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THERMAL PROPERTIES OF MASONRY MATERIALS FOR PASSIVE SOLAR DESIGN - A STATE-OF-THE-ART REVIEW

Final Report

by

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ABSTRACT

This report summarizes available test data, evaluates test methods, and recommends values for thermal properties of masonry to be used in passive solar design. Values of specific heat, conductivity, and diffusivity are given for concrete and clay brick. Variations of these values with other physical properties such as density, moisture content, and temperature are shown. Variations in data due to different test methods are analyzed. Values of absorptivity and emissivity for concrete and clay brick, and associated test methods, are also discussed.

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INTRODUCTION

The design of passive solar systems in buildings is influenced by thermal properties of materials in the system. Masonry, including clay and concrete units, is the principle storage element in passive solar systems. Therefore, it is essential to know the thermal properties of masonry materials for the design of efficient systems.

Passive Solar Systems

Three basic passive solar arrangements are the direct gain system, the thermal storage wall system, and the attached sun-space system. As shown in Fig. 1, solar radiation enters a building through collectors that are generally south-facing windows. Heat is absorbed and stored by the thermal storage mass usually made of concrete or masonry.(1)** At a later time, stored heat is released into the living area. This process provides heat to rooms during cooler night hours.

The simplest passive arrangement is the direct gain system. The floors and walls of the building act as the thermal storage mass as shown in Fig. 1a. Walls and ceilings not part of the thermal storage mass are painted light colors to reflect solar radiation to the thermal storage mass.

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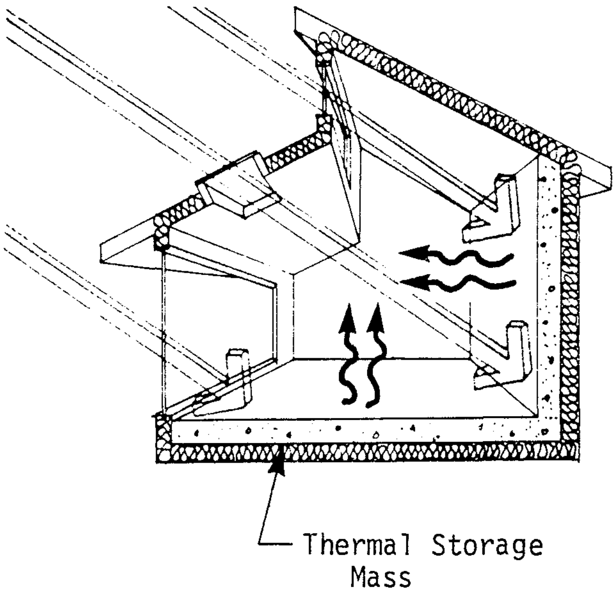
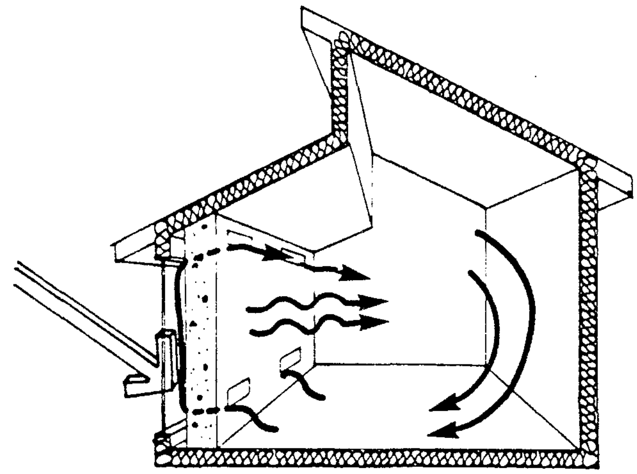
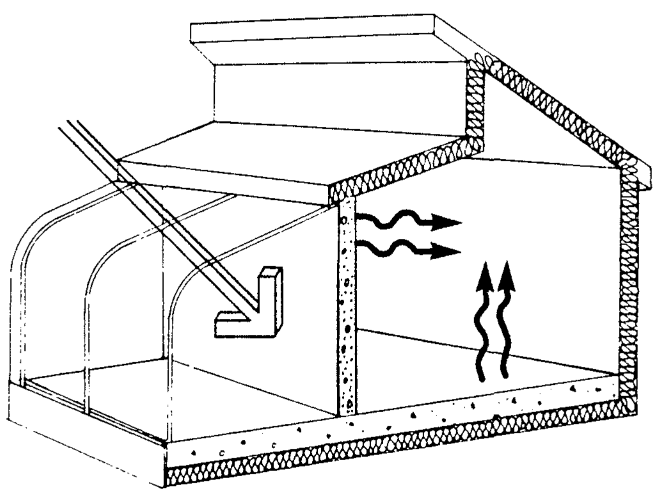
**Superscript numbers in parentheses refer to references listed at the end of this report.



(a) Direct Gain System



(b) Thermal Storage Wall
(Trombe Wall) System



(c) Attached Sunspace (Greenhouse) System

Fig. 1 Passive Solar Systems[1]

In the thermal storage wall system, shown in Fig. 1b, solar radiation is absorbed by the thermal storage wall which is located within about 1 foot of the solar collector. Heat is transferred to the living quarters by natural convection through vents in the upper and lower parts of the wall, and by conduction through the wall.

The third basic passive solar arrangement uses solar radiation to heat an attached sunspace or greenhouse as shown in Fig. 1c. Adjacent rooms may be heated by conduction through the thermal storage mass, or wall, that connects the rooms to the sunspace.

Properly designed passive solar systems provide substantial energy savings when compared to conventional buildings. However, the design process involves numerous variables including the size and type of collector, size and type of thermal storage mass, use of night insulation over the collector area, and location of vents. Design procedures as well as illustrations of actual passive systems are provided in the Passive Solar Design Handbook(2) and the Passive Solar Energy Book.(3)

Thermal Properties

Thermal properties of the storage mass must be known to size auxiliary equipment, to prevent overheating of the building, and to determine the optimal amount and arrangement of the mass. The amount of heat available from the mass to heat the surrounding area depends on the thermal properties of the mass as illustrated in Fig. 2. Solar radiation, or heat energy, is absorbed, stored, and released by the mass.

The amount of solar radiation absorbed by a wall depends on the absorptivity of the wall, and the quantity and composition of solar radiation incident to the wall. The absorptivity of nonmetalic materials is a surface effect largely dependent on surface color and material

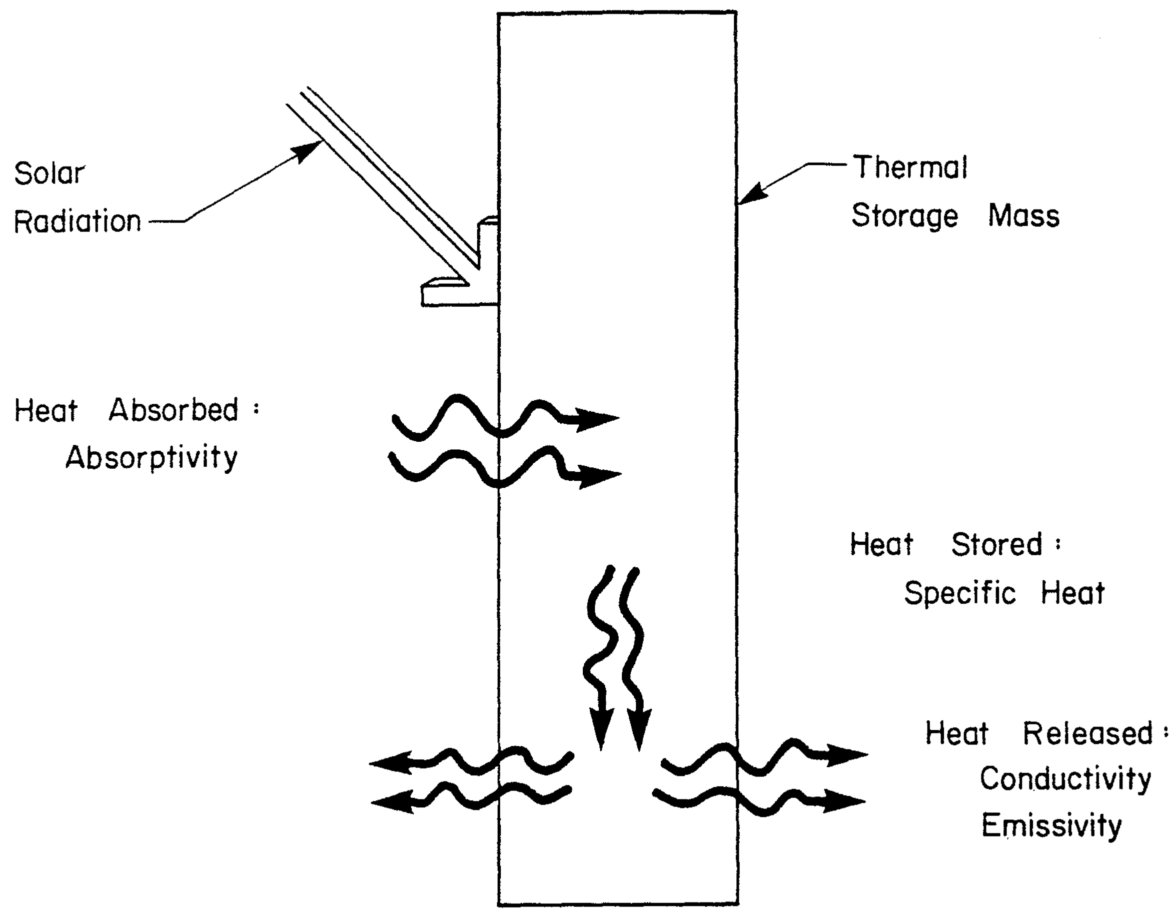


Fig. 2 Thermal Properties Relevant to the Thermal Storage Mass

composition. Generally, absorptivity is higher for dark surfaces than light surfaces. For opaque materials such as concrete and clay masonry, solar radiation not absorbed by the wall is reflected away from the wall.

The quality and composition of solar radiation incident to walls is related to whether the radiation is direct or diffuse. Radiation from the sun is direct radiation. Atmospheric particles reflect and diffuse radiation as it approaches the earth. Clouds and some collector area materials such as glass designed to reduce glare, further reflect and diffuse solar radiation as shown in Fig. 3. According to Incropera and DeWitt[(4)] the amount of diffuse solar radiation will vary from 10% on a clear day to nearly 100% on an overcast day.

For most passive solar design applications, it is desirable that heat energy absorbed during the day be released at night as opposed to the next day. Therefore, the effectiveness of thermal mass for storage depends on the heat storage capacity of the mass as well as the rate of heat flow through the mass.

Heat storage capacity of a wall is determined by its specific heat, density, thickness, and geometry. Specific heat is the ratio of the amount of heat required to raise the temperature of a given mass of material by one degree to the quantity of heat required to raise the temperature of an equal mass of water by one degree. Wall geometry describes the location of openings such as those found in hollow block and brick. Openings, thickness, and density of the thermal storage mass determine the amount of material available for storage.

Steady-state heat flow through a wall or floor can be determined from the thermal transmittance of the material in the system. Thermal transmittance can be calculated from the conductivity, geometry, and

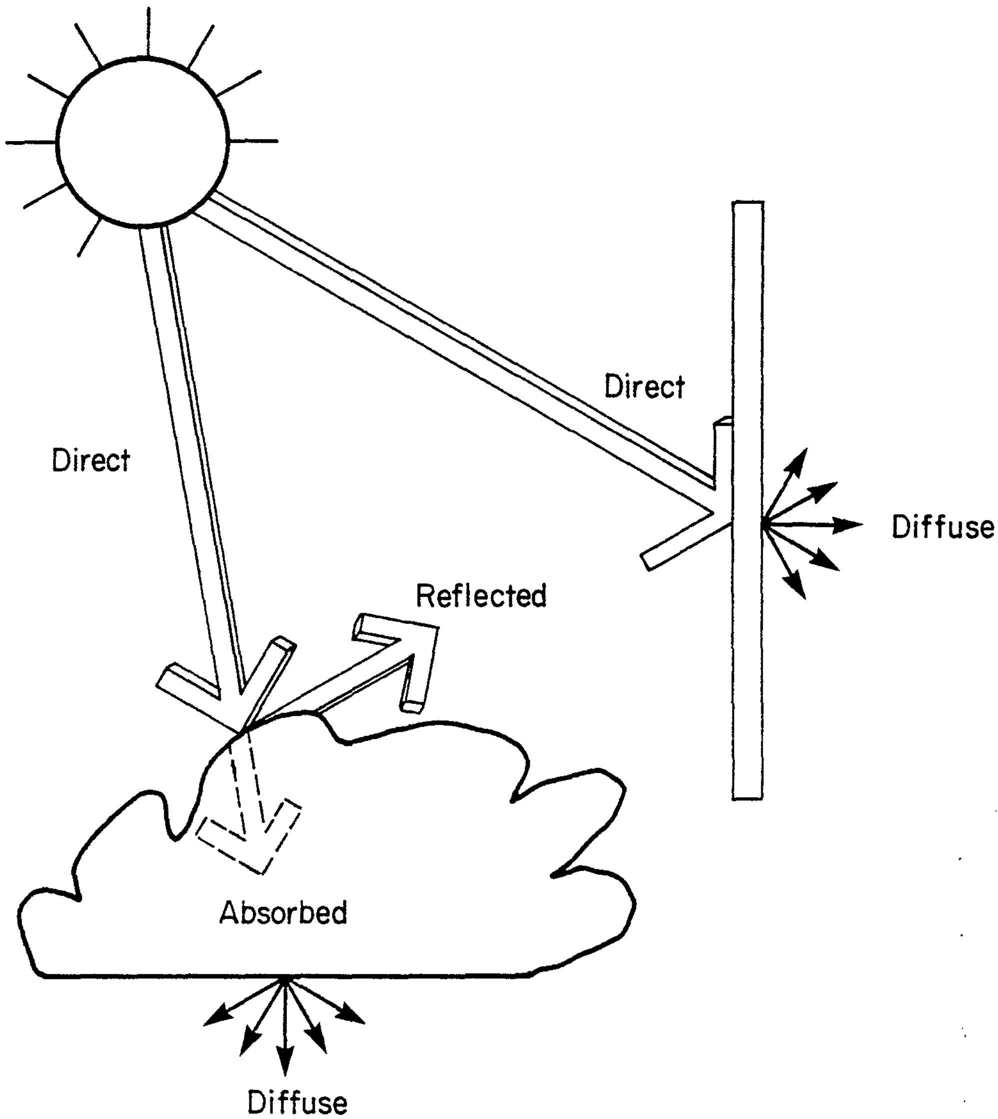


Fig. 3 Direct versus Diffuse Radiation adapted from Mazria[3]

surface conductance of the material. Conductivity, a physical property of the material, is a measure of heat flow through a mass. Surface conductance is determined from emissivity and air velocity. Emissivity is a measure of the amount of heat radiated from the surface of the mass and is also a physical property of the material. Surface conductance, and therefore total heat released, will be greater for greater air velocities near the surface of the thermal storage mass.

Another measure of heat capacity is defined in the Passive Solar Design Handbook.(2) For this measure, capacity is defined as the density times the specific heat times the thermal conductivity of the storage mass. These three properties are useful in describing behavior of the thermal storage mass.

Objective

Since the amount of heat absorbed, stored, and released by the thermal storage mass is dependent on absorptivity, specific heat, conductivity, and emissivity of the materials, reliable values of those thermal properties are needed by designers of passive solar systems. These thermal properties vary for different moisture contents, different constituent materials, and different types of the same material. For example, conductivity of normal-weight concrete is approximately ten times greater than the conductivity of some lightweight concretes.

Many sources of data list one value of a thermal property for all concretes or all clay bricks. In many instances, available sources of data show considerable variation. Furthermore, for the same thermal properties, some test methods give different results than other test methods.

The objective of this report is to summarize available test data, evaluate test methods, and recommend values for thermal properties of masonry as they relate to passive solar design. Values of specific heat, conductivity, and diffusivity are given for concrete and clay brick. Variations of these values with other physical properties such as density, moisture content, and temperature are shown. Variations in data due to different test methods are analyzed. Values of absorptivity and emissivity for concrete and clay brick, and associated test methods, are also discussed.

With more accurate data the designer will be able to improve predictions of the performance of the thermal storage mass. The designer will also be able to choose the type of masonry that has the thermal properties required by a particular design.

COMPOSITION OF CLAY BRICK

Clay brick is a structural clay product made from fired clay or shale. Structural clay products must meet the following standards established by the Federal Trade Commission:[5]

1. Composition is primarily clay, shale, or mixtures of the two.
2. Ingredients are fused together as a result of the application of heat.

Clay is made up of fine grained earth particles and is composed mainly of hydrous aluminum silicate minerals. Clay is produced by the natural weathering of rocks. Shale is a thinly bedded rock formed from compressed clay.

To make brick, the clay is mixed wet and extruded from a die and cut into blocks, or forced into molds. Bricks are then air dried or placed in a drying kiln to remove moisture. After drying, bricks are fired for 50 to 150 hours, depending on the type of kiln, and then cooled.[5]

Face brick and common brick are the two types used most frequently in building construction. Face brick is used where visual appearance is an important consideration. To ensure more uniformity in color and texture, face brick is generally manufactured under more controlled conditions than common brick. Physical properties of clay brick may vary due to impurities in the clay and shale used to manufacture the brick, oxides added to produce certain colors of brick, and firing procedure. For example, BIA Bulletin 43D[6] indicates more metallic oxides generally result in a higher specific heat.

The density of dry clay brick normally ranges from 110 to 145 pcf (1760 to 2320 kg/m^3). Although brick originally contains no free water, the pore structure of brick will allow moisture to be absorbed from the environment.

COMPOSITION OF CONCRETE

Concrete is a heterogeneous material consisting of aggregates and cement paste. Initially aggregates are mixed with paste comprised of portland cement and water. A chemical reaction between the cement and water causes the paste to harden and bind the aggregates into a rocklike mass.[7] Physical properties of concrete are affected by the type of aggregate used, the amount of water used in the paste, air-entraining agents, and other admixtures.

Since aggregates normally make up 60 to 75% of the volume of concrete, the density of the concrete, which can vary from 15 to 400 pcf (240 to 6400 kg/m^3), is affected by density of the aggregate. Normal-weight concrete with a density of 150 pcf (2400 kg/m^3) usually contains aggregates of sand and gravel or crushed stone. Lightweight concretes with densities of 15 to 120 pcf (240 to 1920 kg/m^3) have aggregates of expanded materials such as perlite, vermiculite, blast-furnace slag, fly ash, clay, shale, or slate. Lightweight concretes are also made using a foam that produces a uniform cellular structure of air voids in concrete. Heavyweight concretes, normally used for radiation shielding, may have densities up to 400 pcf (6400 kg/m^3). These use special heavy aggregates such as hematite, magnetite, ferrophosphorus, or steel punchings.[7]

An increase in the volume of voids in concrete results in a decrease in the density of concrete. Three types of voids may exist in hardened concrete. A mix containing excess water that is not used in the cement hydration process will produce voids in concrete. Therefore, a higher water-cement ratio will result in a higher volume of voids in the concrete. These voids may or may not contain water depending on the moisture condition of the environment. Relatively larger microscopic voids are produced when air-entraining agents are added to a concrete mix. Air-entraining agents are used to increase the durability of concrete under freeze-thaw conditions. The largest voids in concrete are caused by accidentally entrapped air. These are usually large enough to be seen with the unaided eye.

The quantity of voids in concrete due to excess water and entrained air can be controlled by mix design. The quantity of voids due to entrapped air is controlled by the method of placement as well as by mix design. A concrete mix can be designed to minimize entrapped air for the particular method of placement used. The presence of any of these three types of voids decreases the density of concrete.[8]

Concrete masonry thermal storage mass in passive solar systems is usually made of normal-weight concrete. Since aggregates make up about 90% of concrete block, the density of block depends primarily on the type of aggregate used.(5)

SPECIFIC HEAT

For passive solar design applications specific heat is used to determine the storage capacity of the thermal mass. Specific heat is defined as the ratio of the change in heat supplied to a body to its corresponding temperature rise divided by the mass of the body. In U.S. units, the specific heat of water is equal to 1.00 Btu/lb·°F (4187 J/kg·°K). Therefore, specific heat may also be defined, for U.S. units, as the ratio of the amount of heat required to raise the temperature of a given mass of a material one degree Fahrenheit to the amount of heat required to raise the temperature of an equal mass of water one degree Fahrenheit.

Test Methods for Determining Specific Heat

The most common test method for determining specific heat of concrete and clay masonry materials is the U.S. Army Corps of Engineers Specification CRD-C124-73, "Method of Test for Specific Heat of Aggregates, Concrete, and Other Materials (Method of Mixtures)."(9) Specific heat of numerous building materials including concrete and clay masonry has also been determined using an adiabatic calorimeter.(10) Both methods will be discussed.

For test method CRD-C124-73 samples of crushed material are heated in a warm bath at 125±1°F (51.7±0.6°C) and then transferred to a calorimeter containing room temperature water. The specific heat is found by measuring the temperature change of the water in the calorimeter. Since this is a wet method, the specific heat determined is that of the saturated material. To determine the specific heat of the material in a dry state, weights of the material in the particular dry state, and the saturated surface dry (SSD) state must be known.

Whiting, Litvin, and Goodwin(11) used the following equation to calculate specific heat of concrete for various moisture conditions:

$$c = \frac{c_{SSD} + \gamma\,(y-1)}{1 + \gamma\,(y-1)} \qquad (1)$$

where:

c = specific heat of samples at any moisture content

c_{SSD} = specific heat of saturated surface dry samples

y = moisture content expressed as a fraction of the SSD moisture content

γ = SSD moisture content

$$\gamma = \frac{W_{SSD} - W_{OD}}{W_{SSD}} \qquad (2)$$

where:

W_{SSD} = SSD weight of sample

W_{OD} = ovendry weight of sample

Equation (1) may also be used to find the specific heat of brick. Although CRD-C124-73 does not specify that the sample must be in the SSD state, the value of specific heat in the SSD state is necessary for use of Eq. (1).

Test methods for thermal properties frequently require either an ovendry or saturated surface dry specimen to eliminate the effects of moisture migration or the change of state of the water. Either effect can produce results that are difficult to interpret.

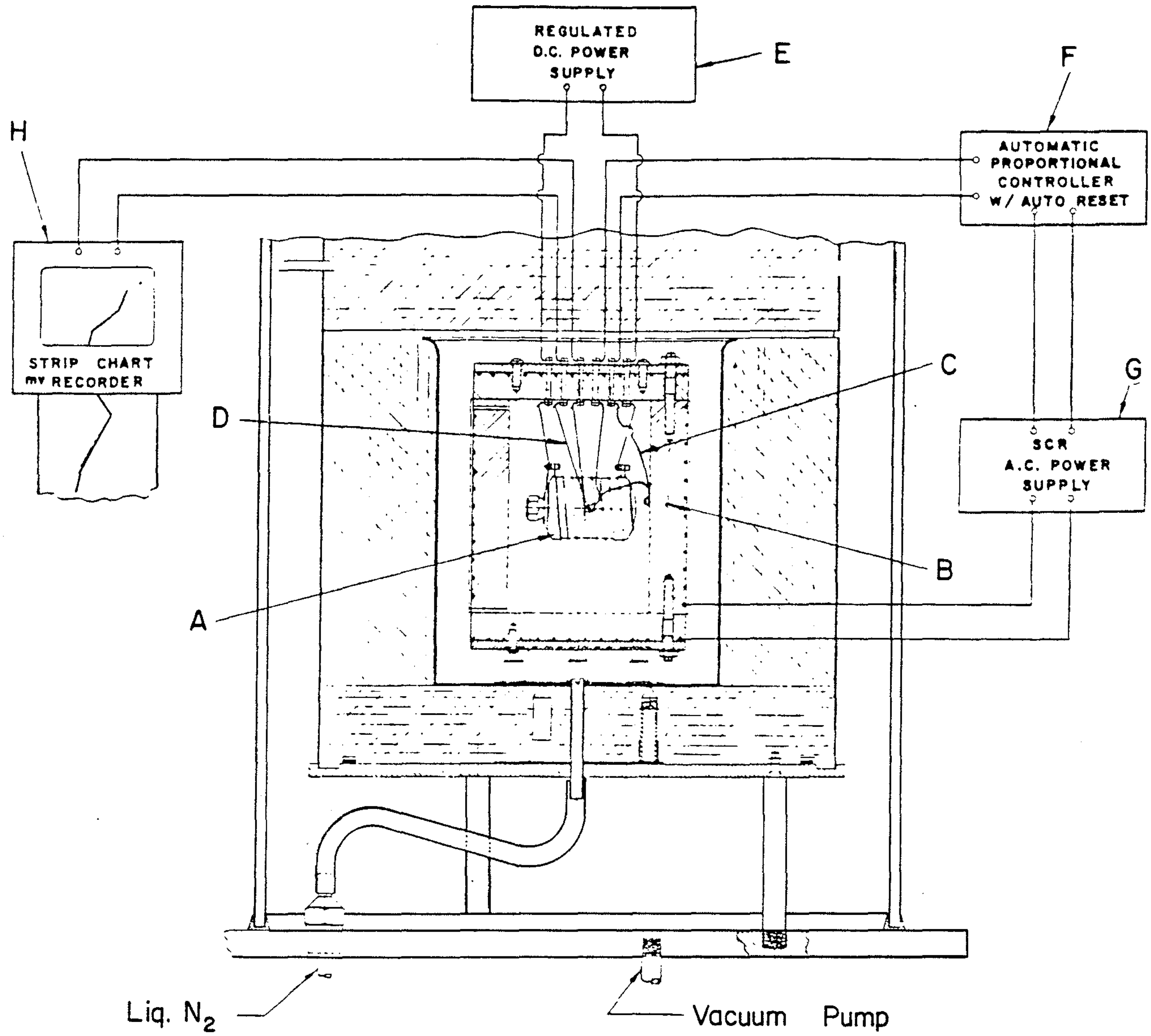
Ovendry specimens were used by Tye and Spinney for evaluation of specific heat using the adiabatic calorimeter.[10] A record of sample and container enthalpy change with temperature is derived using data from a constant output, continuous heater, and a continuous record of the sample temperature variation with time.[10] A schematic diagram of an adiabatic calorimeter is shown in Fig. 4. Since the value of specific heat found using this method is for the ovendry state, the weight of the specimen in both the ovendry and normally dry state is necessary to calculate specific heat for the normally dry state.

Specific Heat of Brick

Figure 5 shows data on the specific heat of clay brick as a function of density. The data were obtained from several sources.[6,10,12,13] For clay brick with densities ranging from 120 to 142 pcf (1920 to 2270 kg/m^3), specific heat ranges from 0.19 to 0.24 Btu/lb·°F (795 to 1005 J/kg·°K). There is no apparent relationship between specific heat and density of brick for these limited data. Brick clays are natural materials that can vary greatly in composition. The range of specific heat values for similar density brick may be due to the variation in brick clays, different test methods, or the effect of moisture.

Effect of moisture content

Specific heat of a given specimen increases as the moisture content increases. Equation (1) which was used to convert the specific heat of a SSD specimen to that of a normally dry specimen is based on the following:[11]



LEGEND

A Sample Container — Heater assembly
B Adiabatic Jacket
C Differential Thermocouple Providing Jacket Control Signal
D Thermocouple for Recording Sample Temp.

Fig. 4 Schematic Diagram of Adiabatic Calorimeter for Determining Specific Heat [10]

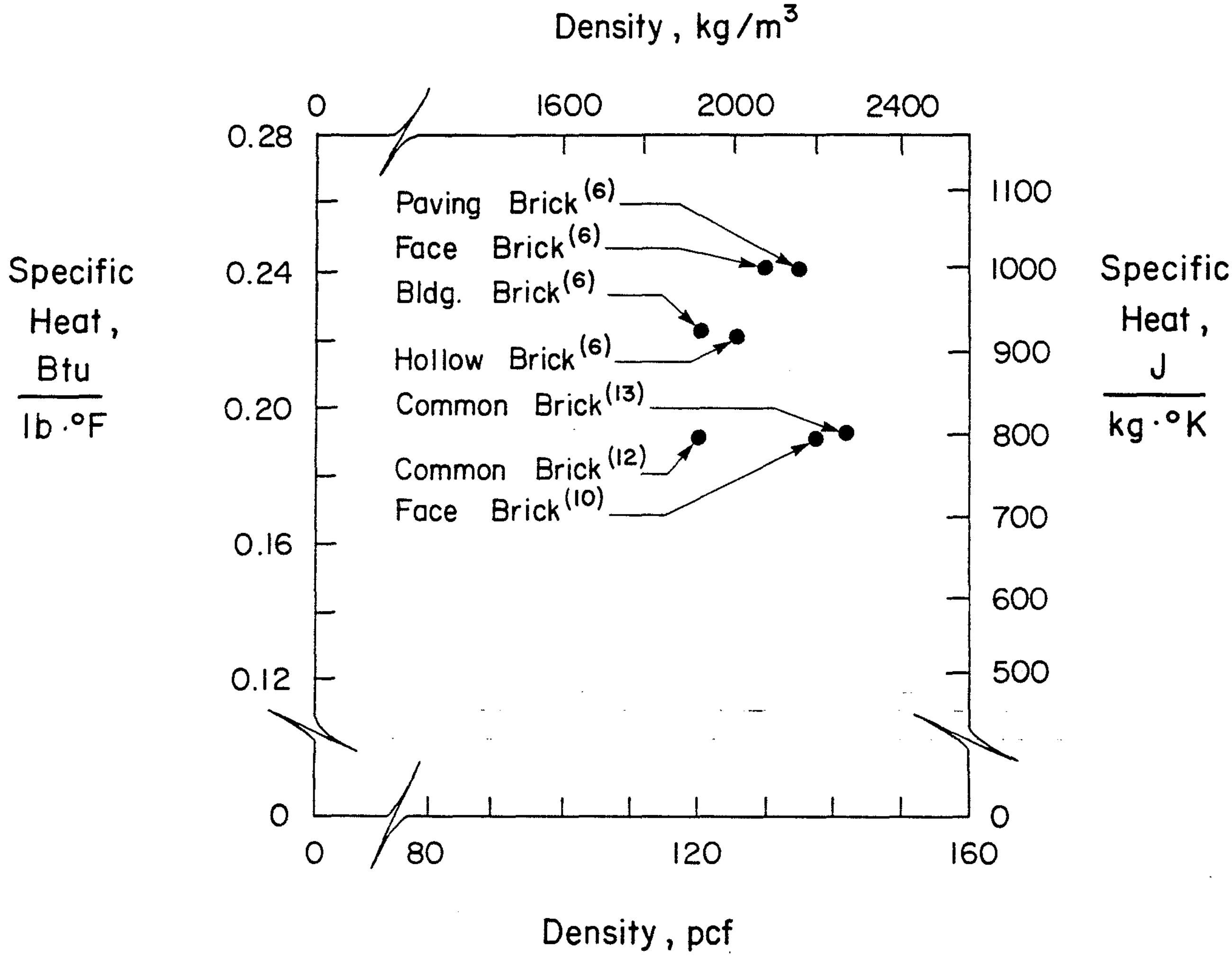


Fig. 5 Specific Heat of Clay Brick as a Function of Density

$$c = c_s W_s + c_w W_w \tag{3}$$

where:

c = specific heat of material

c_s = specific heat of solid phase

W_s = weight fraction of solid phase

c_w = specific heat of free water

= 1.0 Btu/lb·°F (4187 J/kg·°K)

W_w = weight fraction of water

Since specific heat of water is about five times the specific heat of masonry materials, addition of a small amount of water has a large effect on specific heat.

Moisture content of clay brick or concrete is generally expressed in one of three ways. Equation (2) can be used to express moisture content in terms of percent of total saturation. Moisture content can also be expressed in terms of percent moisture by volume and percent moisture by ovendry weight. Published reports on thermal properties frequently do not list sufficient data to convert percent moisture by volume or ovendry weight to percent of total saturation.

The value used for specific heat of a normally dry material depends on the moisture content assumed for the normally dry condition. Values of moisture content for normally dry masonry as recommended by Loudon[14] are shown in Table 1. Exposed values are for building components not protected from rain. These values are approximate and may be raised or lowered depending on the climate, amount of protection, and predominant wind direction.[14]

Therefore, although brick is originally dry, its moisture content may rise to 1 to 3% by volume. This will result in an increase in the value

TABLE 1. STANDARD MOISTURE CONTENTS FOR PROTECTED AND EXPOSED CLAY BRICK AND CONCRETE[14]

Material	Moisture Content, % by Volume	
	Protected Conditions	Exposed Conditions
Brickwork	1.0	3.0
Aerated Concrete and Lightweight Aggregate Concrete	5.0	8.0
Gravel Aggregate Concrete	2.5	5.0

of specific heat that can be determined using Eq. (3). However, no test data were found to confirm the relationship of an increase in the value of specific heat of brick with an increase in moisture content.

Neither test method cited in the literature measures the specific heat of samples at different moisture contents. The data point attributed to Tye and Spinney[10] in Fig. 5 is for an ovendry sample using the adiabatic calorimeter. The value measured by CTL[13] for brick was found by a method similar to CRD-C124-73. The result was converted to an ovendry value. Test methods used to determine the values given in BIA Bulletin 43D[6] and the ASHRAE Handbook[12] are not known. The values are assumed to be for ovendry specimens.

Effect of clay composition

According to BIA Bulletin 43D variations in specific heat of brick are generally due to impurities, particularly metallic oxides in the clay used to produce the brick. Red, brown, and blue bricks may contain high amounts of metallic oxides relative to other bricks. Up to 35% of the brick by weight may be metallic oxides. Face brick may contain more metallic oxides than common brick. Consequently, the specific heat of face brick may be higher than that for common brick.[6]

More research should be done to determine the effects of metallic oxides on the specific heat of clay brick, any significant differences between the specific heat of face brick and that of common brick, and relationship of specific heat versus density for brick at normal temperatures. Most data found in the literature are for clay brick heated to refractory level temperatures.

Specific Heat of Concrete

Specific heat of concrete depends on its moisture content, density, and temperature. Values discussed here include only those found from tests and do not include calculated values obtained from heat transfer equations.

Effect of moisture content

The specific heat of a given concrete increases as its moisture content increases as shown in Fig. 6. The effect of moisture content on specific heat is more pronounced for lightweight concrete than for normal-weight concrete. This occurs for three reasons. First, the $c_w W_w$ term of Eq. (3) is more significant for lightweight concretes because they have a lower value of W_s. Second, lightweight concretes absorb more moisture in their SSD state than normal-weight concretes do. Figure 7 shows that a concrete with a density of 140 pcf (2240 kg/m^3) absorbs less than 10 pcf (160 kg/m^3) of water, whereas a lightweight concrete with a density of 30 pcf (480 kg/m^3) may absorb 35 pcf (560 kg/m^3) of water.(15) Thus, the significance of the W_w term in Eq. (3) is increased for lightweight concretes. Third, the fraction of normally dry weight to SSD weight is subject to greater laboratory error for lightweight concrete because of variations in SSD weights found using different test methods on equivalent specimens. The SSD weight of a lightweight concrete specimen boiled in water is often different from that found by soaking the specimen.(15)

As previously mentioned, the value used for specific heat of a normally dry material depends on the moisture content assumed for the normally dry condition. The moisture content for the normally dry state

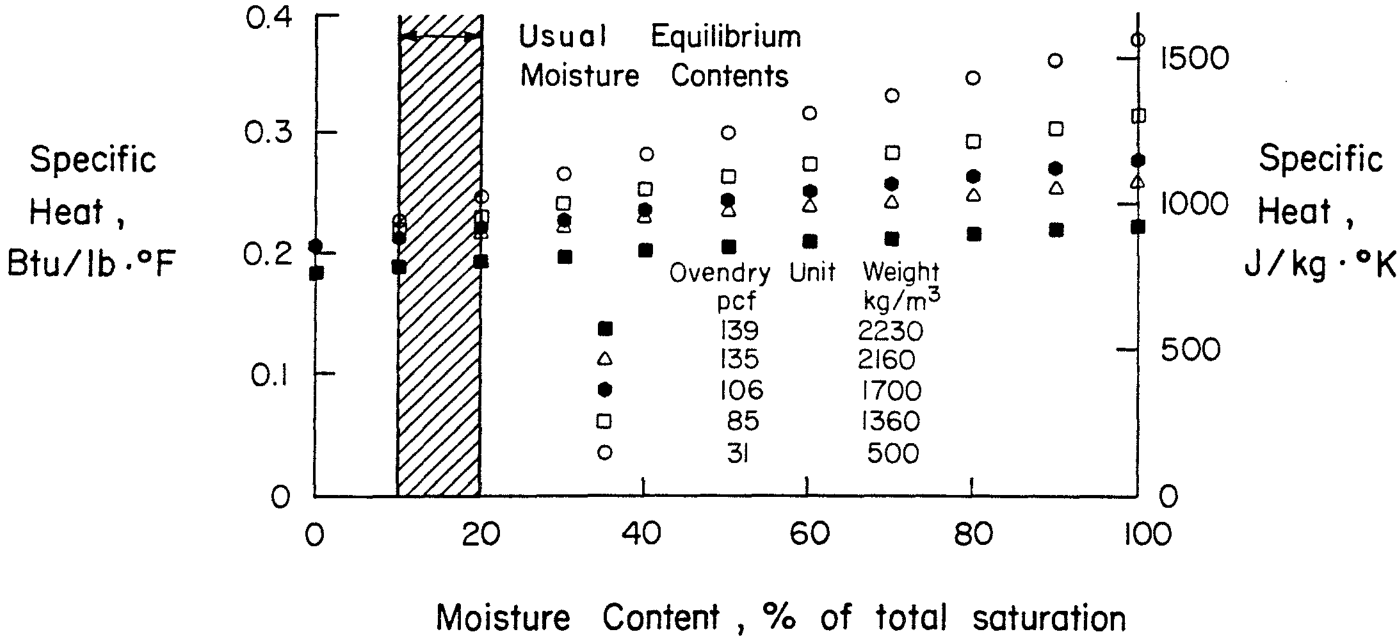


Fig. 6 Specific Heat of Concrete as a Function of Moisture Content(11)

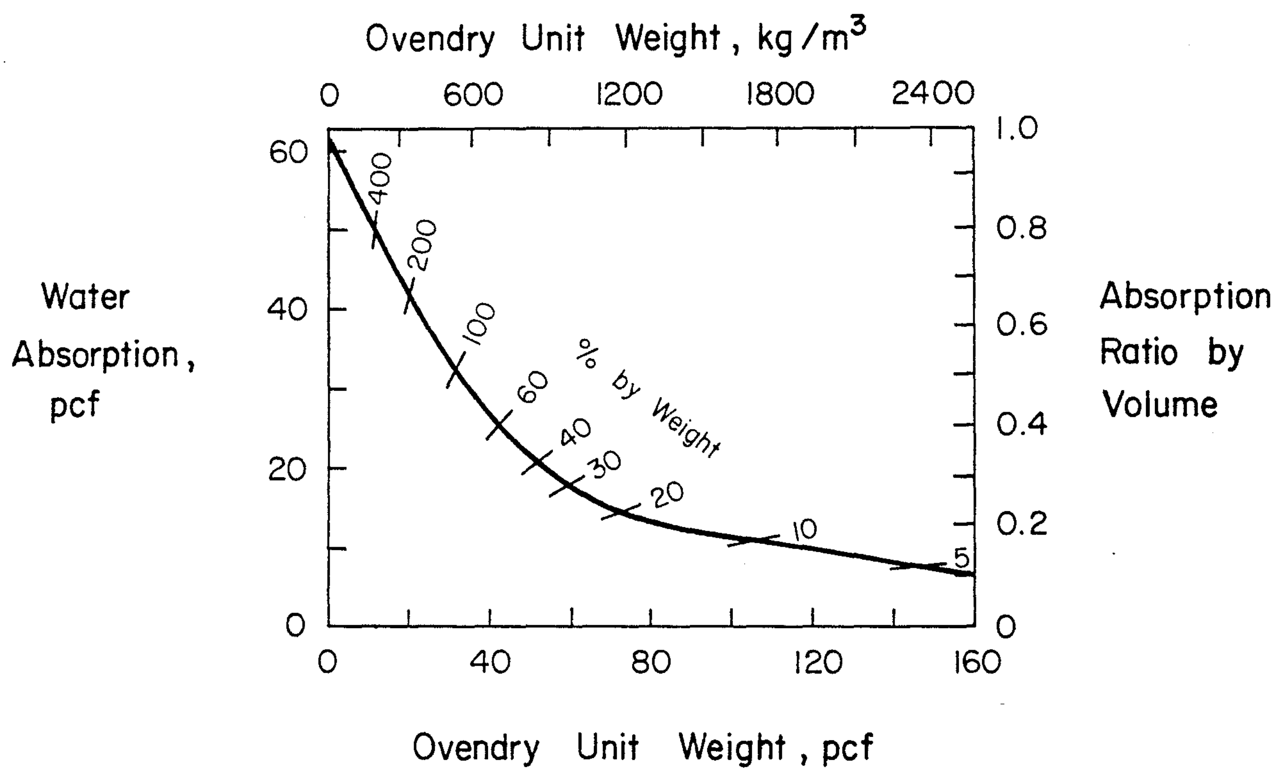


Fig. 7 Average Absorptions of Concretes(15)

is generally taken as the amount of free water retained after an extended period of drying at 35 to 50% relative humidity.[15] According to Brewer[15] this "equilibrium" amount of free water ranges from 7% of total saturation for concrete with an ovendry density of 20 pcf (320 kg/m^3) to 16% of total saturation for normal-weight concrete with an ovendry density of 150 pcf (2400 kg/m^3).

Figure 8 shows published values for moisture contents of normally dry concretes. The data show a wide variation in normally dry moisture contents at a given density. Lightweight concrete values have a larger range of variation than normal-weight concrete values. The curve shown in Fig. 8 represents values of moisture content proposed by Brewer[15] for normally dry concrete. Values recommended by Loudon[14] are shown in Table 1.

The moisture content of normally dry masonry should be determined when specific heat tests are conducted so that the specific heat of the normally dry specimen can be calculated. There is a large variation of values of moisture contents suggested in the literature, particularly for concretes with a density less than 100 pcf (1600 kg/m^3).

Effect of density

The relationship between density and specific heat of concrete in the ovendry, normally dry, and saturated surface dry conditions is of significance for evaluation of thermal responses. Specific heat for ovendry specimens increases with increased density. For normally dry specimens specific heat is essentially constant and dependence on density is not significant. Specific heat for SSD specimens is substantially higher for lightweight concrete than for normal-weight concrete.

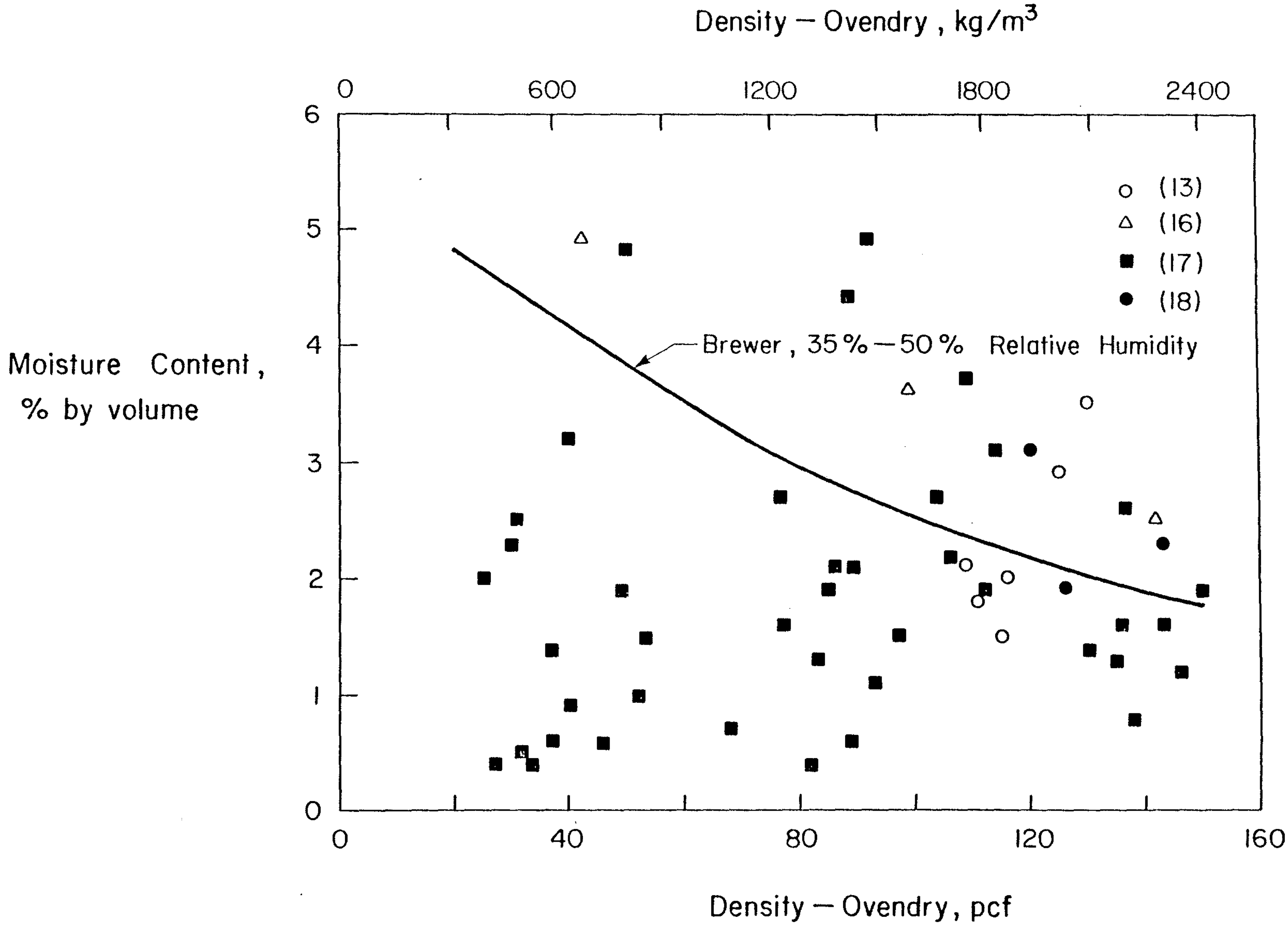


Fig. 8 Moisture Content of Normally Dry Concrete as a Function of Density

Some ovendry lightweight concrete specimens have lower values of specific heat than normal-weight concrete specimens as shown in Fig. 9. This relationship is probably due to the types of aggregates used in lower density concretes. Values of specific heat for ovendry concrete made with perlite aggregate are significantly lower than those for ovendry concrete with polystyrene beads as aggregate.[11,13,16]

When compared to Fig. 9, the data of Fig. 10 indicate specific heat of normally dry concrete is relatively constant for all densities. The normally dry moisture contents used to derive values of specific heat in Fig. 10 are those proposed by Brewer and shown in Fig. 8.

Based on data shown in Fig. 10, the mean value of specific heat for normally dry concrete is 0.19 Btu/lb·°F (800 J/kg·°K). The 95% confidence interval for the data, the mean plus or minus two standard deviations, is from 0.15 to 0.23 Btu/lb·°F (630 to 960 J/kg·°K). Therefore, for a sample of 20 points, about 19 values of specific heat would fall between 0.15 and 0.23 Btu/lb·°F (630 to 960 J/kg·°K) and the expected value would be 0.19 Btu/lb·°F (800 J/kg·°K). The variance is greater for lower density concretes than higher density concretes. As previously discussed, this is probably due to increased variations in measured values of moisture content and the greater effect of type of aggregate used for lower density concretes.

The correlation coefficient for a regression between specific heat and density of the data for normally dry concrete is 0.07. A correlation coefficient of zero indicates no linear relationship between two variables, and a correlation coefficient of 1.0 indicates total dependence of one variable on the other. Therefore, for this set of data, density and specific heat are essentially independent for normally dry concrete.

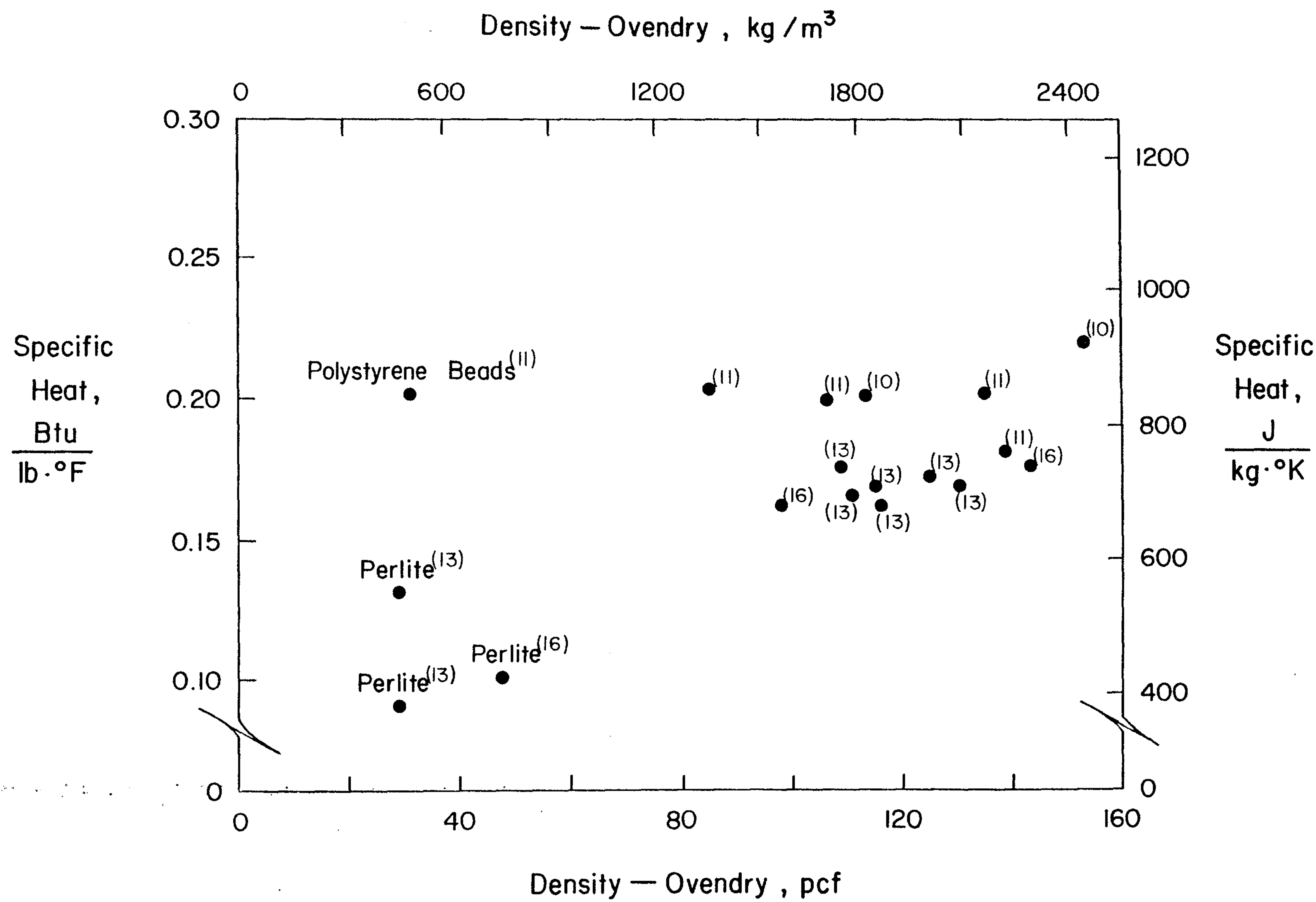


Fig. 9 Specific Heat of Ovendry Concrete as a Function of Density

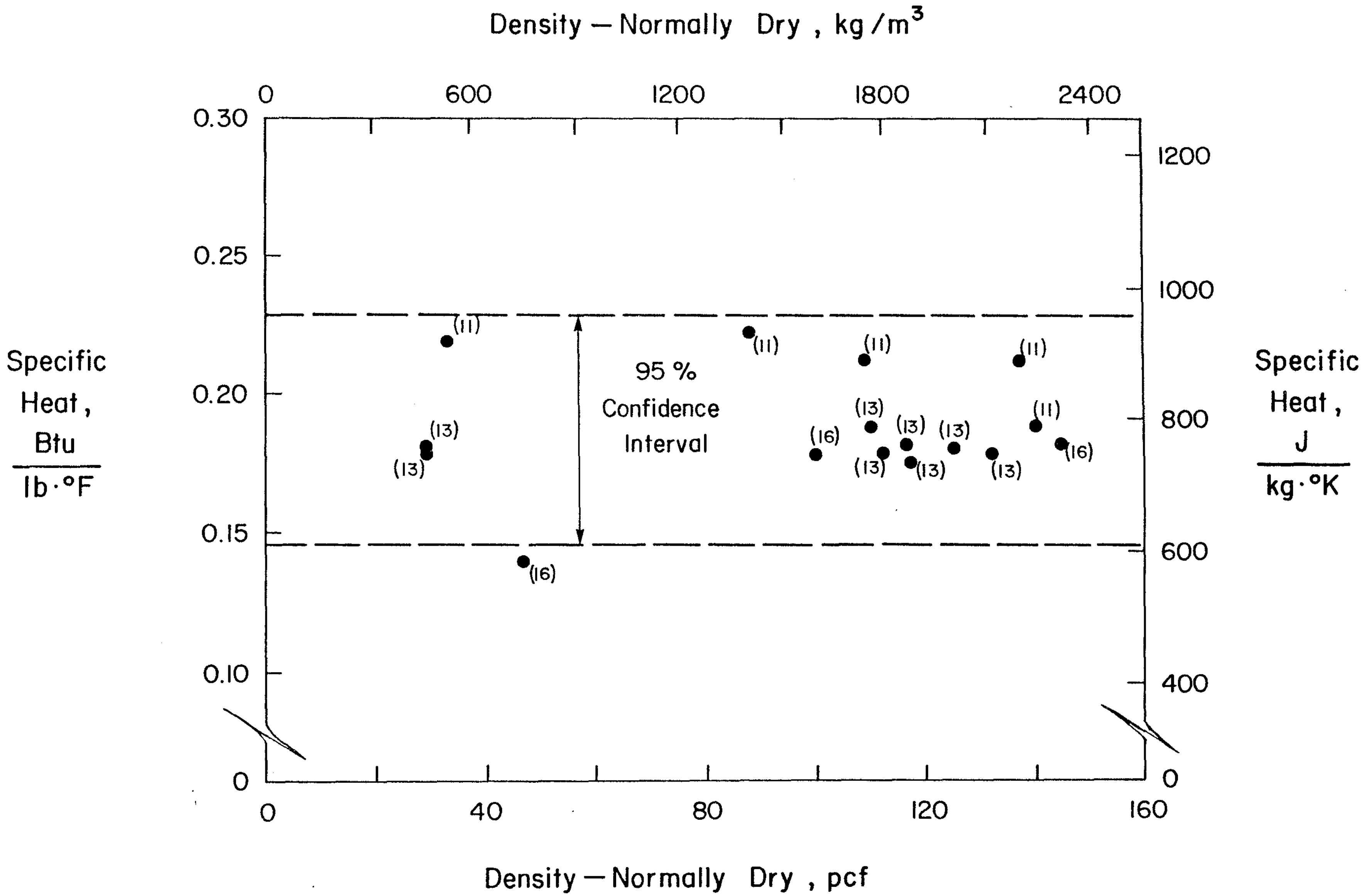


Fig. 10 Specific Heat of Normally Dry Concrete as a Function of Density - Using Moisture Contents of Normally Dry Concrete Proposed by Brewer

However, assuming different moisture contents for normally dry concrete gives different results. Figure 11 shows values of specific heat for normally dry specimens where the moisture content of normally dry concrete is assumed to be 20% of total saturation. For this case specific heat is dependent upon density. Values of specific heat for low density concrete are higher than that those for normal-weight concrete.

Specific heat of lower density SSD concrete is significantly higher than the specific heat of higher density concrete, as shown in Fig. 12. The effect is due to the greater absorption and therefore a greater amount of free water in the lower density concretes.

The curve in Fig. 12 represents the specific heat of SSD samples calculated by the following equation:

$$c_{SSD} = \frac{W_{ND}}{W_{SSD}} \times c_{ND} + \frac{W_{\Delta w}}{W_{SSD}} \times c_w \qquad (4)$$

where:

c_{SSD} = specific heat of SSD specimen

W_{ND} = weight of normally-dry specimen

W_{SSD} = weight of SSD specimen

$W_{\Delta w}$ = weight of additional water in SSD state compared to that in normally dry state

c_{ND} = specific heat of normally dry specimen; assumed to be 0.19 Btu/lb·°F (795 J/kg·°K) for all densities

c_w = specific heat of water = 1.0 Btu/lb·°F (4187 J/kg·°K)

Equation (4) assumes the specific heat of normally dry concrete for all densities to be 0.19 Btu/lb·°F (795 J/kg·°K). Moisture contents used to plot the equation are those used by Brewer and are shown in Table 2.

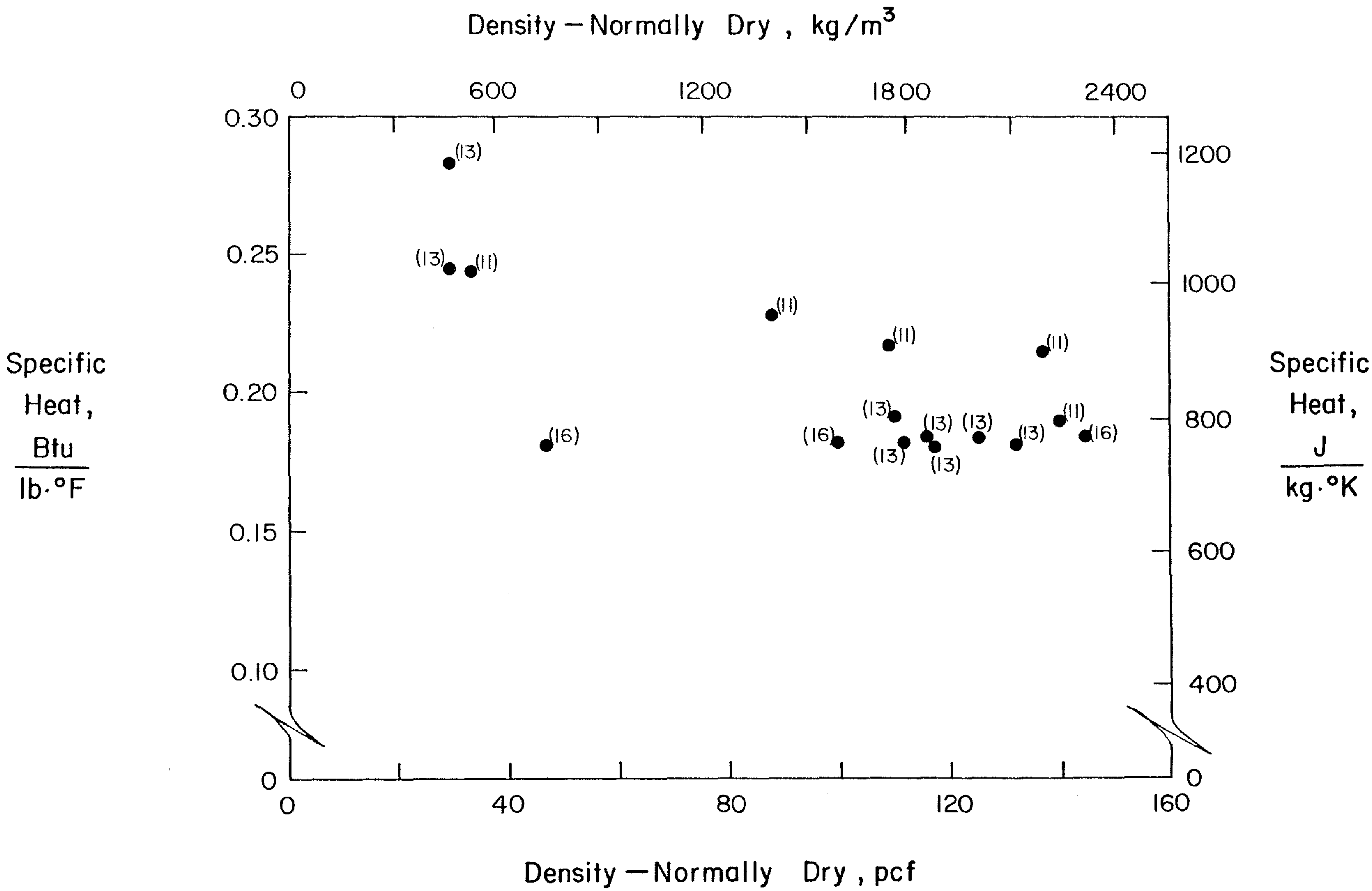


Fig. 11 Specific Heat of Normally Dry Concrete as a Function of Density - Moisture Content in Terms of Percent of Total Saturation is Constant

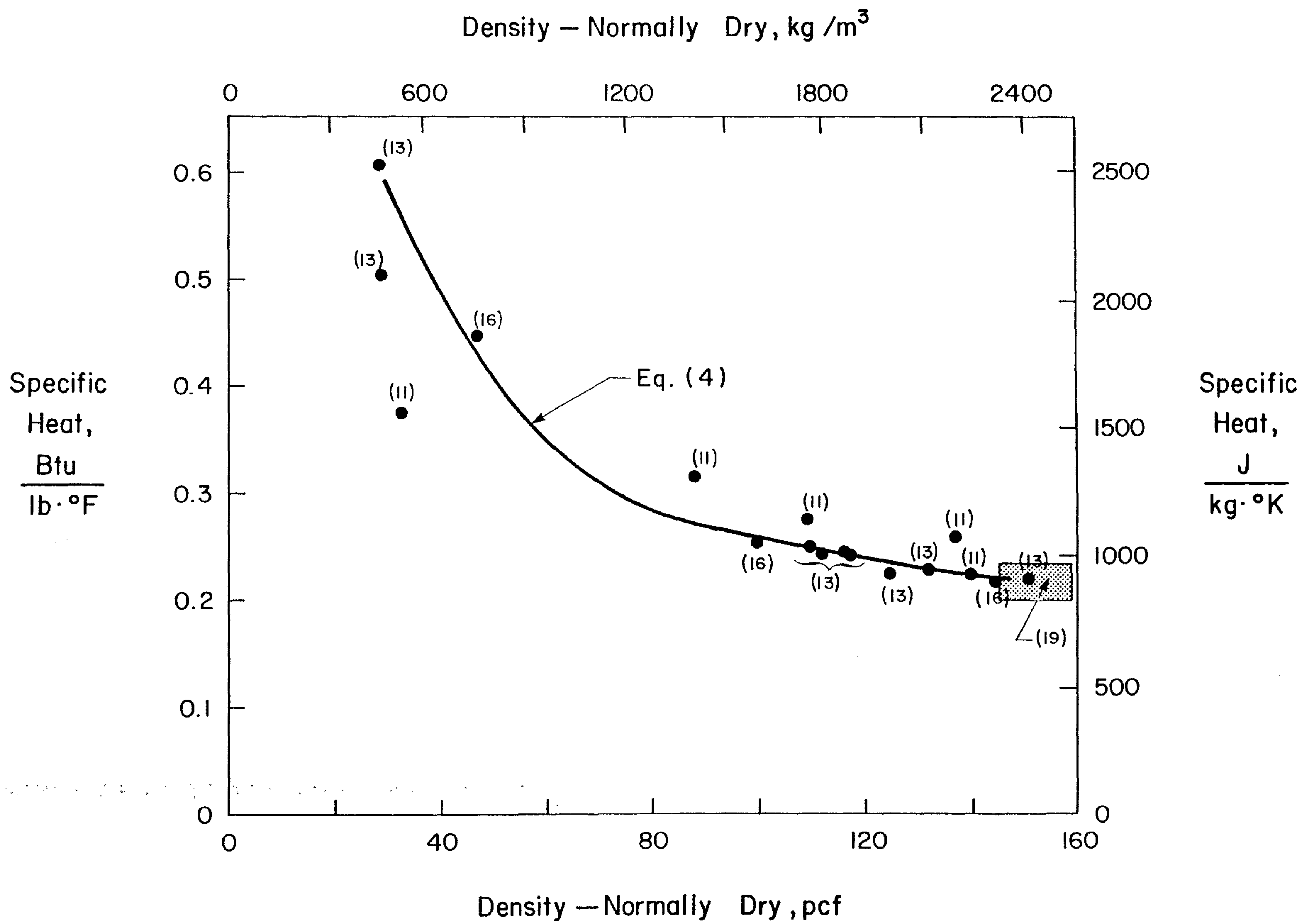


Fig. 12 Specific Heat of SSD Concrete as a Function of Density

TABLE 2. UNIT WEIGHT OF OVENDRY, NORMALLY DRY, AND SATURATED SURFACE DRY CONCRETE PROPOSED BY BREWER[15]

Ovendry Unit Weight pcf (kg/m^3)	Normally Dry		SSD	
	Free Water pcf (kg/m^3)	Unit Weight pcf (kg/m^3)	Free Water pcf (kg/m^3)	Unit Weight pcf (kg/m^3)
20 (320)	3.0 (48)	23.0 (368)	43.0 (689)	63 (1009)
30 (481)	2.8 (45)	32.8 (525)	34.0 (545)	64 (1025)
40 (641)	2.6 (42)	42.6 (682)	27.0 (433)	67 (1073)
50 (801)	2.4 (38)	52.4 (839)	21.7 (348)	71.7 (1149)
60 (961)	2.2 (35)	62.2 (996)	17.3 (277)	77.3 (1238)
70 (1121)	2.0 (32)	72.0 (1153)	15.0 (240)	85.0 (1362)
80 (1282)	1.8 (29)	81.8 (1310)	13.2 (211)	93.2 (1493)
90 (1442)	1.7 (27)	91.7 (1469)	12.0 (192)	102.0 (1634)
100 (1602)	1.6 (26)	101.6 (1627)	11.0 (176)	111.0 (1778)
110 (1762)	1.5 (24)	111.5 (1786)	10.1 (162)	120.1 (1924)
120 (1922)	1.4 (22)	121.4 (1945)	9.3 (149)	129.3 (2071)
130 (2083)	1.3 (21)	131.3 (2103)	8.6 (138)	138.7 (2222)
140 (2243)	1.2 (19)	141.2 (2262)	7.8 (125)	147.8 (2368)
150 (2403)	1.1 (18)	151.1 (2420)	7.0 (112)	157.0 (2515)

Since CRD-C124-73 uses a saturated sample, many data points are available for the specific heat of SSD concrete. Most of these data are for normal-weight concrete used in dams. Reports of these data do not record SSD or submerged weights and the corresponding normally dry weights of specimens. Therefore, determination of the normally dry specific heat for the data is not possible. Additional research is needed to define the specific heat of normally dry and ovendry specimens and to verify the specific heat versus density relationships discussed previously.

Effect of temperature

Specific heat of concrete increases as the mean temperature of the specimen increases. Figure 13 shows this relationship for mean temperatures ranging from 50 to 150°F (10 to 66°C). These data, from Boulder Canyon reports by the U.S. Bureau of Reclamation,[19] are for submerged normal-weight concrete samples and were found using a method similar to CRD-C124-73.

The maximum operating mean temperature range for thermal storage mass would be from approximately 60 to 110°F (16 to 43°C). These temperatures can occur in a trombe wall on a sunny day. For temperature in this 50°F (27°C) range, specific heat increases by about 10%. The same relationship may be true for normally dry and ovendry samples, but no data were found to verify this assumption.

THERMAL CONDUCTIVITY

Thermal conductivity is used to predict steady-state heat flow or heat losses through a thermal storage mass. Thermal conductivity is defined as the rate of heat flow through a body of unit thickness and unit area with

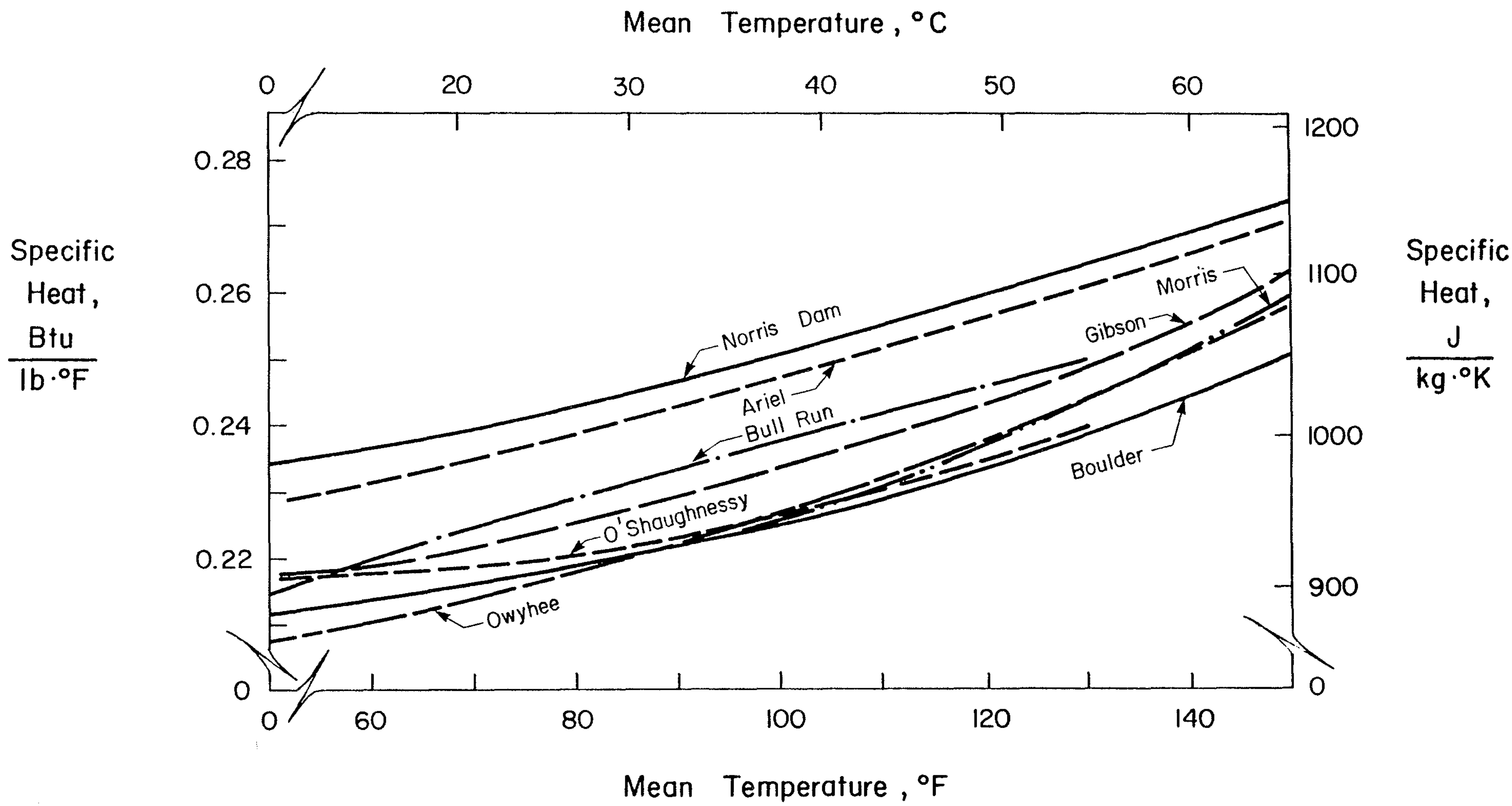


Fig. 13 Specific Heat of Concrete as a Function of Temperature (19)

a unit temperature difference between the two surfaces. Four test methods for determining thermal conductivity of masonry materials are discussed. The dependence of thermal conductivity on moisture content, density, and mean temperature of the material are shown.

Test Methods for Determining Conductivity

The three test methods most commonly used to determine thermal conductivity of clay brick and concrete are the guarded hot plate (ASTM Designation: C 177),[20] the heat flow meter (ASTM Designation: C 518),[21] and the hot wire method. Thermal conductivity may also be derived using the guarded hot box (ASTM Designation: C 236)[22] or the calibrated hot box (ASTM Designation: C 976).[23] Each method has associated advantages and disadvantages. A report by Tye and Spinney, "Thermal Conductivity of Concrete: Measurement Problems and Effect of Moisture,"[24] contains a thorough analysis of the guarded hot plate, guarded hot box, and heat flow meter test methods.

Guarded hot plate

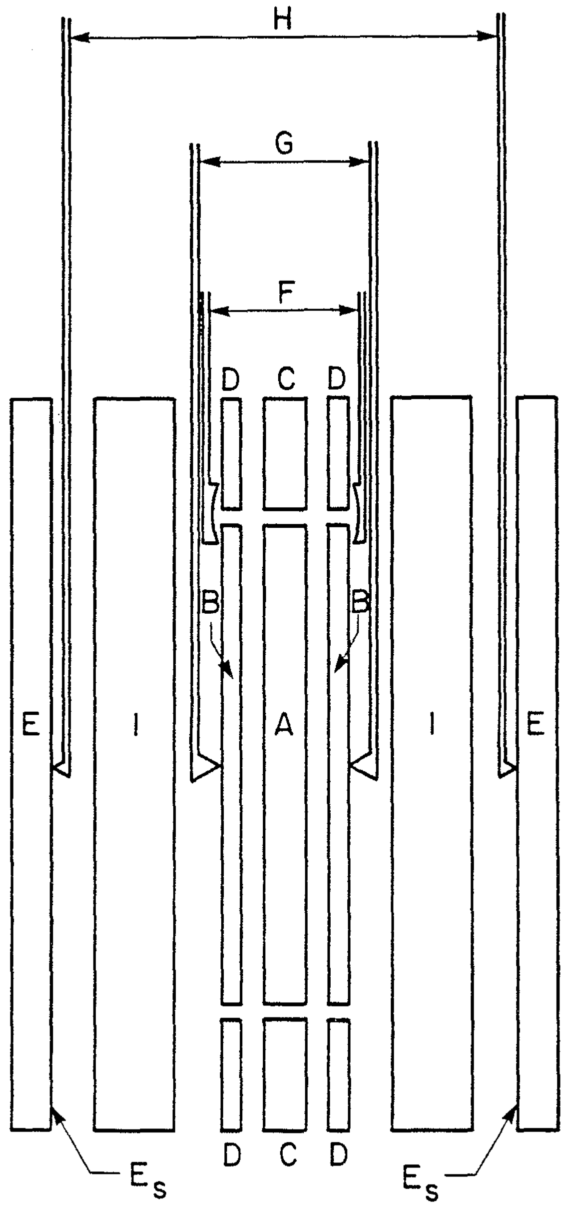
In the guarded hot plate method two thin slabs of test material are placed between "hot" and "cold" plates as illustrated in Fig. 14. When steady-state equilibrium is reached, the temperature of each side of both specimens is measured. Thermal conductivity can then be calculated using the following equation:

$$k = \frac{Q \cdot t}{A \cdot (T_1 - T_2)} \tag{5}$$

where:

k = thermal conductivity of specimen, $\frac{\text{Btu} \cdot \text{in.}}{\text{hr} \cdot \text{ft}^2 \cdot {}^\circ\text{F}} \left(\frac{\text{W}}{\text{m} \cdot {}^\circ\text{K}}\right)$

Q = time rate of heat flow, $\frac{\text{Btu}}{\text{hr}}$ (W)



A-Metering Area Heater
B-Metering Area Surface Plates
C-Guard Heater
D-Guard Surface Plates
E-Cooling Units
E_s-Cooling Unit Surface Plates
F-Differential Thermocouples
G-Heating Unit Surface Thermocouples
H-Cooling Unit Surface Thermocouples
I-Test Specimens

Fig. 14 General Features of the Metal-Surfaced Guarded Hot Plate Apparatus [20]

t = thickness of specimen, in. (m)

A = effective area of hot plate, ft^2 (m^2)

T_1 = temperature of warm surface of specimen, °F (°K)

T_2 = temperature of cold surface of specimen, °F (°K)

In standard practice, thermocouples are placed on the surface of the test specimen. Tye and Spinney(24) advocate the use of embedded thermocouples for materials with a thermal conductivity greater than 0.7 $Btu \cdot in./hr \cdot ft^2 \cdot °F$ (0.1 W/m·°K). This may be done by placing 0.2 mm diameter thermocouples into 0.3 mm wide and 0.3 mm deep grooves cut into the surfaces on each side of the sample. A cement is used to seal voids between the thermocouple and the groove. The depth of one groove is subtracted from the thickness of the specimen to obtain the thickness to be used in calculating conductivity. According to Tye and Spinney, if thermocouples are not embedded in the specimen, a contact resistance may be introduced between the thermocouple junction and the concrete surface. This will result in an artificially large temperature difference (T_1-T_2) across the specimen. Consequently, the calculated value of conductivity will be too low.(24)

The aggregate and paste of concrete may each have unique conductivities. To measure conductivity of the heterogeneous material, thermocouples should not be placed on large pieces of aggregate that may act as a thermal shunt.(24) For the same reason, specimens should be thick enough to avoid measuring the conductivity of the aggregate alone. Tye and Spinney(24) recommend a test specimen thickness of at least 4-1/2 times the maximum aggregate size and a test specimen width of at least 15 times the maximum aggregate size.

Researchers acknowledge that moisture migration takes place in steady-state methods such as the guarded hot plate. According to Ball:[17]

> The process of heat transfer through a porous material such as concrete is complex, involving conduction through the solid component and radiation and convection within the pores or voids. With moist materials latent heat transfer also occurs by evaporation and condensation of moisture within the material. The combined result of these transfer mechanisms is expressed as a single coefficient, thermal conductivity.

Tye and Spinney[24] and Ball[17] publish values of thermal conductivity for moist materials using the guarded hot plate. However, according to Thompson,[25] it is

> impossible to measure the thermal conductivity of concrete by the normal steady-state method, except when the concrete is dried to a constant weight at a temperature above the maximum used in the test, for instance by oven drying.

It can be concluded that a steady-state test method used on a moist sample will result in a value for thermal conductivity that reflects moisture migration as well as heat transfer.

Guarded or calibrated hot box

The guarded hot box is a method that is used to measure the heat transmission properties of wall or roof assemblies. Using a guarded hot box, as illustrated in Fig. 15, the test specimen is placed between a cold box and guard box. A metering box inside the guard box defines the test area. A predetermined temperature differential is maintained across the test specimen until constant heat flow conditions are established. The metering box and the guard box are held at the same temperature. Thus, heat input to the metering box is a measure of heat flow through the test specimen.

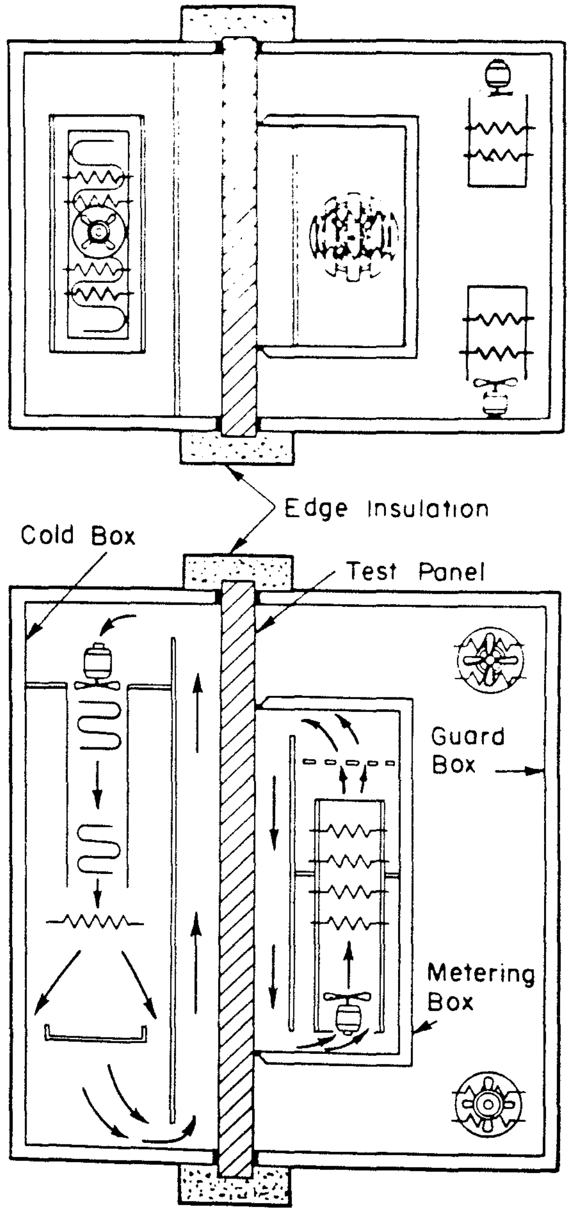


Fig. 15 Schematic Diagram of Guarded Hot Box (22)

After equilibrium conditions are established, measured heat input, air temperatures, surface temperatures, and test area are used to calculate thermal conductance.[26] For a solid homogeneous wall, conductivity of the wall material is equal to the wall thickness times the conductance. For walls with cores or voids, such as masonry walls, calculation of conductivity from conductance requires consideration of heat flow paths.

A calibrated hot box, as illustrated in Fig. 16, is similar to a guarded hot box. However, the calibrated hot box apparatus has no guard box. In effect, the laboratory space in which the apparatus is located serves as the guard.[26] The test specimen is placed between the outdoor and indoor chambers. The amount of energy required to maintain a constant temperature in the indoor chamber is used to calculate conductance of the test specimen.

For guarded or calibrated hot box tests, application of thermocouples is subject to the same surface contact resistance problem as that discussed for the guarded hot plate method. In addition, for concrete block or clay brick walls, thermocouples should be placed on the mortar and the block or brick units in approximately the same ratio that the components occur on the wall surface to obtain an average thermal conductivity. For example, a wall area that consists of 30% mortar and 70% brick should have 30% of the thermocouples placed on the mortar and 70% placed on the brick. Alternatively, thermocouple readings may be weighted according to the cross-sectional area of the components.[24]

Other considerations associated with guarded hot box and calibrated hot box tests are related to the size of the specimen. Enough time must

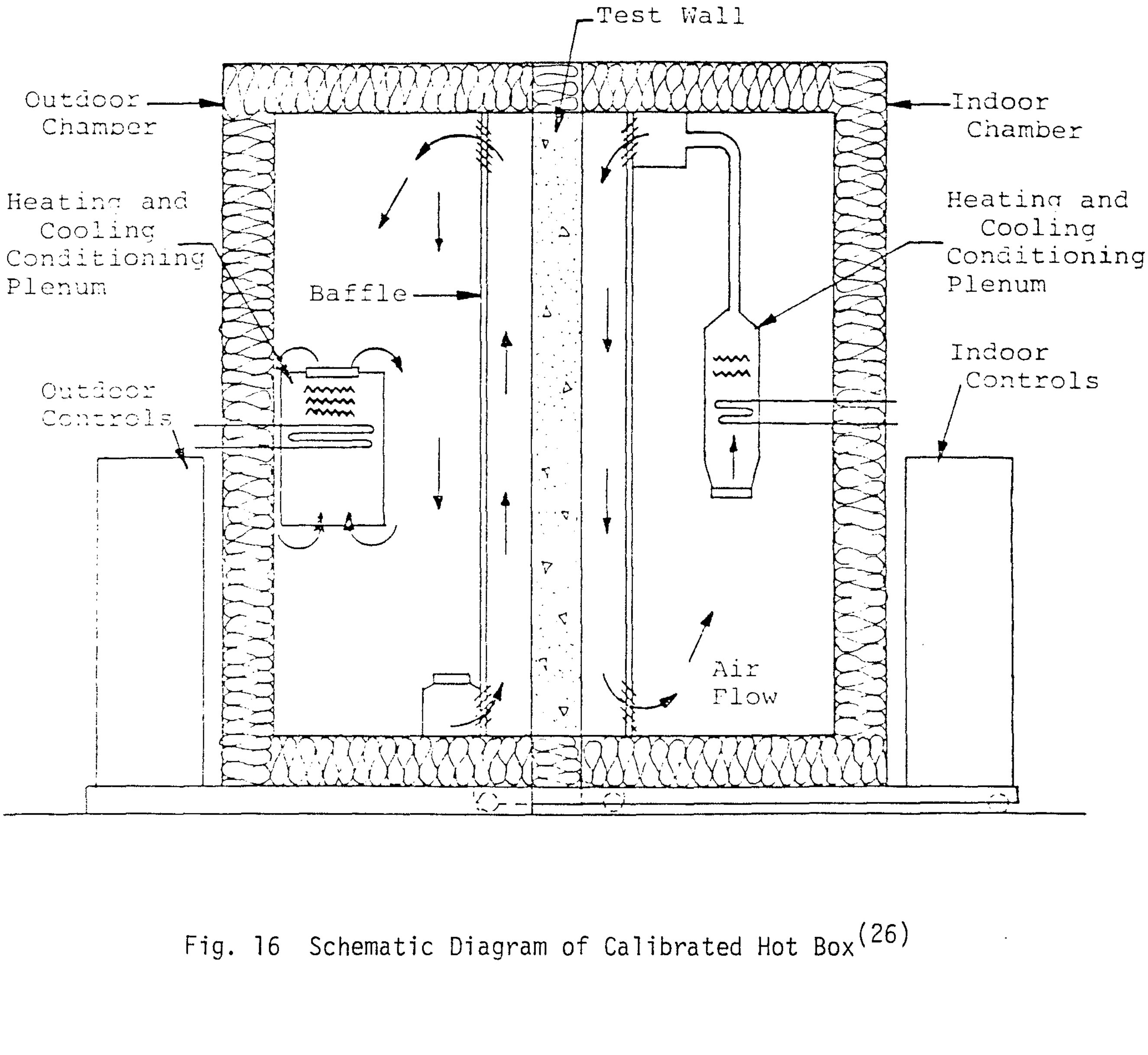


Fig. 16 Schematic Diagram of Calibrated Hot Box(26)

be allowed during the test for the wall to reach a steady-state. Furthermore, moisture content of the wall is difficult to define. Because it is difficult to ovendry walls, tests are generally conducted for the normally dry state. The exact moisture content of this state is often unknown.(24)

Heat flow meter

Another method used to measure conductivity of masonry materials is the heat flow meter. Fig. 17 illustrates basic features of the heat flow meter (ASTM Designation: C 518). Plates 1 and 2 are "hot" and "cold" plates that are maintained at a constant temperature during the test. The temperature difference between the two plates and the voltage output of the meter are used to calculate thermal conductivity. To reduce overall moisture loss from samples containing free water, the test specimen should be contained in a thin plastic bag.(24)

The heat flow meter is simpler but less accurate than the guarded hot plate. During a guarded hot plate test, heat flow to the apparatus is measured. During a heat flow meter test, the temperature difference across the core of the meter is measured and is expressed in terms of voltage. According to Tye and Spinney(24) the heat flow meter should not be used for specimens with a thermal conductivity greater than 3.5 Btu·in./hr·ft^2·°F (0.5 W/m·°K). This is because they found the heat flow meter gives low values for normal-weight concretes.

Hot wire

Although not a standard ASTM test, the hot wire method has also been used to evaluate conductivity of masonry materials.(28) The hot wire method is not a steady-state test. A thermocouple wire is embedded in a specimen. For hardened samples of clay brick or concrete block, specimens

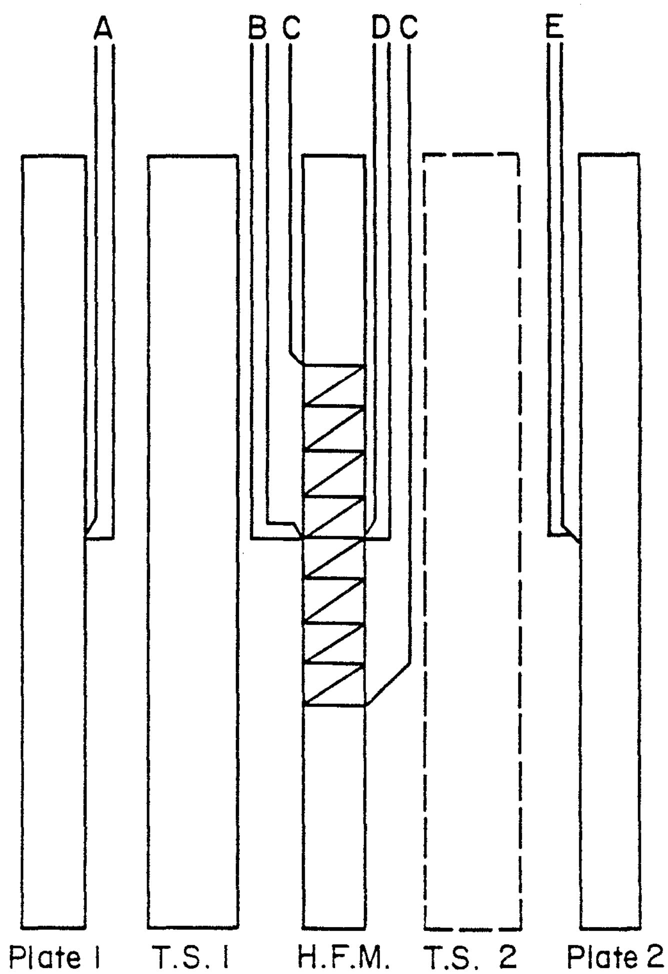


Plate 1-Controlled temperature plate at T1 (or T2)
T.S. 1-Test specimen 1
H.F.M.-Heat flow meter (simplified)
T.S. 2-Test specimen 2 or damping layer
Plate 2-Controlled temperature plate at T2 (or T1)
A and E-Plate surface thermocouples or transducers
B and D-Heat meter surface thermocouples
C-Heat meter thermopile or temperature-difference detector

Fig. 17 Schematic Diagram of Heat Flow Meter [21] may be prepared by sawing the sample into two pieces and lapping the cut surfaces. A groove is then cut into one of the surfaces as illustrated in Fig. 18. After the thermocouple wire is placed in the groove, the two halves are clamped together. Alternatively, the thermocouple wire can be embedded in the plastic material during fabrication of the block or brick.

To test a specimen, a thermocouple reading is taken, electrical current is supplied to the wire, and additional temperature readings are made at one minute intervals for a period of ten minutes. Thermal conductivity is calculated from the measured current, the resistance of the wire, and the thermocouple readings.(28)

Thompson(25) has reported that experimental error for the hot wire method is greater than for steady-state methods. A major source of error is heat loss through the ends of the wire and surfaces of the specimen. Like other test methods, the hot wire method is best for use with ovendry or saturated surface dry samples to avoid moisture migration.(25) However, it has been used to evaluate effects of moisture on conductivity.(18)

Thermal Conductivity of Brick

Reported values of thermal conductivity of clay brick range from 2 to 10 Btu·in./hr·ft^2·°F (0.3 to 1.4 W/m·°K) for densities ranging from 70 to 135 pcf (1120 to 2160 kg/m^3). Figure 19 shows values of conductivity for clay brick as a function of density. The curve in the figure is the relationship proposed by Loudon(14) for given densities of clay brick. Thermal conductivity values increase as the density of clay brick increases.

There is considerable variation in the thermal conductivity values for clay bricks with similar densities. Values of conductivity vary from

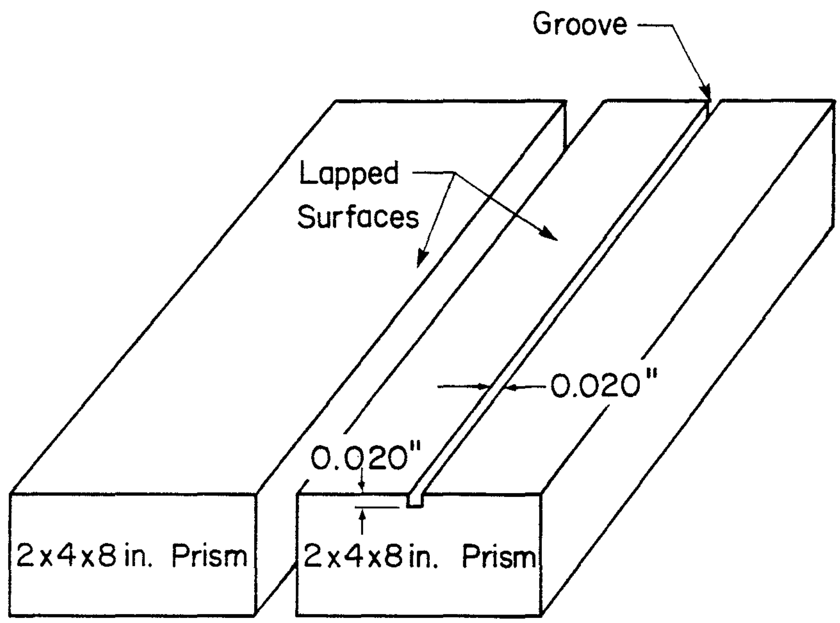


Fig. 18 Split Specimen Used in Hot Wire Method[28]

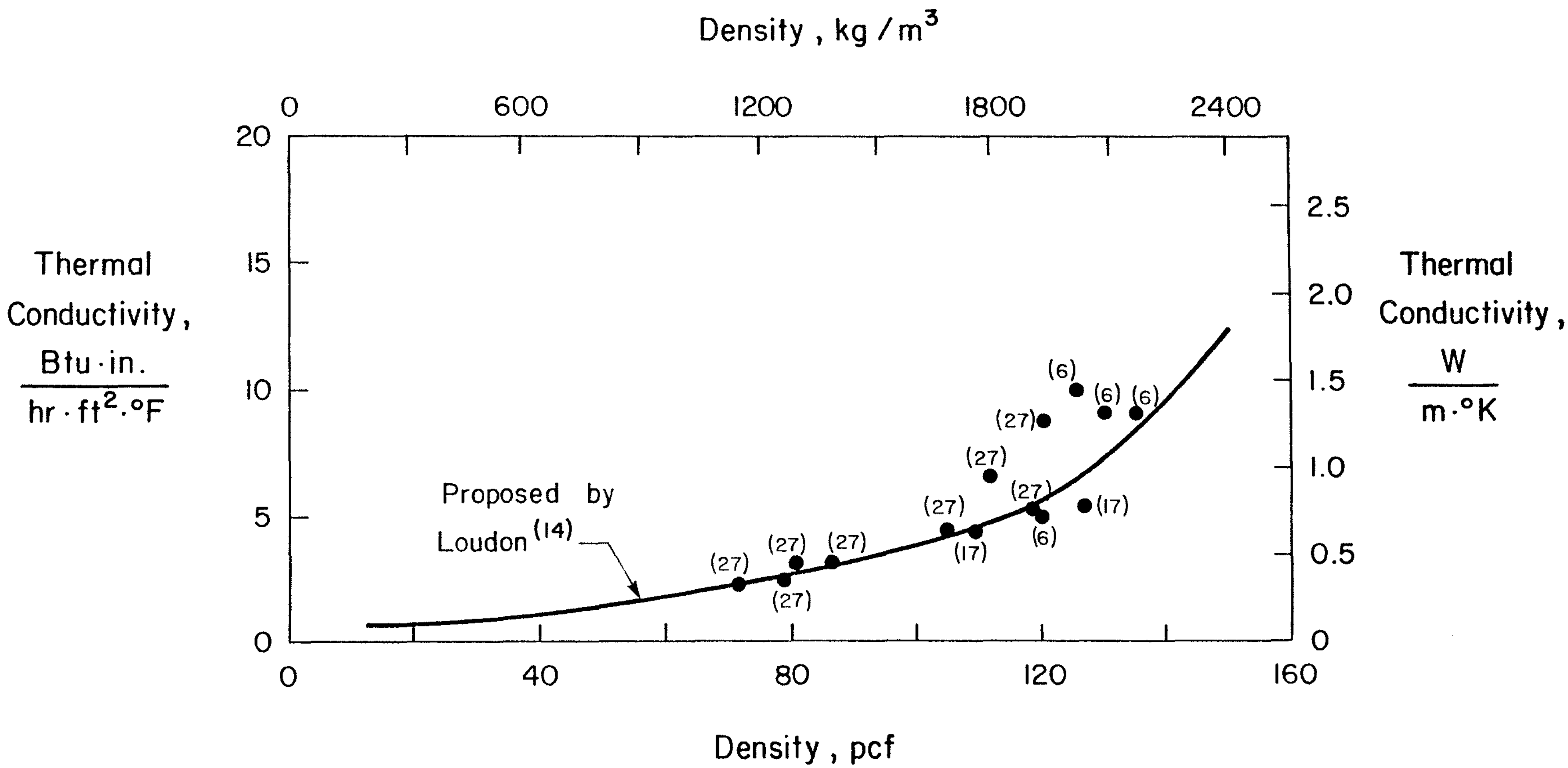


Fig. 19 Thermal Conductivity of Clay Brick as a Function of Density

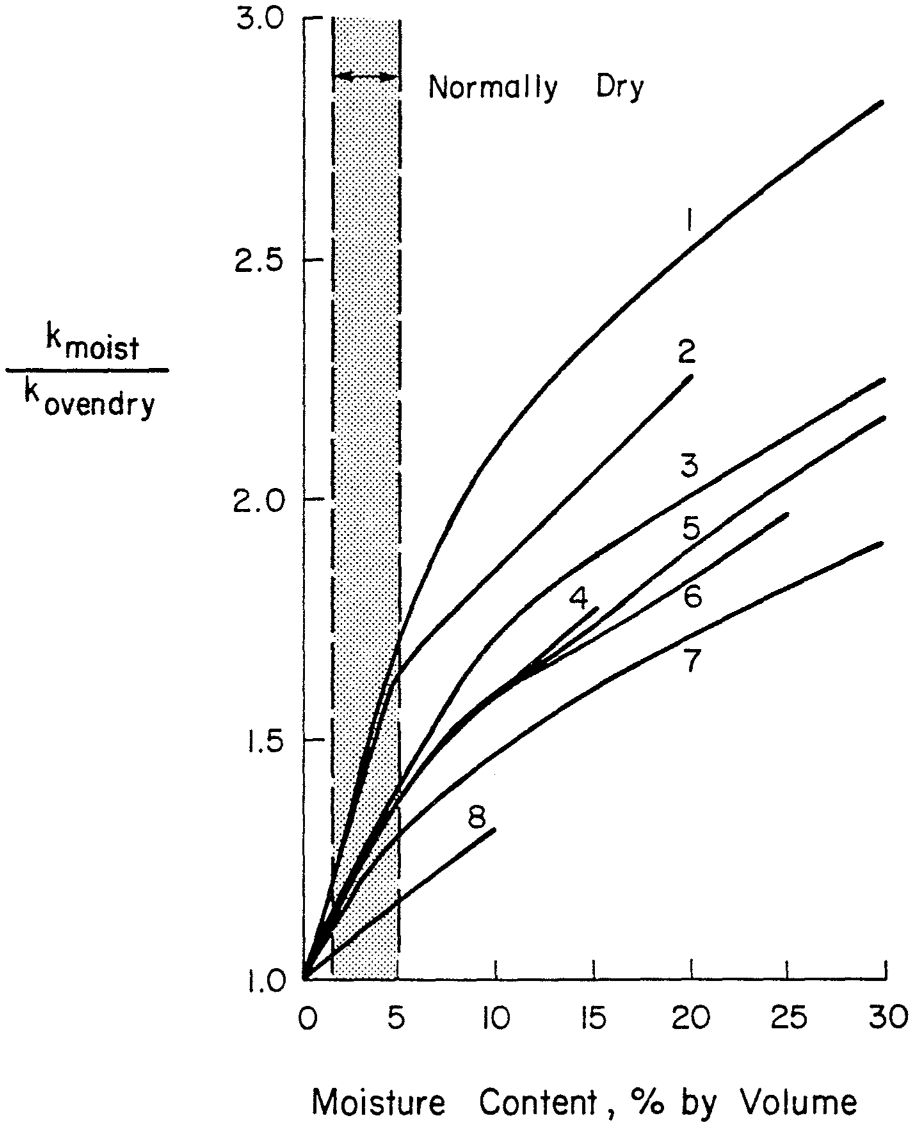
5 to 10 Btu·in./hr·ft^2·°F (0.7 to 1.4 W/m·°K) within a density range of 120 to 130 pcf (1920 to 2080 kg/m^3). This variation is probably due to different test methods giving different results for the same specimen. Ball[16] and Jesperson[27] used a guarded hot plate, but the source of the BIA Bulletin 43D[6] data shown in Fig. 19 is not known.

Variation in conductivity may also be due to different moisture contents or different materials used to produce clay bricks of similar densities. Data reported by Ball[16] and Jesperson[27] are for ovendry specimens. However, the moisture content for values reported in BIA Bulletin 43D[6] are not known. Also, clay bricks with high amounts of metallic oxides may have relatively high values of conductivity.[6]

The cause of the variation in conductivity can not be verified without further research because of the limited amount of test data available. Although numerous sources of data are available for conductivity of clay brick at high temperatures, relatively few sources give values at room temperature.

Jesperson[27] found the thermal conductivity of several clay bricks at moisture contents ranging up to 30% by volume. Results of his research are plotted in Fig. 20. The vertical axis is the ratio of conductivity of clay brick at a particular moisture content to the conductivity of the ovendry specimen. Although moisture content has a significant effect on the thermal conductivity of brick, the effect cannot be predicted on the basis of density. For brick with a 5% moisture content by volume, the increase in conductivity compared to that of ovendry brick varies from 17% to 73%.

To summarize, the thermal conductivity of clay brick is affected by density and moisture content. It may also be influenced by the type of



Curve	Unit Weight pcf	Unit Weight kg/m³
1	79	1260
2	119	1910
3	81	1300
4	112	1800
5	72	1150
6	105	1680
7	87	1400
8	121	1940

Fig. 20 The Ratio of the Conductivity of Moist Clay Brick to the Conductivity of Ovendry Brick as a Function of Moisture Content[27]

material used to produce the brick. Finally, test methods used to determine conductivity may yield different results for equivalent materials.

Thermal Conductivity of Concrete

Thermal conductivity of concrete is influenced by moisture content, density, and mean temperature of the specimen. Conductivity is also affected by thermal properties of constituent materials used to make the specimen.

Effect of moisture content

An increase in the moisture content of concrete increases its conductivity. Figure 21 shows the ratio of conductivity of concrete at a particular moisture content to conductivity of the ovendry concrete plotted as a function of moisture content. Data shown in Fig. 21 were obtained by three different test methods. Lentz and Monfore[18] used the hot wire method. Tye and Spinney[24] used the guarded hot plate method for lightweight concrete and the heat flow meter for insulating concrete. Campbell-Allen[29] used a "quasi steady state method". A linear regression analysis of the data shown in Fig. 21 gives the following equation:

$$\frac{k}{k_{OD}} = 0.99 + 0.04MC \tag{6}$$

where:

MC = moisture content, percent by volume of the concrete

k = thermal conductivity of concrete with moisture content MC

k_{OD} = thermal conductivity of the ovendry concrete

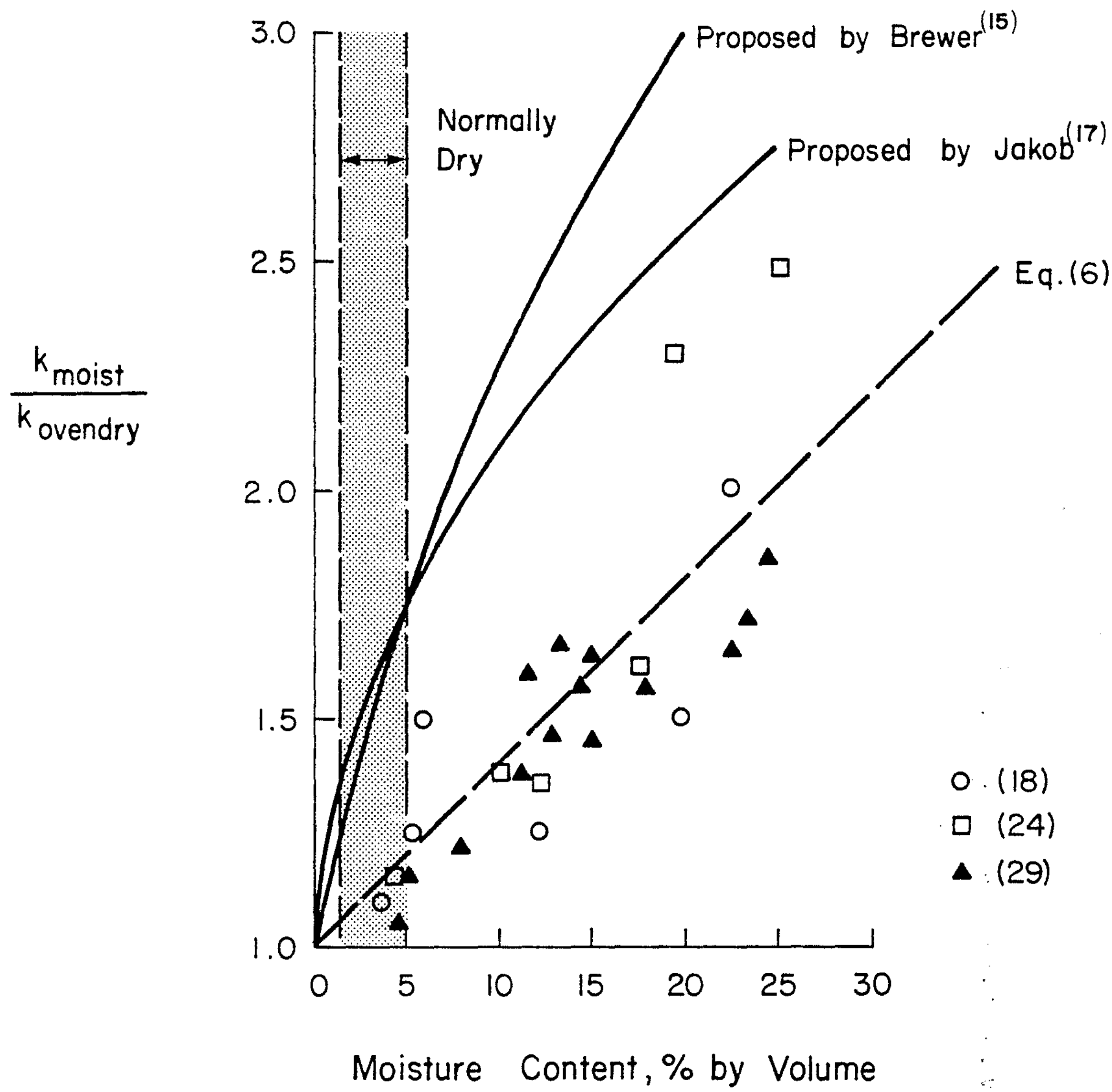


Fig. 21 The Ratio of the Conductivity of Moist Concrete to the Conductivity of Ovendry Concrete as a Function of Moisture Content

Equation (6) indicates that a 5% increase in moisture content leads to an increase in thermal conductivity of 20% over the ovendry value. The correlation coefficient for Eq. (6) is 0.90. This high correlation indicates that the line labeled "Eq. (6)" in Fig. 21 is a "good fit" for the data.

Thermal conductivity versus moisture content relationships proposed by Jakob(17) and Brewer(15) are also shown in Fig. 21. Brewer's relationship is based on data obtained from "several sources that used different methods of measuring saturation."(15) Jakob's relationship is presented as applicable to all inorganic building materials such as pumice stone, brick, gypsum board, sand, plaster, and sandstone.(30) Ball discusses the applicability of Jakob's relationship to concrete.(17)

Relationships proposed by Jakob and Brewer imply higher conductivities than indicated by published test data. For Brewer's and Jakob's relationships, an increase in moisture content from 0 to 5% by volume would result in an increase in conductivity of 75%. Moisture contents of normally dry concrete, based on Brewer's assumptions of normally dry, range from 2 to 5% by volume.

Effect of density

Density of concrete strongly influences its conductivity. Figure 22 shows that as the ovendry or normally dry density increases from 20 to 150 pcf (320 to 2400 kg/m^3), thermal conductivity increases from 1.0 to approximately 15.0 $Btu \cdot in./hr \cdot ft^2 \cdot {}^\circ F$ (0.1 to 2.2 $W/m \cdot {}^\circ K$). For normal-weight concrete measured values of conductivity published in the literature are highly dependent on the test method used. For concrete with a density of approximately 140 pcf (2240 kg/m^3), published values of conductivity range from 8 to 20 $Btu \cdot in./hr \cdot ft^2 \cdot {}^\circ F$ (1.2 to 2.9 $W/m \cdot {}^\circ K$) depending on the test method. With this large variation in values from

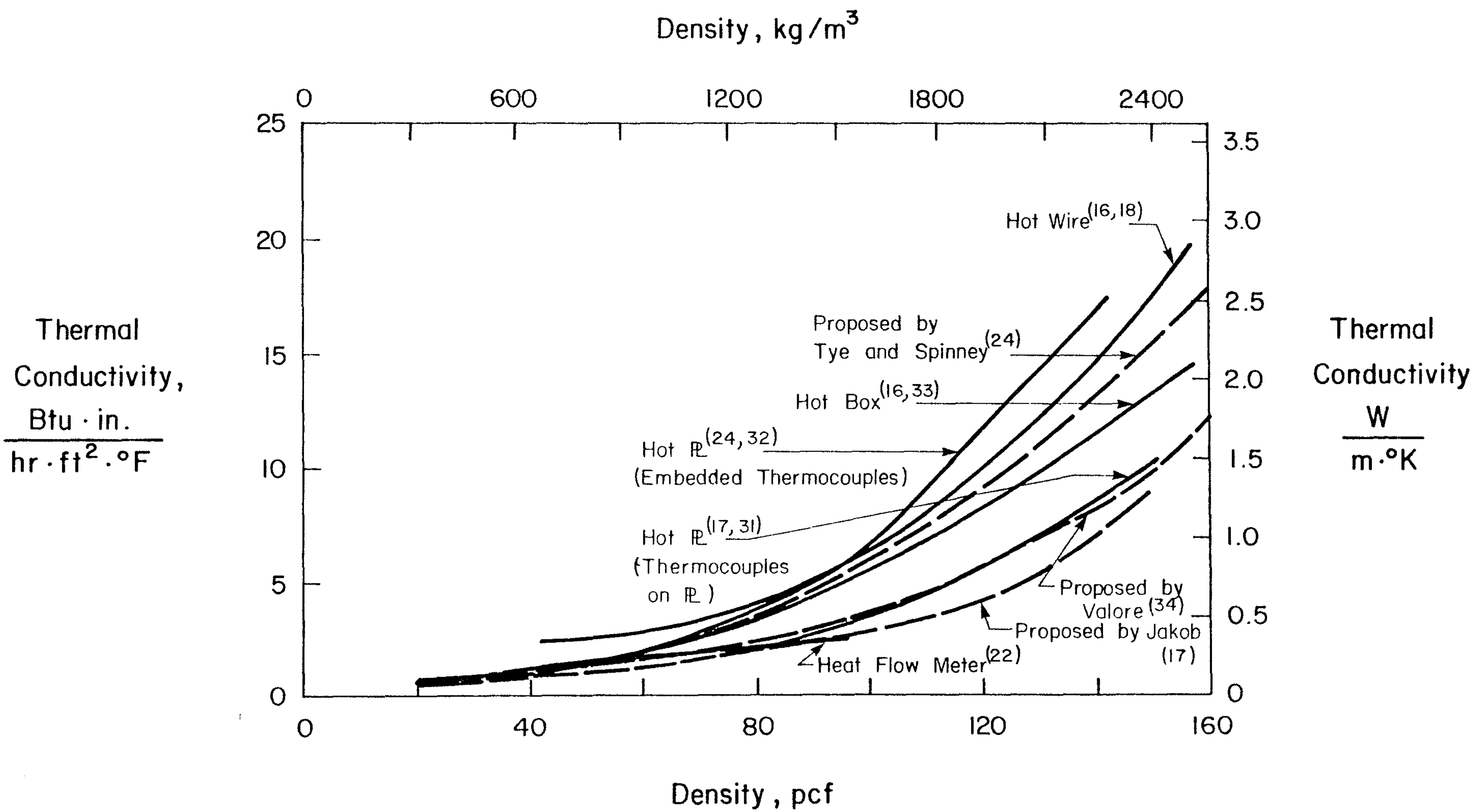


Fig. 22 Thermal Conductivity of Concrete as a Function of Density

different test methods, it is difficult to determine a suitable conductivity for a material.

Curves in Fig. 22 represent average values of conductivity found in the literature. The data are presented according to the particular test method used. The guarded hot plate was used by Ball[17] and Saleh.[31] Values of conductivity found by Tye and Spinney[24,32] using the guarded hot plate are shown separately because of the use of embedded thermocouples. Results of Rowley and Algren[33] and of CTL[16] were obtained by the hot box method. The heat flow meter was used by Tye and Spinney[24] and the hot wire method was used by CTL[16] and Lentz and Monfore.[18] All data used to plot the curves were for ovendry or normally dry specimens.

As previously mentioned, for the guarded hot plate method, thermal conductivity values found using embedded thermocouples are higher than values found using thermocouples on the contact surface. Results of the hot wire method are in the same range as those for the guarded hot plate with embedded thermocouples.

Jakob,[17] Tye and Spinney,[24] and Valore[34] have proposed relationships for estimating thermal conductivity when the density of the concrete is known. These relationships are also shown in Fig. 22. Equations proposed are as follows:

<u>Tye and Spinney</u>:

U.S. units $k = 0.000982\rho^2 - 0.0544\rho + 1.53$ (7)

S.I. units $k = 552{,}000\rho^2 - 490\rho + 0.221$

<u>Valore</u>:

U.S. units $k = 0.5e^{0.02\rho}$ (8)

S.I. units $k = 0.072e^{1250\rho}$

where:

$$k = \text{thermal conductivity}, \frac{\text{Btu}\cdot\text{in.}}{\text{hr}\cdot\text{ft}^2\cdot{}^\circ\text{F}}\left(\frac{\text{W}}{\text{m}\cdot{}^\circ\text{K}}\right)$$

$$\rho = \text{ovendry density of concrete, pcf } (\text{kg/cm}^3)$$

Jakob's relationship is given in Table 3.

Of the three relationships, the one proposed by Tye and Spinney[24] gives the highest values of conductivity for a given density. This is probably due to the fact that Tye and Spinney advocate the use of a test method that gives the highest values. Relationships proposed by Valore[34] and Jakob[17] correlate well with results obtained using the standard guarded hot plate method. Most data in the literature are obtained using this method.

Thermal conductivity values for heavyweight concrete found by Ball[17] and Campbell-Allen[29] are given in Table 4. Estimates based on Eq. (8) are also shown. For four out of the five data points, the thermal conductivity is significantly overestimated using Valore's equation. Therefore caution must be used when extrapolating any of the curves in Fig. 22 to high density concretes.

Effect of constituent materials

In addition to density, constituent materials and proportions of the concrete mix affect conductivity. For a given unit weight, changes in the percent of aggregates in the mix, the type of aggregates, or the water-cement ratio will cause variations in conductivity. Brewer[15] concludes that these variations are small compared to the affects of moisture content. When using Jakob's equation to estimate conductivity of cellular concrete, Loudon[14] suggests reducing the calculated conductivity by 10%.

TABLE 3. THERMAL CONDUCTIVITY OF OVENDRY BUILDING MATERIALS PROPOSED BY JAKOB[30]

Ovendry Density pcf (kg/m^3)	Thermal Conductivity $\frac{Btu \cdot in.}{hr \cdot ft^2 \cdot °F}$ ($W/m \cdot °K$)
12.5 (200)	0.42 (0.061)
25.0 (400)	0.54 (0.078)
37.5 (600)	0.78 (0.112)
49.9 (800)	1.08 (0.156)
62.4 (1000)	1.44 (0.208)
74.9 (1200)	1.86 (0.268)
87.4 (1400)	2.34 (0.337)
99.9 (1600)	2.88 (0.415)
112.4 (1800)	3.60 (0.519)
124.8 (2000)	4.80 (0.692)
137.3 (2200)	6.48 (0.934)
149.8 (2400)	9.18 (1.323)

TABLE 4. THERMAL CONDUCTIVITY OF HEAVYWEIGHT CONCRETE(17,29)

Description	Dry Density pcf (kg/m^3)	Moisture Content % by Volume	Thermal Conductivity $\frac{Btu \cdot in.}{hr \cdot ft^2 \cdot °F} \left(\frac{W}{m \cdot °K} \right)$	
			Actual	Estimated*
Barytes Concrete(29)	180 (2880)	0	8.5 (1.22)	18.3 (2.64)
Haematite Concrete(29)	180 (2880)	0	17.9 (2.58)	18.3 (2.64)
Barytes Concrete(17)	193 (3090)	1.2	7.8 (1.12)	23.7 (3.42)
Ilmanite Concrete(17)	195 (3120)	1.0	9.1 (1.31)	24.7 (3.56)
Magnetite Concrete(17)	207 (3310)	1.0	11.4 (1.64)	31.4 (4.52)

*Estimate using Eq. (8) proposed by Valore.(34)

Campbell-Allen[29] derives the following equation for calculating thermal conductivity of concrete as a function of conductivity of the cement paste and aggregate.

$$k = k_p\,(2rt - r^2t^2) + k_p k_a \frac{(1-rt)^2}{rtk_a + (1-rt)k_p} \qquad (9)$$

where:

k_p = thermal conductivity of cement paste

k_a = thermal conductivity of aggregate

$rt = 1-\sqrt[3]{1-p}$

p = volume of cement paste per unit volume of concrete

An equation for the conductivity of the hydrated cement based on the conductivity of the paste and pore structure is also given in Reference 29. It is difficult to use Eq. (9) in practice because thermal conductivity of the cement paste and aggregate would have to be measured independently. However, the equation is useful for analyzing the effects of different aggregates on the thermal conductivity of concrete. For example, Campbell-Allen finds that a large increase in the conductivity of aggregate will have a small effect on the conductivity of concrete.

Effect of temperature

The change in thermal conductivity of concrete from a mean temperature of 60 to 110°F (16 to 43°C) is not significant. Data for the conductivity of different density concrete specimens at temperatures from 0 to 200°F (-18 to 93°C) are shown in Fig. 23. Various test methods were used to obtain the data. Lentz and Monfore[18] used the hot wire method. Saleh[31] and Tye and Spinney[32] used the guarded hot plate. From 0 to 200°F (-18 to 93°C) the conductivity of normal-weight

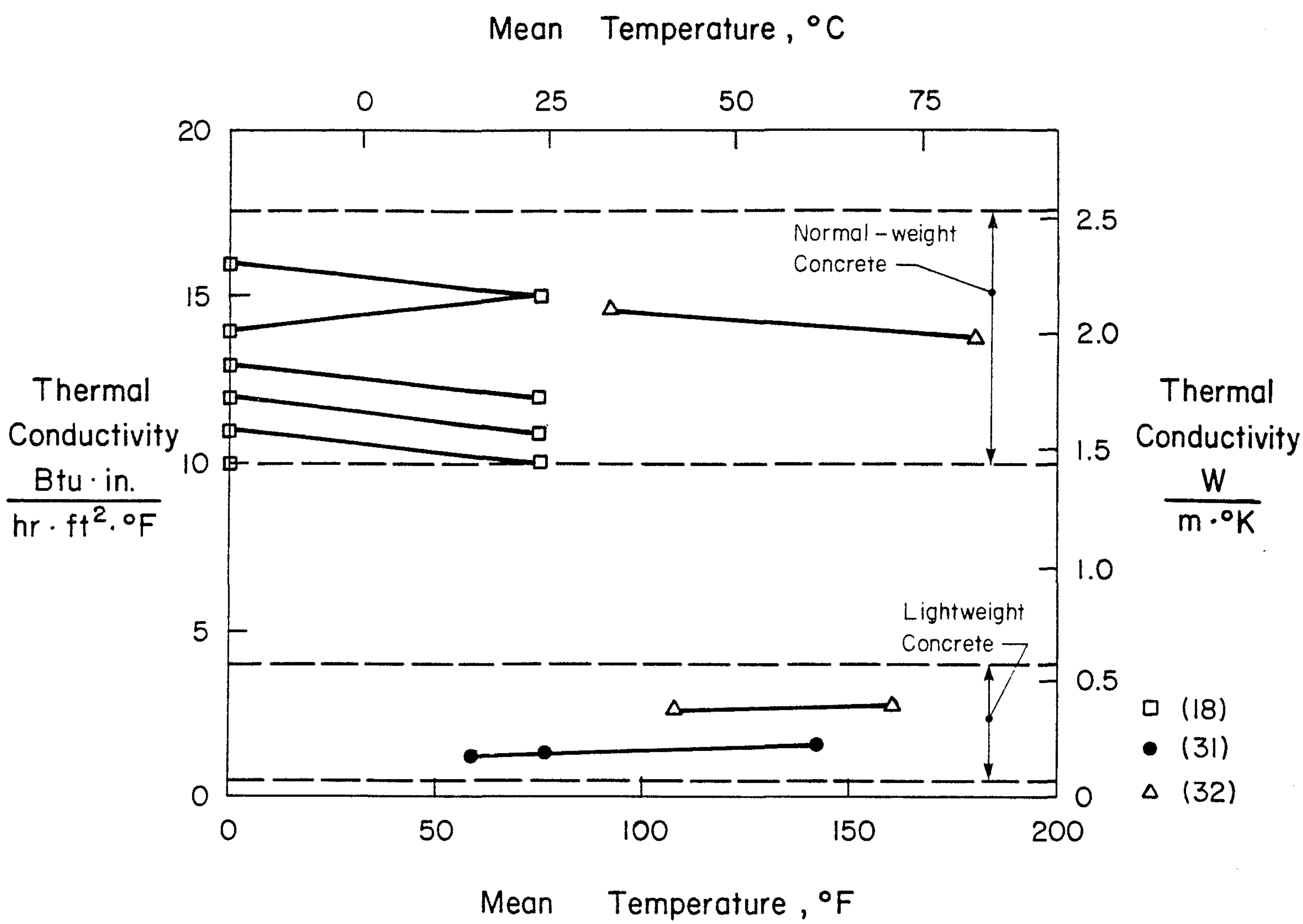


Fig. 23 Thermal Conductivity of Concrete as a Function of Temperature

concrete decreases with temperature while the conductivity of lightweight concrete remains relatively constant or increases slightly. This conclusion is supported by the data presented by Abrams[35] as shown in Fig. 24. The curves represent four limiting cases proposed by Harmathy with respect to thermal properties. Curves 1 and 2 are limiting cases for normal-weight concrete, and curves 3 and 4 are limiting cases for lightweight concretes.

Figures 21 and 22 show that density and moisture content have significant effects on the thermal conductivity of concrete. Mix proportions and mean temperatures in the range found in passive solar systems have relatively small effects on conductivity.

THERMAL DIFFUSIVITY

Thermal diffusivity is a physical property of a material that defines the time rate of change of temperature at any point within a body. In passive solar design applications, diffusivity defines the rate of heating of a thermal storage mass. Diffusivity, conductivity, specific heat, and density are related by the following equation:

$$\alpha = \frac{k}{\rho \cdot c} \tag{10}$$

where:

α = thermal diffusivity, ft^2/hr (m^2/s)

k = thermal conductivity, $\frac{Btu}{hr \cdot ft \cdot {}^\circ F} \left(\frac{W}{m \cdot {}^\circ K}\right)$

ρ = density, pcf (kg/m^3)

c = specific heat, $\frac{Btu}{lb \cdot {}^\circ F} \left(\frac{J}{kg \cdot {}^\circ K}\right)$

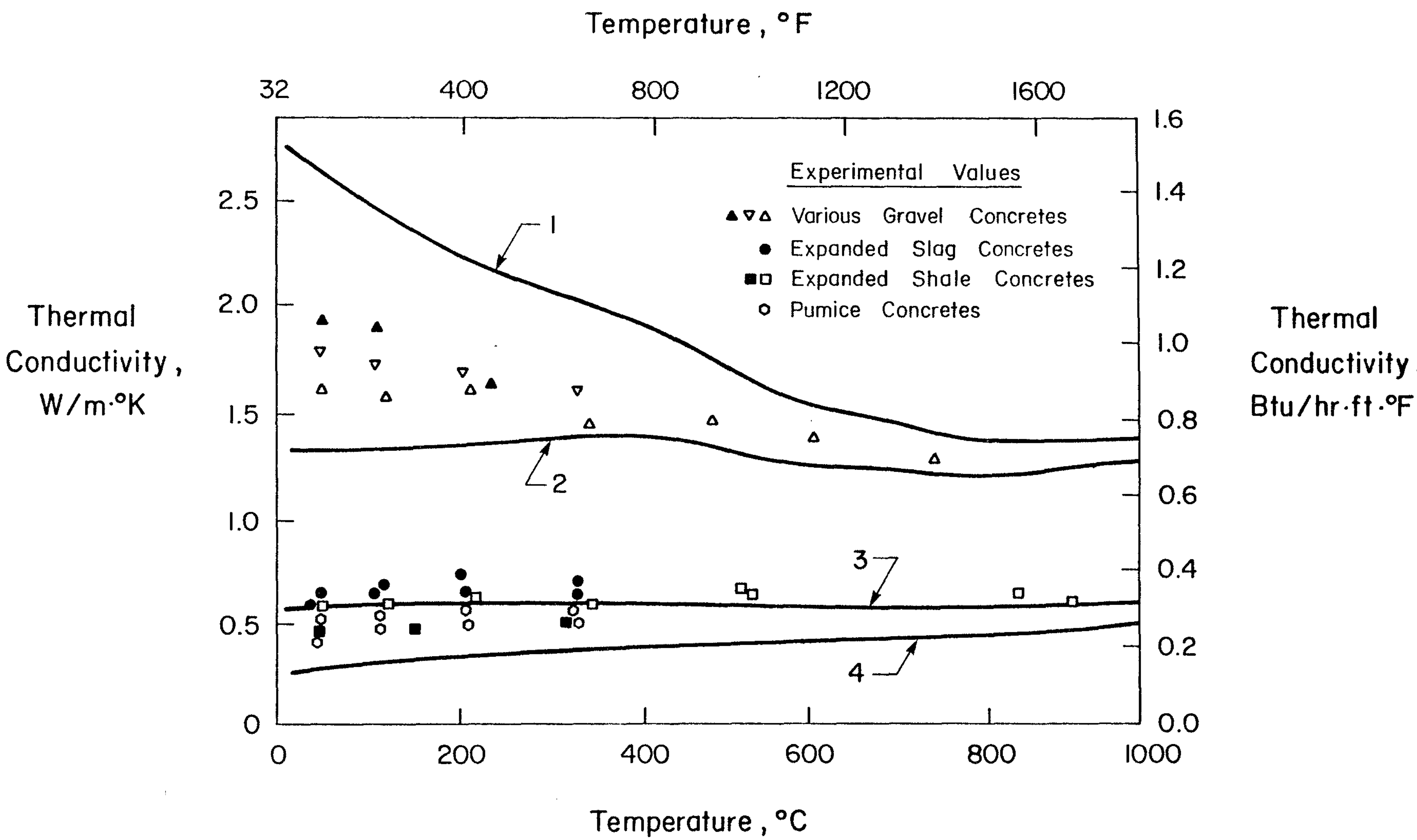


Fig. 24 Thermal Conductivity of Four "Limiting" Concretes as a Function of Temperature(35)

If any three of the values of conductivity, specific heat, density, or diffusivity are known, the fourth can be calculated. Test methods are available to measure each of the four properties.

Test Methods for Determining Thermal Diffusivity

The most common technique for measuring thermal diffusivity in masonry materials is U.S. Army Corps of Engineers Specification CRD-C36-73[36] "Method of Test for Thermal Diffusivity of Concrete." Specimens are immersed in boiling water until an internal temperature of 212°F (100°C) is reached. The specimen is then moved to a cold bath of a known volume of water where the temperature history is recorded. The recorded temperature history and specimen dimensions are used to calculate diffusivity. This method has been used primarily for evaluating concrete specimens from dams.

Billington[37] has used a dry specimen to determine diffusivity. The specimens are alternately heated and cooled. Temperature of the specimen at several points is measured by thermocouples at selected times. The temperature history is used to calculate diffusivity. Thomson[38] has used a method similar to Billington's.

When using Eq. (10), values of diffusivity, conductivity, specific heat, and density must all be for the same moisture content of the material. There is no direct method of correction to account for effects of moisture content on diffusivity. However, if specimens for diffusivity and specific heat are tested in a saturated condition, conductivity can be calculated from Eq. (10). Calculated conductivity values can then be adjusted for moisture on a theoretical basis. For example, one of the relationships shown in Fig. 21 can be used.

Thermal Diffusivity of Brick

Only limited experimental data are available on the thermal diffusivity of clay brick. Diffusivity of clay brick ranges from 0.016 to 0.030 ft^2/hr (0.413 to 0.774 mm^2/s) for densities of 120 to 135 pcf (1920 to 2160 kg/m^3) according to BIA Bulletin 43D[6] and Szoke.[39] The test method used to obtain the data is not identified. Billington[37] found diffusivity of a 100 pcf (1600 kg/m^3) common brick to be 0.021 ft^2/hr (0.542 mm^2/s). These data are shown in Fig. 25.

Not enough data are available to form conclusions about the thermal diffusivity of brick and its relation to brick density. Also, because published data on conductivity and specific heat do not include sufficient data on moisture content of samples, it was not possible to calculate diffusivity relationships.

Thermal Diffusivity of Concrete

Values of diffusivity of concrete using both dry and wet test methods are shown in Fig. 26. Data from Billington[37] and Thomson[38] may be assumed to be for ovendry specimens. It is assumed that BIA Bulletin 43D[6] and Szoke[39] list data for normally dry concrete. Boulder Canyon[19] and CTL[16] data are for saturated specimens. If differences in moisture contents are ignored, there is an increase in diffusivity with an increase in density. However, the variation of diffusivity for approximately equal densities is significant. For the Boulder Canyon project values of diffusivity range from 0.034 to 0.062 ft^2/hr (0.878 to 1.60 mm^2/s) for densities ranging from 146 to 158 pcf (2340 to 2530 kg/m^3).

The curve labeled "dry" in Fig. 26 represents the expected value of diffusivity for dry concrete assuming Valore's relationship for

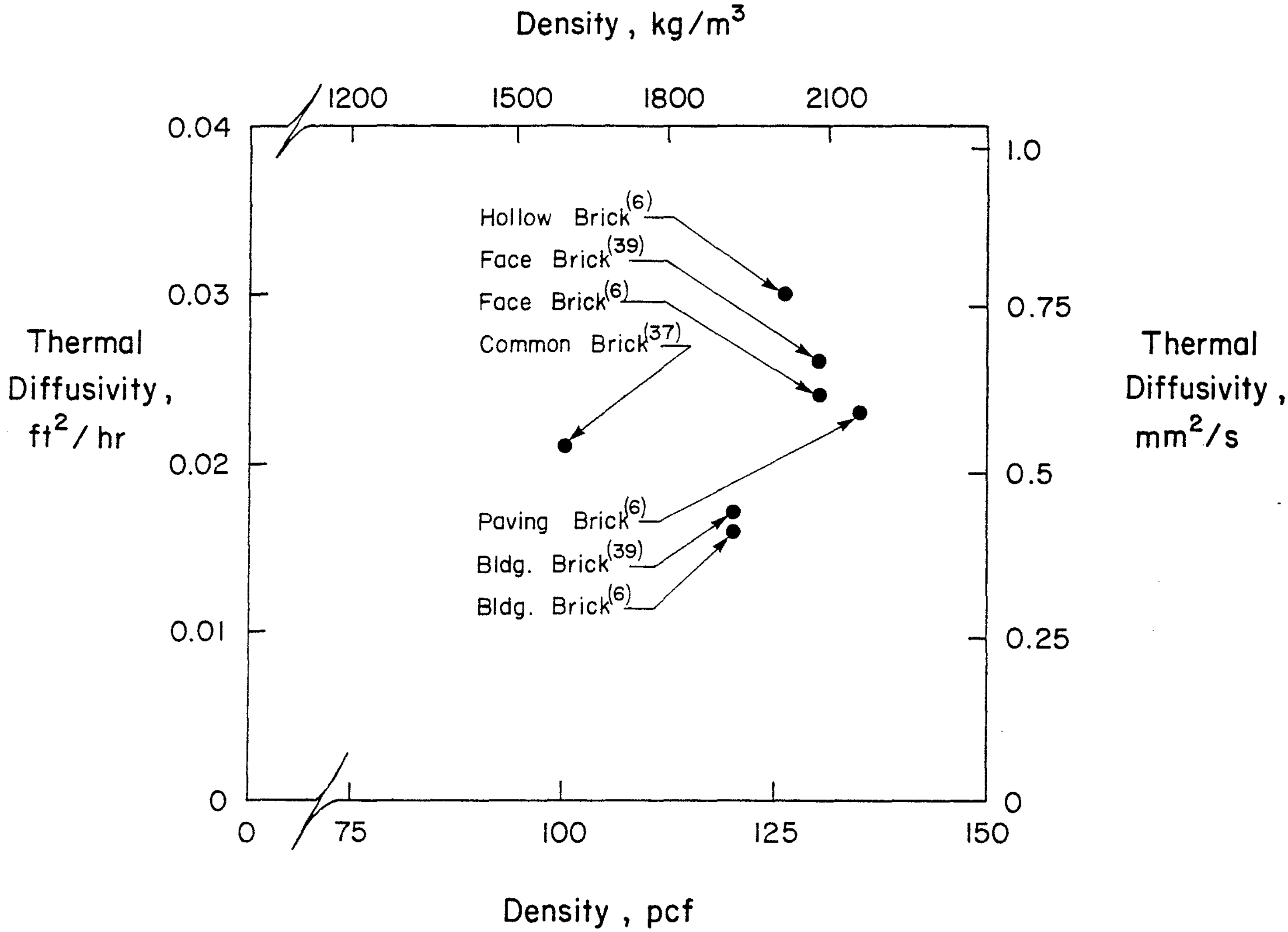


Fig. 25 Thermal Diffusivity of Clay Brick as a Function of Density

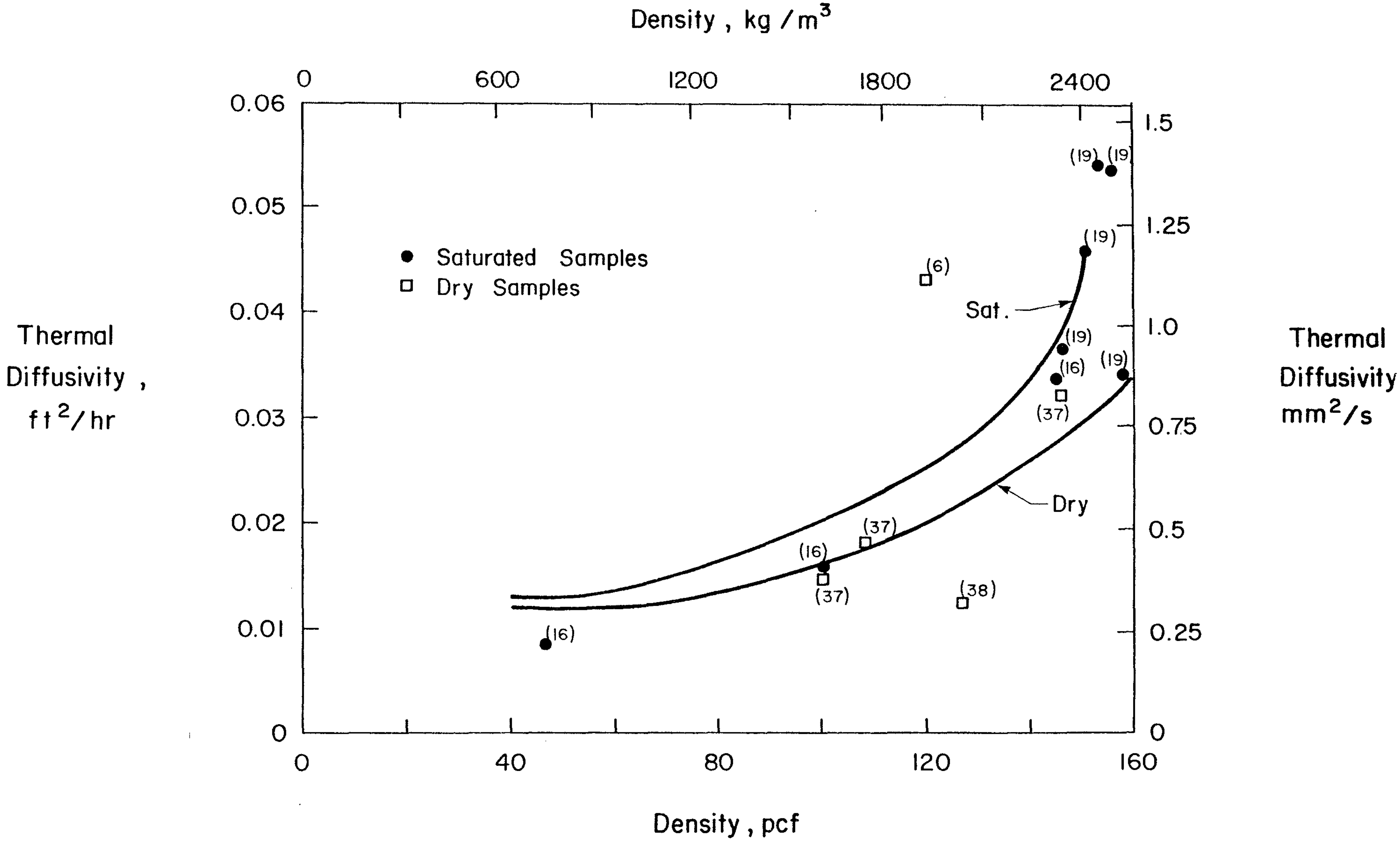


Fig. 26 Thermal Diffusivity of Concrete as a Function of Density

conductivity Eq. (8), and a specific heat of dry concrete of 0.19 Btu/lb·°F (795 J/Kg·°K). These values were chosen for simplicity. Knowing the conductivity and specific heat for a given density, diffusivity was calculated using Eq. (10). As shown by Fig. 26, Billington's[37] values were remarkably close to the expected values for "dry" concrete.

Deriving the expected value of diffusivity for saturated specimens is more complex. To obtain a value of conductivity for saturated samples, a saturated moisture content for a given density must be assumed. For this purpose, values suggested by Brewer and shown in Table 2 were used. Conductivities for saturated samples were then calculated using Eq. (6). The assumed saturated specific heat values for a given density were taken from the curve in Fig. 12. Diffusivity for a given density was then calculated using the values of conductivity and specific heat calculated for saturated concrete. Results are shown in Fig. 26 as the curve marked "sat."

The curve for the expected values of diffusivity for saturated concrete, identified as "sat." in Fig. 26, is sensitive to the saturated moisture content assumed. The scatter in measured data for normal-weight concrete may be due to the variation in saturated moisture contents of the concrete. The Boulder Canyon report[19] concludes that variation in diffusivity is also due to changes in rock type used for aggregate. More data are necessary to confirm either conclusion.

Tokuda and Ito[40] present the following relationship between conductivity and diffusivity of saturated samples:

$$\alpha = 0.0224k \ (140k) \tag{11}$$

where:

α = diffusivity, ft^2/hr (mm^2/s)

k = conductivity, $\frac{Btu}{hr \cdot ft \cdot °F}$ $\left[\frac{W}{m \cdot °K}\right]$

This relationship and data from Boulder Canyon[19] are shown in Fig. 27. These data were used because, of available data, only the Boulder Canyon report lists conductivity and diffusivity for saturated concrete. The Boulder Canyon values for diffusivity are all larger than predicted by Eq. (11). However, the linear trend predicted by Tokuda and Ito is apparent in the measured data.

Diffusivity for normal-weight saturated concrete decreases with increase in mean temperature in the range of 60 to 110°F (16 to 43°C). As shown in Fig. 28, the decrease is between 0 and 10% in this 50°F (27°C) temperature range. No test data are available for diffusivity values of lightweight concrete or dry concrete with respect to changes in mean temperature.

RADIATION PROCESSES

The amount of heat absorbed and released by a thermal storage mass depends on the absorptivity and emissivity, respectively, of the mass. The following introduction to these radiation processes will provide an understanding of the respective test methods.

Emissivity

Emissivity, sometimes called emittance, is defined as the fraction of energy emitted or released from a mass compared to the radiation of a perfect emitter, or blackbody.

A blackbody is both a perfect absorber and a perfect emitter. It is an ideal surface that absorbs all incident radiation. For a given temperature and wavelength, no surface can emit more energy than a blackbody.[4] Although no surface is a perfect blackbody, blackbody behavior can be approximated by a small opening or aperture in a

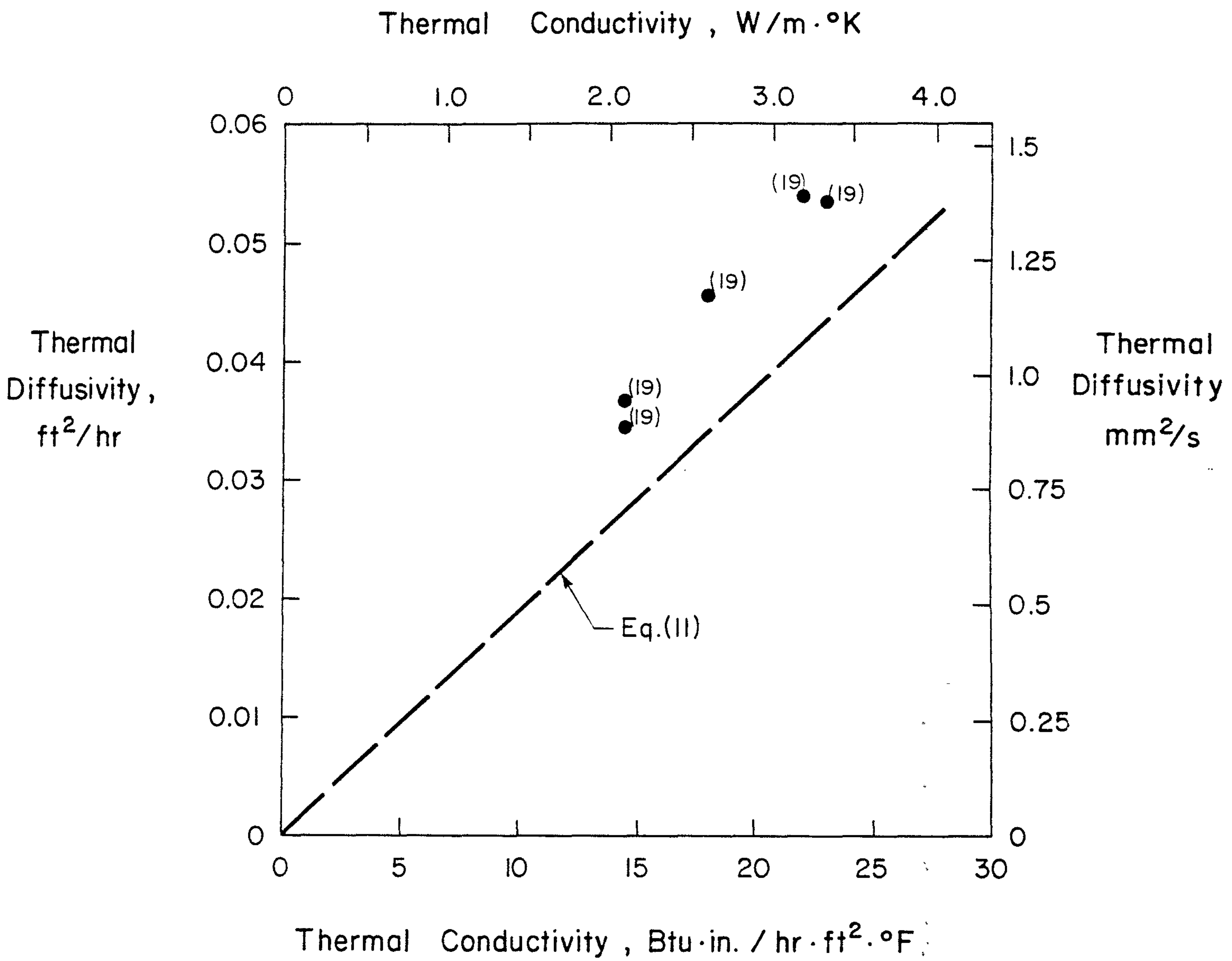


Fig. 27 Thermal Diffusivity of Concrete as a Function of Thermal Conductivity

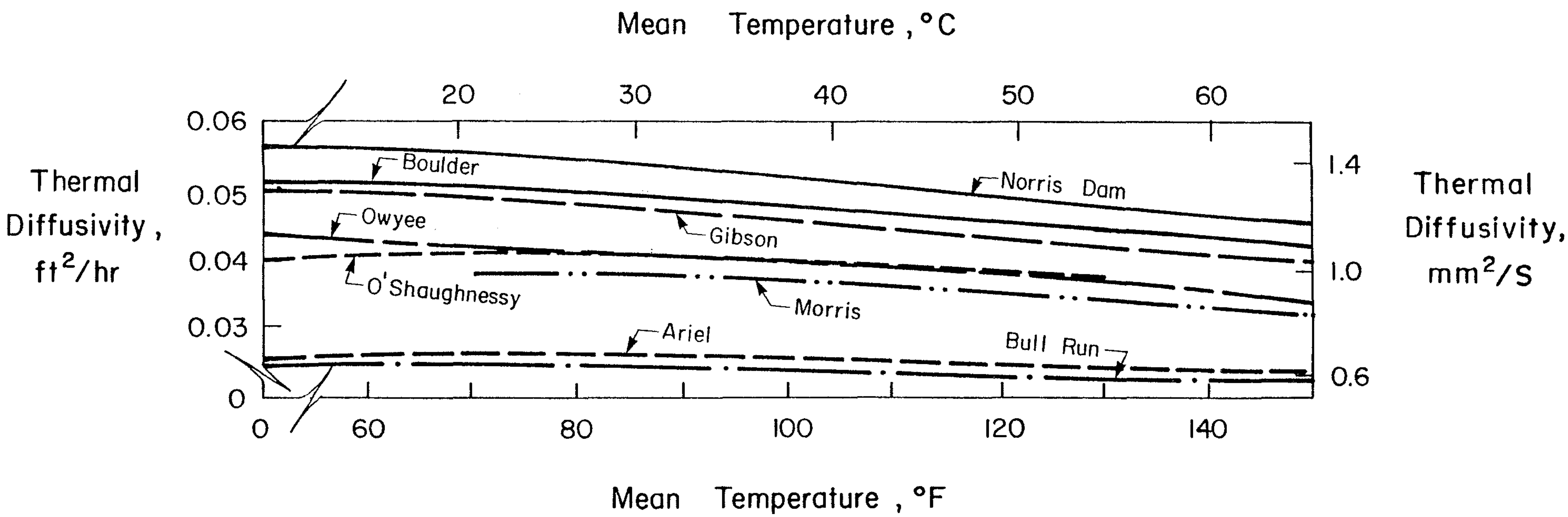


Fig. 28. Thermal Diffusivity of Concrete as a Function of Temperature [19]

relatively large enclosure as shown in Fig. 29.[41] The radiant energy entering the aperture will be reflected many times in the cavity. A portion of the energy will be absorbed at each reflection.

The spectrum of radiation of interest in heat transfer is called thermal radiation. This spectrum, shown in Fig. 30, extends from wavelengths of about 0.1 μm to 100 μm.[4] A surface will emit radiant energy within this range.

The total emissive power of a blackbody depends upon its temperature. The total emissive power of a blackbody over all wavelengths is as follows:[4]

$$E_b = \sigma T^4 \qquad (12)$$

where:

E_b = total emissive power of a blackbody

σ = Stefhan Boltzmann Constant

$$\sigma = 0.00000000171 \frac{\text{Btu}}{\text{ft}^2 \cdot \text{hr} \cdot {}^\circ\text{R}^4} \left[56.7 \frac{\text{nW}}{\text{m}^2 \cdot {}^\circ\text{K}^4} \right]$$

T = temperature, °R (°K)

For a blackbody, total emissive power increases with temperature.

Since emissivity is defined as the ratio of energy emitted by the surface to the energy emitted by a blackbody, and the energy emitted by a blackbody depends on temperature, emissivity values of a mass will be different for different temperatures. In this report, attention will be focused on emissivity values of masonry materials at room temperatures.

Test methods for determining emissivity

ASTM Designation: E 408, "Total Normal Emittance of Surfaces Using Inspection-Meter Techniques"[42] describes two types of instruments used to measure emissivity of large surfaces. Method A measures radiant

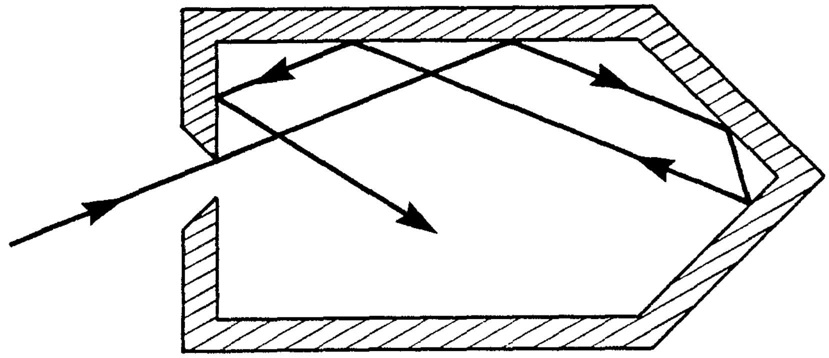


Fig. 29 Blackbody Behavior(41)

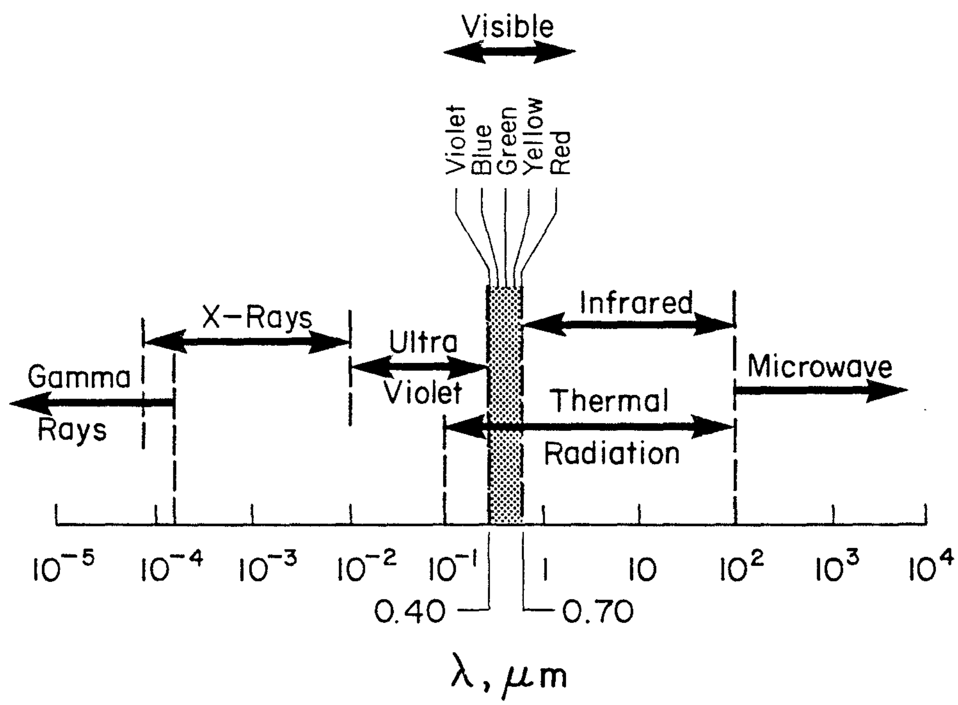


Fig. 30 Spectrum of Electromagnetic Radiation adapted from Incropera and DeWitt(4)

energy reflected from the specimen and Method B measures radiant energy emitted from the specimen.

Method A utilizes a sensing component containing two semicylindrical cavities that are maintained at different temperatures. A detection system measures the difference in energy released from the two cavities and reflected from the surface. Reflectivity values are found by correctly calibrating the equipment. Absorptivity is then calculated by subtracting the reflectivity value from unity. The relationship between absorptivity and reflectivity will be discussed in a later section as a property of absorptivity.

Method B utilizes a thermopile that senses the radiant energy emitted and reflected from the specimen surface. The amount of energy reflected from the surface is minimized by cooling the thermopile and specimen.

Jakob(43) describes several other test methods for measuring emissivity. All such methods can be categorized as either "emitter methods" or "receiver methods." An "emitter method" involves measuring the amount of energy required to heat a specimen and the temperature of the specimen. A "receiver method" measures emitted radiation directed into a sensor. ASTM Designation: E 408 Method B is a "receiver method."

Values of emissivity for masonry materials

Mazria(3) and other researchers frequently assume an emissivity value of 0.90 for all building materials. A summary of published values of emissivity is shown in Table 5. Assuming a value in the range of 0.90 to 0.95 would be consistent with the available test data. Gubareff, Janssen, and Torborg(41) provide the most frequently cited and most comprehensive reference for emissivity values of building materials.

TABLE 5. EMISSIVITY OF MASONRY MATERIALS AT ROOM TEMPERATURE

Description	Emissivity
Brick, type not specified[41]	0.96
Brick wall[41]	0.94
Concrete[41]	0.94
Red brick[4,41]	0.93
Brick and concrete, any color paint[12]	0.85-0.95

Solar Absorptivity

Since the absorptivity of a material is related to its transmissivity and reflectivity,[4] all three properties are defined in this section. A conceptual diagram of absorbed, transmitted, and reflected radiation is shown in Fig. 31.

Absorptivity is a measure of the efficiency of receiving radiation and is defined as the percent of incident radiant energy absorbed by a mass for a given wavelength or averaged over a range of wavelengths.[4] A blackbody has an absorptivity of 1.0. Building materials have an absorptivity less than 1.0.

Transmissivity is the percent radiant energy transmitted through a mass for a given wavelength or averaged over a range of wavelengths.[4] Transmissivity may be close to 1.0 for glass or other clear materials, but is equal to zero for opaque materials.

Reflectivity is the percent radiant energy reflected by a mass for a given wavelength or averaged over a range of wavelengths.[4] A polished mirror has a reflectivity close to 1.0.

For any material, the sum of the absorptivity, transmissivity, and reflectivity must equal one for a given wavelength or a given spectrum.[4] Since opaque materials have a transmissivity of zero, absorptivity plus reflectivity for opaque materials must equal one. These relationships can be expressed as follows:

All materials:

$$\alpha' + \tau + \rho' = 1.0 \qquad (12)$$

Opaque materials:

$$\alpha' + \rho' = 1.0 \qquad (13)$$

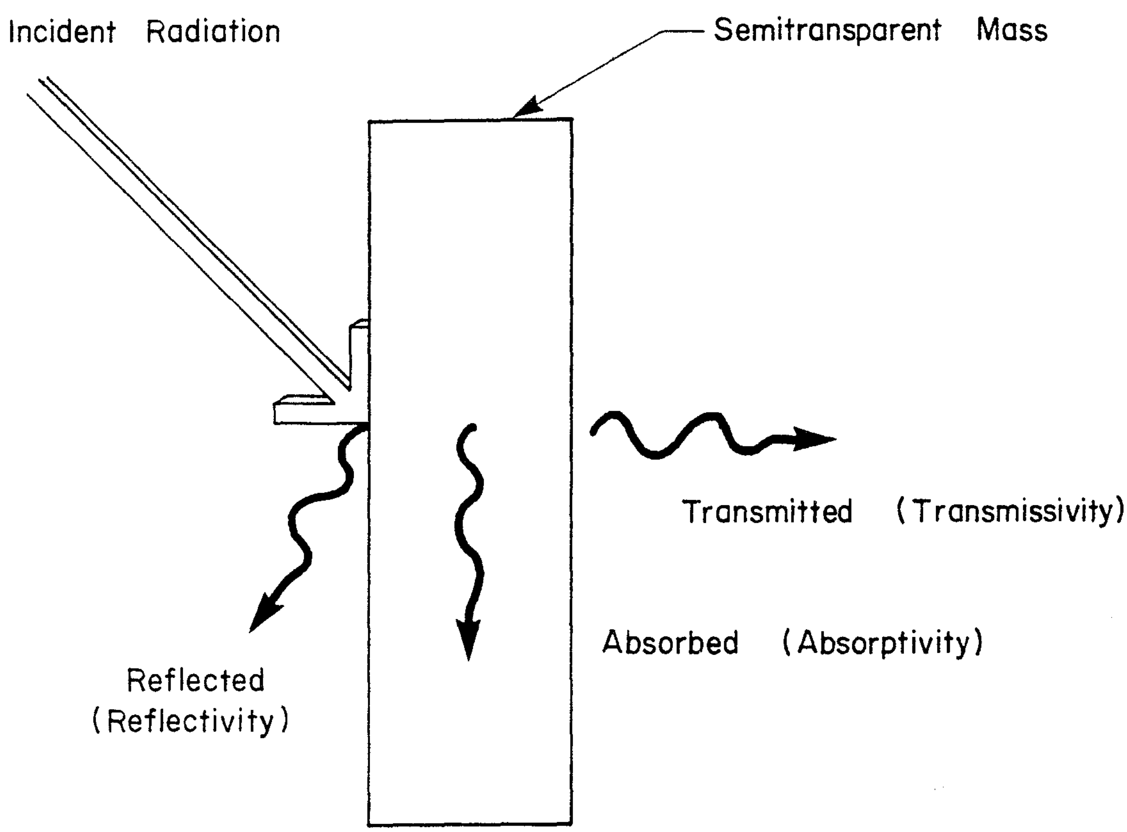


Fig. 31 Absorptivity, Reflectivity, and Transmissivity, adapted from Incropera and DeWitt[4]

where:

α' = absorptivity

τ = transmissivity

ρ' = reflectivity

Absorptivity is equal to emissivity if the incident radiation corresponds to emission from a blackbody at the given surface temperature or if the surface is "gray."[4] Neither of these conditions is generally true for building materials in passive solar design applications. For passive solar design the incident radiation is solar radiation. The spectral distribution of solar radiation at the earth's surface is shown in Fig. 32.[4] This function is not equivalent to the spectral distribution of blackbody emissive power at 80°F (300°K), shown in Fig. 33.[4] Therefore the incident radiation does not correspond to emission from a blackbody.

A surface is "gray" if the spectral emittance and absorptance are constant for all wavelengths.[4] The spectral absorptance in this case again is the spectral distribution of solar radiation shown in Fig. 32 and the emittance is that of a blackbody at 80°F (300°K) shown in Fig. 33. Since the absorptance is concentrated in the low wavelengths of 0.2 to 3 μm and the emittance is concentrated in the wavelengths of 4 μm and higher, most surfaces are not "gray" in their response to solar radiation.

It should be noted that emissivity and <u>thermal</u> absorptivity <u>are</u> equal because the incident <u>thermal</u> radiation includes the wavelengths of the emissive power of a blackbody. The references by Incropera and DeWitt[4] and Gubareff, Jansen and Torborg[41] should be consulted if a more thorough explanation is desired.

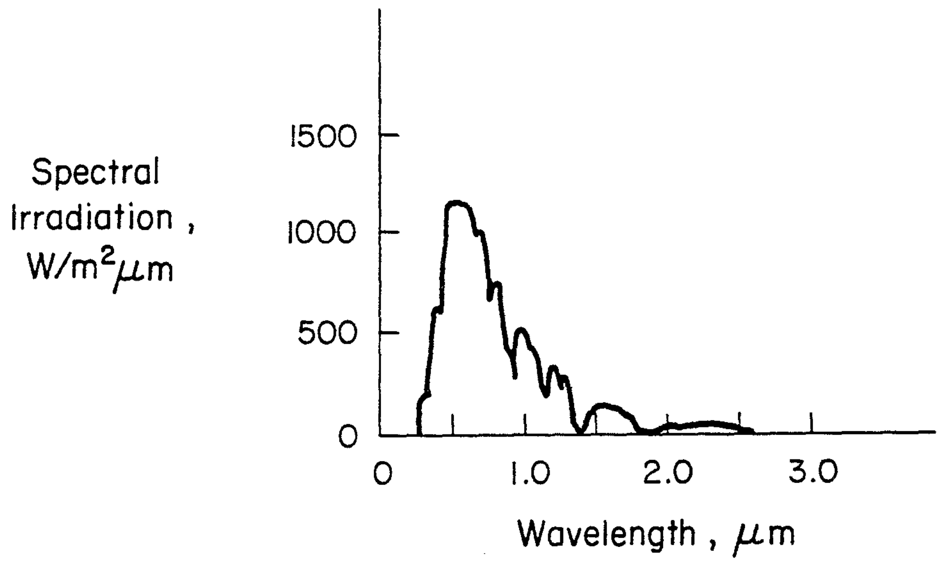


Fig. 32 Spectral Distribution of Solar Radiation at the Earth's Surface
adapted from Incropera and DeWitt(4)

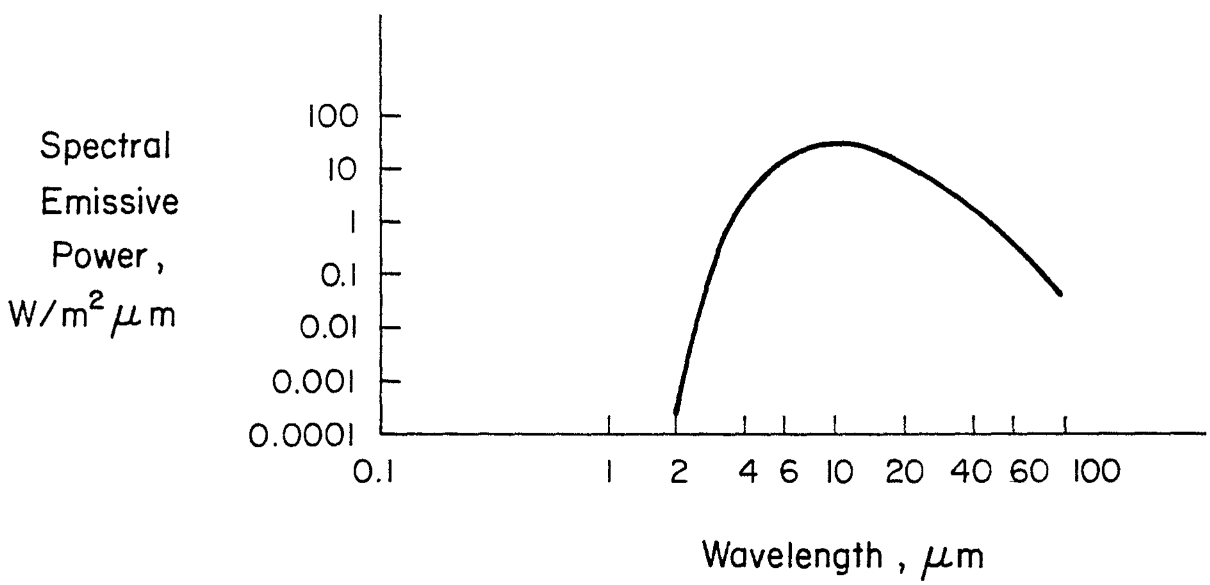


Fig. 33 Spectral Emissive Power of a Blackbody at 80°F (300^0K, 27^0C)
adapted from Incropera and DeWitt(4)

Test methods for determining solar absorptivity

ASTM Designation: E 434 "Calorimetric Determination of Hemispherical Emittance and the Ratio of Solar Absorptance to Hemispherical Emittance Using Solar Simulation"[44] describes a method for determining solar absorptivity. A specimen in a vacuum environment is subjected to simulated solar radiation. The radiant energy absorbed by the specimen and emitted to the surroundings causes the specimen to reach an equilibrium temperature that is dependent on the ratio of absorptivity to emissivity of its surface. Once this ratio is determined, solar absorptivity can be determined if emissivity of the specimen is known.

Values of Solar Absorptivity for Masonry

The surface color of masonry determines its absorptivity. Dark colors have higher values of absorptivity than light colors because light colors reflect solar radiation. The effect of color on absorptivity is demonstrated in Fig. 34. Spectral absorptivity and reflectivity for a range of wavelengths from 0.3 to 20 μm of white paint, black paint, and red brick are shown. In the range of solar radiation, wavelengths from 0.2 to 4 μm, white paint has relatively high reflectivity, black paint has high absorptivity, and red brick varies from high absorptivity to high reflectivity.

Using data from Fig. 34, values of solar absorptivity for white paint, black paint, and red brick are 0.21, 0.97, and 0.63 respectively.[4] These values are obtained by integrating the spectral absorptivity times the spectral irradiation of solar radiation over the range of wavelengths of solar radiation, and dividing by the total amount of solar radiation. Values of solar absorptivity for selected paints and masonry materials are shown in Table 6.

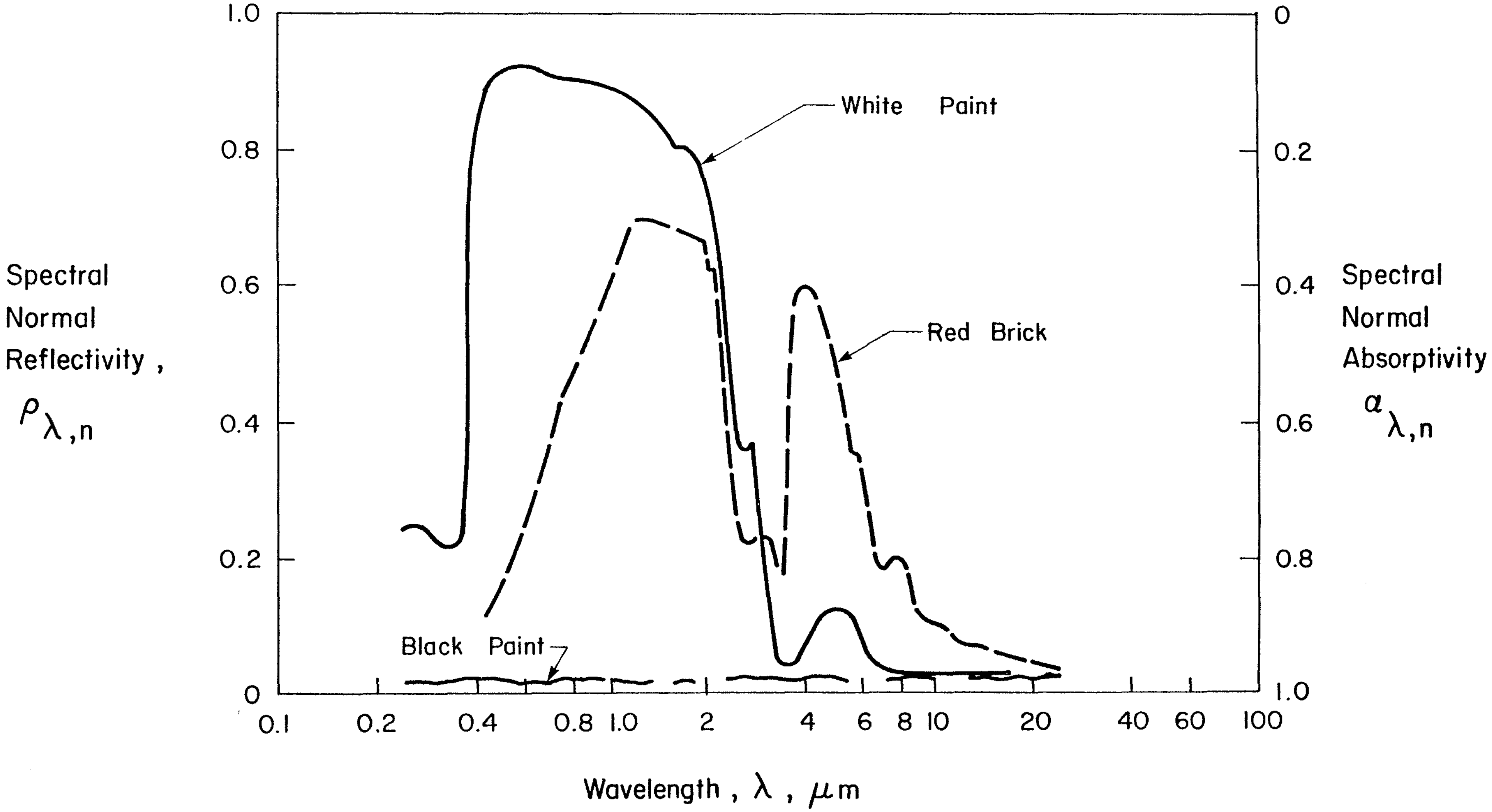


Fig. 34 Spectral Dependence of the Spectral, Normal Absorptivity and Reflectivity of White Paint, Black Paint, and Red Brick adapted from Incropera and DeWitt(4)

TABLE 6. SOLAR ABSORPTIVITY OF CONCRETE, CLAY BRICK, AND PAINT

Concrete		Paints and Lacquers[2]	
Black concrete[2]	0.91	Optical flat black paint	0.98
Brown concrete[2]	0.85	Flat black paint	0.95
Natural concrete[2]	0.65	Black lacquer	0.92
		Dark gray paint	0.91
		Dark blue lacquer	0.91
		Black oil paint	0.90
		Dark olive drab paint	0.89
		Dark brown paint	0.88
		Dark blue-gray paint	0.88
		Azure blue or dark green lacquer	0.88
Brick		Medium brown paint	0.84
		Medium light brown paint	0.80
		Brown or green lacquer	0.79
Stafford blue[41]	0.89	Medium rust paint	0.78
Mottled purple[41]	0.77	Light gray oil paint	0.75
Red[12]	0.65-0.80	Red oil paint	0.74
Red[41]	0.52-0.77	Medium dull green paint	0.59
Yellow and buff[12]	0.50-0.70	Medium orange paint	0.58
Light buff[41]	0.52-0.60	Medium yellow paint	0.57
White or light cream[12]	0.30-0.50	Medium blue paint	0.51
Cream[41]	0.36	Medium kelly green paint	0.51
White glazed[41]	0.25-0.27	Light green paint	0.47
		White semi-gloss paint	0.30
		Bright aluminum paint; gilt or bronze paint	0.30-0.50
		White gloss paint	0.25
		Silver paint	0.25
		White painted surface	0.23-0.49
		White lacquer	0.21

Although high absorptivity of the thermal storage mass is desirable, black walls are often aesthetically objectionable.(2) Furthermore, it may be beneficial to use partially reflecting surfaces to distribute solar radiation more uniformly throughout the building.(2) Robinson concludes that reds and flashed colors (browns, blues, and blacks) will perform adequately for passive solar use, but that lighter colors should be avoided.(45)

A rough textured unit would provide more surface area for collection of solar energy than a smooth textured unit. Although it may seem logical that rough textured brick would absorb more radiant energy than smooth textured brick, no test data are available to support this. Solar absorptivity values are considered independent of texture.(1,45)

SUMMARY AND CONCLUSIONS

This report presents data from published literature on the thermal properties of concrete and clay masonry materials as they relate to passive solar design. Values for specific heat, conductivity, diffusivity, emissivity, and absorptivity are summarized, and test methods used to obtain the values are discussed.

The following conclusions are based on data summarized in this report.

1. Specific heat of clay brick, with a density of 120 to 145 pcf (1920 to 2320 kg/m^3) ranges from 0.19 to 0.24 Btu/lb·°F (795 to 1005 J/kg·°K).
2. Specific heat of normally dry concrete is approximately 0.19 Btu/lb·°F (795 J/kg·°K) for all densities.
3. Moisture content of the normally dry concrete or clay masonry is required when calculating specific heat of a normally dry

specimen. This moisture content should be reported with specific heat test results.

4. Specific heat of saturated surface dry concrete decreases as density increases.

5. Specific heat of concrete increases approximately 10% as temperature increases from 60 to 110°F (16 to 43°C).

6. Thermal conductivity of clay brick with a density of 120 to 130 pcf (1920 to 2080 kg/m^3) ranges from 5 to 10 Btu·in./hr·ft^2·°F (0.7 to 1.4 W/m·°K).

7. Thermal conductivity of concrete increases with density. As the ovendry or normally dry density increases from 20 to 150 pcf (320 to 2400 kg/m^3), thermal conductivity increases from 1.0 to approximately 15.0 Btu·in./hr·ft^2·°F (0.1 to 2.2 W/m·°K).

8. Moisture in clay brick and concrete significantly affects thermal conductivity.

9. A 5% increase in moisture content of concrete results in an increase in thermal conductivity of 20% over the ovendry value.

10. Different test methods give significantly different values of thermal conductivity for nominally identical masonry materials.

11. Changes in concrete mix proportions, for a given density of concrete, will have a small effect on thermal conductivity.

12. For the temperature range relevant to passive solar applications, mean temperature has a small effect on thermal conductivity of concrete.

13. Diffusivity of clay brick ranges from 0.016 to 0.030 ft^2/hr (0.413 to 0.774 mm^2/s) for densities of 120 to 135 pcf (1920 to 2160 kg/m^3).

14. Diffusivity of concrete ranges from 0.0085 ft^2/hr (0.22 mm^2/s) for a density of 47 pcf (750 kg/m^3) to 0.062 ft^2/hr (1.60 mm^2/s) for a density of 152 pcf (2440 kg/m^3).

15. Diffusivity of saturated concrete is not equal to the diffusivity of dry concrete.

16. Diffusivity determined from available test methods of saturated normal-weight concrete cannot be accurately predicted on the basis of density.

17. Concrete and clay brick masonry units have emissivity values between 0.90 and 0.95.

18. Solar absorptivity of concrete and clay brick masonry units depends upon the color of the surface of the material. Recommended values are listed in Table 6.

RECOMMENDATIONS FOR FUTURE RESEARCH

This survey of published literature indicates that only limited experimental data are available, particularly for clay brick materials. In many instances too few data were found to substantiate conclusions. Additional test data are essential for reliable determination of values of thermal properties for masonry. Further research is recommended to determine:

1. Effects of metallic oxides on the specific heat of clay brick
2. The relationship between specific heat and density of clay brick at normal temperatures
3. The effect of moisture content on the specific heat of clay brick
4. Moisture content of normally dry clay brick and normally dry concrete

5. The relationship between specific heat and density of ovendry and normally dry concrete
6. The effect of temperature on the specific heat of ovendry and normally dry concrete
7. Conductivity of clay brick with a density of 120 to 130 pcf
8. The effects of moisture content on thermal conductivity of brick
9. The relationship between diffusivity and density of masonry materials
10. Appropriate test methods for determining values of specific heat, conductivity, diffusivity and other thermal properties relevant to passive solar design

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CONVERSION FACTORS

Density	1 pcf = 16.0 kg/m^3
Specific Heat	1 Btu/lb·°F = 4187 J/kg·°K
	1 Btu/lb·°F = 1 kcal/kg·°C
Conductivity	1 Btu·in./hr·ft^2·°F = 0.144 W/m·°K
	1 Btu·in./hr·ft^2·°F = 0.124 kcal/hr·m·°C
Diffusivity	1 ft^2/hr = 25.8 mm^2/s
	1 ft^2/hr = 0.0929 m^2/hr