

Guide to Thermal Properties of Concrete and Masonry Systems

Reported by ACI/TMS Committee 122



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American Concrete Institute
38800 Country Club Drive
Farmington Hills, MI 48331
Phone: +1.248.848.3700
Fax: +1.248.848.3701

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Guide to Thermal Properties of Concrete and Masonry Systems

Reported by ACI/TMS Committee 122

Stephen S. Szoke, Chair

Maribeth S. Bradfield
Theodore W. Bremner
Dennis W. Graber

Thomas A. Holm
John P. Ries
Jeffrey F. Speck

Martha G. VanGeem

Consulting Member
W. Calvin McCall

This guide reports data on the thermal properties of concrete and masonry constituents, masonry units, and systems of materials and products that form building components. This guide includes consideration of thermal inertia of concrete and masonry, passive solar design, and procedures to limit condensation within assemblages.

Keywords: aggregate; cement paste; concrete masonry unit; moisture; precast/prestressed concrete; specific heat; sustainability; thermal conductivity; thermal diffusivity; thermal resistance.

CONTENTS

CHAPTER 1—INTRODUCTION, p. 2

- 1.1—Introduction, p. 2
- 1.2—Energy conservation with concrete and masonry, p. 2
- 1.3—Building enclosure requirements, p. 2

CHAPTER 2—NOTATION AND DEFINITIONS, p. 2

- 2.1—Notation, p. 2
- 2.2—Definitions, p. 3

CHAPTER 3—THERMAL CONDUCTIVITY OF CONCRETE, AGGREGATE, AND CEMENT PASTE, p. 4

- 3.1—Introduction, p. 4
- 3.2—Thermal conductivity of concrete, p. 4
- 3.3—Influence of moisture, p. 4
- 3.4—Thermal conductivity of aggregates and cement paste, p. 5
- 3.5—Thermal conductivity of concrete used in concrete masonry units, p. 5
- 3.6—Thermal conductivity of two-phase systems, p. 7
- 3.7—Sample thermal conductivity calculations using cubic model, p. 7
- 3.8—Practical thermal conductivity, p. 8

CHAPTER 4—CALCULATION METHODS FOR STEADY-STATE THERMAL RESISTANCE OF WALL SYSTEMS, p. 9

- 4.1—Introduction, p. 9
- 4.2—Thermal resistance of concrete masonry walls, p. 10
- 4.3—Methods for calculating thermal resistance of concrete masonry units, p. 10
- 4.4—Thermal resistance of other concrete wall systems, p. 13

CHAPTER 5—THERMAL INERTIA, p. 16

- 5.1—Introduction, p. 16
- 5.2—Factors affecting thermal inertia effect, p. 16
- 5.3—Determining thermal inertia effects, p. 19
- 5.4—Equivalent R -values for concrete and masonry walls, p. 21

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5.5—Interior thermal inertia, p. 21

CHAPTER 6—THERMAL PROPERTIES FOR PASSIVE SOLAR DESIGN, p. 22

6.1—Introduction, p. 22

6.2—Thermal properties, p. 23

6.3—Incorporating mass into passive solar designs, p. 23

6.4—Summary, p. 24

CHAPTER 7—CONDENSATION CONTROL, p. 24

7.1—Introduction, p. 24

7.2—Prevention of condensation on wall surfaces under steady-state analysis, p. 25

7.3—Prevention of condensation within wall constructions, p. 25

CHAPTER 8—REFERENCES, p. 26

Authored documents, p. 27

APPENDIX A—TEST RESULTS AND CALCULATED THERMAL CONDUCTANCE OF OVEN-DRIED CONCRETE MASONRY, p. 29

CHAPTER 1—INTRODUCTION

1.1—Introduction

To reduce the use of nonrecoverable energy sources, authorities have adopted energy-conservation building codes and standards that apply to the design and construction of buildings. The design of energy-conserving buildings requires an expanded understanding of the thermal properties of the building envelope and the materials that comprise the envelope system.

This guide provides thermal-property data and design techniques that are useful in designing concrete and masonry building envelopes and determining energy code compliance. The guide is intended for use by owners, architects, engineers, building inspectors, code-enforcement officials, and all those interested in the energy-efficient design of buildings containing concrete or masonry components.

1.2—Energy conservation with concrete and masonry

Due to its inherent functionality and the availability of raw materials used in production, concrete and masonry are the world's most widely used building materials. Many civilizations have built structures with concrete and masonry walls that provide uniform and comfortable indoor temperatures despite all types of climatic conditions. Cathedrals composed of massive masonry walls produce an indoor climate with little temperature variation during the entire year despite the absence of a heating system. Even primitive housing in the desert areas of North America used thick masonry walls that resulted in acceptable interior temperatures despite high outside daytime temperatures.

Housing systems have been developed featuring efficient load-bearing concrete or masonry wall systems that provide resistance to weather, temperature changes, fire,

and noise. Many of these wall systems are made with light-weight concrete to enhance both static and dynamic thermal resistance.

Numerous organizations have studied and reported on the steady-state and dynamic energy-conserving contributions that concrete and concrete masonry walls can make to thermal efficiency in buildings (Peavy et al. 1973; Petersen and Barnett 1980; Petersen et al. 1981; U.S. Department of Energy 1989; ASHRAE 2009; ANSI/ASHRAE/IES 90.1; Childs et al. 1983; National Concrete Masonry Association 2010; Portland Cement Association 1981, 1982). This increased energy efficiency may permit reductions in the required size and operating costs of mechanical systems. This reduction in energy usage is not recognized by steady-state calculations (R -values and U -values). Improved calculation methods are required to account for the dynamic, real-world performance of concrete and concrete masonry building elements.

1.3—Building enclosure requirements

In addition to structural requirements, a building envelope should be designed to control the flow of air, heat, sunlight, radiant energy, liquid water, and water vapor. It should also provide the many other attributes generally associated with enclosure materials, including fire protection, noise control, impact damage resistance, durability, aesthetic quality, and economy. Analysis of building enclosure materials should extend beyond heat-flow analysis to also account for their multifunctional purposes. The non-heat-flow subjects are beyond the scope of this guide, but this exclusion should not be taken as an indication that they are not crucial to the total overall performance of a building enclosure.

CHAPTER 2—NOTATION AND DEFINITIONS

2.1—Notation

a	=	fractional area
a_{gr}	=	fractional grouted area of wall
a_i	=	fractional area of insulation
a_{np}	=	fractional area of heat flow path for path number p of thermal layer number n
a_s	=	fractional area of steel
a_{ungr}	=	fractional ungrouted area of wall
a_w	=	fractional area of web of masonry unit determined using the dimensions of web in the same planes as the height and length of the masonry unit
C	=	thermal conductance, Btu/(h·ft ² ·°F) (W/(m ² ·K))
c_p	=	specific heat, Btu/(lb·°F) (J/kg·K)
fs	=	face shell thickness of concrete masonry unit, in. (mm)
h_c	=	heat capacity, Btu(ft ³ ·°F) (J/(m ³ ·K))
I	=	thermal inertia, Btu/(h ^{1/2} ·ft ² ·°F) (J/(m ² ·K·s ^{1/2}))
k_c	=	thermal conductivity of concrete, Btu·in./(h·ft ² ·°F) (W/(m·K))
k_f	=	thermal conductivity of material placed in the cores of masonry units, Btu·in./(h·ft ² ·°F) (W/(m·K))
k_p	=	thermal conductivity of cement paste, Btu·in./(h·ft ² ·°F) (W/(m·K))

k	= thermal conductivity, Btu·in./(h·ft ² ·°F) (W/(m·K))
L	= linear dimension, in. or ft (mm or m)
L_a	= actual length, in. (mm)
L_b	= width of concrete masonry unit, in. (mm)
M	= water-vapor permeance, perm
q	= heat flow rate, Btu/h (W/K)
q_{ss}	= heat flow rate when steady-state conditions are achieved, Btu/h (W/K)
q_w	= heat flow rate for conditions other than steady-state, Btu/h (W/K)
R or R -value	= thermal resistance, (h·ft ² ·°F)/Btu ((m ² ·K)/W))
R_i	= thermal resistance of interior surface-air-film, equal to 0.68 (h·ft ² ·°F)/Btu (0.120 m ² ·K/W) for nonreflective, still air, vertical surfaces with horizontal heat flow
R_{in}	= thermal resistance of insulation, (h·ft ² ·°F)/Btu ((m ² ·K)/W)
R_{np}	= thermal resistance of heat flow path number p of thermal layer number n , (h·ft ² ·°F)/Btu ((m ² ·K)/W))
R_o	= thermal resistance of exterior surface-air-film, equal to 0.17 (h·ft ² ·°F)/Btu for 15 mph wind (0.030 m ² ·K/W for 6.7 m/s wind)
R_s	= thermal resistance of steel, (h·ft ² ·°F)/Btu ((m ² ·K)/W)
R_T	= total thermal resistance of a construction assembly including the thermal resistance of interior and exterior surface air-films, (h·ft ² ·°F)/Btu ((m ² ·K)/W))
R_t	= thermal resistance of the insulating layer, (h·ft ² ·°F)/Btu ((m ² ·K)/W)
t_i	= indoor air temperature, °F (°C)
t_o	= outdoor air temperature, °F (°C)
t_s	= saturation, or dew point temperature, °F (°C)
U or U -value	= overall coefficient of thermal transmittance, Btu/(h·ft ² ·°F) (W/(m ² ·K))
U_{gr}	= overall coefficient of thermal transmittance of fully grouted wall, Btu/(h·ft ² ·°F) (W/m ² ·K)
U_{ungr}	= overall coefficient of thermal transmittance of ungrouted wall, Btu/(h·ft ² ·°F) (W/m ² ·K)
V	= volume, ft ³ (m ³)
V_a	= volume of compacted aggregate, ft ³ (m ³)
V_c	= volume of cement paste, ft ³ (m ³)
w	= web thickness measured perpendicular to face of masonry unit, in (mm)
α	= thermal diffusivity, (in.·ft)/h (m ² /s)
μ	= water-vapor permeability, gr·in./(h·ft ² ·in.-Hg) (Hg/(s·m·Pa))
ρ	= density, lb/ft ³ (kg/m ³) – specific property of a gas, liquid, or solid is a measure of the mass per unit volume
ρ_m	= moist density, lb/ft ³ (kg/m ³) – density of a material where moisture is present
ρ_o	= oven-dry density, lb/ft ³ (kg/m ³)

2.2—Definitions

ACI provides a comprehensive list of definitions through an online resource, “ACI Concrete Terminology,” <http://www.concrete.org/Tools/ConcreteTerminology.aspx>. Definitions provided herein complement that resource.

heat capacity—measure of the amount of heat required to change by one degree a specified object.

moist density—density of a material where moisture is present.

overall coefficient of thermal transmittance, U —heat transfer of a construction assembly is determined by combining the thermal resistance of the interior and exterior surface-air-films with the combined thermal resistance of the total construction materials.

solar reflectance—surface property of a material determined as the ratio of the reflected solar radiation, or electromagnetic flux, to the incident solar radiation measured on a scale of 0.0 to 1.0: from not reflective at 0.0 to 100 percent reflective at 1.0.

solar reflectance index—calculated representation of a material’s surface solar reflectance and emittance using temperature rise to represent the ability of a surface to reflect solar heat.

specific heat—measure of the amount of heat required to change by one degree a specified unit of mass of a gas, liquid, or solid.

thermal conductance—of a gas, liquid, or solid is a measure of the rate at which heat (energy) passes perpendicularly through a unit area of material of specified thickness for a temperature difference of one degree.

thermal conductivity—measure of the rate at which heat (energy) passes perpendicularly through a unit area of thermally homogeneous gas, liquid, or solid of unit thickness for a temperature difference of one degree under steady-state conditions.

thermal diffusivity—measure of the time rate of change of temperature at any point within a gas, liquid, or solid; thermal diffusivity is thermal conductivity divided by the product of density and specific heat, $k/(\rho \times c_p)$.

thermal inertia—thermal inertia is a mathematical representation of the rate of temperature variation of gas, liquid, or solid subjected to heat (energy); thermal inertia is the square root of the product of thermal conductivity, density, and specific heat, $(k \times \rho \times c_p)^{0.5}$.

thermal resistance—the reciprocal of thermal conductance expressed by the symbol R .

water-vapor permeability—the rate of water-vapor transmission per unit area of a material induced by a unit pressure difference between two specified parallel surfaces under specified temperature and humidity conditions; permeability is a property of a material and is the arithmetic product of permeance and thickness.

water-vapor permeance M —the rate of water-vapor transmission per unit area of a material or construction induced by a unit vapor pressure difference between two specified parallel surfaces under specified temperature and humidity conditions, in units of perm.

Table 3.2a—Thermal conductivity of oven-dry lightweight concrete, mortar, and brick (in.-lb units)*

Material, type of aggregate in concrete or data source	Thermal conductivity k_c , Btu·in./[h·ft ² ·°F)															
	Oven-dry density, lb/ft ³															
	15	20	25	30	40	50	60	70	80	90	100	110	120	130	140	150
Equation (3.2) $k_c = 0.5e^{0.02p}$	0.67	0.75	0.82	0.91	1.11	1.36	1.66	2.03	2.48	3.02	3.69	4.51	5.51	6.75	8.22	10.04
Neat cement paste and foam concrete	0.54	0.64	0.75	0.87	1.11	1.39	1.69	2.03	2.41	2.82	3.29	3.80	4.36	—	—	—
Autoclaved aerated (cellular) concrete	0.47	0.57	0.67	0.79	1.05	1.34	1.68	2.06	—	—	—	—	—	—	—	—
Autoclaved microporous silica	0.41	0.51	0.61	0.72	0.96	1.25	1.58	1.95	2.38	—	—	—	—	—	—	—
Expanded polystyrene beads	0.50	0.62	0.74	0.88	1.18	1.53	1.94	—	—	—	—	—	—	—	—	—
Expanded perlite	0.46	0.57	0.69	0.83	1.13	1.48	1.90	—	—	—	—	—	—	—	—	—
Exfoliated vermiculite	0.53	0.63	0.74	0.86	1.10	1.38	1.69	—	—	—	—	—	—	—	—	—
Natural pumice	—	—	—	0.74	1.02	1.35	1.73	2.19	2.71	3.32	4.03	—	—	—	—	—
Sintered fly ash and coal cinders	—	—	—	—	—	—	1.17	2.11	2.56	3.06	3.64	4.28	—	—	—	—
Volcanic slag and scoria	—	—	—	—	—	—	1.67	2.06	2.50	2.99	3.56	—	—	—	—	—
Expanded slag	—	—	—	—	—	—	1.51	1.84	2.21	2.63	3.10	3.62	4.19	—	—	—
Expanded and sintered clay, shale, and slate	—	—	—	0.87	1.16	1.49	1.88	2.23	2.83	3.40	4.05	4.78	—	—	—	—
Sanded expanded clay, shale, and slate	—	—	—	—	—	1.70	2.21	2.81	3.51	4.32	5.26	6.35	7.60	—	—	—
No-fines pumice, and expanded and sintered clay, shale, and slate	—	—	—	0.97	1.27	1.60	1.98	2.40	2.88	3.41	—	—	—	—	—	—
Limestone	—	—	—	—	—	—	—	2.57	3.20	3.94	4.79	5.76	6.88	8.16	9.62	11.27
Cement-sand mortar and foam concrete	—	—	—	—	—	—	2.35	2.98	3.72	4.58	5.58	6.73	8.05	—	—	—
Fired clay bricks	—	—	—	—	—	—	—	2.19	2.62	3.09	3.63	4.22	4.87	5.58	6.39	7.26

*Obtained from density/thermal conductivity linear equations.

CHAPTER 3—THERMAL CONDUCTIVITY OF CONCRETE, AGGREGATE, AND CEMENT PASTE

3.1—Introduction

Many factors influence the thermal conductivity of concrete and concrete products. The thermal properties of concrete are influenced by the thermal properties and amounts of cement paste and aggregates, and the presence of moisture. Further, the overall thermal conductance of nonmonolithic concrete elements is influenced by the product configuration.

3.2—Thermal conductivity of concrete

The measured thermal conductivity of a material, such as concrete or insulation, is usually determined in accordance with **ASTM C177** or **C1363**. Results of many such measurements have been tabulated by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (**ASHRAE 2009**). Several methods for calculating concrete thermal conductivity have been developed. These calculated estimates are useful because the nearly infinite combinations of ingredients in concrete make it nearly impossible to generate test data for all concrete and concrete products.

Basic testing programs demonstrate that, in general, the coefficient of thermal conductivity for concrete, k_c , is dependent on the aggregate types used in the concrete mixture. For simplicity, these data are often correlated to concrete density ρ (**Kluge et al. 1949**; **Price and Cordon 1949**; **Rowley and Algren 1937**). **Valore (1980)** plotted oven-dry density of concrete as a function of the logarithm of k_c , developing a straight line that can be expressed by the equation

$$k_c = 0.5e^{0.02p} \quad (\text{in.-lb units}) \quad (3.2)$$

$$k_c = 0.072e^{0.00125p} \quad (\text{SI units})$$

Thermal conductivity values for concretes with the same density made with different aggregates can differ from the relationship expressed by Eq. (3.2) and may significantly underestimate k_c for some normalweight concretes and for some lightweight concretes containing normalweight supplemental aggregates (**Valore 1980, 1988**). This is due to differences in the thermal properties of specific mineral types in the aggregates. Thermal conductivity values obtained using Eq. (3.2) for concretes with densities from 20 to 100 lb/ft³ (320 to 1600 kg/m³) correlate better to test data than for concretes outside this density range (**Valore 1980**). Oven-dry thermal conductivity values for several concretes made with various aggregates, as well as mortar and brick, are shown in Tables 3.2a and 3.2b. These values are based on linear regression equations developed from test data (**Arnold 1969**; **Granholm 1961**; **Campbell-Allen and Thorn 1963**; **Institution of Heating and Ventilating Engineers 1975**; **Lentz and Monfore 1965a**; **Lewicki 1967**; **Petersen 1949**; **Valore 1958, 1988**; **Valore and Green 1951**; **Zoldners 1971**).

3.3—Influence of moisture

In normal use, concrete is not in moisture-free or oven-dry conditions; thus, concrete conductivity should be corrected for moisture effects (**Valore 1958**; **Plonski 1973a,b**; **Tye and Spinney 1976**). Table 3.3 lists correction factors to adjust oven-dry-concrete thermal conductivities to practical design

Table 3.2b—Thermal conductivity of oven-dry lightweight concrete, mortar, and brick (SI units)*

Material, type of aggregate in concrete or data source	Thermal conductivity k_c , W/(m·K)															
	Oven-dry density, kg/m ³															
	240	320	400	480	640	800	960	1120	1280	1440	1600	1760	1920	2080	2240	2400
Equation (3.2) $k_c = 0.072e^{0.00125p}$	0.097	0.108	0.118	0.131	0.160	0.196	0.239	0.293	0.358	0.435	0.532	0.650	0.795	0.973	1.18	1.45
Neat cement paste and foam concrete	0.078	0.092	0.108	0.125	0.160	0.200	0.243	0.293	0.348	0.407	0.474	0.548	0.629	—	—	—
Autoclaved aerated (cellular) concrete	0.068	0.082	0.097	0.114	0.151	0.193	0.242	0.297	—	—	—	—	—	—	—	—
Autoclaved microporous silica	0.059	0.073	0.088	0.104	0.138	0.180	0.228	0.281	0.343	—	—	—	—	—	—	—
Expanded polystyrene beads	0.072	0.089	0.107	0.127	0.170	0.220	0.280	—	—	—	—	—	—	—	—	—
Expanded perlite	0.066	0.082	0.099	0.119	0.163	0.213	0.274	—	—	—	—	—	—	—	—	—
Exfoliated vermiculite	0.076	0.091	0.107	0.124	0.159	0.199	0.243	—	—	—	—	—	—	—	—	—
Natural pumice	—	—	—	0.107	0.147	0.195	0.249	0.316	0.391	0.479	0.581	—	—	—	—	—
Sintered fly ash and coal cinders	—	—	—	—	—	—	0.169	0.304	0.369	0.441	0.524	0.617	—	—	—	—
Volcanic slag and scoria	—	—	—	—	—	—	0.241	0.297	0.361	0.431	0.513	—	—	—	—	—
Expanded slag	—	—	—	—	—	—	0.218	0.265	0.319	0.379	0.447	0.522	0.604	—	—	—
Expanded and sintered clay, shale, and slate	—	—	—	0.125	0.167	0.214	0.271	0.321	0.408	0.490	0.584	0.689	—	—	—	—
Sanded expanded clay, shale, and slate	—	—	—	—	—	0.245	0.319	0.405	0.506	0.623	0.758	0.915	1.10	—	—	—
No-fines pumice, and expanded and sintered clay, shale, and slate	—	—	—	0.140	0.183	0.231	0.286	0.346	0.415	0.448	—	—	—	—	—	—
Limestone	—	—	—	—	—	—	—	0.371	0.461	0.568	0.691	0.831	0.992	1.18	1.39	1.63
Cement-sand mortar and foam concrete	—	—	—	—	—	—	0.339	0.429	0.536	0.660	0.804	0.970	1.16	—	—	—
Fired clay bricks	—	—	—	—	—	—	—	0.316	0.378	0.446	0.523	0.609	0.702	0.804	0.921	1.05

*Obtained from density/thermal conductivity linear equations.

values. Data in Table 3.3 may be used to estimate k_c values for in-service concrete and concrete masonry elements.

A more accurate value to determine moisture effects may be estimated by increasing the value of k_c by 6 percent for each 1 percent of moisture content by mass (Valore 1980, 1988).

$$k_c (\text{corrected}) = k_c \times [1 + 6(\rho_m - \rho_o)/\rho_o] \quad (3.3a)$$

For most concrete walls, a single factor of 1.2 can be applied to oven-dry k_c values (Valore 1980). Therefore, the constant in Eq. (3.2) is changed from 0.500 (0.072) to 0.600 (0.087) to provide for a 20 percent increase in k_c for air-dry, in-service, concrete or concrete masonry.

$$k_c = 0.600e^{0.02p} \quad (\text{in.-lb units})$$

$$k_c = 0.087e^{0.00125p} \quad (\text{SI units}) \quad (3.3b)$$

3.4—Thermal conductivity of aggregates and cement paste

Tables 3.4a and 3.4b list conductivity values for some natural minerals used as concrete aggregates. Figure 3.4 shows calculated thermal conductivity values for air-dry hardened cement pastes, k_p (Valore 1980). These values are in good agreement with experimental values (Tyner 1946; Spooner 1977) for pastes with five water-cementitious mate-

rial ratios (w/cm) ranging from 0.47 to 0.95. Experimental values averaged approximately 5 percent lower than calculated values for pastes with w/cm in the range of 0.47 to 0.95, and 16 percent lower for paste with 0.35 w/cm . Lentz and Monfore (1965b) showed that conductivity k_p for mature pastes in a moist-cured condition with w/cm of 0.4, 0.5, and 0.6 agreed within 2 percent of those calculated by Eq. (3.2) when corrected to an oven-dry condition. The value for a 0.32 w/cm paste, however, differed from the Eq. (3.2) value by approximately 20 percent.

3.5—Thermal conductivity of concrete used in concrete masonry units

Concrete masonry units (CMU) usually consist of approximately 65 to 70 percent aggregate by volume. The remaining volume consists of voids between aggregate particles, entrapped air, and cement paste. The typical air-void content of concrete used to make lightweight CMU, for example, has been found to be 8 to 12 percent by volume. Expressed as a percentage of the cement paste, void volumes are approximately 25 to 40 percent. For a typical lightweight CMU having a net w/cm of 0.6 and an average cement-paste air-void content of 40 percent, the thermal conductivity is in the range of 1.5 to 1.8 Btu·in./h·ft²·°F (0.22 to 0.26 W/(m·K)). Such values are considerably lower than those in Eq. (3.3a) or Eq. (3.3b) for typical lightweight aggregate concrete (void-free) (Valore 1980) because the air spaces found in the

Table 3.3—Thermal conductivity moisture correction factors*

Material or type of aggregate in concrete	Type of exposure	Relative humidity mean, %	Moisture content, percent by weight	Thermal conductivity moisture correction factor, percent increase in thermal conductivity per 1 percent moisture content	Practical thermal conductivity multiplier
Neat cement paste and foam concrete; expanded polystyrene bead concrete	Pr [†]	80	8.0	3.0	1.25
Autoclaved aerated (cellular) concrete	Pr	80	4.5	4.5	1.20
Expanded perlite and exfoliated vermiculite	Pr	80	6.5	4.5	1.30
Natural pumice	Pr	80	5.5	4.25	1.22
	Uh [‡]	80	7.0	4.25	1.30
Sintered fly ash, scoria, and coal cinders	Pr	60	3.75	6.0	1.22
	Uh	80	5.0	6.0	1.30
Expanded slag	Pr	80	3.5	5.5	1.20
	Uh	80	5.5	5.5	1.30
Expanded and sintered clay, shale, slate (no natural sand); sanded expanded slag	Pr	80	3.5	4.0	1.14
	Uh	80	5.5	4.0	1.22
Sanded expanded and sintered clay, shale, and slate	Pr	60	3.0	5.0	1.15
	Uh	80	5.0	5.0	1.25
Limestone	Pr	60	2.0	7.0	1.15
	Uh	80	3.0	7.0	1.22
Sand gravel, < 50 percent quartz or quartzite	Pr	60	2.0	7.0	1.15
	Uh	80	3.0	7.0	1.22
Sand gravel, > 50 percent quartz or quartzite	Pr	60	2.0	9.0	1.18
	Uh	80	3.0	9.0	1.27
Cement mortar, sanded	Pr	60	2.0	9.0	1.20
Foam concrete	Uh	80	3.0	9.0	1.30
Clay bricks	Pr	60	0.5	30.0	1.15
	Uh	80	2.0	20.0	1.40

*For converting thermal conductivity of oven-dry concretes and clay bricks to practical design values.

[†]Pr = protected exposure: exterior wall stuccoed or coated with cement base, texture, or latex paint; interior wythe or cavity wall or of composite wall with full collar joint.

[‡]Uh = unprotected: exterior wall surface uncoated, or treated with water repellent or thin, clear polymeric sealer only.

Note: Reproduced by permission from Valore (1988).

Table 3.4a—Thermal conductivity of some natural minerals (in.-lb units)

Mineral	Thermal conductivity k_c , Btu· in./ (h·ft ² ·°F)
Quartz (single crystal)*	87, 47
Quartz	40
Quartzite	22 to 37
Hornblende-quartz-gneiss	20
Quartz-monzonite	18
Sandstone	9 to 16
Granite	13 to 28
Marble	14 to 21
Limestone	6 to 22
Chalk	6
Diorite (dolerite)	15.6
Basalt (trap rock)	9.6 to 15
Slate	13.6

*Thermal conductivity of single crystal quartz depends on the axis on which it is measured.

Table 3.4b—Thermal conductivity of some natural minerals (SI units)

Mineral	Thermal conductivity k_c , W/ (m·K)
Quartz (single crystal)*	12.5, 6.8
Quartz	5.8
Quartzite	3.2 to 5.3
Hornblende-quartz-gneiss	2.9
Quartz-monzonite	2.6
Sandstone	1.3 to 2.3
Granite	1.9 to 4.0
Marble	2.0 to 3.0
Limestone	0.8 to 3.2
Chalk	0.8
Diorite (dolerite)	2.2
Basalt (trap rock)	1.4 to 2.2
Slate	2.0

*Thermal conductivity of single crystal quartz depends on the axis on which it is measured.

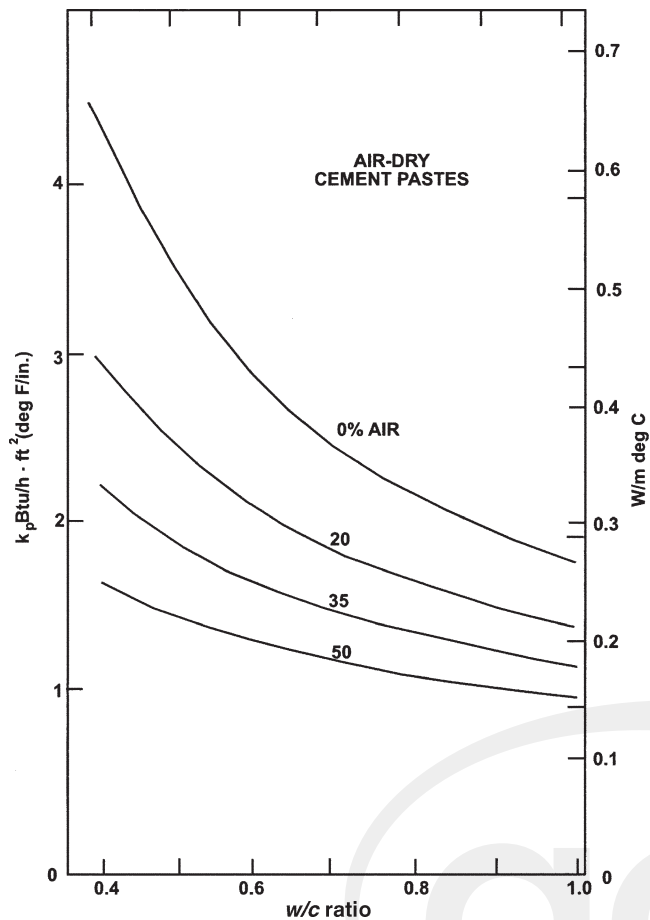


Fig. 3.4—Thermal conductivity k_p for air-dry-hardened portland cement pastes.

zero-slump CMU lightweight concrete provide additional heat flow resistance, thus lowering the conductivity.

3.6—Thermal conductivity of two-phase systems

The cubic model (Valore 1980) described in 3.7 shows that the thermal conductivity of a discrete two-phase system, such as concrete, can also be calculated by knowing the volume fractions and the thermal conductivity values of the cement pastes and aggregates (Fig. 3.6). For lightweight-aggregate concretes, Eq. (3.2) yields k_c values similar to those calculated by using the cubic-model equation (Eq. (3.7)). Equation (3.2) is not always accurate over a wide range of concrete densities (Valore 1980), particularly above 100 lb/ft³ (1600 kg/m³), because aggregate mineralogical characteristics cause a wide range of aggregate thermal conductivities. The cubic-model equation is appropriate for calculating thermal conductivities of concretes having densities above 100 lb/ft³ (1600 kg/m³). The cubic-model equation demonstrates how the factors that influence concrete thermal conductivity k_c impose a ceiling limit on k_c , even for concretes containing hypothetical aggregates with infinitely high thermal conductivities. The insulating effect of the cement paste matrix on k_c is determined by the quantity

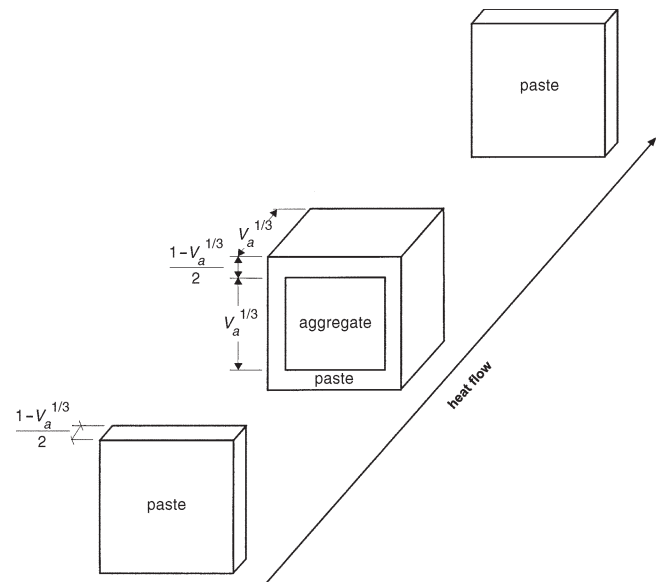


Fig. 3.6—Cubic model for calculating thermal conductivity k_c of concrete as a function of conductivity k_p and k_a of cement paste and aggregate, and volume fraction V_a of aggregate.

and quality of the paste volume fraction and its density. The cubic model also explains how normalweight aggregates produce disproportionately high conductivity values when added to lightweight-aggregate concrete.

At the same concrete density, a coarse-lightweight-aggregate grading provides concrete with a higher thermal-conductivity value than a fine-lightweight-aggregate-grading concrete due to the differences in aggregate (coarse fraction) and paste (fine grading) volume fractions.

3.7—Sample thermal conductivity calculations using cubic model

The cubic model (Valore and Green 1951; Valore 1958) can be used to calculate k_c as a function of cement paste conductivity, aggregate conductivity, and aggregate volume. The cubic model (Fig. 3.6) is a unit volume cube of concrete consisting of a cube of aggregate of volume V_a encased on all sides by a layer of cement paste of unit thickness $(1 - V_a)^{1/3}/2$. The cubic model also accounts for the fact that concrete is a thermally and physically heterogeneous material and may contain highly conductive aggregates that serve as thermal bridges or shunts. Thermal bridges are highly conductive materials, surrounded by materials with relatively low conductivity, that greatly increase the composite system's conductivity. In the case of concrete, highly conductive aggregates are the thermal bridges surrounded by the lower conductive cement paste, fine aggregate matrix, or both. To use the cubic model (Eq. (3.7)), thermal conductivity values for cement paste k_p , aggregate k_a , and aggregate volume V_a are required for estimating the thermal conductivity of concrete. Aggregate volume is obtained from measurements made for compacted aggregate using ASTM C29/C29M.

Table 3.8a—Compiled historical thermal conductivity design values (in.-lb units)*

Practical thermal conductivity, Btu·in./(h·ft ² ·°F)																		
Group	Material or type of aggregate of concrete	Exposure type [†]	Oven-dry density, lb/ft ³															
			15	20	25	30	40	50	60	70	80	90	100	110	120	130	140	150
Matrix insulated	Neat cement paste and foam concrete	Pr	0.7	0.8	0.9	1.1	1.4	0.7	2.1	2.5	3.0	3.5	4.1	4.7	5.4	—	—	—
Insulated structural	Autoclaved aerated (cellular)	Pr	0.6	0.7	0.8	1.0	1.3	1.6	2.0	2.5	—	—	—	—	—	—	—	—
Insulated	Expanded polystyrene beads, perlite, vermiculite, expand, glass	Pr	0.65	0.8	0.95	1.1	1.5	1.9	2.4	—	—	—	—	—	—	—	—	—
Concrete masonry structural	Unsanded, expanded, and sintered clay, shale, slate, fly ash; cinders, scoria, pumice, sanded-expanded slag	Pr	—	—	—	—	1.3	1.7	2.1	2.6	3.25	4.0	4.65	5.5	6.4	—	—	—
		Un	—	—	—	—	1.4	1.8	2.3	2.8	3.5	4.25	5.0	5.9	6.8	—	—	—
Concrete masonry, structural	Unsanded expanded slag	Pr	—	—	—	—	—	—	1.8	2.2	2.7	3.2	3.7	4.3	—	—	—	—
		Un	—	—	—	—	—	—	2.0	2.4	2.9	3.4	4.0	4.7	—	—	—	—
Concrete masonry, structural	Sanded expanded and sintered clay, shale, slate, fly ash; sanded pumice, scoria, cinders	Pr	—	—	—	—	—	1.9	2.5	3.2	4.1	5.1	6.2	7.6	9.1	—	—	—
		Un	—	—	—	—	—	2.1	2.7	3.5	4.4	5.5	6.8	8.2	9.9	—	—	—
Concrete masonry, structural	Limestone	Pr	—	—	—	—	—	—	—	—	—	—	5.5	6.6	7.9	9.4	11.15	13.8
		Un	—	—	—	—	—	—	—	—	—	—	5.85	7.0	8.3	10.0	11.7	13.75
Concrete masonry, structural	Sand gravel, <50 percent quartz or quartzite	Pr	—	—	—	—	—	—	—	—	—	—	—	—	—	10.0	138	18.5
		Un	—	—	—	—	—	—	—	—	—	—	—	—	—	10.7	14.6	19.6
Concrete masonry, structural	Sand gravel, >50 percent quartz or quartzite	Pr	—	—	—	—	—	—	—	—	—	—	—	—	—	11.0	15.3	20.5
		Un	—	—	—	—	—	—	—	—	—	—	—	—	—	11.8	16.5	22.0
Concrete masonry, insulated structural	Cement-sand mortar; sanded foam concrete solid clay bricks	Pr	—	—	—	—	—	—	2.8	3.6	4.5	5.5	6.7	8.1	9.7	11.5	13.5	—
		Un	—	—	—	—	—	—	3.1	3.9	4.8	6.0	7.3	8.7	10.5	12.4	14.7	—
		Pr	—	—	—	—	—	—	—	2.5	3.0	3.6	4.2	4.9	5.6	6.4	7.4	8.4
		Un	—	—	—	—	—	—	—	3.1	3.7	4.3	5.1	5.9	6.8	7.8	9.0	10.2

*For normalweight and lightweight concretes, solid clay bricks, and cement mortars.

[†]Pr = protected exposure; mean relative humidity in wall up to 60 percent. Exterior wall surface coated with stucco, cement-based paint, or continuous coating of latex paint; or inner wythe of composite wall with a full collar joint, or inner wythe of cavity wall. Un = unprotected exposure; mean relative humidity in wall up to 80 percent. Exterior wall surface uncoated or treated with a water repellent or clear sealer only. Pr Un = densities above 100 lb/ft³ do not apply to pumice or expanded clay or shale concretes.

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$$k_c = k_p \left[\frac{V_a^{2/3}}{V_a^{2/3} - V_a + \left(\frac{V_a}{\left(\frac{k_a V_a^{2/3}}{k_p} \right) + 1 - V_a^{2/3}} \right)} \right] \quad (3.7)$$

When fine and coarse aggregate k_a values differ, k_c is calculated for the paste/fine aggregate mortar first and the

calculation is then repeated for the paste/coarse aggregate combination using the appropriate V_a value in each step. For concretes weighing 120 lb/ft³ (1920 kg/m³) or less, thermal conductivities determined using Eq. (3.7) show good agreement with the thermal conductivity determined using the simpler conductivity/density relationship of Eq. (3.2). For normalweight concretes with densities greater than 120 lb/ft³ (1920 kg/m³), results obtained using Eq. (3.7) yield more accurate k_c values than Eq. (3.2) when compared to test data shown in Tables 3.2a and 3.2b.

3.8—Practical thermal conductivity

Practical thermal conductivity design values for normalweight and lightweight concrete, solid clay brick, cement mortar, and gypsum materials are suggested in Tables 3.8a and 3.8b (Valore 1988).

Table 3.8b—Compiled historical thermal conductivity design values (SI units)*

Group	Material or type of aggregate of concrete	Exposure type†	Practical thermal conductivity, W/(m·K)															
			Oven-dry density, kg/m³															
			240	320	400	480	640	800	960	1120	1280	1440	1600	1760	1920	2080	2240	2400
Matrix insulated	Neat cement paste and foam concrete	Pr	0.101	0.115	0.130	0.159	0.202	0.101	0.303	0.361	0.433	0.505	0.591	0.678	0.779	—	—	—
Insulated structural	Autoclaved aerated (cellular)	Pr	0.087	0.101	0.115	0.144	0.187	0.231	0.288	0.361	—	—	—	—	—	—	—	—
Insulated	Expanded polystyrene beads, perlite, vermiculite, expand, glass	Pr	0.094	0.115	0.137	0.159	0.216	0.274	0.346	—	—	—	—	—	—	—	—	—
Concrete masonry structural	Unsanded, expanded, and sintered clay, shale, slate, fly ash; cinders, scoria, pumice, sanded-expanded slag	Pr	—	—	—	—	0.187	0.245	0.303	0.375	0.469	0.577	0.671	0.793	0.923	—	—	—
		Un	—	—	—	—	0.202	0.260	0.332	0.404	0.505	0.613	0.721	0.851	0.981	—	—	—
Concrete masonry, structural	Unsanded expanded slag	Pr	—	—	—	—	—	—	0.260	0.317	0.389	0.461	0.534	0.620	—	—	—	—
		Un	—	—	—	—	—	—	0.288	0.346	0.418	0.490	0.577	0.678	—	—	—	—
Concrete masonry, structural	Sanded expanded and sintered clay, shale, slate, fly ash; sanded pumice, scoria, cinders	Pr	—	—	—	—	—	0.274	0.361	0.461	0.591	0.735	0.894	1.10	1.31	—	—	—
		Un	—	—	—	—	—	0.303	0.389	0.505	0.634	0.793	0.981	1.18	1.38	—	—	—
Concrete masonry, structural	Limestone	Pr	—	—	—	—	—	—	—	—	—	—	0.793	0.952	1.14	1.36	1.61	1.99
		Un	—	—	—	—	—	—	—	—	—	—	0.844	1.01	1.20	1.44	1.69	1.98
Concrete masonry, structural	Sand gravel, <50 percent quartz or quartzite	Pr	—	—	—	—	—	—	—	—	—	—	—	—	—	1.44	1.99	2.67
		Un	—	—	—	—	—	—	—	—	—	—	—	—	—	1.54	1.67	2.82
Concrete masonry, structural	Sand gravel, >50 percent quartz or quartzite	Pr	—	—	—	—	—	—	—	—	—	—	—	—	—	1.59	2.21	2.96
		Un	—	—	—	—	—	—	—	—	—	—	—	—	—	1.70	2.38	3.17
Concrete masonry, insulated	Cement-sand mortar; sanded foam concrete solid clay bricks	Pr	—	—	—	—	—	—	0.404	0.519	0.649	0.793	0.996	1.17	1.40	1.66	1.95	—
		Un	—	—	—	—	—	—	0.447	0.562	0.692	0.865	1.05	1.25	1.51	1.79	2.12	—
		Pr	—	—	—	—	—	—	—	0.361	0.433	0.519	0.605	0.706	0.706	0.923	1.07	—
		Un	—	—	—	—	—	—	—	0.447	0.534	0.620	0.735	0.851	0.851	1.12	1.30	—

*For normalweight and lightweight concretes, solid clay bricks, and cement mortars.

†Pr = protected exposure; mean relative humidity in wall up to 60 percent. Exterior wall surface coated with stucco, cement-based paint, or continuous coating of latex paint; or inner wythe of composite wall with a full collar joint, or inner wythe of cavity wall. Un = unprotected exposure; mean relative humidity in wall up to 80 percent. Exterior wall surface uncoated or treated with a water repellent or clear sealer only. Pr Un = densities above 100 lb/ft³ do not apply to pumice or expanded clay or shale concretes.

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CHAPTER 4—CALCULATION METHODS FOR STEADY-STATE THERMAL RESISTANCE OF WALL SYSTEMS

4.1—Introduction

Thermal resistance R is the most widely used and recognized thermal property. Building codes generally prescribe requirements for minimum R -values or maximum thermal transmittance, U -value, for elements of a building envelope. There are multiple methods for calculating the thermal

properties of building assemblies. The methods include the series method, parallel path method, isothermal planes method (also referred to as the series parallel method), and zone method. Each of these methods may be used to determine compliance with the building code for specific building assembly constructions. Actual test data or data determined using more sophisticated modeling techniques, such as two- or three-dimensional finite element or finite difference methods (which are not addressed in this guide), are generally accepted by the building code official.