a k of 6 at 3 percent moisture and 12 at 15 percent. The increase continues up to the point of saturation. The moisture content has a like effect in the frozen state.

Texture

If soils of different texture are tested at equal moisture contents and densities it will be found in general that the coarse-grained materials, such as gravels and sands, will have high conductivities; fine-grained soils such as silt loams and clays, low conductivities; and intermediate-textured soils values between these two. Baver (1) cites several investigations which show this variation. Smith (15) states that soils with high organic contents have the lowest conductivity, those high in clay an intermediate ability to transmit heat, and those of sandy texture the greatest ability. It should be noted, however, that in the field sandy soils ordinarily exist at higher densities and lower

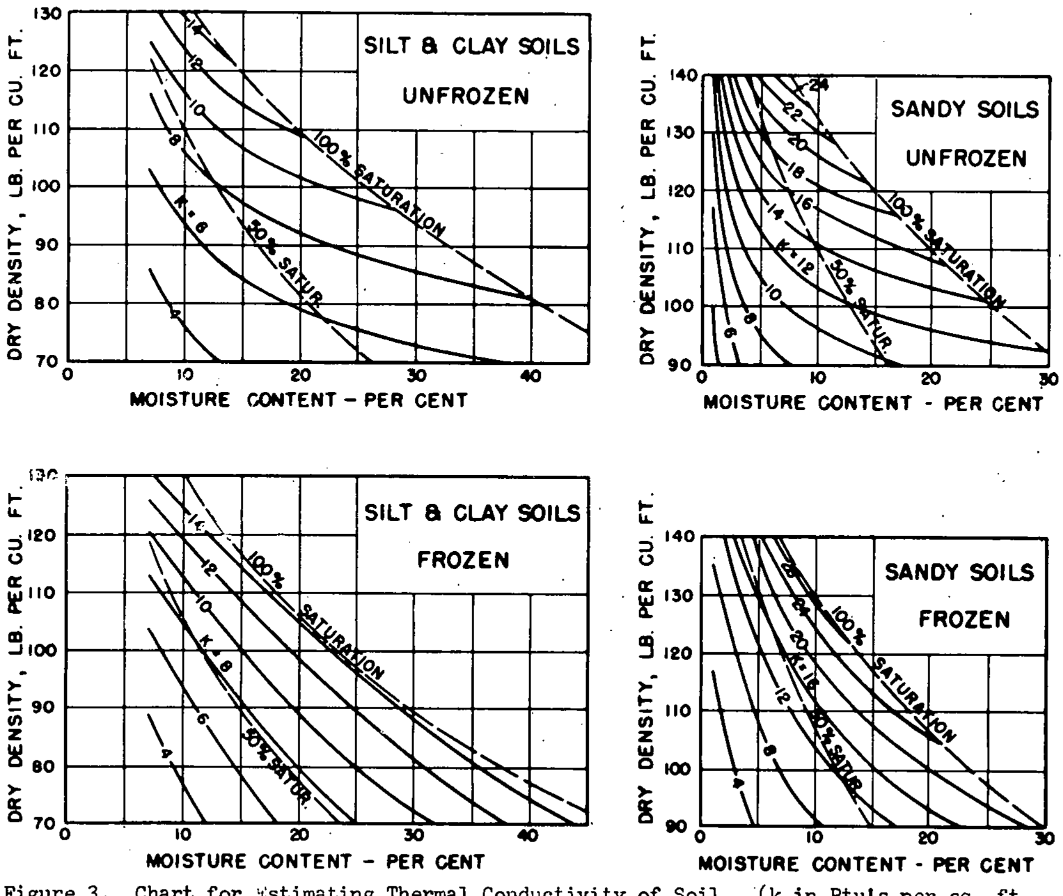

Figure 3. Chart for Estimating Thermal Conductivity of Soil. (k in Btu's per sq. ft. per inch per hour per deg. F.)

moisture contents than silt or clay soils. Hence the differences noted in laboratory testing may not occur in soils in their natural position. It has been found expedient at the University of Minnesota to divide soils into two general classes for construction of thermal conductivity charts, i. e., sandy soils, and silt and clay soils.

Mineral Composition

Consideration of mineral composition has shown that this factor does have some effect on the thermal conductivity of a soil. It is a factor, however, which is difficult to evaluate, since mineral composition is not commonly determined in soil testing. Compiled tables (for example, Table 17-4, Bibl. 2) indicate that the conductivity of the various rocks of which soils are composed vary over a wide range. Quartz, for example, is reported as having thermal conductivity values from 50 to 85 Btu's per sq. ft. per in. per hr. per deg. F. whereas basalts, trap rock, and gabbro vary from 11 to 17. In general, tests indicate that 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 high contents of kaolinite and other clay minerals have relatively low conductivities. It appears rather difficult on the basis of available information, however, to take mineral composition into account when estimating thermal conductivity . Smith has suggested an equation for k in which the conductivity of the rock constituents is taken into account. (13)

Structure

Most thermal conductivity studies on soil have been on so-called "disturbed" samples. Soils in the field may have distinctive structure or laminations which may have a large effect on their conductivity. Smith has considered this factor in his studies (13). He found that for granular structured soils, there was little, if any, differences in test results on undisturbed soils and materials which had been broken down and recompacted. However, for most other structure patterns, k values for the undisturbed materials are greater than those on the same soil after a breaking down of the structure. In some cases it may be twice as great as that observed for the reduced state. These results are for dry soils. Smith has suggested a structure factor to take this soil condition into account.

In frozen soils, particularly those with ice lenses, the effect of stratification may be very important. This factor requires additional study.

Prediction of Thermal Conductivity

For most field calculations it will not be feasible to make thermal conductivity tests of the soil under consideration. For this reason it is highly desirable to make use of present knowledge to estimate a k value for the soil. Four charts for this purpose were published in the 1948 Proceedings of the Highway Research Board (6). It is hoped to modify and correct these charts as additional information is obtained. In fact, changes have already been incorporated in two of them. The four charts are shown in Figure 3. Two are for sandy soils and two for silt and clay soils; for both classes of soil, one chart is for frozen soil, and the other for unfrozen. The division point in texture may be based on silt and clay contents (particles smaller than 0.05 mm.). Soils with more than 50 percent silt and clay are in the fine textured group, those with less than 50 percent in the sandy group.

Diffusivity

Diffusivity values are of interest in frost calculations since they indicate the rate at which a soil will change temperature when the temperature of the surrounding medium changes. Since this constant can be determined if its volumetric heat capacity and thermal conductivity are known, no specific values need be given herein. However, it should be noted that for soils with high moisture contents, the diffusivity of a frozen soil is appreciably higher than for the unfrozen condition. At 15 percent moisture content, for example, the diffusivity of a frozen soil may be 50 percent greater than that of the unfrozen soil. Thus the average temperature of a frozen body of wet soil will change more rapidly than a similar body of unfrozen soil at a given temperature differential between the soil and the surrounding medium.

In calculations involving the freezing or thawing of a soil it is necessary to take into account the latent heat of fusion of the ice. This amounts to about 144 Btu's per lb. If a soil is thawing, the temperature change is delayed because of the latent heat of fusion.

Conclusion

Our knowledge of the thermal properties has increased considerably during the last few years. Numerical values of the various constants permit mathematical checks of various heat-transfer problems in connection with frost action in soils. The numerical values of specific heat and thermal conductivity given in this paper, with which diffusivities may also be calculated, are offered for use in such calculations. It is hoped that use of these values and additional research may lead to corrections and improvements in the stated values.

It should be noted that most of the thermal property information available is from laboratory tests. The need for field checks is apparent.

Bibliography

1. Baver, L. D., "Soil Physics," New York, John Wiley and Sons, 370 pp., pp. 153-155 and 275-289, 1940.
2. Beskow, G., "Soil Freezing and Frost Heaving with Special Application to Roads and Railroads," Swedish Geological Society, Ser. C., No. 375, 26th Yearbook, No. 3, 1935. With a special supplement for the English translation of progress from 1935 to 1946. Evanston, Illinois: Northwestern University, Technological Institute, Nov., 1947. (Translated by J. O. Osterberg).
3. Ingersoll, L. R. and Koepp, E., "Thermal Diffusivity and Conductivity of Soils and Materials," Physical Review, July, 1924.
4. Kennelly, A. E. and Shepard, E. R., "The Heating of Copper Wires by Electric Currents," Transactions American Institute of Electrical Engineers, Vol. 26, p. 969, 1907.
5. Kersten, M. S., "Specific Heat Tests on Soils," Proceedings Second International Conference on Soil Mechanics and Foundation Engineering, Vol. 3, 1948.
6. Kersten, M. S., "The Thermal Conductivity of Soils," Proceedings, Highway Research Board, Vol. 28, 1948.
7. Kersten, M. S., "Thermal Properties of Soils," Bulletin 28, Engineering Experiment Station, University of Minnesota, June, 1949.
8. Muller, S. W., "Permafrost or Permanently Frozen Ground and Related Engineering Problems," U. S. Geological Survey, Special Report, Strategic Engineering Study No. 62, Prepared for Military Intelligence Division, Office, Chief of Engineers, U. S. Army, 1945. 2nd Printing. Ann Arbor, Michigan. J. W. Edwards, Inc., 1947. Reprint. 231 pp.
9. Patten, H. E. "Heat Transference in Soils," United States Department of Agriculture, Bureau of Soils, Bulletin No. 59, September, 1909.
10. Penrod, E. B. and others, "Earth Heat Pump Research," Bulletin No. 14, Engineering Experiment Station, University of Kentucky, December, 1949.
11. Shanklin, G. B., "Effects of Moisture on Thermal Conductivity of Soils," Journal of A. I. E. E., February, 1922.
12. Shannon, W. L. and Wells, W. A., "Tests for Thermal Diffusivity of Granular Materials," Proceedings American Society for Testing Materials, Vol. 47, 1947.
13. Smith, W. O., "Thermal Conductivity of Dry Soils," Soil Science, Vol. 53, June, 1942.
14. Smith, W. O., "The Thermal Conductivity of Dry Soils of Certain of the Great Soil Groups," Proceedings Soil Science Society of American, Vol. 3, 1938.
15. Smith, W. O., "Thermal Conductivity of Moist Soils," Proceedings Soil Science of America, Vol. 4, 1939.
16. U. S. Department of the Interior, Bureau of Reclamation, "Thermal Properties of Concrete," Part VII, Bulletin I, Boulder Canyon Project, Final Reports.
17. Vestal, D. M., Jr., "Heat Pump Buried Coil Design - The Soil Problem", Refrigerating Engineering, Vol. 47, p. 573, 1949.