and thickness of the homogeneous material, the conductance of non-homogeneous materials (such as concrete blocks), the surface conductances of both sides of the construction, and the conductances of any contained air spaces. These items are discussed in the pages that follow.

Conductivities and Conductances

The method of calculating the overall coefficient of heat transmission for a given construction is comparatively simple, but accurate values of conductivities and conductances must be used to obtain satisfactory results. In addition, there are sometimes parallel heat-flow paths of different resistances in the same wall, and these may necessitate modification of the formula. In such cases calculated results should be checked by test.

The determination of the fundamental conductivities and conductances requires considerable skill and experience to obtain accurate results. It is recommended that thermal conductivities of homogeneous materials be determined by means of the Guarded Hot Plate.[1] For determination of conductances, a Guarded Hot Box method[2] is generally used.

Conductivity of Homogeneous Materials

Thermal conductivity is a property of a homogeneous material and of types of building materials such as lumber, brick, and stone, which may be considered homogeneous. Most insulating materials, except reflective types, are of a porous nature and consist of combinations of solid matter with small voids. Such materials including fibrous, cellular, or granular matter are generally known as mass or bulk insulations. The thermal conductivity of these materials will vary with density; mean temperature; size of voids, fibers, or particles; degree and extent of bond between particles; moisture present; and the arrangement of fibers or particles within the material.

The effect of density upon conductivity (at constant mean temperature) is illustrated for two fibrous materials in Fig. 1. Typical variation of conductivity with mean temperature is shown in Fig. 2.

Thermal Conductivity of Soil

The following statements are based largely on results of a study[3] made in the Engineering Experiment Station, University of Minnesota, and published in *Bulletin* No. 28. Tests were made on nineteen different soils which represented a wide textural variety, including gravel, sand, sandy loam, silt loam, and clay, as well as some crushed rocks and a fibrous peat. Moisture contents in tests varied from air-dried values

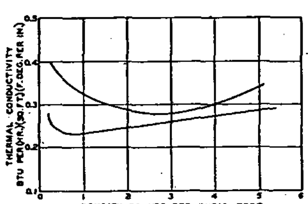

Fig. 1 . . . . Typical Variation of Thermal Conductivity with Density—for Fibrous Material

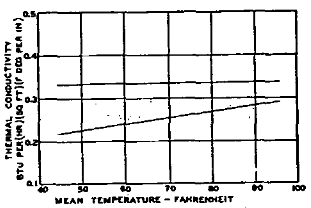

Fig. 2 . . . . Typical Variation of Thermal Conductivity with Mean Temperature

to those greater than the optimum moisture content; densities varied from a loosely-poured condition to the maximum density obtainable by heavy ramming. The general findings of the investigation are as follows:

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

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

Effect of Moisture. An increase in moisture content, up to the point of saturation, causes an increase in thermal conductivity. The rate of increase in typical soils was as follows: average conductivities, in Btu per (square foot) (hour) (Fahrenheit degree per inch), of four sands at a density of 110 lb per cu ft were: 6.8 at 2.5 percent moisture, 8.9 at 5 percent moisture, 11.2 at 10 percent moisture. Five soils of a fine texture at a density of 100 lb per cu ft, gave average conductivities of 6.7 at 10 percent moisture, and 9.5 at 20 percent. Thus, the doubling of moisture content within the ranges cited increases the conductivity by approximately 30 or 40 percent. At higher moisture contents the percentage increase would be less.

Effect of Soil Characteristics. The thermal conductivity of the soil, at a given density and moisture content, varies in general with the texture of a soil, being relatively high for coarse-textured soils and relatively low for fine-textured soils. The mineral composition of the soils also affects the conductivity. Quartz tends to give high values, whereas minerals such as plagioclase-feldspar and pyroxene, which are constituents of basic rocks tend to give low values of thermal conductivity. These points are illustrated by the values in Table 1 which lists seventeen soils in approximate order of their magnitude of thermal conductivity from greatest to least for seven different density-moisture content conditions. Some of the values in this table have been determined by extrapolation and are consequently approximate. Blank spaces in the table indicate that the density or moisture content, or both, are such that no tests were possible for that condition or that no tests were sufficiently close to permit a reasonable extrapolation of the data. Granular soils, particularly those with high quartz contents, head the tabulation or have the greatest conductivity

Table 1 . . . . Thermal Conductivity (*k*) Values of Soils in Approximate Order of Decreasing Values*

Mean Temperature—40 F

Soil Designation	*Mechanical Analysis % by Weight*				*Moisture Content—%*						
	Gravel	Sand	Silt	Clay	4			10		20	
					Dry Density-lb per cu ft						
	Over 2.0 mm	0.5 to 2.00 mm	0.005 to 0.05 mm	Under 0.005 mm	100	110	120	90	110	90	100
Fine Crushed Quartz	0.0	100.0	0.0	0.0	12.0	16.0					
Crushed Quartz	15.5	79.0	5.5		11.5	16.0	22.0				
Graded Ottawa Sand	0.0	99.9	0.1		10.0	14.0					
Fairbanks Sand	27.5	70.0	2.5		8.5±	10.5	13.5		15.0		
Lowell Sand	0.0	100.0	0.0	0.0	8.5	11.0			13.5		
Chena River Gravel	80.0	19.4	0.6			9.0±	13.0				
Crushed Feldspar	25.5	70.3	4.2		6.0	7.5	9.5				
Crushed Granite	16.2	77.0	6.8		5.5	7.5	10.0				
Dakota Sandy Loam	10.9	57.9	21.2	10.0		6.5	9.5		13±		
Crushed Trap Rock	27.0	63.0	10.0		5.0	6.0	7.0				
Ramsey Sandy Loam	0.4	53.6	27.5	18.5	4.5	6.5			10.0		
Northway Fine Sand	0.0	97.0	3.0	0.0	4.5	5.5			8.5		
Northway Sand	3.0	97.0	0.0	0.0	4.5	6.0			7.5±		
Healy Clay	0.0	1.9	20.1	78.0	4.0±			5.5	9.0±	8.0	10.0
Fairbanks Silt Loam	0.0	7.6	80.9	11.5				5.0	9.0±	7.5	10.0
Fairbanks Silty Clay Loam	0.0	9.2	63.8	27.0				5.0	9.0±	7.5	9.5
Northway Silt Loam	1.0	21.0	64.4	13.6				4.0±	7.0±	6.0±	7.0±

* k = Btu per (square foot) (hour) (Fahrenheit degree per inch).

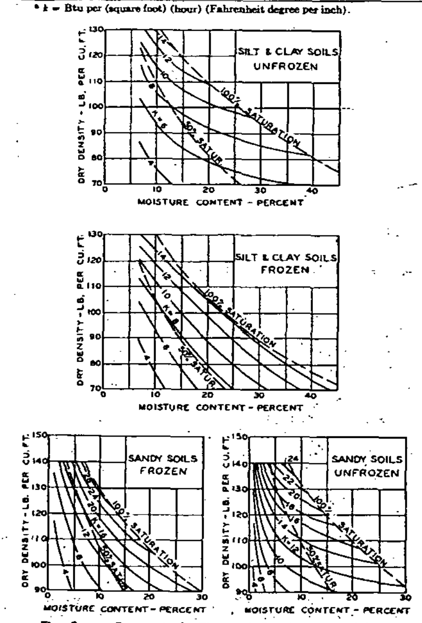

Fig. 3 . . . . Determining Thermal Conductivity of Soils from Density and Moisture Content

at a given condition. Sandy loam soils are midway in the table and fine grained soils such as clay and silt loam are last.

Estimating Thermal Conductivity. The four diagrams of Fig. 3 are presented to aid in the estimate of the thermal conductivity of any soil. Two of the charts are for sands or sandy soils, and two for silt and clay soils. One of the diagrams for each type of soils is for the frozen, and the other for the unfrozen condition. It is expected that these charts will give conductivity values with a precision of 25 percent. The effect of such factors as density, moisture content, freezing, or texture may be easily approximated by use of these graphs.

Specific Heat of Soils

Tests to determine specific heat were run on twelve soils. On five of the soils, tests were made at three or four mean temperatures varying from about 10 to 140 F. The specific heat values of all twelve soils varied by only a small amount (about 0.01), and averaged 0.19 at 140 F. The specific heat values of the soils decreased with a decrease in temperature. The average value at zero F would be about 0.16. Values at temperatures between zero and 140 F can be estimated by considering a straight-line relationship between the two values given.

Surface Conductance

The surface conductance of a wall is the combined heat transfer to or from the wall by radiation, convection, and conduction. Each of the three portions making up the total may vary, independently of the others, thus affecting the total conductance. The heat transfer by radiation between two surfaces is controlled by the character of the surfaces (emissivity), the temperature difference between them, and the solid angle through which they see each other. The heat transfer by convection and conduction is controlled by the roughness of the surface, by air movement, and temperature difference between the air and the surface.

The importance of the effect of temperature of *surrounding surfaces* on the surface conductance, due to the effect on radia-